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เจ้าของ	คณะศิลปศาสตร์และวิทยาศาสตร์ มหาวิทยาลัยราชภัฏศรีสะเกษ	
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 มหาวิทยาลัยเทคโนโลยีราชมงคล
 วิทยาเขตสกลนคร

วัตถุประสงค์

Journal of SciTech-ASEAN (JSTA) มีวัตถุประสงค์เพื่อเป็นพื้นที่ทางวิชาการสำหรับเผยแพร่บทความวิจัยและบทความวิชาการคุณภาพสูงด้านวิทยาศาสตร์ประยุกต์ เทคโนโลยี และนวัตกรรม ที่มีฐานคิดทางวิชาการชัดเจน มีความเข้มแข็งด้านระเบียบวิธีวิจัยหรือการวิเคราะห์เชิงวิชาการ มีความใหม่หรือคุณูปการต่อองค์ความรู้ และสามารถนำไปใช้ประโยชน์ในการแก้ปัญหาเชิงปฏิบัติหรือสนับสนุนการพัฒนาในบริบทของประเทศไทยและภูมิภาคอาเซียน โดยครอบคลุมประเด็นด้านสุขภาพ สุขภาวะ และสมรรถนะมนุษย์ เทคโนโลยีดิจิทัลและระบบอัจฉริยะ เกษตร อาหาร สิ่งแวดล้อม และทรัพยากรชีวภาพ อุตสาหกรรม โลจิสติกส์ และวิศวกรรมประยุกต์ ตลอดจนการบูรณาการวิทยาศาสตร์และเทคโนโลยีเพื่อการพัฒนาชุมชนท้องถิ่นอย่างยั่งยืน

ขอบเขตการรับบทความ

Journal of SciTech-ASEAN (JSTA) รับพิจารณาบทความวิจัยและบทความวิชาการด้านวิทยาศาสตร์ประยุกต์ เทคโนโลยี และนวัตกรรม โดยมีขอบเขตครอบคลุมประเด็นหลัก ดังนี้

- 1) **สุขภาพ สุขภาวะ และสมรรถนะมนุษย์** ครอบคลุมวิทยาศาสตร์สุขภาพ สาธารณสุข อาชีวอนามัยและความปลอดภัย วิทยาศาสตร์การกีฬา กิจกรรมทางกาย นันทนาการ สังคมสูงวัย สุขภาพชุมชน และคุณภาพชีวิต
- 2) **เทคโนโลยีดิจิทัลและระบบอัจฉริยะ** ครอบคลุมปัญญาประดิษฐ์ วิทยาการข้อมูล ระบบสารสนเทศ การพัฒนาซอฟต์แวร์ อินเทอร์เน็ตของสรรพสิ่ง บล็อกเชน แบบจำลองเชิงคำนวณ และระบบสนับสนุนการตัดสินใจ
- 3) **เกษตร อาหาร สิ่งแวดล้อม และทรัพยากรชีวภาพ** ครอบคลุมวิทยาศาสตร์และเทคโนโลยีการเกษตร วิทยาศาสตร์และเทคโนโลยีการอาหาร ทรัพยากรชีวภาพ สารออกฤทธิ์ทางชีวภาพ วิทยาศาสตร์สิ่งแวดล้อม การจัดการทรัพยากร การควบคุมมลพิษ และระบบการผลิตที่ยั่งยืน
- 4) **อุตสาหกรรม โลจิสติกส์ และวิศวกรรมประยุกต์** ครอบคลุมเทคโนโลยี อุตสาหกรรม วิศวกรรมประยุกต์ การออกแบบและพัฒนาผลิตภัณฑ์ การปรับปรุงกระบวนการ ระบบการผลิต ระบบคุณภาพ ความปลอดภัยในงานอุตสาหกรรม โลจิสติกส์ ห่วงโซ่อุปทาน การขนส่ง และการจัดการการดำเนินงาน
- 5) **การบูรณาการวิทยาศาสตร์และเทคโนโลยีเพื่อการพัฒนาชุมชนท้องถิ่น** ครอบคลุมงานวิจัยและบทความวิชาการที่ประยุกต์ใช้วิทยาศาสตร์ เทคโนโลยี หรือนวัตกรรมในการแก้ปัญหาเชิงพื้นที่ การยกระดับคุณภาพชีวิต การเพิ่มมูลค่าทรัพยากรท้องถิ่น การพัฒนาระบบบริการ หรือการส่งเสริมความยั่งยืนของชุมชน โดยต้องมีความคิด วิธีการศึกษา หรือหลักฐานเชิงวิชาการที่ชัดเจน

**นโยบายการใช้เทคโนโลยี
ปัญญาประดิษฐ์ (AI)**

Journal of SciTech-ASEAN (JSTA) อนุญาตให้ผู้เขียนใช้เครื่องมือปัญญาประดิษฐ์หรือเทคโนโลยีที่มีปัญญาประดิษฐ์ช่วยสนับสนุนในการเตรียมต้นฉบับได้อย่างเหมาะสม เช่น การตรวจสอบภาษา การปรับปรุงความชัดเจนของข้อความ การแปลเบื้องต้น การจัดโครงสร้างเนื้อหา หรือการสนับสนุนการวิเคราะห์ข้อมูล ทั้งนี้เครื่องมือปัญญาประดิษฐ์ไม่สามารถระบุเป็นผู้แต่งหรือผู้มีส่วนร่วมในบทความได้ และผู้เขียนต้องรับผิดชอบต่อความถูกต้อง ความน่าเชื่อถือ ความเป็นต้นฉบับ จริยธรรมการวิจัย และเนื้อหาทางวิชาการทั้งหมดของบทความ

ผู้เขียนที่ใช้เครื่องมือปัญญาประดิษฐ์ในการเตรียมต้นฉบับต้องเปิดเผยการใช้งานอย่างชัดเจน โดยระบุชื่อเครื่องมือ วัตถุประสงค์ และขอบเขตของการใช้ในต้นฉบับ วารสารไม่อนุญาตให้ใช้ปัญญาประดิษฐ์เพื่อสร้างข้อมูล ผลการวิจัย ภาพ ตาราง หรือเอกสารอ้างอิงที่ไม่มีอยู่จริง บิดเบือนข้อมูล คัดลอกผลงานผู้อื่น หรือแทนที่การวิเคราะห์และการตัดสินใจทางวิชาการของผู้เขียน หากพบการใช้ปัญญาประดิษฐ์โดยไม่เปิดเผยหรือใช้ในลักษณะที่กระทบต่อความถูกต้องและจริยธรรมการตีพิมพ์ วารสารอาจพิจารณาปฏิเสธบทความหรือดำเนินการตามหลักจริยธรรมการตีพิมพ์ทางวิชาการ

ลิขสิทธิ์

กองบรรณาธิการวารสาร จะไม่รับพิจารณาบทความที่เป็นการละเมิดลิขสิทธิ์ ในกรณีที่มีการละเมิดลิขสิทธิ์ขึ้น ทางผู้เขียนเป็นผู้รับผิดชอบแต่เพียงฝ่ายเดียว

หมายเหตุ

วารสารเผยแพร่ทุก 6 เดือน (ฉบับต้นปี มกราคม - มิถุนายน และฉบับปลายปี กรกฎาคม - ธันวาคม ของทุกปี) บทความที่ตีพิมพ์ในวารสารเป็นทัศนะ ลิขสิทธิ์ และความรับผิดชอบของผู้เขียนเจ้าของผลงาน

บทบรรณาธิการ

Journal of SciTech-ASEAN (JSTA) ปีที่ 6 ฉบับที่ 1 นี้ จัดทำขึ้นเพื่อเป็นพื้นที่ทางวิชาการในการเผยแพร่บทความวิจัยและบทความวิชาการด้านวิทยาศาสตร์ประยุกต์ เทคโนโลยี และนวัตกรรม ที่มีคุณภาพทางวิชาการ มีความน่าเชื่อถือ และสามารถนำไปใช้ประโยชน์ในการแก้ปัญหาเชิงปฏิบัติหรือสนับสนุนการพัฒนาในบริบทของประเทศไทยและภูมิภาคอาเซียน โดยบทความในฉบับนี้สะท้อนบทบาทของวารสารในการเป็นเวทีแลกเปลี่ยนองค์ความรู้ข้ามศาสตร์ ครอบคลุมประเด็นที่เกี่ยวข้องกับสุขภาพและคุณภาพชีวิต เทคโนโลยีดิจิทัล เกษตรและอาหาร สิ่งแวดล้อม อุตสาหกรรม โลจิสติกส์ และการบูรณาการวิทยาศาสตร์และเทคโนโลยีเพื่อการพัฒนาชุมชนท้องถิ่นอย่างยั่งยืน

ในช่วงเวลาที่ระบบการเผยแพร่ผลงานวิชาการให้ความสำคัญมากขึ้นกับคุณภาพ ความโปร่งใส ความถูกต้องของข้อมูล จริยธรรมการวิจัยและการตีพิมพ์ ตลอดจนการใช้เทคโนโลยีดิจิทัลและปัญญาประดิษฐ์อย่างรับผิดชอบ กองบรรณาธิการมุ่งดำเนินงานวารสารให้สอดคล้องกับมาตรฐานทางวิชาการ และรักษาคุณภาพของวารสารในฐานะวารสารที่ได้รับการรับรองในฐานะข้อมูล TCI กลุ่มที่ 1 บทความทุกเรื่องยังคงผ่านกระบวนการกลั่นกรองคุณภาพแบบผู้ประเมินและผู้พิมพ์ไม่ทราบชื่อกันและกัน (Double-blind peer review) โดยผู้ทรงคุณวุฒิจากหลากหลายสถาบัน จำนวน 3 ท่านต่อบทความ เพื่อให้การพิจารณาบทความเป็นไปอย่างรอบคอบ เป็นธรรม และยึดมั่นในหลักวิชาการ จริยธรรมการตีพิมพ์ และแนวปฏิบัติของวารสารอย่างเคร่งครัด

ในนามของกองบรรณาธิการ ขอขอบคุณผู้พิมพ์ทุกท่านที่ให้ความไว้วางใจส่งผลงานมายังวารสาร ขอขอบคุณผู้ทรงคุณวุฒิที่สละเวลาและความเชี่ยวชาญในการประเมินบทความอย่างรอบคอบ และขอขอบคุณกองบรรณาธิการ ตลอดจนผู้มีส่วนเกี่ยวข้องทุกฝ่ายที่ร่วมสนับสนุนการดำเนินงานของวารสารให้เป็นไปด้วยความเรียบร้อย กองบรรณาธิการหวังเป็นอย่างยิ่งว่า Journal of SciTech-ASEAN ฉบับนี้ จะเป็นประโยชน์ต่อคณาจารย์ นักวิจัย นักศึกษา และผู้สนใจทั่วไป อีกทั้งจะมีส่วนในการส่งเสริมการแลกเปลี่ยนองค์ความรู้ การพัฒนางานวิจัยที่มีคุณภาพ และการยกระดับวิทยาศาสตร์และเทคโนโลยีเพื่อการพัฒนาที่ยั่งยืน



(ผู้ช่วยศาสตราจารย์ ดร.เตชภณ ทองเต็ม)

บรรณาธิการวารสาร

สารบัญ

	หน้า
การพัฒนาแพลตฟอร์มดิจิทัลเพื่อส่งเสริมการเรียนรู้และการท่องเที่ยวเชิงวัฒนธรรมของพิพิธภัณฑ์ท้องถิ่นในกรุงเทพมหานคร อมฤตา ฤทธิภักดี	1-19
อิทธิพลของเทคนิคการอบแห้งที่แตกต่างกันต่อสารออกฤทธิ์ทางชีวภาพและฤทธิ์ต้านอนุมูลอิสระของใบกระต้อม (<i>Mitragyna speciosa</i> (Korth.) Havil): ปริมาณไมทราจีนในเทคนิคที่เหมาะสมที่ได้รับคัดเลือก จิระนันท์ วงศ์วัฏญู เกียรติพงษ์ เจริญจิตต์ และ อภิญญา ภูมิสายตอน	20-34
การพัฒนาโปรแกรมการฝึก เอส เอ คิว ร่วมกับโปรแกรมฝึกความอ่อนตัวที่มีต่อความเร็วและความคล่องแคล่วว่องไวของนักกีฬาฟุตบอล พงษ์เอก สุขใส	35-51
ผลของโพแทสเซียมเพอร์แมงกาเนตต่อตัวเร่งปฏิกิริยา CZA/13X สำหรับการสังเคราะห์แอลพีจีโดยตรง มนตรี ทองคำ ภิเชก รุ่งโรจน์ชัยพร สมสุข ไตรศุภกิตติ และ มาวิน ปูนอน	52-74
การบูรณาการ IOT บล็อกเชน และ AI เพื่อเพิ่มความสามารถในการตรวจสอบย้อนกลับและสมรรถนะการปฏิบัติการในห่วงโซ่อุปทานอาหาร: การทบทวนวรรณกรรมอย่างเป็นระบบและการวิเคราะห์ตามกรอบ TOE ในประเทศไทย ชนิกานต์ กมลสุข และ วัชรพล สุขโหด	75-91
ปัจจัยที่มีผลต่อการพัฒนาสมรรถภาพทางกายของนักศึกษาในมหาวิทยาลัยมณฑลชานซี โจว ชุนเหมย และ พรชัย นุ่แก้ว	92-103
การเพิ่มประสิทธิภาพการเผาไหม้ด้วยชุดอุปกรณ์เผาไหม้ อำนาจ คำบุญ วรพจน์ ศิริรักษ์ พีรวัตร ลือสีก อมรรัตน์ ปิ่นชัยมูล และ ศุภศานต์ รักสกุล	104-122
การพัฒนากรอบการพยากรณ์ด้วย LSTM สำหรับการทำนายทิศทางราคารายวันของ EUR/USD ในตลาดแลกเปลี่ยนเงินตราต่างประเทศ วรรณะ พงษ์เสนา	123-143
ผลการฝึกแบบผสมผสานที่มีต่อสมรรถภาพทางกายในนักกีฬาฟุตบอลชายมหาวิทยาลัยราชภัฏสุรินทร์ ภัทรพล ทองน้ำ	144-155
ปัจจัยที่มีผลต่อภาวะการมีงานทำของกลุ่มอาชีพส่งเสริมสุขภาพของประเทศไทย จำแนกตามเพศ รัชต์ ตะนาวศรี	156-173

สารบัญ

	หน้า
การศึกษาเปรียบเทียบฤทธิ์ด้านการอักเสบและฤทธิ์ต้านอนุมูลอิสระของสารสกัดจากกระท่อมสายพันธุ์ก้านแดงและก้านขาว	174-186
ณิชนน มุขสมบัติ กันตา ปราณวีระไพบุลย์ ภูริทัต กนกกั้งสตาล มหัทธน พูลเกษร ศุณิศา มากชูชิต สหภูมิ คูประชามิตร กิริติยา แผ่นคำ นริศา คำสิงห์ และ อรุณพร อิฐรัตน์	
การพัฒนาผลิตภัณฑ์วาล์วเฟิลกรอบผสมปุทะเล	187-195
สรรเพชญ บรรลือวงศ์ กฤษณะ ช่องศรี และ วียารัตน์ ภูมิทนาถ	
การรับสัมผัสองค์ประกอบธาตุฟลูออไรด์จากการเชื่อมอาร์กโลหะฐานเหล็กกล้าคาร์บอนต่ำและเหล็กเคลือบสังกะสีด้วยกระบวนการเชื่อมอาร์กด้วยลวดหุ้มฟลักซ์และโลหะแก๊สคลุม	196-208
กัญญารัตน์ เทียมแก้ว อัญมณี สร้างบุญ รศิกายุจน์ อินธนู อภิญา มณีรัตน์ ปิยฉัตร กลิ่นมาก มณฑาทิพย์ ธนาวิชิตฤกษ์ และ กฤษดา เพ็งอารีย์	
การพัฒนากรอบการจัดการแบบบูรณาการสินค้าชีวภาพ และแบบจำลองอ้างอิงการดำเนินงานของซัพพลายเชนปาล์มในจังหวัดอุบลราชธานี	209-226
ปวิณญดา บุญมัย จุริรัตน์ บุตรเหลา ธนัฐดา แก้วสุข อายุพร ขาวฟอง พนิดา ยิ่งยืน จริยา พันธะ และ นันทพงศ์ นันทสำเร็จ	
การจัดการความรู้การใช้สมุนไพรในครัวเรือนเพื่อการดูแลสุขภาพของผู้สูงอายุจังหวัดลำปาง	227-239
สุพุมล ทองดี	



การพัฒนาแพลตฟอร์มดิจิทัลเพื่อส่งเสริมการเรียนรู้และการท่องเที่ยวเชิงวัฒนธรรม
ของพิพิธภัณฑ์ท้องถิ่นในกรุงเทพมหานคร

Development of a Digital Platform to Promote Learning and
Cultural Tourism for Local Museums in Bangkok

อมฤตา ฤทธิภักดี^{1*}

Amarita Ritthipakdee^{1*}

¹คณะวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยราชภัฏพระนคร กรุงเทพมหานคร

¹Faculty of Science and Technology, Phranakhon Rajabhat University, Bangkok

*Corresponding Author: amarita@pnru.ac.th

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อรวบรวมข้อมูลพิพิธภัณฑ์ท้องถิ่นในกรุงเทพมหานคร และพัฒนาดิจิทัลแพลตฟอร์มเครื่องมือในการส่งเสริมการเรียนรู้ทางวัฒนธรรมและเพิ่มคุณค่าการท่องเที่ยวอย่างยั่งยืนตลอดจนประเมินความพึงพอใจของผู้ใช้ต่อแพลตฟอร์มดังกล่าว แพลตฟอร์มได้รับการออกแบบและพัฒนาให้รองรับทั้งระบบปฏิบัติการ iOS และ Android พร้อมทั้งบูรณาการ LINE Official Account (LINE OA) เป็นช่องทางหลักในการสื่อสาร การแจ้งเตือน และการมีปฏิสัมพันธ์กับผู้ใช้ นอกจากนี้ ยังได้นำเทคโนโลยีระบุตำแหน่งทางภูมิศาสตร์และแผนที่ดิจิทัล (Google Maps Location Services) มาใช้เพื่อสนับสนุนการแสดงตำแหน่งพิพิธภัณฑ์ การวางแผนการเดินทาง และการเข้าถึงข้อมูลเชิงพื้นที่อย่างมีประสิทธิภาพ ฟังก์ชันหลักของแพลตฟอร์มประกอบด้วยการค้นหาข้อมูลพิพิธภัณฑ์ การแสดงแผนที่ตำแหน่งทางภูมิศาสตร์ ฟังก์ชันการแสดงความคิดเห็นและการมีส่วนร่วมของผู้ใช้ รวมถึงการแบ่งปันข้อมูลผ่านสื่อสังคมออนไลน์ ผลการประเมินความพึงพอใจของผู้ใช้พบว่ามีความพึงพอใจโดยรวมต่อแพลตฟอร์มอยู่ในระดับสูง (ค่าเฉลี่ยรวม = 4.08) โดยด้านการใช้งานได้ค่าเฉลี่ย 4.03 ด้านการทำงานของระบบได้ค่าเฉลี่ย 4.10 และด้านความสวยงามได้ค่าเฉลี่ย 4.10 ผลการวิจัยสะท้อนให้เห็นว่าแพลตฟอร์มดิจิทัลที่พัฒนาขึ้นสามารถตอบสนองความต้องการของผู้ใช้ได้อย่างมีประสิทธิภาพ และแสดงให้เห็นถึงศักยภาพของการประยุกต์ใช้เทคโนโลยีดิจิทัลในการสนับสนุนการเรียนรู้ทางวัฒนธรรมและส่งเสริมการท่องเที่ยวอย่างยั่งยืนสำหรับพิพิธภัณฑ์ท้องถิ่น

คำสำคัญ: แพลตฟอร์มดิจิทัล, พิพิธภัณฑ์ท้องถิ่น, การท่องเที่ยวเชิงวัฒนธรรม

Abstract

This research aims to consolidate information on local museums in Bangkok and to develop a digital platform as a tool to promote cultural learning and enhance sustainable tourism value and to evaluate user satisfaction toward the platform. The platform was designed and developed to support both iOS and Android operating systems, with the integration of a LINE Official Account (LINE OA) as the primary channel for communication, notifications, and user interaction. In addition, geolocation and digital mapping technologies, specifically Google Maps Location Services, were employed to support museum location visualization, travel planning, and efficient access to spatial information. The core functionalities of the platform include museum information search, geographical location mapping, user commenting and participation features, and information sharing through social media. The results of the user satisfaction evaluation indicate a high overall level of satisfaction with the platform (overall mean = 4.08). Specifically, the usability aspect achieved a mean score of 4.03, system functionality recorded a mean score of 4.10, aesthetics also recorded a mean score of 4.10. These findings demonstrate that the developed digital platform effectively meets user needs and highlight the potential of applying digital technologies to support cultural learning and promote sustainable tourism for local museums.

Keywords: Digital platform, Local museum, Cultural tourism

1. Introduction

The preservation and sustainable continuation of arts and crafts, culture, and community ways of life are fundamental to maintaining cultural identity and national heritage. Such efforts strengthen community resilience and pride while facilitating the transmission of local knowledge and wisdom to younger generations. At present, the use of digital technology has increased significantly. Smartphones and internet networks have become highly accessible, enabling people to conveniently and rapidly access various services online. Within this context, museums play a crucial role as key institutions for safeguarding and disseminating cultural heritage while adapting to technological advancements.

A museum is defined as a non-profit organization open to the public and operating as a permanent institution that serves society and contributes to its development through the collection, preservation, research, dissemination, and exhibition of objects related to humans and their environment for purposes of research, education, and enjoyment. With advancements in digital technology, the concept of the museum has evolved into a virtual museum, which represents a transformed form of traditional museum exhibitions designed to attract visitors and enhance learning experiences through computer technology, communication systems, and the internet. Virtual museums employ multimedia or mixed media, such as static or animated three-dimensional images, often accompanied by audio narration or brief explanatory texts. Supporting this transformation, a digital platform functions as the underlying infrastructure that enables such services; according to, in this research, Lerdloompheephan (2019) a digital platform is defined as a digital infrastructure that connects providers and users for the exchange of data and services. It enables

collaboration among stakeholders, supports the sharing economy, and reduces operational and transaction costs. Plungsricharoensuk & Jongwutiwes (2018) explored a participatory lifelong learning model using museums and local learning resources. The results showed that the model effectively promoted creative learning and supported the conservation of local arts and culture. Limpinan (2019) improved the AR Maha Sarakham application using augmented reality to promote five tourist attractions in Maha Sarakham Province. The system included AR markers, animated 3D models, and an Android application, with evaluation results showing high usability and user satisfaction. Related studies indicate that virtual reality (VR) enhances user immersion and improves information understanding through interactive and sensory experiences. Building on this technological foundation, Disara (2019) developed the Thung Wa Prehistoric Elephant Virtual Museum using virtual reality technology. The results showed that the system met the 80/80 efficiency criterion, significantly improved visitors' learning outcomes, and achieved the highest level of user satisfaction. Similarly, supporting the effectiveness of virtual museums, Tammarakkul (2022) investigated the application of Augmented Reality (AR) technology in museums to support sustainable tourism. The findings indicate that AR enhances user engagement, improves learning experiences, and promotes virtual tourism. Beler (2004) examined the use of online communities in learning organizations, particularly museums. It emphasizes the importance of personalization and web-based tools in enhancing user engagement, collaboration, and knowledge sharing. The study concludes that effective community development relies on user-centered design and interactive technologies. Satmune et al. (2019) developed a public relations management support system for an educational institution using the SDLC approach. The system integrates database management, spatial data display, and data processing, with evaluation results indicating high efficiency and effectiveness in supporting data management, decision-making, and public relations operations. Butsaba (2025) developed a tourism recommendation website for attractions in Japan using the SDLC approach. Evaluation results from 30 users indicated a high level of satisfaction (mean = 4.41), suggesting that the system was effective and user-friendly, though improvements in design and information coverage were recommended. Bonis (2008) and Nuasut et al. (2024) improved an online marketing platform to enhance community products by expanding market access and sales opportunities. The platform integrates digital marketing functions to support community entrepreneurs, with results indicating improved product visibility and support for sustainable community economic development.

Existing research has largely concentrated on specific or regional museums, with limited attention given to local museums across multiple districts in a large metropolitan area such as Bangkok, where cultural diversity and community contexts vary significantly.

Recognizing the importance of applying technology to maximize its benefits in promoting the sustainable preservation of culture and community life, as well as the research gap arising from the limited focus on local museums in metropolitan contexts, the researcher develops a digital platform for local museums in Bangkok. To operationalize this platform and ensure comprehensive representation, the study focuses on a wide range of museums across Bangkok. Specifically, this study examines various types of museums across 27 districts in Bangkok. It includes museums related to history and historical sites, such as

Phra Ratchawang Derm Museum (Former Royal Palace Museum) in Bangkok Yai District, as well as the Bangkok Local Museum and the Sunthorn Phu Museum in Phra Nakhon District. In addition, the study examines local museums and community ways of life, which reflect the everyday lives, beliefs, and cultural practices of local communities. These include Bangkok Local Museums located in Thon Buri, Rat Burana, Don Mueang, Nong Chok, Suan Luang, and Samphanthawong Districts, among others. Moreover, the research incorporates museums of art, crafts, and Thai local wisdom, which showcase artistic works, traditional craftsmanship, and local knowledge. Examples include the Benjarong House Museum in Wang Thonglang District and the Thai Kite Museum in Bang Khun Thian District. Furthermore, this study embraces museums of religion, literature, and spiritual culture, which promote learning about religious beliefs, literary heritage, and moral and spiritual values, such as the Sunthorn Phu Museum in Phra Nakhon District and the educational museum at Wat Nang Ratchaworawihan in Chom Thong District. The study also covers museums of science, nature, and technology, which foster learning in science, nature, and technological innovation. These include the Ant Museum in Chatuchak District, the National Aviation and Aerospace Museum of the Royal Thai Air Force in Don Mueang District, and the Public Relations Department Museum and Archives in Phaya Thai District. Finally, the research encompasses specialized museums and contemporary culture, which present specific themes and aspects of modern cultural expression. Notable examples are the Batcat Museum in Bang Kapi District, the Nong Khaem Metropolitan Police Station Museum in Nong Khaem District, and the Suksasom Museum in Thawi Watthana District. In summary, this study investigates a wide range of museum types across Bangkok, reflecting the city's rich cultural, historical, and educational diversity.

2. Materials and Methods

This platform aims to provide inclusive access to knowledge regardless of gender or age, encourage self-directed learning, and stimulate imagination, creativity, and the development of diverse skills, which ultimately contribute to national development. The study is intended to enhance the value of tourism resources in Bangkok by serving as a bridge between the past and the present, thereby fostering public awareness, learning, and the preservation of valuable community heritage.

Figure 1 illustrates the conceptual framework of the proposed digital platform for promoting learning and cultural tourism at local museums. The framework presents a systematic relationship between platform components, user interactions, and evaluation outcomes. At the system level, the Digital Platform (Museum Information Platform) functions as the core infrastructure, providing multiple functional modules, including popular location displays, museum detail presentations, geographical location services using maps and GPS technologies, and a user comment interface. These modules collectively enable comprehensive access to museum-related information and support location-based navigation. The platform integrates a LINE Official Account (LINE OA) as the primary communication and engagement channel. LINE OA facilitates messaging-based interaction, real-time notifications, and user participation, serving as an intermediary layer that connects system functionalities with end-users. Through this integration, users can interact with the platform efficiently and receive updated cultural and tourism-related information. User interaction with the

platform leads to the formation of user interaction and experience, which represents users' perceptions and engagement during system usage. This experience is evaluated through three key dimensions: usability, reflecting ease of use and accessibility; functionality, representing system performance and operational reliability; and aesthetics, indicating visual design quality and interface appeal (Figure 1).

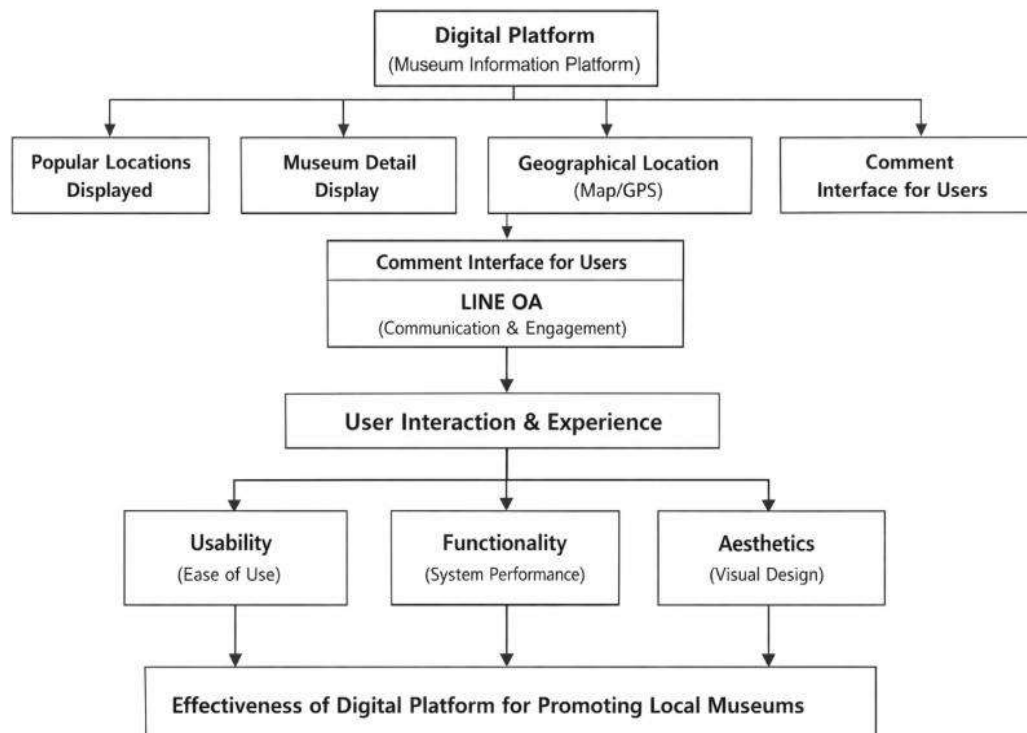


Figure 1. Conceptual framework of the Bangkok Museum Digital Platform and evaluation metrics.

Finally, the combined effects of these evaluation dimensions determine the effectiveness of the digital platform for promoting local museums. The framework demonstrates how technical platform features and communication mechanisms influence user experience, which in turn contributes to the platform's effectiveness in supporting cultural learning and enhancing cultural tourism in a metropolitan context. Based on the research gap and the importance of digital transformation in the museum sector, this study aims to develop a digital platform to promote learning and cultural tourism for local museums in Bangkok and to evaluate user satisfaction toward the developed platform

2.1 Research instruments

This study uses two research instruments: a digital platform for local museums and a satisfaction questionnaire.

1) The digital platform was designed and developed by the researcher following the steps illustrated in the figure below.

The development of the digital platform followed a systematic and structured process. Initially, a user requirement analysis was conducted to identify the platform's functional requirements,

including user registration, information content, location details, and related features. Subsequently, wireframes, mockups, and prototypes were developed to design the user interface, define the database structure, and establish access logic and system workflows.

Figure 2 shows that illustrates the architecture of the digital platform designed to promote learning and cultural tourism at local museums in Bangkok. The system integrates the LINE Official Account (LINE OA) and Google Maps Location Services to enhance user engagement, improve information accessibility, and support location-based services.

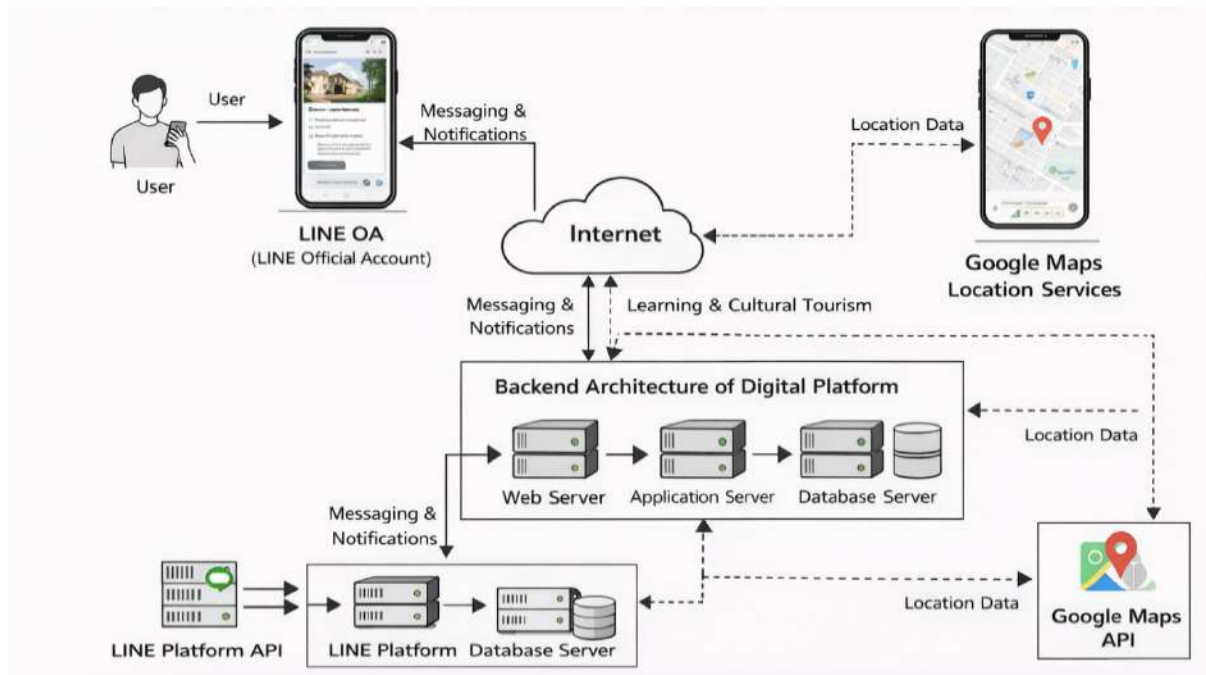


Figure 2. Architecture overview of the digital platform to promote learning and cultural tourism.

At the user interaction layer, users access the platform through their mobile devices via LINE OA. This interface enables users to receive museum information, learning content, cultural tourism updates, and real-time notifications. Communication between users and the platform is conducted through messaging and notification services over the Internet.

The backend architecture consists of a web server, an application server, and a database server. The web server manages incoming requests, while the application server handles business logic, including content management, learning activities, and tourism-related services. The database server stores museum information, user interaction data, and location-related data. This backend layer serves as the core of the digital platform, ensuring data consistency, reliability, and efficient system performance.

Integration with the LINE Platform API enables seamless message delivery, user interaction management, and automated notifications. This functionality allows the platform to disseminate learning materials and cultural tourism information effectively through LINE OA.

For location-based functionality, the platform connects to the Google Maps API and Google Maps Location Services, enabling users to view museum locations, access geographical information, and receive navigation support. Location data flows between the backend system and Google Maps services, supporting spatial visualization and enhancing the cultural tourism experience.

The platform was then implemented using cross-platform and native development approaches to ensure compatibility with multiple operating systems, including iOS and Android. Following implementation, testing was conducted to verify that all system functions operated correctly, efficiently, and in accordance with the specified requirements. After successful testing, the application was deployed for actual use by end users. Finally, ongoing maintenance and improvement were carried out to ensure system stability and to enhance functionality based on user feedback and performance evaluation.

Overall, the system architecture demonstrates how the integration of messaging platforms (LINE OA) and geographical services (Google Maps) within a digital platform can effectively support learning and promote cultural tourism at local museums in Bangkok.

Figure 3 shows that the framework is structured into four main layers. Flutter is an application development framework developed by Google, with Dart as its primary programming language. It enables developers to build application user interfaces (UIs) for both iOS and Android operating systems using a single codebase. This cross-platform development approach allows a single development process to support multiple platforms, thereby reducing development complexity, time, and cost. Flutter also provides a wide range of plugins and packages that assist developers in creating diverse, visually appealing, and highly customizable user interfaces efficiently. These features enhance flexibility and efficiency in application design and development. In addition, a cloud-based database developed by Google Cloud and integrated within the Firebase platform is utilized. Cloud Firestore is a NoSQL, document-oriented database that stores data in collections of documents. Each document is represented as a JSON-like object consisting of key-value pairs, allowing it to handle both structured and unstructured data. Due to its flexibility and scalability, Cloud Firestore is well-suited for applications that require diverse data structures and real-time data management.



Figure 3. Framework of the LINE Official Account integrated with system development and the database.

2) The satisfaction questionnaire was developed to collect user feedback and focused on three aspects: functionality, usability, aesthetics, and performance metrics. A five-point Likert scale was employed, where 5 represented very high satisfaction, 4 high satisfaction, 3 moderate satisfaction, 2 low satisfaction, and 1 very low satisfaction. The interpretation of the mean scores was defined as follows: mean scores ranging from 4.50 to 5.00 indicated very high satisfaction; 3.50 to 4.49 indicated high satisfaction; 2.50 to 3.49 indicated moderate satisfaction; 1.50 to 2.49 indicated low satisfaction; and 1.00 to 1.49 indicated very low satisfaction.

2.2 Research Procedure

To achieve its objectives, this research followed the procedures below:

- 1) The researcher studied and collected information related to museums to preserve objects, artifacts, and valuable information of historical, artistic, cultural, scientific, and natural significance for future generations.
- 2) The researcher constructed the digital platform.
- 3) The researcher distributed a satisfaction questionnaire to evaluate the digital platform.

3. Results

This study was framed by two research objectives: 1) to develop a digital platform to promote learning and cultural tourism for local museums in Bangkok, and 2) to evaluate user satisfaction toward the platform.

3.1 The Digital Platform

With careful consideration of users' functionality, usability, and aesthetic needs, the researcher developed the digital platform as presented below.

The digital platform is delivered through a LINE Official Account (LINE OA), an official business communication platform provided by LINE that enables organizations, enterprises, and institutions to communicate with users in an efficient and structured manner. The platform incorporates two key functions. First, it features a location map function that supports navigation by displaying geographic information within the mobile interface. This function integrates location-based services (LBS) with digital mapping technology to assist users in identifying destinations and navigating to selected locations. Second, the platform provides a social media connectivity function, allowing users to share information from the application directly to external platforms such as LINE and Facebook. This function enhances communication, information dissemination, and user engagement by enabling content to be shared easily with others.

The platform's features and functions include the following:

1) Platform Installation and Access

To use the platform, users are required to install the LINE application on their smartphones. The application can be downloaded from the Google Play Store or the Apple App Store and is compatible with both iOS and Android operating systems. The platform requires minimal storage

space and features a simple and modern user interface. Alternatively, users may access the platform by scanning a QR code (Figure 4).



Figure 4. QR code for platform installation.

2) Log in to Access the Platform

After users have completed downloading and installing the platform on their devices, the system will display the “Add Friend” screen. At this stage, users will be directed to the login screen, where they can log in to access the platform (Figure 5).

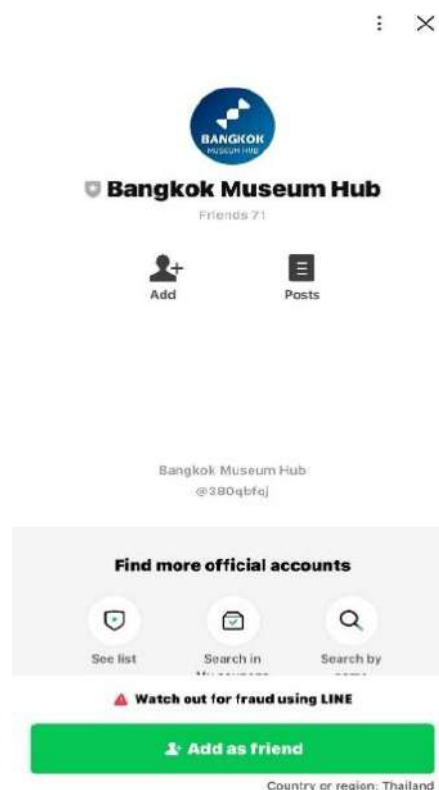


Figure 5. Adding a friend to access the platform.

3) User Registration

When users register, they complete the required registration process to access and use the platform (Figure 6).

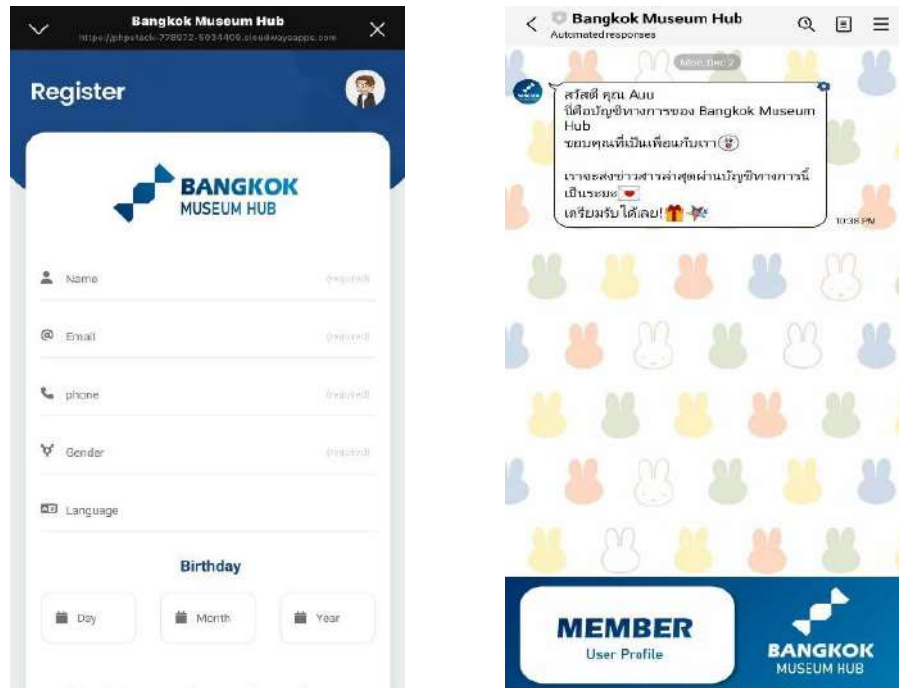


Figure 6. Main registration screen.

After users have completed downloading and installing the platform on their devices, the system will display the login interface. At this stage, users will encounter the login screen to access the platform. For first-time use, users are required to complete a registration process, referred to as user registration, by selecting the Member User Profile menu. This initial registration is conducted to collect essential information necessary for system usage, such as the user's full name, email address, and phone number. As shown in Figure 7.

To use the Register menu, users are required to provide a username, email address, and phone number, as well as select their gender and preferred application language. Both Thai and English language options are available. Users must then create a password and confirm it to complete the registration process. After selecting the SUBMIT button, the system will display the initial application screen, indicating that the platform is ready for use (Figure 8).

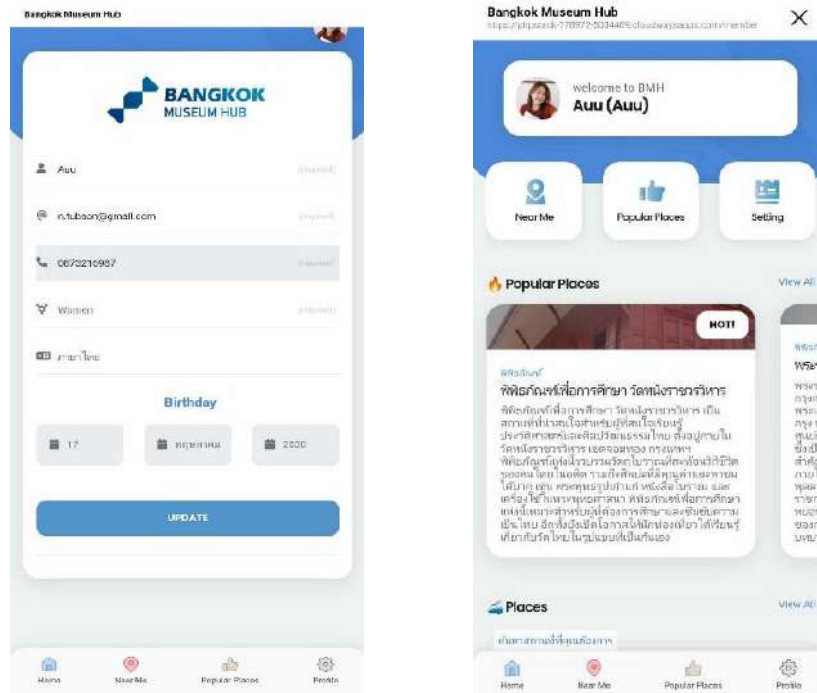


Figure 7. Accessing the Platform.

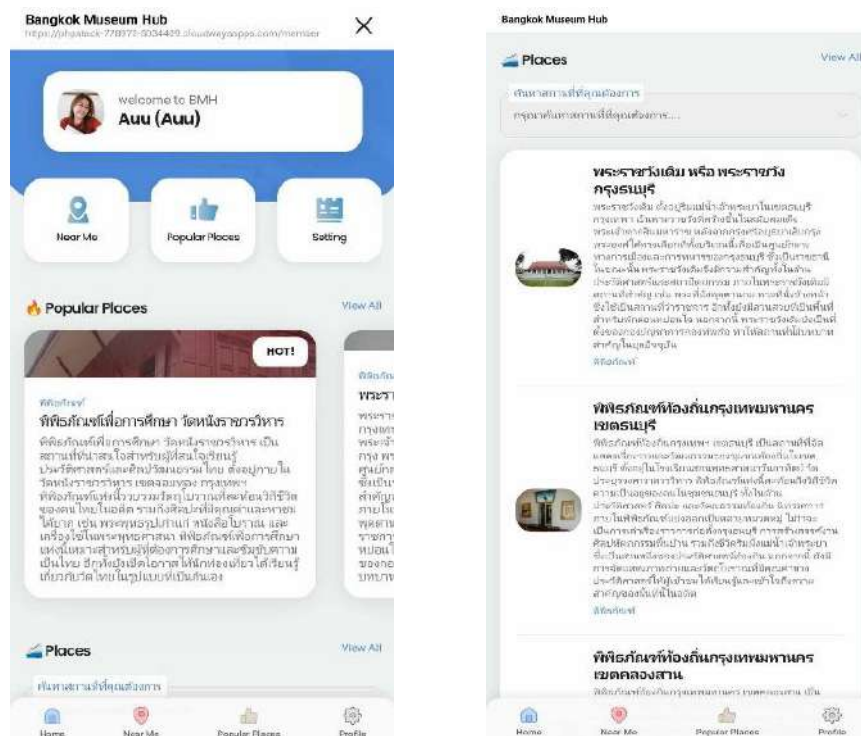


Figure 8. Main system interface.

4) Main Platform Interface

On the main interface of the platform, the top section displays the username of the logged-in user. The main screen of the application consists of the following key menus and functional features, as shown in Figure 9.



Figure 9. User status screen.

5) Near Me Menu Function

This function displays geographical location information. The system shows the locations of all museums in Bangkok. Users can search for a desired museum through the search menu, which displays all available locations within the system. If users do not know the name of a specific museum, they may select a location directly from those displayed on the platform (Figure 10).

6) Popular Place Menu

This function displays the top 10 most popular places. The menu presents locations that are widely favored by tourists and visitors—places they have previously visited and rated positively. The system collects and stores data on popular locations based on user ratings within the Bangkok Museum Hub. This feature helps users who have not yet decided by providing useful information that can support their travel planning (Figure 11).

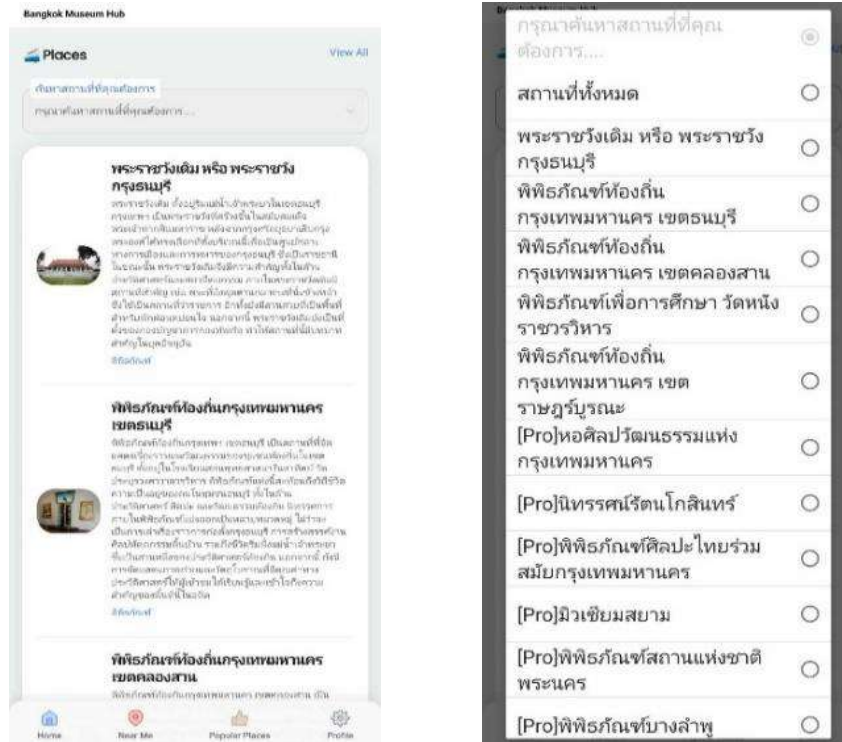


Figure 10. List of museum locations displayed.

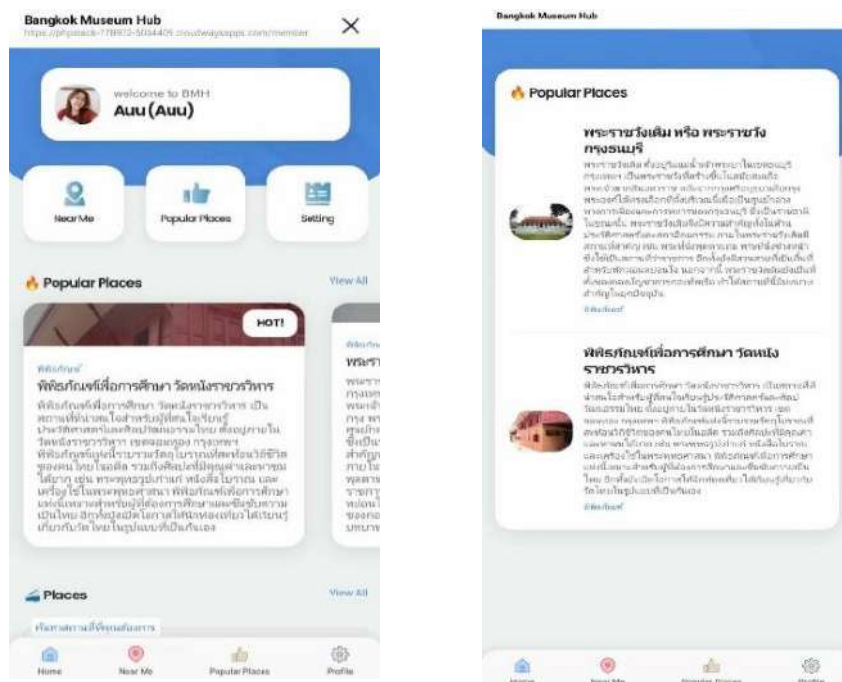


Figure 11. Popular locations displayed.

7) Museum Information Display Function

This function is a key component of the system, allowing users to view detailed information about each museum. The information can be accessed in both Thai and English. In addition to essential details such as the museum's background, history, opening hours, and directions, users can share museum information via other platforms, including the LINE application and Facebook. Furthermore, if users are impressed by a particular museum, they can express their appreciation by selecting the “like” option represented by a heart icon (Figure 12).

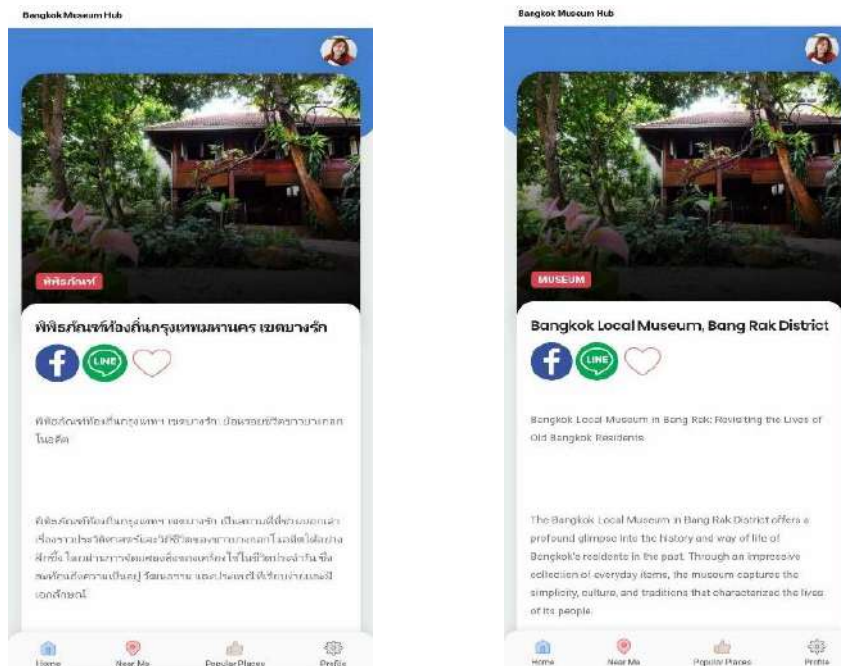


Figure 12. Museum detail display.

8) Geographical Location Display via Google Maps

This function displays the geographical location of each museum. Users can select the option to connect to Google Maps to view an enlarged map and independently search for travel routes to the museum location (Figure 13).

9) Comment Function

This function allows users to write comments to share their opinions, feelings, and relevant information with other users. Comments on museum sites may serve as a source of accurate information and provide motivation and inspiration for others who view the content to visit the museums as shown in Figure 14.



Figure 13. Geographical Location Display.

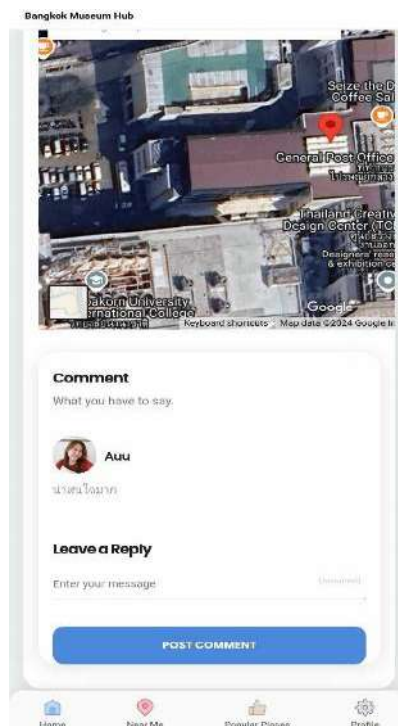


Figure 14. Comment interface for users.

3.2 User Satisfaction

User satisfaction was evaluated using a 5-point Likert scale questionnaire, in which responses were classified into five levels: strongly agree, agree, neutral, disagree, and strongly disagree, with corresponding scores ranging from 5 to 1, respectively. The questionnaire covered three main dimensions:

usability, system functionality, platform aesthetics and performance metrics. Data were collected through an online survey using Google Forms and analyzed using descriptive statistics, including the mean ($\bar{x}$) and standard deviation (SD). The evaluation results indicate a high overall level of user satisfaction, demonstrating that the developed digital platform effectively meets user needs across all evaluated dimensions.

The sample group consisted of 100 platform users who had experience using the digital platform and completed the questionnaire via Google Forms. The participants were selected through purposive sampling, specifically targeting users who accessed the platform through the LINE Official Account and responded to the user satisfaction survey. The research instrument was a satisfaction questionnaire comprising four dimensions: usability, functionality, aesthetics, and performance. The reliability of the questionnaire was assessed using Cronbach's alpha coefficient, yielding values of 0.716 for usability, 0.711 for functionality, 0.713 for aesthetics, and 0.713 for performance, indicating acceptable internal consistency.

Table 1. User Satisfaction toward the Use of the Digital Platform

Order	Item	$\bar{x}$	S.D.	Level of Satisfaction
Usability		4.03	0.8	High
1.	The platform's menus and icons are easy to use.	4.28	0.73	High
2.	The platform's main functions and operations are appropriate.	4.04	0.88	High
3.	The platform provides accurate search functions and information access for museums.	3.76	0.77	High
4.	The platform processes data quickly.	4.04	0.88	High
5.	The platform provides accurate and reliable system performance.	4.04	0.84	High
6.	The platform provides useful information.	4.36	0.75	High
Functionality		4.1	0.76	High
1.	The platform is user-friendly.	4.36	0.75	High
2.	The platform features simple, user-friendly menus.	4.04	0.78	High
3.	The platform has an appropriate overall display.	3.92	0.75	High

Table 1. User Satisfaction toward the Use of the Digital Platform (Cont.)

Order	Item	$\bar{x}$	S.D.	Level of Satisfaction
Aesthetics		4.1	0.77	High
1.	The platform features a modern and visually appealing interface.	4.12	0.88	High
2.	The platform employs readable and aesthetically pleasing font sizes and styles.	4.24	0.66	High
3.	The platform appropriately uses icons or images to convey meanings clearly and easily.	4.04	0.78	High
Performance metrics		4.16	0.76	High
1	Response time	4.20	0.75	High
2	System stability	4.12	0.78	High

4. Discussion

This research is grounded in the premise that a digital platform can be effectively utilized to promote learning and cultural tourism for local museums. In alignment with the first research objective, the platform was developed through a systematic process encompassing user requirement analysis, UI/UX design, and mobile application implementation. The system was operationalized through a LINE Official Account (LINE OA) to enhance accessibility and communication efficiency, enabling users to access cultural and tourism-related information conveniently via a widely adopted messaging platform.

The discussion of the research findings is presented in two key dimensions: technological implications and policy and museum management implications, as outlined below.

4.1 Technological Implications

From a technological perspective, the findings demonstrate that the integration of LINE Official Account with a cloud-based backend infrastructure effectively supports the development of an interactive and scalable digital platform. The use of LINE OA as the primary user interface reduces barriers to access by eliminating the need for separate application installation, while maintaining compatibility across iOS and Android devices. This approach highlights the potential of leveraging existing messaging platforms as alternative digital service infrastructures for information systems.

The incorporation of application programming interfaces (APIs) enables seamless integration between the communication layer, backend services, and external systems, facilitating real-time data exchange, automated messaging, and personalized user interaction. In addition, the integration of location-based services (LBS) with digital mapping technology supports navigation and travel planning by providing accurate geographic visualization and route guidance. These functionalities enhance system usability and improve the overall user experience, as reflected in the high user satisfaction ratings across usability, functionality, aesthetics, and performance metrics.

Furthermore, the inclusion of social media connectivity features transforms the platform from a static information repository into an interactive digital environment. Features such as commenting, content sharing, and user engagement mechanisms support participatory system design principles and enable the platform to function as a small online community. This finding aligns with previous studies emphasizing the role of interactivity and social participation in enhancing the effectiveness and sustainability of digital platforms for cultural tourism and learning.

4.2 Policy and Museum Management Implications

In terms of policy and museum management implications, the proposed digital platform offers a practical tool for enhancing the management, promotion, and accessibility of local museums, particularly in metropolitan contexts characterized by cultural diversity. The platform enables museum administrators and local authorities to disseminate information efficiently, reduce reliance on traditional promotional methods, and reach broader audiences through digital communication channels.

The use of a centralized digital platform supports data-driven decision-making by allowing museums to monitor user interactions, popular locations, and engagement patterns. Such information can be utilized to inform cultural tourism policies, improve resource allocation, and design targeted promotional strategies. Moreover, the platform supports sustainable tourism management by encouraging informed travel planning and fostering public awareness of local cultural heritage.

From a broader policy perspective, the findings suggest that integrating digital platforms into museum and cultural tourism management can contribute to the development of smart tourism ecosystems. By linking cultural learning resources with digital infrastructure, local governments and cultural institutions can enhance lifelong learning opportunities, promote community participation, and strengthen the role of museums as dynamic learning hubs in the digital society.

5. Conclusion and recommendations

Overall, the results confirm that the proposed digital platform aligns with contemporary technological development trends by integrating accessibility, interactivity, and social participation. The platform demonstrates strong potential for supporting museum information dissemination, promoting cultural tourism, and fostering digital learning communities. This research contributes to digital platform development and offers insights for technological innovation and museum management. Future studies should further enhance platform features, expand content coverage, and examine long-term user engagement and system effectiveness.

6. Acknowledgements

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อิทธิพลของเทคนิคการอบแห้งที่แตกต่างกันต่อสารออกฤทธิ์ทางชีวภาพและฤทธิ์ต้านอนุมูลอิสระ
ของใบกระท่อม (*Mitragyna speciosa* (Korth.) Havil): ปริมาณไมทราจินีน
ในเทคนิคที่เหมาะสมที่ได้รับคัดเลือก

Influence of Different Drying Techniques on Bioactive Compounds and Antioxidant
Activity of Kratom (*Mitragyna speciosa* (Korth.) Havil) Leaves:
Mitragynine Content in the Selected Optimal Technique

จิระนันท์ วงศ์วัฒนยoo¹ เกียรติพงษ์ เจริญจิตต์² และ อภิญญา ภูมิสาธิตอน^{2*}

Jeeranan Wongwatanyoo¹, Kaittipong Chareonjit² and Apinya Bhumsaidon^{2*}

¹คณะศิลปศาสตร์และวิทยาศาสตร์ มหาวิทยาลัยราชภัฏศรีสะเกษ จังหวัดศรีสะเกษ

²คณะเทคโนโลยีการเกษตร มหาวิทยาลัยกาฬสินธุ์ จังหวัดกาฬสินธุ์

¹Faculty of Liberal Arts and Science, Sisaket Rajabhat University, Sisaket Province

²Faculty of Agricultural Technology, Kalasin University, Kalasin Province

*Corresponding Author: apinya.bh@ksu.ac.th

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อประเมินอิทธิพลของวิธีการอบแห้งที่แตกต่างกันต่อสมบัติทางเคมีและกายภาพ ปริมาณสารฟีนอลิกทั้งหมด และฤทธิ์ต้านอนุมูลอิสระของใบกระท่อม (*Mitragyna speciosa* (Korth.) Havil.) โดยเปรียบเทียบวิธีการอบแห้ง 4 วิธี คือ การตากแดดโดยตรง การอบแห้งด้วยโรงอบแห้งพลังงานแสงอาทิตย์แบบพาราโบลา การอบแห้งด้วยตู้อบลมร้อนแบบถาด และการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสง ผลการทดลองพบว่าการอบแห้งทุกวิธีสามารถลดปริมาณความชื้น (8.7 – 10.4 % w.b.) และค่า water activity (a_w) อยู่ในช่วง 0.36 - 0.52 อย่างไรก็ตามพบความแตกต่างอย่างมีนัยสำคัญทางสถิติ ($p \leq 0.05$) ในค่าสีและฤทธิ์ต้านอนุมูลอิสระ โดยวิธีอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงให้ค่าปริมาณสารฟีนอลิกทั้งหมดสูงที่สุด ($196.64 \text{ mg GAE g}^{-1}$) และไม่แตกต่างอย่างมีนัยสำคัญ ($p > 0.05$) จากการตากแดดโดยตรง ($195.07 \text{ mg GAE g}^{-1}$) ทั้งนี้ใบกระท่อมที่ผ่านการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงแสดงค่าความเข้มสี (Chroma) และค่ามุมเฉดสี ($^\circ\text{h}$) ที่สูงกว่า สามารถรักษาค่าความเป็นสีเขียว ($-a^*$) ได้ดีกว่า รวมทั้งยังมีคุณลักษณะในการผลิตที่เหมาะสมกว่าอีกด้วย นอกจากนี้ฤทธิ์ต้านอนุมูลอิสระที่ประเมินด้วยวิธี DPPH และ ABTS⁺ มีค่าสูงสุด (74.03 % และ 97.14 % ตามลำดับ) ภายใต้การอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงเช่นกัน เมื่อพิจารณาจากปริมาณสารสำคัญที่ยังคงเหลือและคุณภาพของผลิตภัณฑ์จากการอบแห้งแล้ว วิธีการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงได้รับคัดเลือกสำหรับการวิเคราะห์ปริมาณไมทราจินีนในขั้นตอนถัดไป โดยใบกระท่อมอบแห้งที่ได้มีปริมาณไมทราจินีนเท่ากับ 9.83 mg g^{-1} (น้ำหนักแห้ง) อย่างไรก็ตาม เนื่องจากงานวิจัยนี้ทำการวิเคราะห์ปริมาณไมทราจินีนเฉพาะในวิธีการอบแห้งที่ได้รับการคัดเลือกว่ามีความเหมาะสมที่สุด จึงไม่สามารถสรุปเปรียบเทียบการคงอยู่ของไมทราจินีนระหว่างวิธีการอบแห้งทั้งหมดได้ โดยผลการศึกษาชี้ให้เห็นว่าการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงเป็นแนวทางที่เหมาะสม สามารถรักษาสารออกฤทธิ์ทางชีวภาพและฤทธิ์ต้านอนุมูลอิสระที่สำคัญไว้ได้ และประหยัดพลังงานสำหรับการแปรรูปใบกระท่อมอบแห้งในระดับชุมชน

คำสำคัญ: ใบกระท่อม, ไมทราจินีน, โรงเรือนอบแห้งแบบทึบแสง, ฤทธิ์ต้านอนุมูลอิสระ, สารฟีนอลิกทั้งหมด

Abstract

This study aimed to evaluate the influence of different drying methods on the chemical and physical properties, total phenolic content (TPC), and antioxidant activity of kratom (*Mitragyna speciosa* (Korth.) Havil.) leaves. Four drying techniques were compared: direct sunlight drying, parabolic solar drying, hot-air tray drying, and opaque greenhouse drying. The results showed that all drying methods effectively reduced moisture content (8.7–10.4 % w.b.) and water activity (a_w) values ranging from 0.36 to 0.52. However, significant differences ($p \leq 0.05$) were observed in color parameters and antioxidant activity among treatments. Opaque greenhouse drying yielded the highest TPC (196.64 mg GAE g⁻¹), which was not significantly different ($p > 0.05$) from direct sunlight drying (195.07 mg GAE g⁻¹). Nevertheless, leaves dried using the opaque greenhouse drying exhibited higher color intensity (chroma), a greater hue angle (h°), improved retention of greenness ($-a^*$), and improved hygienic conditions. Antioxidant activity, evaluated by DPPH and ABTS⁺ assays, was also highest under opaque greenhouse drying (74.03% and 97.14%, respectively). Based on the retention of bioactive compounds and overall product quality, opaque greenhouse drying was selected for subsequent mitragynine analysis, yielding a content of 9.83 mg g⁻¹ (dry weight). However, since mitragynine was quantified only in the selected optimal treatment, direct comparisons of mitragynine retention among all drying methods could not be established. Collectively, the results suggest that opaque greenhouse drying offers a practical, preserves key bioactive compounds and antioxidant activity, and energy-efficient solution for community-scale kratom processing.

Keywords: Kratom leaves, Mitragynine, Opaque greenhouse dryer, Antioxidant activity, Total phenolic content

1. Introduction

Kratom (*Mitragyna speciosa* (Korth.) Havil.) is a tropical medicinal plant indigenous to Southeast Asia that has been traditionally utilized for its analgesic, anti-inflammatory, hypolipidemic, and stimulant-related properties (Nawaka et al., 2025; Singh et al., 2019; Hossain et al., 2023; Sornsenee et al., 2025). Recent scientific investigations have demonstrated that kratom leaves are a rich source of bioactive phytochemicals, including polyphenols, flavonoids, and indole alkaloids—most notably mitragynine—which contribute significantly to their antioxidant and anti-inflammatory activities (Eastlack et al., 2020). Mitragynine, the most abundant alkaloid in kratom, has been reported to range from 0.7% to 38.7% in traditional and commercial kratom products (Sharma et al., 2019), and from 7.5 to 26.6 mg g⁻¹ dry leaf weight in kratom leaves (Leksungnoen et al., 2022). As global demand for kratom-based products continues to rise, ensuring consistent quality and bioactive compound retention during postharvest processing has become increasingly important.

Drying is a critical postharvest operation for kratom leaves due to their susceptibility to enzymatic degradation, microbial growth, and phytochemical loss. In medicinal plants, drying conditions can markedly influence phenolic retention, antioxidant capacity, and color stability (Arslan & Özcan, 2011; Puranik et al.,

2012). Therefore, four drying methods were selected to represent contrasting thermal and environmental conditions commonly used in practice. Open-sun drying (direct sunlight) was included as a traditional, low-cost approach characterized by fluctuating temperature and direct UV exposure. Parabolic solar drying was selected as an intensified solar method that can shorten drying time but requires higher initial investment. Hot-air tray drying served as a conventional controlled benchmark with stable temperature and airflow; however, it may promote thermal degradation of heat-sensitive compounds and relies on electricity. Finally, opaque greenhouse drying was included to protect UV-sensitive materials and reduce hygiene-related contamination (Kaveh et al., 2025). In addition, the hot-air exhaust and moisture-removal fans are powered by solar energy, eliminating the need for grid electricity and enabling a fully self-sustaining drying system.

Previous research on kratom has primarily focused on the analytical determination of alkaloid content in raw materials and commercial products (Citti et al., 2023; Todd et al., 2020; Sengnon et al., 2023), as well as on the pharmacological and toxicological properties of mitragynine (Meireles et al., 2019). Reported mitragynine contents range from 0.7 to 38.7% (w/w) in traditional and commercial products (Sharma & McCurdy, 2021) and from 0.31 to 4.94% (w/w) in kratom plants cultivated in Thailand, depending on seasonal and geographical conditions (Sengnon et al., 2023). Extraction studies have further confirmed mitragynine as the predominant alkaloid, with concentrations of 58.75, 35.87, and 3.85 mg g⁻¹ obtained from ethanol, methanol, and aqueous extracts, respectively (Limcharoen et al., 2022). In addition to alkaloids, kratom leaves contain considerable phenolic compounds and antioxidant activity, with reported total phenolic content of 252.92 mg GAE g⁻¹ (Limcharoen et al., 2022), while total phenolic content, total flavonoid content, and DPPH radical scavenging activity have also been reported as 90.88 mg GAE g⁻¹, 50.43 mg QE g⁻¹, and an IC₅₀ of 0.0397 mg mL⁻¹, respectively (Syed Azhar et al., 2023). However, although studies on other medicinal plants have demonstrated that drying method selection strongly influences phenolic retention and antioxidant capacity, systematic investigations linking drying methods to phenolic compounds, antioxidant activity, and mitragynine preservation in kratom leaves remain limited.

The present study addressed the lack of systematic evidence comparing color attributes, phenolic retention, and antioxidant preservation of kratom leaves under different drying technologies, with emphasis on an opaque solar-assisted greenhouse dryer with zero-energy airflow control. The objectives were to evaluate and compare four drying methods—direct sunlight drying, parabolic solar drying, hot-air tray drying, and the opaque greenhouse dryer with forced convection—in terms of physicochemical quality, total phenolic content, and antioxidant activity (DPPH and ABTS⁺ assays), and to identify the drying condition that provides the most favorable quality attributes for subsequent determination of mitragynine concentration. It was expected that solar-assisted low-temperature drying in the opaque greenhouse system would better preserve color, phenolic compounds, and antioxidant capacity than open sun drying while improving energy efficiency relative to hot-air tray drying.

2. Materials and methods

2.1 Materials and chemicals

Fresh kratom leaves (*Mitragyna speciosa* (Korth.) Havil.) were obtained from the Green Farmer Kalasin Community Enterprise, Non Buri Subdistrict, Sahatsakhan District, Kalasin Province, Thailand. All leaves were harvested at a similar maturity stage and transported to the laboratory within 6 h in insulated containers to minimize deterioration. Analytical-grade methanol, Folin–Ciocalteu reagent, sodium carbonate, 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), potassium persulfate, Trolox, and gallic acid standards. Mitragynine reference standard (purity $\geq$ 98%).

2.2 Sample preparation

The harvested leaves, including fresh controls, were washed with clean water and soaked in 0.1% (w/w) potassium metabisulfite (KMS) solution for 15 min to reduce enzymatic browning and microbial contamination prior to analysis. After soaking, the leaves were drained and gently air-dried to remove surface moisture. The initial moisture content of fresh leaves was determined using a drying method at 105 °C to constant weight (AOAC, 2000) and expressed on a wet basis (% w.b.).

A completely randomized design was applied to compare four drying methods: (i) direct sunlight drying, (ii) parabolic solar drying, (iii) hot-air tray drying, and (iv) an opaque solar-assisted drying system modified from a greenhouse using a blackout plastic cover (opaque greenhouse drying). For each method, kratom leaves were dried in triplicates ($n=3$). In all treatments, the loading density was standardized at 0.625 kg m⁻² and leaf thickness single layer was maintained. Drying was continued until the final moisture content reached 10 $\pm$ 2 % w.b. After drying, samples were packed in aluminum-laminated pouches, and stored at -18 °C until analysis.

2.3 Drying methods

2.3.1 Direct sunlight drying

Kratom leaves were spread in a single layer on stainless steel mesh trays and dried under direct sunlight from 8.00 A.M. to 5.00 P.M. Trays were positioned at 0.80 m. above ground. Ambient temperature, relative humidity and air velocity (Table 1) were recorded at 30 min intervals using a thermocouple (Testo 925, Germany) and hot-wire anemometer (AN510, Extech, USA). Simultaneously, solar radiation intensity was measured using a SOLAR meter (SM206-SOLAR, B'Angle, China). Leaves were turned every 2 h to promote uniform drying.

2.3.2 Parabolic solar drying

A parabolic solar dryer, based on the design proposed by Sudsuansee et al. (2023), was used, with samples prepared in the same manner as for direct sun drying. Kratom leaves were placed on perforated stainless steel trays inside the drying chamber. Drying temperature, relative humidity, and air velocity (Table 1) were recorded at 30 min intervals, and the drying process continued until the target moisture content was reached.

2.3.3 Hot-air tray drying

Hot-air tray drying (electric tray drying) was performed using a tray dryer (TD-10A, OFM, Thailand). Leaves were dried at 50 °C with an air velocity of 0.2 m s^{-1} (Table 1). Samples were placed in a single layer on trays and rotated every 2 h to reduce spatial variability. Drying was terminated at the target moisture content.

2.3.4 Opaque greenhouse drying

An opaque solar-assisted drying system was developed by modifying a plant greenhouse structure into a drying chamber and applying a blackout filter (opaque covering) to eliminate direct solar radiation. The system was designed to promote solar-driven convective hot-air circulation and improve hygienic drying conditions. The blackout filter was installed on all greenhouse surfaces using a UV-stabilized blackout film (black-and-white panda film, Toyotani™, China) to prevent light penetration while retaining heat. Heated air was circulated through the chamber using a solar-powered fan, with airflow directed from beneath the solar panel to the drying chamber. Drying temperature, relative humidity and air velocity (Table 1) inside the chamber were recorded from 8:00 a.m. to 5:00 p.m. at multiple locations to assess spatial uniformity. Kratom leaves were dried on mesh trays at a loading density of 0.625 kg m^{-2} until the target moisture content was reached.

Table 1. Drying conditions and operational parameters of different drying methods

Drying method	Drying temperature (°C)	Relative humidity (%)	Air velocity (m s^{-1})	Total drying time (h)	Heater power (W)
Direct sunlight	26.4–46.9	65.8–99.9 (Ambient)	0–1.3 (Natural airflow)	10	None
Parabolic solar	26.5–54.5	32.6–98.8	0–4.4 (Solar-driven airflow)	8	Solar energy
Hot-air tray	50.0±2.00	24.5–78.0	0.20±0.02	6	6 × 1000 W electric heaters
Opaque greenhouse	25.0–42.0	42.2–98.8	0–4.4 (Solar-driven airflow)	10	Solar energy

2.4 Chemical and physical properties analysis

2.4.1 Water activity measurement

Water activity (a_w) was measured by a water activity meter (Series 3TE, AquaLab, USA). Approximately 2.0 g of ground sample was placed in a container and placed in the water activity meter at 25°C.

2.4.2 Colorimetric analysis

Color values of fresh and dried kratom leaf samples were determined using a Colorimeter (UltraScan PRO, HunterLab, USA). The color parameters L* (lightness), a* (red–green), and b* (yellow–blue) were measured according to the CIELAB color system. Chroma (C*) and hue angle (°Hue) were subsequently calculated using Equations (1) and (2), respectively.

$$\text{Chroma (} c^* \text{)} = \sqrt{a^{*2} + b^{*2}} \quad \dots\dots\dots(1)$$

$$\text{Hue angle (} ^\circ\text{Hue)} = \tan^{-1} \frac{b^*}{a^*} \quad \dots\dots\dots(2)$$

These values provide insight into the visual quality and color stability of the kratom leaves during the drying process.

2.4.3 Proximate analysis

Proximate composition was assessed according to AOAC. (2000) methods. Moisture content was measured via hot-air oven drying; crude protein was analyzed using the Kjeldahl method; crude fat was extracted with a Soxhlet apparatus; ash content was determined by incineration in a muffle furnace; and crude fiber was analyzed through acid-base digestion. Carbohydrate content was calculated by difference. All data were reported on a wet basis (% w.b.).

2.5 Determination of total phenolic content and antioxidant activity

2.5.1 Preparation of the extract

The powdered kratom leaf sample (0.1 g) was extracted with 9 mL of 95% (v/v) ethanol, sonicated at 25 °C for 15 min, and subsequently centrifuged to separate the supernatant. The clear extract was transferred to a light-protective container and stored at –20 °C until further analysis.

2.5.2 Determination of total phenolic content (TPC)

Total phenolic content (TPC) of dried kratom leaf extracts was determined using the Folin–Ciocalteu spectrophotometric method, as described by Singleton & Rossi (1965), with minor modifications. Gallic acid was used as a standard, and results were expressed as mg gallic acid equivalents per gram of extract (mg GAE g^{–1}). Standard gallic acid solutions were prepared in methanol at concentrations of 0.05, 0.075, 0.10, 0.125, 0.150, 0.175, and 0.20 mg mL^{–1}. Kratom leaf extracts were also prepared in methanol at concentrations of 0.1 and 1.0 mg mL^{–1}. An aliquot of 0.5 mL of each standard or sample solution was mixed with 2.5 mL of tenfold-diluted Folin–Ciocalteu reagent, followed by the addition of 2.0 mL of 7.5% (w/v) sodium carbonate solution. The reaction mixtures were incubated at room temperature for 30 min, and absorbance was measured at 760 nm using a UV–Vis spectrophotometer (UV-1800, Shimadzu, Japan). All determinations were performed in triplicate.

2.5.3 DPPH radical scavenging activity

DPPH radical scavenging activity was determined according to the method described by Brand-Williams et al. (1995) with minor modifications. A DPPH working solution (0.1 mM) was prepared in

95% ethanol. An aliquot of the extract (50 µL) was mixed with 2.0 mL of the DPPH solution and incubated in the dark at room temperature for 30 minutes. The absorbance was measured at 517 nm using a UV–Vis spectrophotometer. Trolox was used as the reference standard, and antioxidant activity was expressed as the percentage of inhibition was calculated using in equation (3):

$$\text{Inhibition (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad \dots\dots\dots(3)$$

where A_{control} is the absorbance of the DPPH solution without extract and A_{sample} is the absorbance with extract.

2.5.4 ABTS⁺ radical cation decolorization assay

The ABTS⁺ radical scavenging assay was conducted according to the method described by Re et al. (1999) with minor modifications. The ABTS⁺ radical cation was generated by reacting ABTS solution (7 mM) with 2.45 mM potassium persulfate, followed by incubation in the dark at room temperature for 16 h. Prior to analysis, the ABTS⁺ solution was diluted with distilled water to obtain an absorbance of 0.70 ± 0.02 at 734 nm. An aliquot of the extract (50 µL) was mixed with the ABTS⁺ solution (3,000 µL) and incubated for 6 min at room temperature. Absorbance was then measured at 734 nm using a UV–Vis spectrophotometer. The percentage of radical scavenging activity was calculated using in equation (4):

$$\text{Radical Scavenging (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad \dots\dots\dots(4)$$

Where A_{control} is the absorbance of the ABTS⁺ solution without extract and A_{sample} is the absorbance with extract.

The selection of dried kratom leaves was based on a comparative evaluation of four different drying methods. The selection criteria integrated physical properties, chemical properties, and antioxidant activities, the latter of which were determined using total phenolic contents, DPPH radical scavenging activity and ABTS radical cation decolorization assays. The drying treatment yielding the most favorable attributes was identified as the optimal method.

2.6 Determination of mitragynine concentration

Mitragynine analysis was performed using a method adapted from the experimental procedures described by Subtaeng et al. (2023) and Mudge & Brown (2017). Briefly, 0.200 g of powdered kratom leaf sample was weighed into a 15 mL centrifuge tube, extracted with 10 mL methanol, vortex-mixed for 30 s, and subjected to ultrasonic extraction at 60 °C for 30 min using an ultrasonic sonicator (LUC-405, LabTech, Korea). The extract was centrifuged at 7,000 rpm for 10 min (UNIVERSAL 320, Hettich, Germany), and the residue was re-extracted under identical conditions. The combined supernatants were filtered through a 0.22 µm PTFE membrane prior to analysis. Mitragynine quantification was carried out using HPLC–PDA (Waters 2998, Waters, USA) equipped with a C18 column (LiChrospher®, Merck, Germany; 4.6 mm × 250 mm, 5 µm). Chromatographic separation was performed under isocratic conditions using 20 mM ammonium

acetate buffer (pH 6.0) and acetonitrile (35:65, v/v) at a flow rate of 1.0 mL min^{-1} , with an injection volume of 5 μL and detection at 226 nm. The total run time was 15 min, and the retention time of mitragynine was approximately 11.28 min. Mitragynine content was calculated from the calibration curve and expressed as milligrams per gram of dry weight (mg g^{-1}).

2.7 Statistical analysis

The experiments were conducted using a Completely Randomized Design (CRD). All treatments and subsequent analyses were performed in triplicate ($n=3$) to ensure the reproducibility of the data. Experimental results are expressed as mean $\pm$ standard deviation (SD). Statistical significance was evaluated through One-way Analysis of Variance (ANOVA) to determine the differences between treatments. In cases where significant differences were detected, the comparison of means was performed using Duncan's New Multiple Range Test (DMRT) at a confidence level of 95% ($p \leq 0.05$). All statistical computations and data processing were executed using the SPSS software package, version 23.0 (IBM Corp., Armonk, NY, USA).

3. Result

3.1 Chemical and physical properties

3.1.1 Proximate composition

The proximate composition of dried kratom leaves differed significantly among drying methods ($p \leq 0.05$), as shown in Table 2; however, fresh samples were not included in the statistical comparison because their initial moisture contents were not equivalent to those of the dried samples, which could lead to biased interpretation of compositional differences. Hot-air tray drying produced the lowest moisture content ($8.66 \pm 0.64\%$), while direct sunlight drying showed the highest ($10.36 \pm 0.49\%$). Fat content was highest in parabolic solar drying ($4.09 \pm 0.09\%$), whereas protein content was the highest under direct sunlight ($13.25 \pm 0.03\%$) and parabolic solar drying ($13.35 \pm 0.08\%$). Hot-air tray drying was the highest ash content ($5.71 \pm 0.09\%$). The opaque greenhouse drying was the highest carbohydrate content ($56.43 \pm 0.65\%$).

Table 2. Proximate composition of fresh and dried kratom leaves

Approximately composition (%w.b.)	Fresh kratom leaves	Drying method			
		Direct sunlight	Parabolic solar	Hor-air tray	Opaque greenhouse
Moisture	56.33 ± 0.30	10.36 ± 0.49^a	9.07 ± 0.85^b	8.66 ± 0.64^b	9.19 ± 0.39^b
Fat	2.05 ± 0.04	3.58 ± 0.11^b	4.09 ± 0.09^a	4.01 ± 0.09^a	3.46 ± 0.04^b
Protein	18.35 ± 0.12	13.25 ± 0.03^a	13.35 ± 0.08^a	12.59 ± 0.18^b	12.07 ± 0.04^c
Fiber	15.09 ± 0.19	15.83 ± 0.20^a	15.35 ± 0.20^c	15.79 ± 0.22^{ab}	15.57 ± 0.10^{bc}
Ash	2.05 ± 0.04	4.32 ± 0.20^b	4.05 ± 0.43^b	5.71 ± 0.09^a	3.27 ± 0.25^c
Carbohydrate	6.13 ± 0.78	52.66 ± 0.44^c	54.09 ± 0.60^b	53.25 ± 0.79^{bc}	56.43 ± 0.65^a

Values are Means $\pm$ Standard deviation.

Different superscript letters within a row indicate significant differences ($p \leq 0.05$).

3.1.2 Water activity

Water activity of kratom leaves was significantly affected by drying method ($p \leq 0.05$) (Table 3). The lowest water activity was observed in hot-air tray-dried samples ($a_w = 0.361 \pm 0.002$), followed by parabolic solar drying (0.381 ± 0.003), opaque greenhouse drying (0.417 ± 0.009), and direct sunlight drying (0.517 ± 0.006). All treatments achieved a_w values below 0.60, indicating conditions appropriate for the microbiological stability of dried herbal products.

Table 3. Water activity and color parameters of dried kratom leaves

Quality properties	Drying method			
	Direct sunlight	Parabolic solar	Hot-air tray	Opaque greenhouse
Water activity (a_w)	0.517 ± 0.006^a	0.381 ± 0.003^c	0.361 ± 0.002^d	0.417 ± 0.009^b
L*	52.08 ± 1.18^b	50.03 ± 0.36^c	46.63 ± 0.86^d	54.36 ± 0.54^a
a*	0.77 ± 0.06^c	2.22 ± 0.05^b	5.20 ± 0.26^a	-1.65 ± 0.15^d
b*	20.30 ± 1.37^b	21.21 ± 0.54^b	17.38 ± 1.16^c	23.14 ± 1.10^a
Chroma	20.32 ± 1.37^b	21.32 ± 0.54^b	18.14 ± 1.18^c	23.20 ± 1.11^a
°Hue	171.84 ± 0.45^b	168.02 ± 0.41^c	146.65 ± 0.87^d	175.64 ± 0.39^a

Values are Means $\pm$ Standard deviation.

Different superscript letters within a row indicate significant differences ($p \leq 0.05$).

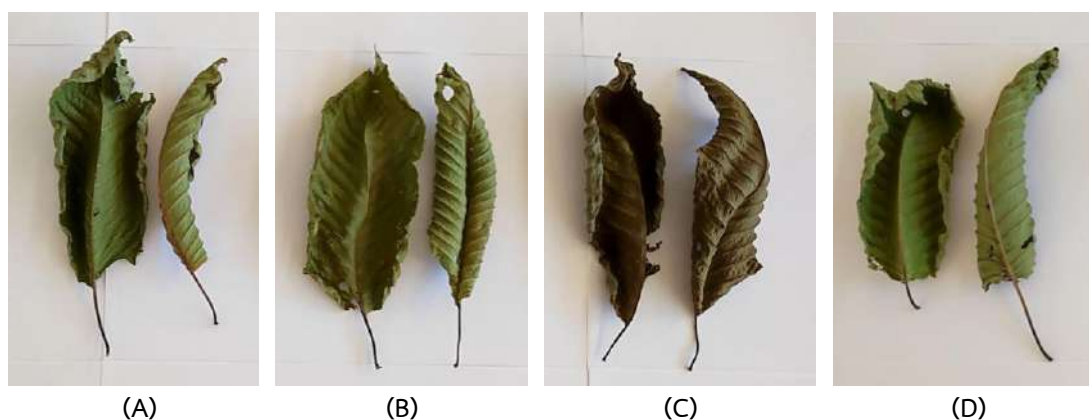


Figure 1. Visual appearance of dried kratom leaves obtained by different drying methods :

(A) Direct sunlight (B) Parabolic solar (C) Hot-air tray (D) Opaque greenhouse

3.1.3 Color parameters

Significant differences were observed in all color parameters among the drying methods (Table 2). Opaque greenhouse drying yielded the highest lightness ($L^* = 54.36 \pm 0.54$), whereas hot-air tray drying produced the lowest L^* value (46.63 ± 0.86), indicating darker coloration. The a^* values revealed a pronounced shift toward redness in hot-air tray-dried samples (5.20 ± 0.26), while opaque greenhouse drying exhibited negative a^* values (-1.65 ± 0.15), indicating greater retention of green coloration.

Regarding yellowness (b^*) and chroma, opaque greenhouse–dried leaves showed the highest values ($b^* = 23.14 \pm 1.10$; chroma = 23.20 ± 1.11), whereas hot-air tray drying resulted in the lowest values ($b^* = 17.38 \pm 1.16$; chroma = 18.14 ± 1.18). Hue angle ($^\circ\text{Hue}$) also differed markedly among methods; opaque greenhouse drying presented the highest $^\circ\text{Hue}$ (175.64 ± 0.39), followed by direct sunlight (171.84 ± 0.45), parabolic solar (168.02 ± 0.41), and hot-air tray drying (146.65 ± 0.87). Visual appearance of dried kratom leaves obtained by different drying methods is shown in Figure 1.

3.2 Total phenolic content and antioxidant activity

The total phenolic content (TPC) and antioxidant activity of dried kratom leaves were significantly influenced by the drying method applied (Table 4). Among the evaluated techniques, the opaque greenhouse drying and direct sunlight drying exhibited the highest phenolic contents, with values of 196.64 ± 1.53 and 195.07 ± 1.23 mg GAE g^{-1} extract, respectively, and no statistically significant difference was observed between these two methods ($p \leq 0.05$). This result indicates that both drying approaches were effective in preserving phenolic compounds under relatively mild thermal conditions.

In contrast, kratom leaves dried using the hot-air tray dryer showed a markedly lower phenolic content (83.82 ± 0.91 mg GAE g^{-1} extract), suggesting substantial degradation of phenolic compounds due to elevated temperature and prolonged heat exposure. The parabolic solar dryer yielded intermediate phenolic values (185.88 ± 1.20 mg GAE g^{-1} extract), indicating partial preservation of phenolic compounds compared with the opaque greenhouse drying and direct sunlight drying methods.

Table 4. Phenolic content and antioxidant activity of dried kratom leaves

Drying method	Phenolic content (mg GAE/g extract)	DPPH radical scavenging activities (%inhibition)	ABTS ⁺ assays (%radical scavenging)
Direct sunlight	195.07 ± 1.23^a	73.37 ± 1.06^b	96.79 ± 1.84^b
Parabolic solar	185.88 ± 1.20^b	71.51 ± 0.93^b	94.27 ± 2.02^c
Hot-air tray	83.82 ± 0.91^c	66.77 ± 1.03^c	83.46 ± 1.72^d
Opaque greenhouse	196.64 ± 1.53^a	74.03 ± 0.82^a	97.14 ± 1.29^a

Values are Means $\pm$ Standard deviation (S.D.).

Different superscript letters within a column indicate significant differences ($p \leq 0.05$).

Antioxidant activity, as determined by DPPH radical scavenging activity and ABTS⁺ radical cation decolorization assays, followed trends consistent with total phenolic content. The opaque greenhouse drying system exhibited the highest antioxidant activity, with DPPH inhibition of $74.03 \pm 0.82\%$ and ABTS⁺ radical scavenging of $97.14 \pm 1.29\%$, which were significantly higher than those observed for the other drying methods ($p \leq 0.05$). Direct sunlight drying showed comparable but slightly lower antioxidant activity ($73.37 \pm 1.06\%$ for DPPH and $96.79 \pm 1.84\%$ for ABTS⁺). Conversely, the hot-air tray drying resulted in the lowest antioxidant activity, with DPPH and ABTS⁺ inhibition values of $66.77 \pm 1.03\%$ and $83.46 \pm 1.72\%$, respectively.

Based on these results, opaque greenhouse drying with controlled hot-air circulation was identified as the most effective method for preserving color, total phenolic content, and antioxidant activity in dried kratom leaves. Consequently, this technique was selected as the optimal drying method for kratom leaves for subsequent determination of mitragynine content.

3.3 Mitragynine content of the fresh and dried kratom leaves

Mitragynine content was also strongly affected by the drying process. Fresh kratom leaves contained $6.54 \pm 15.03 \text{ mg g}^{-1}$, whereas leaves dried using the opaque greenhouse drying system as the most suitable drying method exhibited concentration of $9.83 \pm 14.68 \text{ mg g}^{-1}$.

4. Discussion

The present study demonstrated that the selection of drying method significantly influences the physicochemical quality of kratom leaves, particularly water activity and color attributes, which are critical indicators of product safety and consumer acceptance. All drying methods successfully reduced water activity to below 0.60, a threshold widely recognized as limiting microbial growth and enzymatic activity in dried plant materials (Prokopov & Tanchev, 2007).

Color preservation is another critical quality parameter for dried herbal products. The higher L^* values and lower a^* values observed in greenhouse-dried kratom leaves indicate reduced browning and improved retention of green pigments. This outcome aligns with the work of Maskan (2001) and Rubinskienė et al., (2015), reported that excessive thermal exposure and direct solar radiation accelerate chlorophyll degradation and non-enzymatic browning reactions. The use of a blackout filter in the opaque greenhouse drying system likely minimized photo-oxidative degradation, supporting earlier findings that shielding plant materials from ultraviolet radiation is essential for preserving visual quality in medicinal plants (Branisa et al., 2017).

Total phenolic content (TPC) and antioxidant activity are key indicators of the functional quality of kratom leaves. The present results showed that TPC and antioxidant activity of leaves dried in the opaque greenhouse system were comparable to those obtained by direct sunlight drying, as determined by both DPPH and ABTS⁺ assays. Although no significant difference in TPC was observed between these two methods, the opaque greenhouse system provided additional advantages, including more stable color attributes, lower water activity, and improved hygienic conditions due to protection from direct UV exposure and environmental contaminants. These combined quality factors support the selection of opaque greenhouse drying over direct sunlight drying, consistent with previous studies reporting that low-temperature, UV-shielded drying environments are effective in preserving phenolic compounds and antioxidant capacity while enhancing overall product quality (Arslan & Özcan, 2011; Puranik et al., 2012).

In contrast, hot-air tray drying resulted in a marked reduction in TPC and antioxidant activity, which can be attributed to the higher and constant drying temperature (50 °C for 6 h) compared with the milder conditions of the solar-based methods (opaque greenhouse 25–42 °C for 10 h; direct sunlight 26.4–46.9 °C for 10 h; parabolic solar 26.5–54.5 °C for 8 h). Prolonged exposure to elevated temperature is known to

accelerate thermal degradation, oxidation, and polymerization of phenolic compounds, leading to decreased radical scavenging capacity (Vega-Gálvez et al., 2009; Deng et al., 2019). Similar temperature-dependent losses have been reported in red pepper, oregano, and *Andrographis paniculata*, where drying above 45–50 °C significantly reduced TPC and antioxidant activity (Vega-Gálvez et al., 2009; Soiklom et al., 2024).

Additionally, antioxidant activity assessed via DPPH and ABTS⁺ assays were better preserved in kratom leaves processed with the opaque greenhouse drying system operated at lower and fluctuating temperatures with UV shielding (25–42 °C). These results are consistent with previous findings that drying systems with moderate thermal load and protection from ultraviolet radiation help maintain the integrity of polyphenolic and flavonoid compounds in medicinal plants (Ng et al., 2020; Rajurkar & Hande, 2011).

The mitragynine content obtained in the present study, expressed on a dry weight basis (mg g⁻¹), was consistent with the range reported by Leksungnoen et al. (2022), who found concentrations in Thai-grown kratom leaves varying from 7.5 to 26.6 mg g⁻¹. In this experiment, fresh kratom leaves contained 6.54±0.15 mg g⁻¹, while leaves dried using the opaque greenhouse system—the selected optimal method—exhibited a concentration of 9.83±0.14 mg g⁻¹. The differences between studies may be attributed to several factors, including variations in cultivar and genetic background, geographical and seasonal growing conditions, leaf maturity, and analytical procedures such as extraction efficiency and chromatographic protocols.

5. Conclusion and suggestions

5.1 Conclusion

This study evaluated the effects of different drying techniques on the chemical and physical properties, total phenolic content, and antioxidant activity retention of kratom leaves. All drying methods successfully reduced moisture content and water activity to levels suitable for safe storage. However, notable differences were observed, with the opaque greenhouse drying system exhibiting the most favorable color characteristics and antioxidant activity. Although the total phenolic content was comparable to that obtained by direct sunlight drying, the opaque greenhouse method provided superior hygienic attributes. In contrast, hot-air tray drying resulted in greater reductions in phenolic content and antioxidant capacity, likely due to thermal degradation. Mitragynine was quantified only in samples from the selected optimal drying condition; therefore, comparative conclusions regarding mitragynine preservation among drying methods cannot be drawn, and this represents a limitation of the present study. From a practical perspective, opaque greenhouse drying achieved target moisture and water activity levels appropriate for commercial storage while operating with minimal external energy input. These findings support the application of solar-assisted, low-temperature greenhouse drying as a feasible approach for community-scale kratom processing in Thailand, consistent with requirements for product quality, hygiene, and energy sustainability.

5.2 Suggestions for future research

5.2.1 Drying Kinetics and Compound Degradation Modeling

Further research is recommended to develop comprehensive drying kinetic and degradation models for kratom leaves, particularly for phenolic compounds and mitragynine, using a thin layer drying model. In addition, the establishment of such models would support process optimization and provide predictive tools for preserving product quality during drying.

5.2.2 Scale-Up and Techno-Economic Evaluation

Subsequent studies should evaluate the scalability, energy efficiency, and economic feasibility of the modified greenhouse drying system at pilot and industrial scales. Moreover, techno-economic assessment should incorporate key indicators such as payback period, energy consumption per kilogram of dried product, greenhouse dryer capacity, and operational and maintenance costs. Furthermore, life-cycle and cost-benefit analyses would facilitate the adoption of this technology for sustainable community and commercial kratom processing.

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และความคล่องแคล่วว่องไวของนักกีฬาฟุตบอล
The Development of SAQ and Flexibility Training Programs on the Speed
and Agility of Football Players

พงษ์เอก สุขใส^{1*}

Phong-ek Suksai^{1*}

¹ภาควิชาพลศึกษาและวิทยาศาสตร์การออกกำลังกาย คณะศึกษาศาสตร์ มหาวิทยาลัยนเรศวร

¹Department of Physical Education and Exercise Science, Faculty of Education, Naresuan University

*Corresponding Author: phoneks@nu.ac.th

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บทคัดย่อ

การวิจัยครั้งนี้มีวัตถุประสงค์เพื่อพัฒนาโปรแกรมการฝึกเอส เอ คิว ร่วมกับโปรแกรมฝึกความอ่อนตัว และศึกษาผลของโปรแกรมต่อความเร็วและความคล่องแคล่วว่องไวของนักกีฬาฟุตบอล โดยใช้รูปแบบการวิจัยและพัฒนา แบ่งเป็น 2 ระยะ ระยะที่ 1 เป็นการศึกษาเชิงพรรณนาและสำรวจสภาพจริง เก็บรวบรวมข้อมูลภาคสนามจากผู้ฝึกสอนฟุตบอล 5 คน และนักกีฬาฟุตบอลเพศชาย 15 คน ด้วยการสัมภาษณ์ถึงโครงสร้างร่วมกับการทบทวนเอกสารและงานวิจัยที่เกี่ยวข้อง นำข้อมูลมาวิเคราะห์และสังเคราะห์เพื่อออกแบบโปรแกรมการฝึกเอส เอ คิวร่วมกับโปรแกรมฝึกความอ่อนตัวให้สอดคล้องกับความต้องการของเกมการแข่งขันจริง ระยะที่ 2 เป็นการวิจัยเชิงกึ่งทดลอง กลุ่มตัวอย่างเป็นนักกีฬาฟุตบอลเพศชายระดับมหาวิทยาลัย จำนวน 30 คน แบ่งเป็นกลุ่มควบคุม 15 คน และกลุ่มทดลอง 15 คน กลุ่มควบคุมได้รับการฝึกซ้อมตามโปรแกรมปกติของทีม ขณะที่กลุ่มทดลองได้รับโปรแกรมการฝึกเอส เอ คิวร่วมกับโปรแกรมฝึกความอ่อนตัว เป็นเวลา 8 สัปดาห์ ทำการทดสอบความเร็ววิ่งระยะ 30 เมตร และความคล่องแคล่วว่องไวด้วยแบบทดสอบ Illinois Agility Test โดยเวลาเฉลี่ยจากทดสอบ 3 ครั้งของแต่ละแบบทดสอบ ในก่อนการฝึก หลังการฝึก 4 สัปดาห์ และหลังการฝึก 8 สัปดาห์ วิเคราะห์ข้อมูลด้วยค่าเฉลี่ย ส่วนเบี่ยงเบนมาตรฐาน และทดสอบความแตกต่างโดยการทดสอบค่า t กำหนดระดับนัยสำคัญทางสถิติที่ระดับ .05 ผลการวิจัยพบว่า ระยะที่ 1 นักฟุตบอลยังมีข้อจำกัดด้านความเร็ว การเปลี่ยนทิศทาง ความอ่อนตัว และการควบคุมร่างกายในการเล่นจริง ซึ่งผลดังกล่าวได้นำมาใช้เป็นข้อมูลพื้นฐานในการออกแบบโปรแกรมการฝึกเอส เอ คิวร่วมกับโปรแกรมฝึกความอ่อนตัว ในระยะที่ 2 หลังการทดลอง 4 สัปดาห์ กลุ่มทดลองมีผลการทดสอบเวลา Illinois Agility Test ดีกว่ากลุ่มควบคุมอย่างมีนัยสำคัญ และหลังการทดลอง 8 สัปดาห์ กลุ่มทดลองมีผลการทดสอบดีกว่ากลุ่มควบคุมทั้งในตัวแปร 30-Meter Sprint และ Illinois Agility Test อย่างมีนัยสำคัญทางสถิติที่ระดับ .05 แสดงให้เห็นว่าโปรแกรมการฝึกเอส เอ คิวร่วมกับโปรแกรมฝึกความอ่อนตัวที่พัฒนาขึ้นสามารถช่วยเพิ่มความเร็วและความคล่องแคล่วว่องไวของนักกีฬาฟุตบอลชายระดับมหาวิทยาลัยได้อย่างมีประสิทธิภาพ และเป็นแนวทางหนึ่งที่ผู้ฝึกสอนสามารถนำไปประยุกต์ใช้ในการเตรียมสมรรถภาพให้สอดคล้องกับความต้องการของการแข่งขันฟุตบอล

คำสำคัญ: โปรแกรมเอส เอ คิว, โปรแกรมฝึกความอ่อนตัว, ความเร็ว, ความคล่องแคล่วว่องไว, นักกีฬาฟุตบอล

Abstract

This study aimed to develop a Speed, Agility and Quickness (SAQ) training program combined with a flexibility training program, and to examine their effects on speed and agility in football players. A research and development (R&D) design was employed and divided into two phases. Phase 1 was a descriptive and field-based exploratory study where data were collected from five football coaches and fifteen male football players through semi-structured interviews along with a review of relevant documents and research. The information obtained was analyzed and synthesized to design an SAQ plus flexibility training program that corresponded to the demands of actual football competition. Phase 2 used a quasi-experimental research design. The sample consisted of 30 male university football players, divided into a control group ($n = 15$) and an experimental group ($n = 15$). The control group followed the team's regular training program, whereas the experimental group received the SAQ plus flexibility training program for 8 weeks. Speed was assessed using a 30-meter sprint test, and agility was assessed using the Illinois Agility Test, recording the mean time of three trials for each test at pre-training, after 4 weeks of training, and after 8 weeks of training. Data were analyzed using mean and standard deviation, and differences were tested using the independent t-test with the level of statistical significance set at .05.

The results showed that, in Phase 1, players exhibited limitations in speed, change-of-direction ability, flexibility, and body control during actual match play. These findings were used as baseline information for designing the SAQ plus flexibility training program in Phase 2. After 4 weeks of intervention in phase 2, the experimental group achieved significantly better Illinois Agility Test times than the control group. After 8 weeks, the experimental group also outperformed the control group on both the 30-meter sprint and the Illinois Agility Test at the .05 level of statistical significance. These findings indicate that the combined SAQ and flexibility training program developed in this study can effectively enhance speed and agility in male university football players and provides a practical guideline for coaches to prepare players' physical fitness for the demands of competitive football.

Keywords: SAQ training, Speed, Agility, Flexibility training, Football players

1. Introduction

Football (soccer) is one of the most popular sports, and in the present era, coaches are continually required to search for and apply diverse training methods to enhance players' performance. Football players need to possess not only well-developed technical skills but also a high level of physical fitness to achieve success in competition. Components of optimal physical fitness for football include muscular strength, power, endurance, speed, balance, neuromuscular coordination, flexibility and, most importantly, agility.

Movement in football can be broadly classified into two types: movement without the ball, which involves repeated acceleration, deceleration, and rapid changes of direction to evade opponents; and movement while in possession of the ball, which requires controlling and manipulating the ball with the

feet. Given these demands, agility, or the ability to change direction quickly, is regarded as a fundamental physical fitness attribute in football, as players must constantly use agile movements to gain an advantage over opponents. Therefore, the development of agility in football players is considered a critical component of performance enhancement (Thachaila, 2018).

In football competitions, players must perform movements without the ball that involve acceleration, deceleration, and changes of direction to evade marking and defensive pressure, create space to receive the ball and move into goal-scoring positions. These actions are sport-specific motor skills and collectively represent agility in football. Therefore, agility forms a crucial foundation of physical fitness in this sport. In any type of sport, if athletes can control their movements efficiently and in accordance with the sequential demands of sport-specific motor skills during competition, it will be beneficial to their performance.

The ability to move and change position rapidly in harmony with the required movement patterns provides athletes with an advantage at every opportunity and every moment of play. Coaches should therefore understand the principles and methods of training to develop agility in ways that align with the specific movement skills and movement demands of each sport, because every sport has its own distinctive movement patterns (Krabuanrat, 2014). Consequently, training programs must be designed in ways that are appropriate for and specific to the skills and demands of each sport.

Speed, agility and quickness (SAQ) training is a widely implemented and well accepted method for developing agility, and consists of drills that specifically target speed, agility and quickness. Hale (2004) noted that most SAQ drills are based on the principle of neuromuscular coordination training, which refers to the ability of the central nervous system and the muscles to work together to perform complex movements efficiently and accurately. Athletes who demonstrate superior neuromuscular coordination can learn new skills more rapidly and perform these skills with a high level of proficiency. Athletes with a high degree of agility gain a clear advantage in many aspects of performance, particularly in changing direction quickly to evade opponents and in dribbling the ball at speed, both of which depend on speed, agility and rapid reaction. When these movement patterns are practiced correctly and to a high degree of mastery, athletes can express their skills effectively in competitive situations. Furthermore, the enhancement of agility in football players also depends on flexibility training, because the changes that occur in tendons and joints during running and changes of direction directly influence the efficiency of movement in football (Andrašić et al., 2021).

Several empirical studies have provided direct evidence that SAQ-based interventions can improve speed- and agility-related performance in football players. Milanović et al. (2013) reported that a 12-week SAQ conditioning program produced significant improvements in multiple field-based agility tests, both with and without the ball, in young male soccer players compared to a control group. Similarly, Lee et al. (2024) showed that eight weeks of SAQ training led to greater gains in acceleration, maximal sprint speed and change-of-direction performance than general football training in highly trained under-20 female football players. At a broader level, a recent meta-analysis by Sun et al. (2025) synthesized nine intervention studies and found that SAQ training produced small-to-moderate improvements in sprint speed, change-of-

direction ability, change-of-direction dribbling and lower-limb power in adolescent soccer players when compared with control conditions. Collectively, these findings support the use of SAQ training as an evidence-based approach for enhancing speed and agility in football, in line with the conceptual rationale outlined above.

In addition, flexibility-oriented interventions have also been shown to contribute to agility performance while lowering injury risk. Behm (2023), in a narrative review on dynamic stretching, reported that incorporating dynamic flexibility exercises into warm-up routines can acutely increase the range of motion. When combined with sport-specific dynamic activities, it is also associated with reductions in musculotendinous injury incidence in sports that require rapid accelerations and frequent changes of direction, such as football.

Given the importance of physical fitness components related to rapid movement and changes of direction, it is evident that these attributes are indispensable in both the training and competitive performance of football players. Numerous investigations have explored the development of agility through various integrated training modalities in different athletic populations and across diverse training formats. Therefore, the present study was designed to develop and evaluate a combined training program that integrates speed, agility, and quickness (SAQ) training with flexibility training, and to examine their effects on speed and agility in football players. This combined protocol is expected to serve as an additional, potentially more effective modality for enhancing the physical fitness of Thai football players, and to provide football coaches with evidence-based guidelines for selecting training methods that are optimally aligned with the goal of maximizing athletes' performance development.

2. Materials and methods

This study was designed to develop a training program that integrates speed, agility, and quickness (SAQ) training with flexibility exercises to improve speed and agility in football players. Additionally, it aimed to experimentally examine and evaluate the effects of this combined SAQ and flexibility training program on the speed and agility of football players in control and experimental groups before training and after 4 and 8 weeks of training. The investigation was conducted in two phases as follows

Phase 1 Field investigation for the development of a combined speed, agility and quickness (SAQ) and flexibility training program to enhance speed and agility in football players.

1. Permission was obtained from the relevant institutional authorities, and the football team coaches to conduct field data collection.

2. The research objectives were explained to the coaches and players, and informed consent was obtained from all participants.

3. The sample for the Phase 1 field study was selected using purposive sampling from individuals involved in university-level football training. The sample consisted of five football coaches, all of whom were responsible for coaching university football teams, had at least two years of experience in training and supervising football players, and were serving as coaches during the current competitive season; and 15

male football players, all of whom were members of the university football team, had participated regularly in team training for at least six months, and had no medical contraindications or severe injuries that would prevent participation in training during the data collection period.

Thus, the total sample in Phase 1 comprised 20 participants. All participants were informed of the research objectives and provided consent prior to data collection. Phase 1 took the form of a descriptive survey-based investigation of the current situation and needs of relevant stakeholders, to generate baseline information for the development of the training program. The sample size was therefore determined based on contextual appropriateness within the population of university football coaches and players.

4. Semi-structured interviews were conducted individually with each football coach, focusing on questions related to current problems and constraints in physical fitness training. Audio recordings and field notes were used to document the interviews, including the coaches' perspectives on integrating SAQ drills and flexibility training within a combined training program.

5. Data obtained from questionnaires, interviews, and observations were analyzed and synthesized in conjunction with a review of relevant literature and research. This process was used to develop a combined SAQ, and flexibility training program aimed at improving speed and agility in football players.

6. The combined SAQ and flexibility training program to improve speed and agility in football players was tried out with football players who were not part of the study sample, and the combined SAQ and flexibility training program was then revised to be appropriate for developing a training program model to improve speed and agility in football players. The research instruments used in the study were also constructed and tested for quality.

The procedures for constructing the instruments were as follows:

6.1 Relevant documents, books, textbooks, and research studies concerning the development of a combined SAQ and flexibility training program were reviewed.

6.2 A combined SAQ and flexibility training program to improve speed and agility for football players was developed.

6.3 The program developed by the researcher was discussed with the co-researchers to check its accuracy.

6.4 The developed program was submitted to three experts to examine content validity. The experts evaluated the consistency of each drill with the intended construction and assigned scores. The index of item-objective congruence (IOC) was then calculated, and only training drills and tests with an IOC value of .50 or higher were retained for use in training and testing.

6.5 The researcher revised the speed and agility training program based on the experts' suggestions.

7. The revised speed and agility training program, which integrated five SAQ-based agility exercises (running in T- and Y-shaped patterns and short multi-directional movements followed by 10-metre straight and lateral sprints) with a 16-exercise flexibility routine targeting the major muscle groups of the lower limbs, hips, trunk and shoulders, was then implemented with the sample in Phase 2 of the study. The program was designed in accordance with the principles of training specificity, progressive overload and

neuromuscular coordination, with the aim of improving short-distance sprint speed, change-of-direction ability and functional range of motion while reducing muscle tightness and injury risk.

Phase 2 Experimental implementation and evaluation of the combined SAQ and flexibility training program on the speed and agility of football players in the control and experimental groups before training and after 4 and 8 weeks of training. In this phase, the program was applied in actual training sessions with the sample, as detailed below.

1. Permission was obtained from the relevant institutional authorities, and the football team coaches to collect data on the implementation of the combined speed, agility, and quickness (SAQ) and flexibility training program.

2. The research objectives were explained to the coaches and athletes, and informed consent was obtained from all participants.

3. The sample consisted of 30 male football players from the Naresuan University football team, selected by purposive sampling from the entire population. The sample size was determined according to the general guideline that, for experimental research, at least 15 participants per group are required (McMillan & Schumacher, 2014). This is consistent with statistical criteria for comparing mean differences between two groups, with an effect size (ES) of 0.95 and a Type I error (level of statistical significance) of $\alpha = .05$. Using the G*Power program (Version 3.1), the minimum required sample size was thus 15 participants per group. Subsequently, purposively selected volunteers who were in good health and able to participate throughout the training program were recruited. They underwent testing before training, during training at week 4, and after training at week 8. Participants in both groups were assessed for speed using a 30-metre sprint test with timing (Taşkın, 2008), and for agility using the Illinois Agility Test (Hachana et al., 2013). Inclusion criteria were applied prior to participation in the training program. All 30 eligible participants were then randomly assigned by drawing lots into two groups: an experimental group ($n = 15$) and a control group ($n = 15$). All participants met the inclusion and exclusion criteria described below.

Inclusion criteria were as follows:

1. Participants were required to volunteer to take part in the study and to provide written informed consent from their parents or legal guardians.

2. Participants were required to have no chronic diseases or medical conditions that would interfere with participation in the study.

3. Participants agreed and acknowledged that they might take part in other football skill training programs in addition to the training program implemented in this research project.

4. Participants were male football players who had been selected by their coaches as members of the Naresuan University representative team, were in good health, and were between 18 and 23 years of age in the 2023 academic year at Naresuan University, Phitsanulok Province, with a total of 30 players.

Exclusion criteria were as follows

1. Participants who developed health problems or sustained injuries that, in the judgment of the researcher, posed a risk to the participant or constituted an obstacle to the conduct of the study.

2. Participants who engaged in additional football skill training beyond the training program

prescribed in this research program.

3. Participants whose attendance at the training sessions was less than 80% of the total duration of the research program.

4. The intervention was implemented by assigning different types of training according to the research groups, as follows:

4.1 Training for the control group consisted of the regular training program used weekly by the male football team coach at Naresuan University, Phitsanulok. This routine included warm-up and stretching, football skill training such as passing and receiving, dribbling and shooting, as well as tactical play such as defensive and offensive organization, followed by a cool-down using stretching exercises.

4.2 Training for the experimental group consisted of the regular coach-led team training program supplemented, within the same training sessions, by the SAQ and flexibility training components. In each session, players first completed the coach-prescribed warm-up, followed by the SAQ exercises, and then performed the 16-exercise flexibility routine as part of the cool-down, as detailed below.

4.2.1 SAQ Training

The training program was implemented over a period of 8 weeks. In weeks 1–2, training was conducted twice per week; in weeks 3–4, three times per week; in weeks 5–6, four times per week; and in weeks 7–8, five times per week, following a progressive overload principle. All training drills were performed at maximal effort, with a 1-minute rest interval between sets. The program comprised five training drills as follows

Exercise 1: running in a T-shaped pattern.

Exercise 2: running in a Y-shaped pattern.

Exercise 3: alternating changes of direction followed by a 10-metre sprint.

Exercise 4: straight-line running with alternating leg movements followed by a 10-metre sprint.

Exercise 5: lateral running with alternating leg movements followed by a 10-metre sprint.

Each exercise was performed for three sets, in addition to the regular futsal training, which was identical to that of the control group and was prescribed daily by the Naresuan University football team coach in Phitsanulok.

4.2.2 Flexibility Training

The flexibility training program was implemented as a static stretching protocol over 8 weeks, with training conducted twice per week in weeks 1 and 2, three times per week in weeks 3 and 4, four times per week in weeks 5 and 6, and five times per week in weeks 7 and 8. The stretching component consisted of 16 muscle-stretching exercises, each performed for two repetitions of 10–15 seconds, organized according to the following muscle groups.

4.2.2.1 Shoulder and posterior upper arm stretching

4.2.2.2 Thigh muscle stretching

4.2.2.3 Hip muscle stretching

4.2.2.4 Thigh muscle stretching

4.2.2.5 Posterior upper arm and posterior shoulder stretching

4.2.2.6 Trunk muscle stretching

4.2.2.7 Posterior shoulder and shoulder-rotator muscle stretching

This was carried out in addition to the regular football training, which was identical to that of the control group and was prescribed daily by the Naresuan University football team coach in Phitsanulok. Before the training period, at week 4 during the training, and after week 8 of the training program, participants in both groups were assessed for speed using a timed 30-m sprint and for agility using the Illinois Agility Test. The data obtained from these assessments were then analyzed.

5. Analysis of the experimental outcomes and evaluation of the effects of the combined SAQ and flexibility training program on speed and agility in football players in the control and experimental groups before training and after weeks 4 and 8 of the training programs.

3. Result

3.1 Qualitative findings on current problems and constraints in physical fitness training from the perspectives of coaches and athletes.

3.1.1 Coaches

From the interviews with all five football coaches, several common themes emerged regarding problems and limitations in players' physical fitness during competition, which directly affect their ability to execute the team's game plan, as follows

3.1.1.1 Speed and change of direction abilities did not match the tempo of actual match play. Several coaches reported that players accelerated and changed direction more slowly than required by the tactical game plan, which resulted in the loss of crucial moments both in attack, such as fast counterattacks, and in defense, such as closing space or shifting the defensive line. Consequently, opponents were able to penetrate dangerous areas more easily.

3.1.1.2 The capacity for continuous movement declined toward the end of the match. Fatigue in the second half was identified as a common problem, leading to slower movement, reduced responsiveness to game situations, and a marked decrease in the planned intensity of play. As a result, the team lost compactness and overall tactical effectiveness.

3.1.1.3 The existing training formats were not aligned with real match situations. Coaches agreed that training which emphasized long-distance running or laps around the field did not adequately develop short, intensive movements that require stopping, accelerating, turning, and changing direction, which are key movement behaviors in football. This mismatch limited the practical application of tactics that depend on speed and complex movement patterns.

3.1.1.4 Limitations in flexibility and body control affected both injury risk and movement quality. Some coaches observed that many players had high levels of muscle tightness and an incomplete range of motion, which negatively influenced agility and dribbling in attacking play and increased the risk of injury, particularly during rapid acceleration or sharp changes of direction.

3.1.1.5 There was a lack of a clearly structured training program and no systematic monitoring of outcomes. Coaches indicated that current fitness training lacked an organized framework and regular assessment of progress, making it impossible to determine whether training truly improved physical fitness. This led to inconsistent quality of performance, especially in high pressure situations.

3.1.2 Football players

Based on in-depth interviews with all 15 football players, the primary factors constraining their ability to implement the match plan were found to be directly associated with several components of physical fitness, including speed, acceleration, change of direction, flexibility, endurance, and body control.

3.1.2.1 Speed and acceleration that do not match the tempo of play. Many players reported feeling that their initial acceleration was slow or that they could not increase their speed quickly enough to keep up with teammates, resulting in missed positions in counterattacking situations or during transitions from defense to attack, and consequently disrupting the team's offensive rhythm.

3.1.2.2 Insufficient agility in changing direction and turning. A substantial number of players experienced difficulties under pressure or in confined spaces, reporting that they were unable to turn quickly enough, were easily dispossessed, and frequently lost the ball. One-on-one situations and high-speed dribbling were also perceived as less effective due to suboptimal body control.

3.1.2.3 Inability to keep pace with offensive–defensive transitions. Many players reported that they were “unable to move up and down the pitch in time” or “could not transition from attack to defense quickly enough,” which resulted in loss of defensive positioning or incomplete support in attack. Although they understood the tactical requirements, their physical responses were not fast enough to meet the demands of the game.

3.1.2.4 End-of-match fatigue affecting tactical execution. Several players indicated that their speed and agility decreased markedly toward the end of the match. This decline led to a loss of compactness in defense and an inability to execute attacking movements in accordance with the patterns prescribed by the coach.

3.1.2.5 Insufficient flexibility and accumulated muscle tightness. Some players reported tightness in the hamstrings and hip muscles, which limited their ability to turn, change direction while running, and accelerate through the full range of motion. This not only reduced performance effectiveness in actual match play but also increased the risk of injury.

3.1.2.6 Suboptimal short-distance speed and situational responsiveness. Many players noted that they frequently lost timing on second balls or challenges because they initiated movement too slowly and were unable to respond quickly enough to opponent's movements.

3.2 Experimental results and evaluation of the effects of the combined SAQ and flexibility training program on the speed and agility of football players in the control and experimental groups before training and after 4 and 8 weeks of training in this study.

3.2.1 The participants in the control group had a mean height of 172.93 ± 6.76 kilograms, a mean body weight of 61.60 ± 6.90 centimeters, and a mean body mass index of 20.57 ± 1.71 kg/m². Their mean heart rate was 68.60 ± 6.96 beats per minute, with a mean systolic blood pressure of 124.47 ± 7.41 mmHg and a mean diastolic blood pressure of 78.80 ± 7.02 mmHg. In the experimental group, the mean height was 174.13 ± 5.57 kilograms, the mean body weight was 64.67 ± 7.50 centimeters, and the mean body mass index was 21.27 ± 1.56 kg/m². The mean heart rate in this group was 67.53 ± 6.30 beats per minute, with a mean systolic blood pressure of 121.20 ± 7.99 mmHg and a mean diastolic blood pressure of 73.53 ± 7.98 mmHg in Table 1.

Table 1. The mean and standard deviation of the participants' baseline characteristics in the study.

Participant Characteristics	Control Group (n = 15)		Experimental Group (n = 15)	
	$\bar{X}$	S.D.	$\bar{X}$	S.D.
Height (cm.)	172.93	6.76	174.13	5.57
Weight (kg.)	61.60	6.90	64.67	7.50
Body mass index (kg/m ²)	20.57	1.71	21.27	1.56
Pulse (Time/min ⁻¹)	68.60	6.96	67.53	6.30
Systolic blood pressure (mmHg)	124.47	7.41	121.20	7.99
Diastolic blood pressure (mmHg)	78.80	7.02	73.53	7.98

3.2.2 The 30-metre sprint and Illinois Agility Test data were examined for normality. In both the control and experimental groups, the distributions did not significantly deviate from a normal distribution at the .05 level (Table 2). As the assumption of normality was satisfied, differences between the experimental and control groups were analyzed using independent t-tests. At baseline, no statistically significant differences were found between the groups in mean 30-metre sprint time or agility scores ($p > .05$). After 4 weeks of training, the experimental group demonstrated significantly better Illinois Agility Test scores than the control group ($t = 3.431$, $p = .002$). After 8 weeks, significant between-group differences were observed in both the 30-metre sprint ($t = -4.455$, $p < .001$) and the Illinois Agility Test ($t = 1.344$, $p < .01$) (Table 3).

Table 2. The results of the normality analysis (Normal distribution) of speed and agility data using the Shapiro–Wilk test for the control and experimental groups (n = 30)

List of tests	Test of normality (Shapiro-Wilk)			normality of the data
	Statistic	df	Sig.	
Control Group (n = 15)				
Pre-test				
30-Meters Sprint	.908	15	.127	Normal
Illinois Agility Test	.983	15	.986	Normal
Mid-test (After 4 weeks)				
30-Meters Sprint	.897	15	.087	Normal
Illinois Agility Test	.985	15	.992	Normal
Post-test (After 8 weeks)				
30-Meters Sprint	.909	15	.132	Normal
Illinois Agility Test	.985	15	.994	Normal
Experimental Group (n = 15)				
Pre-test				
30-Meters Sprint	.908	15	.128	Normal
Illinois Agility Test	.963	15	.737	Normal
Mid-test (After 4 weeks)				
30-Meters Sprint	.901	15	.097	Normal
Illinois Agility Test	.952	15	.551	Normal
Post-test (After 8 weeks)				
30-Meters Sprint	.912	15	.148	Normal
Illinois Agility Test	.922	15	.203	Normal

*P-value < .05

Table 3. The results of the analysis of differences in speed and agility among football players between the two groups using the independent t-test.

List of tests	Control Group		Experimental Group		t	Sig.
	(n = 15)		(n = 15)			
	$\bar{X}$	S.D.	$\bar{X}$	S.D.		
Pre-test						
30-Meters Sprint	4.43	0.22	4.43	0.22	.016	.987
Illinois Agility Test	16.72	0.55	16.54	0.75	.735	.468
Mid-test (After 4 weeks)						
30-Meters Sprint	4.41	0.21	4.39	0.21	.250	.805
Illinois Agility Test	16.70	0.55	15.95	0.63	3.431	.002*
Post-test (After 8 weeks)						
30-Meters Sprint	4.38	0.21	4.13	0.06	4.445	<.001*
Illinois Agility Test	16.66	0.54	15.74	0.63	1.344	<.001*

*p-value <.05

4. Discussion

4.1 Discussion of the qualitative analysis of current problems and limitations in physical fitness training from the perspectives of coaches and football players, as follows:

4.1.1 The synthesis of the coaches' accounts. It emerged that the main problems related to players' physical fitness were directly linked to actual match performance. Many players were unable to accelerate and change direction in line with the tempo of the game, which resulted in lost opportunities both in fast counterattacking situations and in defensive moments when closing space. Consequently, opponents were able to penetrate dangerous areas more easily. In addition, toward the end of matches, players commonly experienced fatigue, moved more slowly, and responded less effectively to changing situations. The overall intensity of play declined, making it difficult for the team to maintain its tactical structure and compactness. Moreover, the coaches also indicated that the current training formats largely emphasized long-distance running or laps around the field, which do not correspond to the actual movement demands of football, where players must frequently stop, accelerate, turn, and change direction rapidly over short distances. Some players were reported to have pronounced muscle tightness and limited range of motion, which reduced their agility in dribbling and evasive movements and increased their risk of injury, particularly during high-speed accelerations or sharp changes of direction. Furthermore, the coaches noted that fitness training lacked a clearly structured program and systematic monitoring. As a result, it was difficult to determine the extent to which the existing training improved players' physical fitness and prepared them to cope with high-pressure match situations.

4.1.2 The synthesis of the football players' accounts indicated that key deficiencies in physical fitness exerted a clear influence on on-field performance. Many players reported that they were slow off the mark and unable to accelerate quickly enough to keep pace with teammates, resulting in failure to reach the positions required for counterattacks or for rapid transitions from defense to attack. Although they understood where they were supposed to run according to the tactical plan, their bodies could not respond quickly enough. When confronted with opponents pressing aggressively or when play became fast in restricted spaces, they often could not turn in time, were easily forced into losing possession, and were unable to perform high-speed dribbling or one-on-one situations effectively due to insufficient body control. In addition, many players noted a marked decline in speed and agility toward the end of matches. This reduction led to a looser defensive shape, less effective space coverage, and attacking movements that could not be executed in accordance with the patterns prescribed by the coach. Some reported pronounced muscle tightness, particularly in the hamstrings and hip region, which limited their ability to turn, change direction while running, and accelerate to full speed, thereby increasing the risk of injury. In second-ball situations or challenges for possession, they frequently reacted more slowly than their opponents because they initiated movement late and were unable to respond promptly to opponents' movements. Overall, these findings indicate that the players' speed, agility, flexibility, and situational responsiveness were not yet sufficient to fully support the tactical demands required in competitive play.

Based on the accounts of both coaches and players, the physical fitness of the athletes did not adequately meet the demands of competitive match play, particularly in terms of speed, acceleration, change of direction, and body control. Therefore, players were often unable to respond to the tempo of the game in accordance with the tactical plan, whether in situations involving counterattacks, closing down space, or transitioning from attack to defense. In addition, players experienced pronounced fatigue toward the end of matches, which led to a decline in movement efficiency and an inability to maintain the intended tactical intensity. Many players also reported tightness in the hamstrings and hip muscles, resulting in a reduced range of motion and increased injury risk, especially during high-speed acceleration or abrupt changes of direction.

At the same time, the existing training formats were not well aligned with the movement demands of modern football, which requires frequent stopping, accelerating, turning and changing direction over short distances; instead, training predominantly emphasized long-distance running or laps around the pitch. Moreover, the lack of a clearly structured program and an associated monitoring system made it difficult to evaluate progress consistently. Collectively, these observations indicate that players require targeted development of specific fitness components to execute tactical game plans effectively under real match conditions. This is consistent with Gonçalves et al. (2021), who examined the relationship between physical fitness levels and running performance during competition in adult female football players using a cohort study design. Their findings showed that physical fitness indicators such as repeated-sprint ability, aerobic endurance and muscular power were associated with high-speed running distance and sprinting during actual matches, with better-conditioned players able to sustain high-speed running and respond more effectively to game tempo. This accords with the present findings, which suggest that insufficient speed and

change-of-direction capacity limit players' ability to perform tactically as intended. Similarly, Hosseini et al. (2025) investigated the effects of an 8-week dynamic hamstring stretching program, specifically Nordic hamstring training, on balance, range of motion, agility and muscle performance in male football players with short hamstrings, using a randomized controlled trial design. Their results demonstrated that a structured 8-week stretching and strengthening program for the hamstrings significantly improved range of motion, balance, agility and muscle performance in players with hamstring tightness. These findings are in line with the present study's conclusion that tightness in the hamstrings and hip muscles restricts the range of motion, increases injury risk, and negatively affects sprint performance and change of direction during actual match play.

4.2 Discussion of the differences in speed and agility between the experimental and control groups, and within groups across pre-test, 4-week post-test, and 8-week post-test measurements.

After 4 weeks of training, the experimental group showed better Illinois Agility Test times than the control group, and after 8 weeks the experimental group outperformed the control group in both the 30-metre sprint and the Illinois Agility Test, with differences that were statistically significant at the .05 level. These improvements can be attributed to the training program, which emphasized short-distance movements, stopping, accelerating and changing direction, combined with exercises to enhance muscle and joint flexibility. Such training enabled players to respond more effectively to game tempo, move more rapidly, and control their movement direction on the pitch more efficiently.

Physiologically, the changes observed as early as the first 4 weeks are likely related to neural adaptations, whereby the brain and nervous system become more familiar with the required movement patterns, allowing muscles to be activated more rapidly and in better coordination. Concurrent flexibility training reduced muscle tightness, particularly in the hip and hamstring regions, thereby facilitating smoother strides, turning and changes of direction without restriction. With continued training over the full 8-week period, these adaptations translated into clearer gains in both sprint speed and overall agility. These findings are consistent with Hosseini et al. (2025), who reported that an 8-week program of hamstring stretching and strengthening produced significant improvements in range of motion, balance and agility among football players. In line with their results, the present study indicates that a flexibility-oriented program combined with high-velocity movement and change-of-direction training has a positive effect on athletes' physical performance.

When the training was completed at 8 weeks, the experimental group showed clear improvements in both short-distance speed over 30 meters and agility. This finding is consistent with the principle that when training stimuli are sufficiently specific and continuous, adaptive changes occur in both the neuromuscular system and the muscle–tendon mechanism. As a result, the rate of force development improves, and the muscle–tendon stretch–shortening cycle operates more efficiently during sprinting and changes of direction, thereby reducing the time required for short accelerations and directional changes. These results are in line with the study by Gołaś et al. (2024), which examined the effects of an 8-week pre-season specialized training program on sprint performance, agility, and lower-limb muscle imbalance in

professional football players. Their 8-week position- and task-specific program, designed to closely replicate football movement patterns, produced significant improvements in short sprint speed (5 m and 30 m) and change-of-direction ability, as well as reductions in lower-limb muscle imbalance. Taken together, these findings indicate that a well-designed and football-specific training program can effectively enhance speed and agility and better support the physical demands of competitive match play.

In terms of flexibility, the findings of this study indicate that flexibility training combined with high-velocity movement contributes to improvements in both sprint speed and change-of-direction ability. This is consistent with Bogalho et al. (2022), who reported that greater flexibility of the hip and knee musculature particularly the hamstrings is significantly associated with better short-distance sprint performance over 5, 10 and 20 meters. They concluded that hamstring flexibility is a key component underpinning football-specific skills such as jumping, sprinting, and high-agility movements. Thus, training programs that simultaneously target flexibility and body control play an important role in reducing muscular tightness in the hip and thigh region, lowering the risk of injury, and enhancing the efficiency of acceleration and directional changes during competitive match play.

5. Conclusion and suggestions

5.1 Conclusion

The present study developed a combined speed, agility, and quickness (SAQ) training program together with a flexibility training program. Field data obtained from coaches and football players indicated that athletes' speed and agility were still not fully aligned with the demands of actual competition, particularly in terms of initial acceleration, change of direction, and maintaining high playing intensity throughout the match. When this program was implemented with male university football players over 8 weeks, the results showed that after 4 weeks of training the experimental group achieved significantly better Illinois Agility Test scores than the control group. After 8 weeks, the experimental group also outperformed the control group on both the 30 meters sprint and the Illinois Agility Test at the .05 level of statistical significance. These findings demonstrate that the SAQ training program combined with flexibility exercises developed in this study can effectively enhance speed and agility in football players.

The weekly training frequency was intentionally increased from two to five sessions across the 8-week period in accordance with the principles of progressive overload and progression. Therefore, the differences observed between the 4-week, and 8-week assessments reflect both the longer exposure time and the higher accumulated training load, which is consistent with real-world periodized conditioning practice rather than a fixed-dose laboratory protocol.

5.2 Suggestion

5.2.1 University and club-level football coaches should consider incorporating the combined SAQ and flexibility training program into their regular weekly training routines, particularly during the pre-season and throughout the competitive season. This approach can help develop players' speed

and agility in line with the specific demands of match play, while also reducing problems related to muscle tightness and lowering the risk of injuries arising from rapid sprinting and sudden changes of direction.

5.2.2 Future research should involve a more diverse sample in terms of sex, playing level, and type of sport, and should also examine the effects of the program on match-derived performance indicators, such as the number of high-speed runs or statistics related to involvement in offensive and defensive actions. Such evidence would provide more comprehensive information for designing training programs that are optimally suited to the specific contexts and needs of different teams.

6. Human Research Ethics Approval

The research project entitled “Development of a Speed, Agility and Quickness (SAQ) Training Program Combined with Flexibility Training on Speed and Agility in Football Players” was approved in accordance with international ethical standards for research involving human participants, including the Declaration of Helsinki, the Belmont Report, the CIOMS Guidelines, and the International Conference on Harmonization in Good Clinical Practice (ICH-GCP) (IRB No. P1-0177/2567).

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ผลของโพแทสเซียมเปอร์แมงกาเนตต่อตัวเร่งปฏิกิริยา CZA/13X สำหรับการสังเคราะห์แอลพีจีโดยตรง

Impact of KMnO_4 on CZA/13X Catalysts for Direct LPG Synthesisมนตรี ทองคำ¹ ภิเชก รุ่งโรจน์ชัยพร¹ สมสุข ไตรศุกิตติ² และ มาวิน ปูนอน^{2*}Montree Thongkam¹, Pesak Rungrojchaipon¹, Somsuk Trisupakitti² and Mavin Punon^{2*}¹คณะวิทยาศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง กรุงเทพมหานคร²คณะวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยราชภัฏมหาสารคาม จังหวัดมหาสารคาม¹Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok²Faculty of Science and Technology, Rajabhat Maha Sarakham University, Mahasarakham Province

*Corresponding Author: mavin.pu@gmail.com

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บทคัดย่อ

การสังเคราะห์ก๊าซหุงต้ม (LPG) โดยตรงจากก๊าซสังเคราะห์ถือเป็นแนวทางที่ยั่งยืนและมีความมุ่งหวังสูงสำหรับการผลิตเชื้อเพลิงทางเลือก งานวิจัยนี้มุ่งเน้นศึกษาสมรรถนะการเร่งปฏิกิริยาของตัวเร่งปฏิกิริยาคอปเปอร์-ซิงค์-อะลูมิเนียมออกไซด์ ($\text{CuO-ZnO-Al}_2\text{O}_3$; CZA) ที่อัตราส่วนโมล 2:2:1 ซึ่งเตรียมด้วยวิธีตกตะกอนร่วมและนำมาผสมทางกายภาพกับซีโอไลต์ 13X ทั้งนี้ ได้มีการศึกษาวิจัยเป็นพิเศษเกี่ยวกับการปรับปรุงสมบัติของตัวเร่งปฏิกิริยาด้วยโพแทสเซียมเปอร์แมงกาเนต (KMnO_4) เพื่อประเมินศักยภาพในการปรับความเป็นกรดของซีโอไลต์ผ่านการส่งเสริมด้วยความเป็นด่างของโพแทสเซียม (K) และการเพิ่มการกระจายตัวของโลหะด้วยผลทางรีดอกซ์ของแมงกานีส (Mn) ระบบตัวเร่งปฏิกิริยาที่ใช้ในการประเมินมี 3 ระบบ ได้แก่ CZA/13X, CZA/10% KMnO_4 -13X และ CZA/20% KMnO_4 -13X โดยเตรียมด้วยวิธีการเคลือบฝัง KMnO_4 ลงบนซีโอไลต์ 13X ที่ความเข้มข้นร้อยละ 10 และ 20 โดยน้ำหนักต่อปริมาตร ตามลำดับ การประเมินสมรรถนะการเร่งปฏิกิริยาทดสอบภายใต้สภาวะปฏิกิริยาในเครื่องปฏิกรณ์แบบเบดนิ่ง (Fixed-bed reactor) ที่อุณหภูมิ 350 องศาเซลเซียส ความดัน 40 บาร์ และอัตราส่วนก๊าซ H_2 :CO เท่ากับ 2:1 เป็นเวลา 4 ชั่วโมง ผลการวิเคราะห์ด้วยเทคนิคก๊าซโครมาโทกราฟีพบว่าตัวเร่งปฏิกิริยา CZA/13X ที่ไม่มีการปรับปรุงให้สมรรถนะการเร่งปฏิกิริยาสูงที่สุด โดยมีค่าการเปลี่ยนก๊าซคาร์บอนมอนอกไซด์ (CO Conversion) ร้อยละ 87.64 ค่าการเลือกเกิดก๊าซ LPG (LPG Selectivity) ร้อยละ 38.16 และผลผลิตก๊าซ LPG (LPG Yield) ร้อยละ 33.47 ในขณะที่ระบบตัวเร่งปฏิกิริยาที่ปรับปรุงด้วย KMnO_4 มีสมรรถนะลดลง โดยมีค่าการเปลี่ยนก๊าซ CO ลดลงเหลือร้อยละ 86.83 และ 83.14 สำหรับปริมาณการเติมร้อยละ 10 และ 20 ตามลำดับ ผลการทดลองดังกล่าวชี้ให้เห็นว่า การดูดซับของตำแหน่งว่องไวที่เป็นกรดบนซีโอไลต์โดยสารประกอบโพแทสเซียมและแมงกานีสที่มีปริมาณมากเกินไป ส่งผลกระทบเชิงลบที่รุนแรงกว่าข้อดีที่คาดว่าจะได้รับการส่งเสริมทางรีดอกซ์หรือความเป็นด่าง จึงเป็นการขัดขวางขั้นตอนการเปลี่ยนเมทานอลไปเป็นไฮโดรคาร์บอน (Methanol-to-hydrocarbon dehydration step) ข้อค้นพบเหล่านี้เน้นย้ำถึงความสำคัญของความสมดุลระหว่างฟังก์ชันโลหะและฟังก์ชันกรด และบ่งชี้ว่าแม้การปรับปรุงด้วย KMnO_4 จะถูกคาดหวังเพื่อใช้ในการควบคุมค่าการเลือกเกิดผลิตภัณฑ์ แต่ในสภาวะที่ทำการศึกษานี้กลับให้ผลในทางตรงกันข้ามเนื่องจากการเข้ายั่วยุตำแหน่งว่องไวหลักของตัวเร่งปฏิกิริยา

คำสำคัญ: การสังเคราะห์แอลพีจี, ตัวเร่งปฏิกิริยาสองฟังก์ชัน, การดัดแปลงด้วย KMnO_4 , ตัวเร่งปฏิกิริยาคอปเปอร์-ซิงค์-อะลูมิเนียม

Abstract

The direct synthesis of liquefied petroleum gas (LPG) from synthesis gas represents a promising sustainable pathway for alternative fuel production. This study investigates the catalytic performance of copper-zinc-aluminum oxide catalysts ($\text{CuO-ZnO-Al}_2\text{O}_3$; CZA) with molar ratio 2:2:1, prepared via a co-precipitation method and physically mixed with zeolite 13X. The modification using KMnO_4 was specifically explored to evaluate its potential in tuning zeolite acidity through alkali (K) promotion and enhancing metal dispersion via manganese (Mn) redox effects. Three catalyst systems were evaluated: CZA/13X, CZA/10% KMnO_4 -13X, and CZA/20% KMnO_4 -13X, where potassium permanganate was impregnated onto zeolite 13X at concentrations of 10% and 20% w/v respectively. Catalytic performance was assessed using a fixed-bed reactor at 350°C, 40 bar, with H_2 :CO ratio of 2:1 for 4 h. Gas chromatography analysis revealed that unmodified CZA/13X exhibited the highest catalytic activity with a CO conversion of 87.64%, LPG selectivity of 38.16%, and LPG yield of 33.47%. In comparison, the KMnO_4 -modified systems showed decreased performance, with CO conversions of 86.83% and 83.14% for the 10% and 20% loading, respectively. These results suggest that the excessive blockage of zeolite acid sites by potassium and manganese species outweighs any potential benefits from redox or basic promotion, thereby hindering the methanol-to-hydrocarbon dehydration step. These findings highlight the critical balance of the metal-acid functions and indicate that while KMnO_4 modification was expected to tune selectivity, it proved counterproductive under the studied conditions due to the suppression of key active sites.

Keywords: LPG synthesis, Bifunctional catalyst, KMnO_4 modification, Copper-zinc-aluminum catalyst

1. Introduction

The global energy paradigm is currently undergoing an unprecedented transition, catalyzed by the surging demand for sustainable energy alternatives, the depletion of conventional hydrocarbon reserves, and the critical need to mitigate greenhouse gas emissions (Chu & Majumdar, 2012; Gielen et al., 2019). In this shifting landscape, Liquefied Petroleum Gas (LPG), primarily a blend of propane (C_3H_8) and butane (C_4H_{10}), has gained significant recognition as a strategic transitional fuel. Its high energy density, versatile applications across residential and industrial sectors, and relatively low emission profile render it a superior alternative to traditional solid and liquid fuels (Raslavičius et al., 2014). In the context of Thailand, LPG is integral to the domestic energy framework, serving as a primary fuel source for households and the transportation sector. Within the strategic framework of the Bio-Circular-Green (BCG) Economy and the national Alternative Energy Development Plan (AEDP), there is an intensifying focus on enhancing energy self-sufficiency. Consequently, the development of advanced technologies for the direct synthesis of LPG from indigenous carbon sources such as agricultural waste or biogas represents a critical step toward reducing reliance on energy imports and achieving carbon neutrality.

Traditionally, LPG production is tethered to petroleum refining and natural gas processing; however, the inherent volatility of crude oil markets and the diminishing accessibility of fossil reserves present

significant risks to energy security (Apergis & Miller, 2009). To address these challenges, the direct synthesis of LPG from syngas ($\text{CO} + \text{H}_2$) has emerged as a promising thermo-chemical pathway. This process allows for the utilization of diverse feedstocks, including biomass-derived syngas and captured CO_2 , thereby aligning with circular economy principles and providing a sustainable route for fuel production (Palgunadi et al., 2010).

The Fischer-Tropsch (FT) process, discovered in the 1920s, converts syngas to liquid hydrocarbons through surface polymerization reactions over metal catalysts. While conventional FT synthesis typically targets longer-chain hydrocarbons, modified approaches can be tailored for LPG production (Mahmoudi et al., 2017). Recent studies have demonstrated that bifunctional catalyst systems combining methanol synthesis functionality with acid catalysis can achieve direct conversion of CO and H_2 to LPG through a modified methanol-to-hydrocarbons pathway (Weber et al., 2024). Research by Tavares et al. (2022) showed that Cu-Zn-Al catalysts modified with various zeolites could achieve CO conversions exceeding 80% with significant LPG selectivity. Similarly, Ramirez et al. (2019) demonstrated that the acid strength and pore structure of zeolite supports critically influence product distribution in syngas conversion processes. To further optimize this system, the introduction of promoters such as manganese (Mn) and potassium (K) has been explored. Manganese is known to act as a redox promoter that enhances Cu dispersion and CO adsorption, which can significantly improve catalytic activity (Palgunadi et al., 2010). Concurrently, the use of KMnO_4 as a precursor provides inherent alkalinity from potassium (K), which serves as an electronic modifier to tune the surface acidity of the zeolite. This modification is crucial for neutralizing overly strong acid sites that otherwise lead to excessive cracking and methane formation, thereby shifting the selectivity towards the desired $\text{C}_3\text{-C}_4$ range (Ao et al., 2020). Furthermore, manganese oxides can act as structural stabilizers, preventing the sintering of active metal phases under high-temperature reaction conditions (Beerthuis et al., 2021).

The direct synthesis of LPG from syngas involves a complex reaction network that can be simplified into key sequential steps:

Primary methanol synthesis reaction:



Methanol dehydration to dimethyl ether:



DME and methanol conversion to hydrocarbons:



Water-gas-shift side reaction:



The overall process is thermodynamically favored and exothermic, with an approximate enthalpy change of -210 kJ/mol. The methanol synthesis step (Equation 1) is catalyzed by the Cu-Zn-Al component and is thermodynamically limited by equilibrium. Subsequently, methanol undergoes acid-catalyzed dehydration and oligomerization reactions on zeolite acid sites to form longer-chain hydrocarbons including LPG components (Equations 2-4). The water-gas-shift reaction (Equation 5) represents a significant side reaction that can influence overall carbon efficiency (Ma et al., 2015; Xiangang et al., 2011). Recent mechanistic studies using in-situ spectroscopic techniques have revealed that the balance between metal and acid functions is crucial for optimizing LPG selectivity while minimizing undesired products such as methane and higher hydrocarbons (Liu et al., 2018). The proximity and interaction between Cu-based methanol synthesis sites and zeolite acid sites significantly impact intermediate species diffusion and subsequent conversion pathways.

The conceptual framework of this research is built upon the synergy between the CZA metallic function and the modified 13X zeolite acid function, where the KMnO_4 loading serves as a critical independent variable to balance these two pathways. This study aims to systematically evaluate the catalytic performance of $\text{CuO-ZnO-Al}_2\text{O}_3/13\text{X}$ zeolite bifunctional catalysts for direct LPG synthesis from syngas, with particular focus on understanding the effects of KMnO_4 modification on zeolite 13X support. While previous studies have explored various metal oxide promoters, the specific role of manganese oxide species in modulating acid-base properties and their impact on LPG selectivity remains understudied.

The key objectives of this work include: (1) systematic comparison of unmodified versus KMnO_4 -modified 13X zeolite supports, (2) evaluation of physical mixing ratios between methanol synthesis and acid catalysis components, and (3) comprehensive characterization linking catalyst structure to performance for direct LPG synthesis applications.

2. Materials and Methods

2.1 Catalyst Preparation

2.1.1 Co-Precipitation of $\text{CuO-ZnO-Al}_2\text{O}_3$ (CZA)

The $\text{CuO-ZnO-Al}_2\text{O}_3$ catalyst was synthesized via a co-precipitation method following optimized procedures from literature (Janjira & Promarin, 2022). Aqueous solutions of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (Sigma-Aldrich, 99% purity) were prepared to achieve a $\text{CuO:ZnO:Al}_2\text{O}_3$ molar ratio of 2:2:1. The mixed metal nitrate solution (total metal concentration: 2.0 M) was added dropwise to 500 mL of Na_2CO_3 solution (0.05 M) under continuous stirring (600 rpm) while maintaining pH at 7.0 ± 0.1 and temperature at 70 °C using an automated pH control system.

After complete precipitation, the suspension was aged for 24 h at room temperature, followed by washing with deionized water (80 °C) until nitrate-free (confirmed by AgNO_3 test). The precipitate was dried at 80 °C for 12 h and calcined at 350 °C for 5 h with a heating rate of 2°C/min under air atmosphere.

2.1.2 Zeolite 13X Preparation and Modification

Commercial grade NaX zeolite (Zeochem, Si/Al = 1.2) was used as received. Prior to use, the zeolite was thermally treated at 110 °C for 3 hours to remove physisorbed water, followed by calcination at 350 °C for 5 h to ensure complete activation.

For KMnO₄ modification, incipient wetness impregnation was employed. KMnO₄ solutions with concentrations of 10% and 20% w/v were prepared using deionized water. The calculated amount of KMnO₄ solution was slowly added to pre-dried zeolite 13X (3.5 g KMnO₄ in 35 mL water for 10% loading; 7.0 g KMnO₄ in 35 mL water for 20% loading) until complete absorption. The impregnated materials were stirred for 1 h, dried at 110 °C for 12 h, and finally calcined at 350 °C for 5 h to decompose KMnO₄ into MnO₂ and K₂O species.

2.1.3 Catalyst Pelletization and Physical Mixing

All catalyst components were pelletized using a hydraulic press at 3000 psi and sieved to 850 μm particle size to ensure uniform flow characteristics in the fixed-bed reactor. Bifunctional catalysts were prepared by physical mixing of 0.33 g CZA with 0.17 g of acid catalyst (13X, 10% KMnO₄-13X, or 20% KMnO₄-13X) to achieve a 2:1 mass ratio, along with 0.5 g quartz sand as a diluent to minimize hot spot formation.

2.2 Catalyst Characterization

2.2.1 Structural Characterization

X-ray diffraction (XRD) patterns were recorded using a Rigaku Mini Flex diffractometer with Cu Kα-radiation ($\lambda = 1.5418 \text{ \AA}$) operating at 40 kV and 15 mA. Scans were performed over a 2θ range of 10–90° with a step size of 0.02° and counting time of 2 s per step. Phase identification was accomplished using the JCPDS database, and crystallite sizes were calculated using the Scherrer equation:

$$d_{\text{crystallite}} = \frac{K\lambda}{\beta \cos\theta} \quad (6)$$

Where K is the Scherrer constant (0.94 for spherical crystals with cubic symmetry) and λ represents the wavelength of the incident radiation. β is the full width at half maximum (FWHM) and θ is the position of the diffraction peak. The surface area of the reduced copper particles (S_{Cu} , in $\text{m}_{\text{Cu}}^2\text{-g}_{\text{Cat}}^{-1}$) was calculated using equation (7), where ρ_{Cu} is 8.93 g-cm^{-3} (density of copper), and W is the mass fraction of copper in the catalyst (Nanchaphak, 2021; Laksika & Runarat, 2020).

$$S_{\text{Cu}} = \frac{6000 \times W}{\rho_{\text{Cu}}} d_{\text{Cu}} \quad (7)$$

2.2.2 Surface Properties and Acidity Analysis

Brunauer-Emmett-Teller (BET) surface area, pore volume, and pore size distribution were determined using N₂ physisorption at -196 °C (Micromeritics ASAP 2020). Samples were degassed at 350 °C for 4 h prior to analysis.

Acid site concentration and strength distribution were characterized using temperature-programmed desorption of ammonia (NH₃-TPD) on a Micromeritics AutoChem II 2920 analyzer. Samples (100 mg) were pretreated at 350 °C under He flow, cooled to 100°C, and saturated with 10% NH₃/He. After purging with He, TPD was conducted from 100-800 °C at 10°C/min a heating rate while monitoring NH₃ desorption by thermal conductivity detector.

2.3 Catalytic Performance Evaluation

Catalytic testing was performed in a fixed-bed stainless steel reactor (inner diameter: 10 mm; length: 300 mm) equipped with temperature and pressure control systems. The catalyst activation protocol consisted of: (1) purging with N₂ at 150 °C for 24 min, (2) reduction with 5% H₂/N₂ at 250 °C for 2 h, and (3) final temperature adjustment to reaction conditions.

Reaction conditions were optimized based on literature recommendations: 350 °C, 40 bar, H₂:CO = 2:1, a total flow rate of 20 mL/min (STP), and a reaction time of 4 h. Product analysis was performed using online Gas Chromatography. Permanent gases (H₂, CO, CO₂, and N₂) were quantified using a Thermal Conductivity Detector (TCD), while hydrocarbons (C₁-C₅) were analyzed via a Flame Ionization Detector (FID) using appropriate capillary columns.

The catalytic performance metrics, including CO conversion, LPG selectivity, and LPG yield, were calculated based on the carbon mole balance as follows:

$$\text{CO Conversion (\%X}_{\text{CO}}) = (\text{nCO}_{\text{in}} - \text{nCO}_{\text{out}}) / \text{nCO}_{\text{in}} \times 100$$

where nCO_{in} and nCO_{out} are the molar flow rates of CO at the inlet and outlet, respectively.

$$\text{LPG Selectivity (\%S}_{\text{LPG}}) = \sum(i \cdot \text{nC}_{i,\text{out}}) / \sum(j \cdot \text{nC}_{j,\text{out}}) \times 100$$

where i represents carbon numbers in the LPG range (C₃ and C₄), j represents all carbon-containing products except CO₂ (unless specified), and nC is the molar flow rate of the respective hydrocarbon product.

$$\text{LPG Yield (\%Y}_{\text{LPG}}) = \text{X}_{\text{CO}} \times \text{S}_{\text{LPG}} / 100$$

3. Results

3.1 Catalyst Characterization Results

3.1.1 XRD Analysis and Phase Composition

The X-ray diffraction (XRD) patterns of the prepared catalysts are presented in Figure 1, which clearly demonstrates the crystalline phases present in each catalyst system and provides crucial insights into the structural properties of the bifunctional catalysts. The diffraction analysis confirms the successful formation of all expected phases and reveals important information about crystallite sizes and phase interactions. For the CZA/13X catalyst system, the XRD pattern shows characteristic peaks for each component. The CuO phase, which serves as the primary active component for methanol synthesis, exhibited sharp and intense peaks at $2\theta = 35.90^\circ$, 62.34° , and 68.16° corresponding to the (111), (113), and (220) crystal planes respectively. These peaks indicate a well-crystallized monoclinic CuO structure, which is essential for catalytic activity. The peak intensities suggest good dispersion of copper oxide throughout the catalyst matrix.

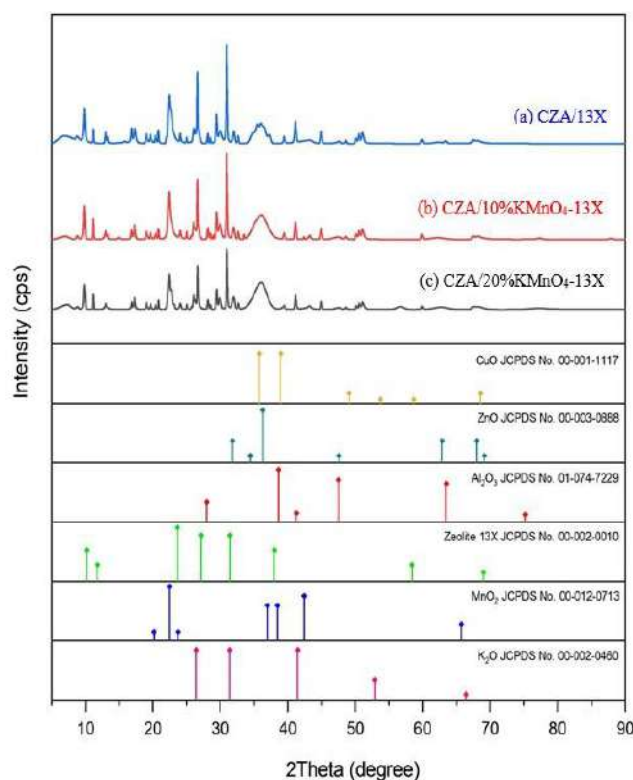


Figure 1. XRD patterns of the metal oxide catalysts showing phase identification for (a) CZA/13X, (b) CZA/10%KMnO₄-13X, and (c) CZA/20%KMnO₄-13X with corresponding reference peak positions.

The ZnO component, acting as a structural and electronic promoter for the copper phase, showed characteristic reflections at $2\theta = 31.91^\circ$, 34.74° , and 36.39° corresponding to the (100), (002), and (101) planes of the hexagonal wurtzite structure. The presence of these peaks confirms that zinc oxide maintains its crystalline integrity during the co-precipitation and calcination processes. The relatively high intensity of the (002) peak suggests preferred orientation along the c-axis, which is known to influence the promotional effect on copper catalysts.

Al₂O₃ exhibited typical γ -alumina reflections at $2\theta = 28.07^\circ$, 50.51° , and 67.41° for the (012), (202), and (122) planes respectively. The broad nature of these peaks is characteristic of the poorly crystalline γ -Al₂O₃ phase, which provides structural stability and prevents sintering of the active copper and zinc oxide phases under reaction conditions. The presence of γ -alumina is particularly important for maintaining catalyst stability during long-term operation.

The 13X zeolite framework was confirmed by its characteristic diffraction pattern with peaks at $2\theta = 10.16^\circ$, 11.74° , 23.60° , 27.11° , and 31.40° . These peaks correspond to the faujasite structure with its three-dimensional pore system, which is crucial for the acid-catalyzed conversion of methanol to hydrocarbons. The sharpness of these peaks indicates that the zeolite structure remains intact throughout the catalyst preparation process, preserving its microporous properties and acid site accessibility.

The KMnO₄-modified catalysts displayed additional diffraction features that provide important insights into the modification effects. Both 10% and 20% KMnO₄-modified systems showed new peaks

corresponding to MnO_2 at $2\theta = 20.34^\circ$, 22.36° , 43.16° , and 67.87° , which correspond to the (110), (101), (211), and (301) reflections of $\beta\text{-MnO}_2$ (pyrolusite structure). The intensity of these peaks increased proportionally with KMnO_4 loading, confirming quantitative decomposition of the permanganate precursor during calcination. The formation of $\beta\text{-MnO}_2$ rather than other manganese oxide phases is significant because this polymorph typically exhibits different catalytic and electronic properties.

Additionally, the modified catalysts showed reflections characteristic of K_2O at $2\theta = 29.58^\circ$, 41.13° , and 44.93° , corresponding to the (111), (200), and (220) planes of the cubic potassium oxide structure. The presence of these peaks confirms that potassium species are not merely dispersed on the surface but form distinct crystalline domains. This crystalline K_2O may contribute to changes in the catalyst's basicity and electronic properties.

Quantitative analysis using the Scherrer equation provided valuable information about crystallite sizes and dispersion characteristics. The calculated data are summarized in Table 1, which shows that the CuO crystallite size in the CZA component is 12.25 nm, corresponding to a metallic copper particle size of 9.19 nm after reduction. This results in a copper dispersion of 10.45%, which is within the optimal range for methanol synthesis activity.

The results presented in Table 1 reveal that the CuO crystallite size obtained in this study (12.25 nm) is larger than previously reported values (6.30 nm), which may be attributed to differences in synthesis conditions, particularly calcination temperature and time, or variations in precipitation pH. The larger crystallite size results in lower copper dispersion (10.45% vs 20.32%), but this value remains within the range considered suitable for methanol synthesis applications. The moderate dispersion may actually be beneficial for stability, as highly dispersed copper particles are more susceptible to sintering under reaction conditions.

Table 1. Particle diameters and copper surface areas of the different catalysts.

Catalysts	d (CuO)	d (Cu^0)	Dispersion (%)	Reference
CZA (2:2:1)	12.25	9.19	10.45	This study
CZA (2:2:1)	6.30	4.73	20.32	Nanchaphak (2021)

The peak broadening analysis also revealed that KMnO_4 modification does not significantly affect the crystallite sizes of the primary CZA components, suggesting that the impregnation process does not cause substantial structural changes to the methanol synthesis catalyst. However, the presence of MnO_2 and K_2O phases may influence the local electronic environment and affect the reducibility and catalytic properties of the copper phase.

3.1.2 Surface Morphology and Composition

SEM analysis provided comprehensive insights into the morphological characteristics and spatial distribution of components in each catalyst system. The morphological investigation is crucial for

understanding how the physical mixing process affects catalyst performance and provides evidence for the successful integration of methanol synthesis and acid catalysis functionalities.

Energy dispersive X-ray spectroscopy (EDS) results are presented in Figure 2, which confirms the elemental composition of all three catalyst systems and validates the theoretical stoichiometry. The EDS analysis demonstrates that the co-precipitation method successfully produced the intended 2:2:1 molar ratio of $\text{CuO}:\text{ZnO}:\text{Al}_2\text{O}_3$, with measured compositions closely matching the intended theoretical stoichiometry. The mapping of elemental signals showed a uniform distribution of copper (Cu), zinc (Zn), and aluminum (Al) across the analyzed microscopic regions. For the modified catalysts, the EDS results further validated the presence of manganese and potassium, consistent with the added KMnO_4 loadings.

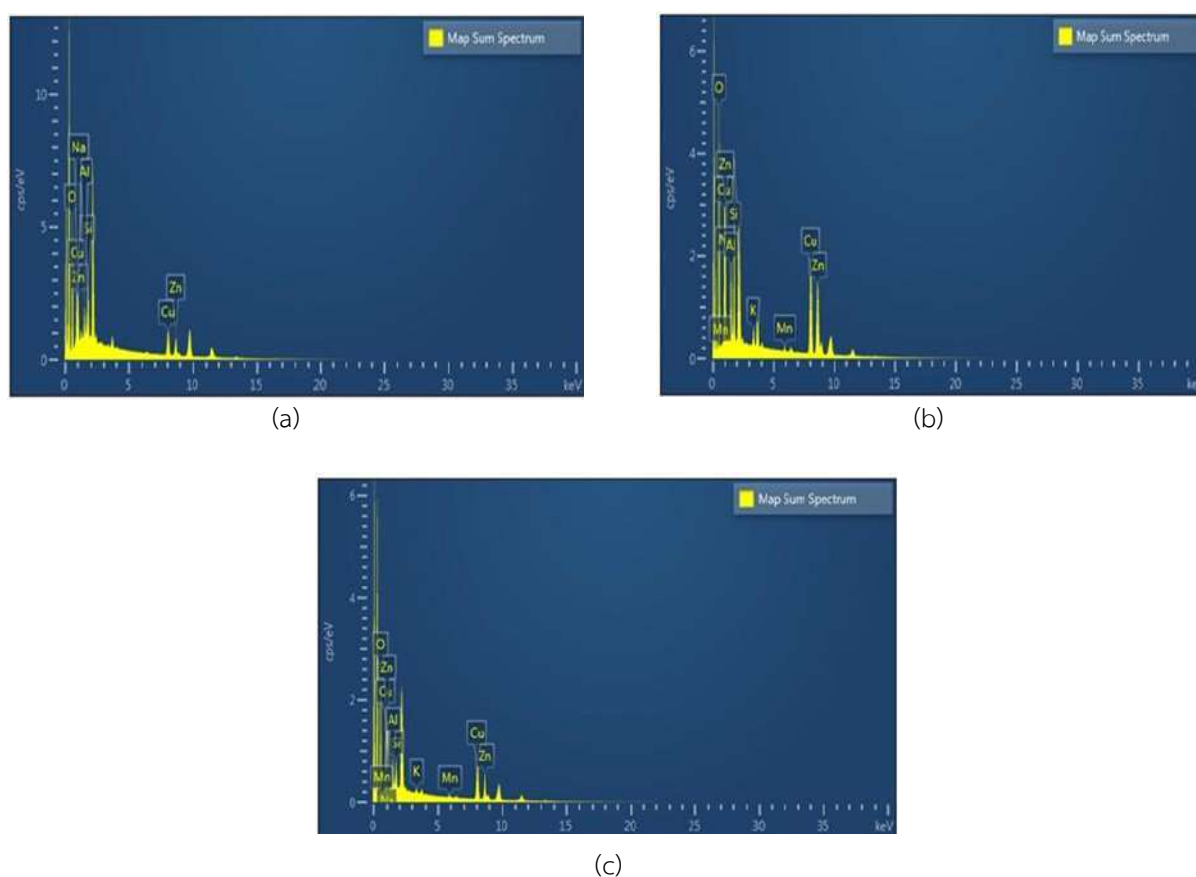


Figure 2. EDS spectra of (a) CZA/13X, (b) CZA/10%KMnO₄-13X and (c) CZA/20%KMnO₄-13X, catalysts showing elemental composition validation.

3.1.3 Surface area and Porosity (BET) Analysis

For the modified catalysts, EDS analysis clearly detected manganese and potassium peaks, confirming successful impregnation of KMnO_4 and its subsequent decomposition to MnO_2 and K_2O during calcination. The intensity of manganese signals increased proportionally with loading levels, validating the quantitative nature of the impregnation process.

The morphological characteristics are detailed in the SEM micrographs, which provide multi-scale visualization of catalyst architecture from macro-aggregates to surface details. Figure 3 presents the CZA/13X catalyst morphology at various magnifications, revealing particle aggregates ranging from 10–50 μm in diameter, which is suitable for fixed-bed reactor applications as it minimizes pressure drop while maintaining good mass transfer characteristics according to Mahmoudi et al. (2017).

At higher magnifications (10,000–40,000 $\times$), the distinct morphological characteristics of each component become apparent. The CZA particles exhibit rough, cauliflower-like surfaces with high surface roughness, which is typical of co-precipitated metal oxide catalysts and beneficial for providing high surface area for methanol synthesis reactions (Tavares et al., 2022). The interface between CZA and zeolite particles is of particular importance for bifunctional catalysis, as emphasized by Liu et al. (2018) in their mechanistic studies using in-situ spectroscopic techniques.

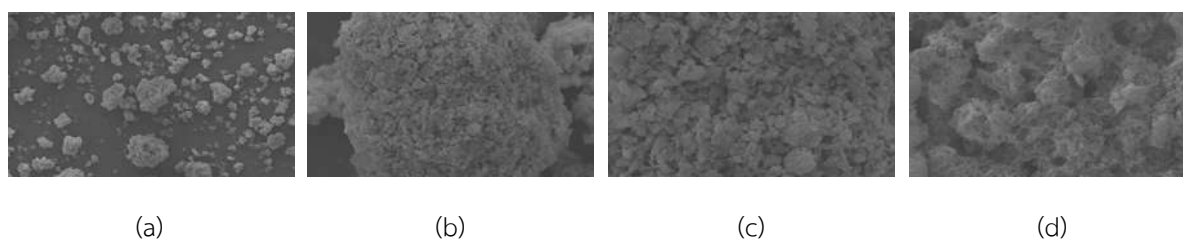


Figure 3. SEM micrographs of CZA/13X catalysts at magnifications of (a) 1,500 $\times$, (b) 10,000 $\times$, (c) 20,000 $\times$, and (d) 40,000 $\times$, showing the physical mixing of CZA particles with 13X zeolite crystals.

Figure 4 shows the morphology of CZA/10%KMnO₄-13X catalysts, where the effects of permanganate impregnation become clearly visible. The rod-shaped and needle-like MnO₂ structures observed are characteristic of β -MnO₂ formation during thermal decomposition, as documented by Weber et al. (2024) in their studies of manganese oxide phase transformations.

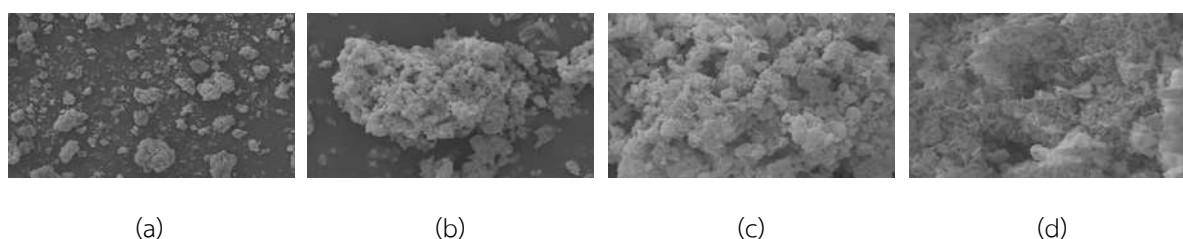


Figure 4. SEM micrographs of CZA/10%KMnO₄-13X catalysts at magnifications of (a) 1,500 $\times$, (b) 10,000 $\times$, (c) 20,000 $\times$, and (d) 40,000 $\times$, displaying rod-shaped MnO₂ aggregates on zeolite surfaces.

The preferential deposition pattern observed near zeolite pore openings and crystal edges suggests that the impregnation process is controlled by capillary forces and surface energy

considerations, which align with the theoretical framework proposed by Ramirez et al. (2019) for understanding metal oxide distribution in zeolite supports.

The progressive blocking of zeolite pores observed at higher loadings correlates well with studies by Argyle & Bartholomew (2015) on catalyst deactivation mechanisms, where pore blockage was identified as a primary cause of reduced activity in modified zeolite catalysts.

The textural properties of the catalysts, as determined by nitrogen physisorption and BET analysis, provide critical insights into the effects of KMnO_4 modification on the porous structure of the zeolite support and its implications for catalytic performance. The comprehensive data presented in Table 2 reveal significant differences in surface area, pore volume, and pore size distribution among the catalyst systems, which directly correlate with the observed catalytic behavior.

The pristine CZA component exhibits a moderate surface area of $174.45 \text{ m}^2/\text{g}$ with a relatively large average pore size of $128.10 \text{ \AA}$, which is characteristic of co-precipitated metal oxide catalysts. This pore structure is predominantly mesoporous, resulting from the aggregation of small oxide crystallites during the co-precipitation and calcination processes. The large pore size facilitates reactant and product diffusion, which is particularly important for preventing mass-transfer limitations during methanol synthesis from syngas. The pore volume of $0.58 \text{ cm}^3/\text{g}$ indicates a well-developed porous structure that provides adequate space for gas-phase reactions.

Table 2. Surface area and porosity analysis of catalyst components.

Catalysts	Surface area (m^2/g)	Pore volume (cm^3/g)	Pore size ($\text{\AA}$)	Reference
CZA	174.45	0.58	128.10	Praphaporn & Satawat (2021)
13X	637.91	0.51	32.09	Thanaporn & Pisek (2021)
10% KMnO_4 -13X	495.92	0.39	31.34	Thanaporn & Pisek (2021)
20% KMnO_4 -13X	313.89	0.27	34.62	Thanaporn & Pisek (2021)

In contrast, the pristine 13X zeolite displays a significantly higher surface area of $637.91 \text{ m}^2/\text{g}$, which is typical for Faujasite-type zeolites with their three-dimensional microporous framework. The average pore size of $32.09 \text{ \AA}$ corresponds to the supercage dimensions of the faujasite structure, where the main catalytic reactions involving acid sites occur. The pore volume of $0.51 \text{ cm}^3/\text{g}$ reflects the high micropore volume characteristic of 13X zeolite, which is essential for providing a large number of accessible acid sites for methanol dehydration and subsequent oligomerization reactions.

The effects of KMnO_4 impregnation on the textural properties are clearly evident from the data in Table 2. The 10% KMnO_4 -13X sample shows a substantial decrease in surface area to $495.92 \text{ m}^2/\text{g}$, representing a 22% reduction compared to the pristine zeolite. This decrease is accompanied by a reduction in pore volume from 0.51 to $0.39 \text{ cm}^3/\text{g}$ (24% decreased), while the average pore size remains relatively unchanged at $31.34 \text{ \AA}$. These changes indicate that the MnO_2 and K_2O deposits formed during

KMnO₄ decomposition partially block the zeolite pores without significantly altering the remaining accessible pore dimensions.

Figure 5 shows that the morphology of CZA/20%KMnO₄-13X sample exhibits even more pronounced textural changes, with the surface area dropping dramatically to 313.89 m²/g (51% reduction) and pore volume decreasing to 0.27 cm³/g (47% reduction). The average pore size increases slightly to 34.62 Å, suggesting that smaller pores are preferentially blocked while larger pores remain accessible. This pore size distribution shift indicates that the impregnation process affects pores of different sizes to varying degrees.

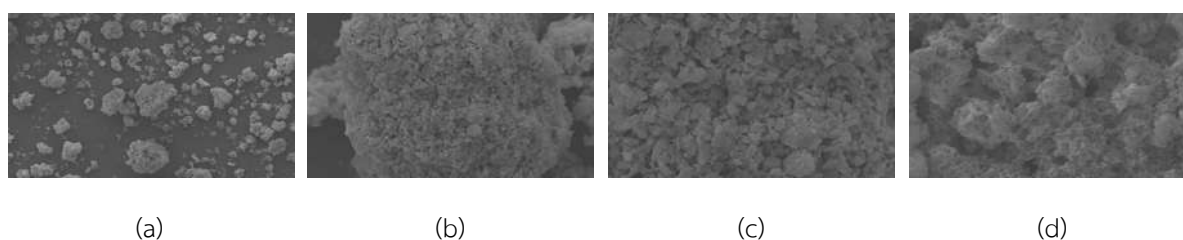


Figure 5. SEM micrographs of CZA/20%KMnO₄-13X catalysts at magnifications of (a) 1,500X, (b) 10,000X, (c) 20,000X, and (d) 40,000X, showing increased density of MnO₂ deposits due to higher KMnO₄ loading.

3.1.4 Acidity Characterization

The acid site properties of the 13X zeolite were characterized using NH₃-TPD analysis, as shown in Figure 6. The desorption profile exhibits a complex pattern with multiple overlapping peaks, which can be deconvoluted into two primary regions based on temperature (David & Armeanu, 2022).

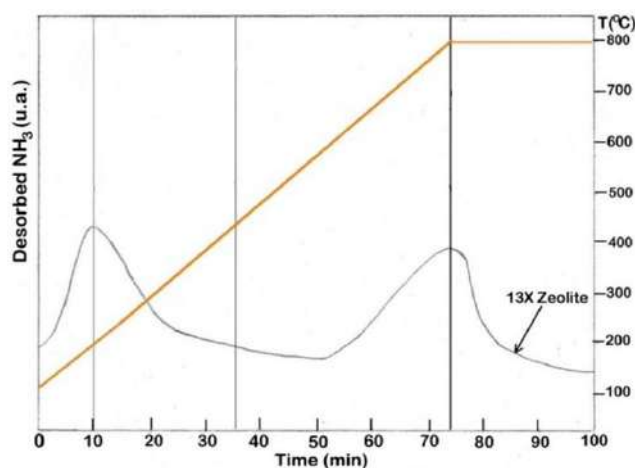


Figure 6. NH₃-TPD analysis results of 13X zeolite showing temperature-programmed desorption profile with weak and strong acid site distributions (David & Armeanu, 2022).

The low-temperature desorption peak, centered around 125°C, corresponds to ammonia molecules weakly bound to Brønsted acid sites or physisorbed on the zeolite surface. These sites typically exhibit acid strength in the range of 26-35 $\mu\text{mol/g}$ and are associated with silanol groups or weakly acidic bridging hydroxyl groups located primarily on the external surface or in the larger cavities of the zeolite structure. While these weak acid sites contribute to the total acidity, they are generally not sufficient alone to catalyze the dehydration and oligomerization reactions required for LPG formation.

The high-temperature desorption region, with a broad peak extending from 300 °C to approximately 500 °C and centered around 400°C, represents ammonia desorbing from strong Brønsted acid sites. These sites are primarily associated with bridging hydroxyl groups (Si-OH-Al) located within the zeolite framework, particularly in the sodalite cages and hexagonal prisms of the faujasite structure. The total concentration of these strong acid sites ranges from 62-750 $\mu\text{mol/g}$, representing the primary catalytically active centers for methanol dehydration and subsequent hydrocarbon formation reactions.

The analysis also reveals that substantial ammonia desorption occurs only at temperatures surpassing 300°C, providing data on the thermal stability of these sites under the research reaction temperature of 350°C.

3.2 Catalytic Performance Evaluation

3.2.1 CO Conversion Analysis

The catalytic activity results provide evidence for the different performance of the unmodified CZA/13X system compared to the KMnO_4 -modified alternatives, with CO conversion serving as a primary indicator of overall catalyst effectiveness. The CO conversion data, presented in Figure 7, demonstrate clear performance differences among the catalyst systems and reveal important insights into the effects of zeolite modification on syngas conversion activity.

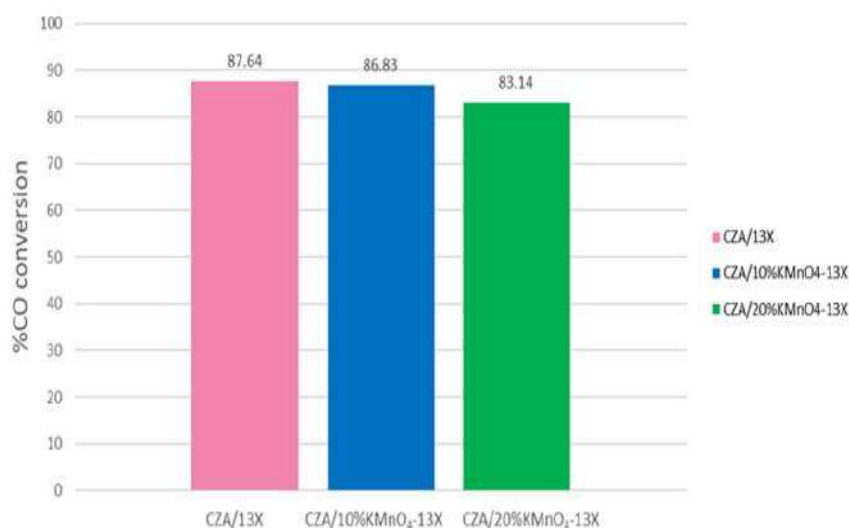


Figure 7. %CO conversion of different catalyst systems showing superior performance of unmodified CZA/13X catalyst.

The catalytic activity results provide evidence for the different performance of the unmodified CZA/13X system compared to the KMnO_4 -modified alternatives, with CO conversion serving as a primary indicator of overall catalyst effectiveness. The CO conversion data demonstrate clear performance differences among the catalyst systems and reveal important insights into the effects of zeolite modification on syngas conversion activity. The unmodified CZA/13X catalyst achieved the highest CO conversion of 87.64%, which represents good performance for direct syngas conversion under the employed reaction conditions. This conversion level indicates that the combination of Cu-Zn-Al methanol synthesis functionality with the acid catalysis capability of 13X zeolite creates an effective bifunctional system. The thermodynamic equilibrium for methanol synthesis at 350 °C and 40 bar typically limits CO conversion in conventional methanol synthesis, but the presence of acid sites that continuously remove methanol through dehydration and oligomerization reactions drives the equilibrium forward, resulting in enhanced CO conversion. In contrast, the KMnO_4 -modified catalysts showed progressively decreasing CO conversions: 86.83% for CZA/10% KMnO_4 -13X and 83.14% for CZA/20% KMnO_4 -13X.

3.2.2 Product Selectivity and Distribution

The product selectivity results provide crucial insights into how catalyst composition affects the distribution of products formed during syngas conversion, with particular emphasis on the formation of desired LPG components versus other hydrocarbons and byproducts. The LPG selectivity data, illustrated in Figure 8, reveal striking and unexpected differences among the catalysts that highlight the importance of maintaining unobstructed access to acid sites.

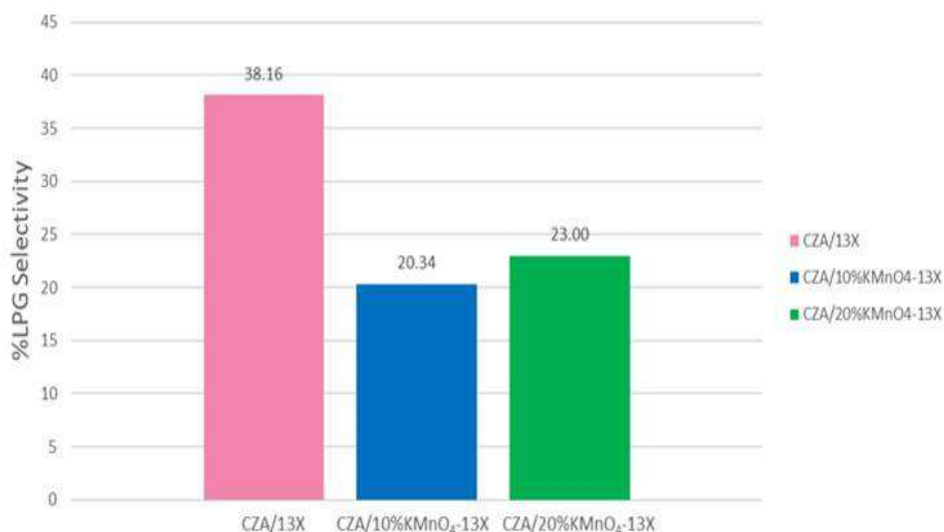


Figure 8. LPG selectivity (%) of different catalyst systems demonstrating the advantage of unmodified zeolite support.

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reveal striking and unexpected differences among the catalysts that highlight the importance of maintaining unobstructed access to acid sites. The most notable finding is the substantially higher LPG selectivity achieved by the unmodified CZA/13X system (38.16%) compared to both modified catalysts: CZA/20%KMnO₄-13X (23.00%) and CZA/10%KMnO₄-13X (20.34%).

3.2.3 Overall LPG Yield Performance

The LPG yield results represent the most practically important performance metric as they combine both conversion and selectivity effects to provide a comprehensive measure of catalyst effectiveness for the intended application. The yield data, presented in Figure 9, demonstrate the higher performance of the unmodified CZA/13X system and provide quantitative evidence for the negative effects of KMnO₄ modification.

The LPG yield results represent the most practically important performance metric as they combine both conversion and selectivity effects to provide a comprehensive measure of catalyst effectiveness for the intended application. The yield data demonstrate the superior performance of the unmodified CZA/13X system and provide quantitative evidence for the negative effects of KMnO₄ modification. The CZA/13X catalyst achieved the highest LPG yield of 33.47%, while the modified catalysts showed significantly lower yields: 17.66% for CZA/10%KMnO₄-13X and 19.12% for CZA/20%KMnO₄-13X.

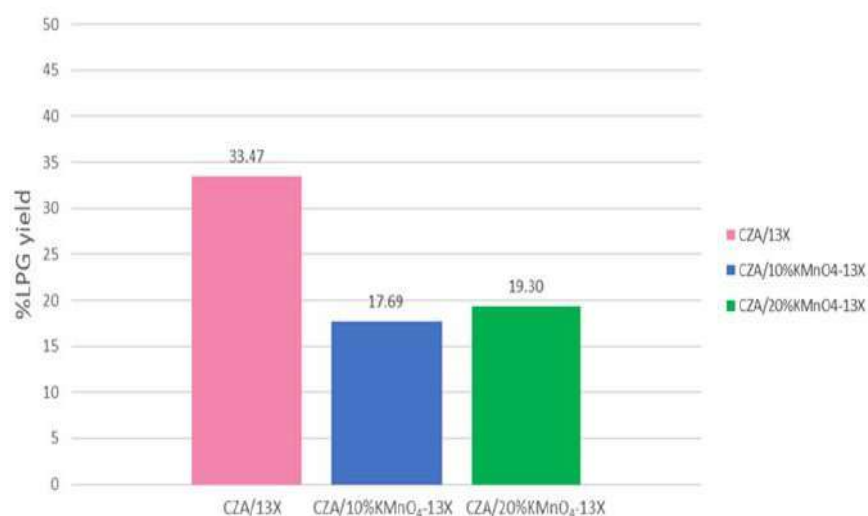


Figure 9. LPG yield (%) for different catalyst systems, showing the superior performance of the unmodified CZA/13X bifunctional catalyst.

The data presented in Table 3 reveal several important trends that provide insights into the underlying causes of performance differences, consistent with structure-activity relationships established by Tavares et al. (2022) in their systematic catalyst optimization studies. First, the decline in CO conversion with increasing KMnO₄ loading follows a clear trend, suggesting that the negative effects of

modification are cumulative and become more severe at higher loadings, which aligns with threshold behavior models proposed by Liu et al. (2018).

Table 3. Carbon monoxide conversion (%), product selectivity (%), and LPG yield (%).

Catalysts	CO conversion (%)	LPG selectivity (%)	HC Selectivity (%)	DME selectivity (%)	LPG yield (%)
CZA/13X	87.64	38.16	99.92	0.14	33.47
CZA/10%KMnO ₄ -13X	89.83	20.34	99.90	0.13	17.69
CZA/20%KMnO ₄ -13X	83.14	23.00	99.99	0.01	19.30

Second, the LPG selectivity shows an even more dramatic decline than CO conversion, indicating that the modification affects product distribution more severely than overall activity. This finding suggests that the modification disrupts the delicate balance of reaction conditions required for selective LPG formation, possibly through changes in acid site distribution or the introduction of competing reaction pathways, as demonstrated by Weber et al. (2024) in their mechanistic studies of modified zeolite catalysts.

The yield data provide significant insights into the economic viability of catalyst selection for industrial-scale operations. The substantially higher yields achieved by the unmodified system directly correlate with enhanced product recovery rates, which is a primary driver for optimizing process economics. Furthermore, the streamlined preparation protocol for the unmodified catalyst offers a distinct advantage by eliminating the additional impregnation and drying steps required for modification. This reduction in synthesis complexity not only lowers manufacturing costs but also minimizes the potential for batch-to-batch variability, representing a significant economic and operational benefit as identified by Ramirez et al. (2019) in their process optimization studies.

3.3 Structure-Performance Relationships

The experimental data reveal a strong correlation between the structural integrity of the catalysts and their catalytic performance. The unmodified CZA/13X system, characterized by unobstructed 13X zeolite supercages and moderate Brønsted acidity, consistently yielded the highest LPG selectivity (38.16%). In contrast, the KMnO₄-modified catalysts exhibited progressive pore blockage and a reduction in acid site density as the loading of MnO₂ and K₂O increased. SEM and BET data confirm that these deposits are non-uniformly distributed, creating a heterogeneous surface that corresponds with the cumulative decline in CO conversion and LPG yield observed in the performance tests.

4. Discussion

4.1 Catalyst Characterization Results

4.1.1 XRD Analysis and Phase Composition

The diffraction analysis confirms the successful formation of all expected phases and the structural integrity of the bifunctional catalysts. The sharp and intense CuO peaks indicate a well-crystallized structure, which is essential for catalytic activity, while the peak intensities suggest a uniform dispersion of copper oxide within the catalyst matrix. The preservation of 13X zeolite peaks confirms that the faujasite structure and its microporous properties remain intact throughout the co-precipitation and calcination processes, ensuring acid site accessibility for methanol conversion.

The formation of β -MnO₂ and K₂O crystalline domains, rather than mere surface dispersion, indicates that the permanganate precursor underwent quantitative decomposition. The presence of these phases is significant as they may influence the local electronic environment, potentially affecting the reducibility and catalytic properties of the copper phase.

Regarding the crystallite size, the CuO size obtained in this study (12.25 nm) is larger than some previously reported values (e.g., 6.30 nm). This difference may be attributed to variations in synthesis conditions, such as calcination temperature, duration, or precipitation pH. While the larger crystallite size leads to a relatively lower copper dispersion (10.45% vs 20.32%), this value remains within the optimal range for methanol synthesis applications. Furthermore, moderate dispersion might enhance catalyst stability, as highly dispersed copper particles are often more susceptible to sintering under demanding reaction conditions.

4.1.2 Surface Morphology and Composition

The SEM/EDS results provide evidence for the successful integration of methanol synthesis and acid catalysis functionalities. The confirmation of the intended 2:2:1 stoichiometry validates the reliability of the co-precipitation method used in this study.

The homogeneous mixing of copper, zinc, and aluminum at the microscopic level is particularly significant, as it is essential for creating the active sites and promoter interfaces required for optimal catalytic performance in methanol synthesis. This uniform spatial distribution suggests that the physical mixing process effectively combined the metallic oxide components with the zeolite framework, ensuring that the bifunctional nature of the catalyst is maintained throughout the structure.

4.1.3 Surface Area and Porosity (BET) Analysis

The heterogeneous nature of the catalyst morphology is typical of physically mixed bifunctional catalysts (Liu et al., 2021). The observed CZA aggregate size (10–50 μ m) is considered suitable for fixed-bed reactors as it minimizes pressure drop while maintaining mass transfer characteristics (Mahmoudi et al., 2017). The rough, cauliflower-like surface of CZA is characteristic of co-precipitated oxides and is beneficial for providing the high surface area required for methanol synthesis (Tavares et al., 2022). Furthermore, the interface between CZA and zeolite is critical for bifunctional catalysis, facilitating the conversion of intermediates (Liu et al., 2018).

The formation of rod-shaped structures in modified catalysts corresponds to β - MnO_2 phases produced during thermal decomposition (Weber et al., 2024). The preferential deposition of manganese on the zeolite surface, rather than within the matrix, aligns with findings by Kar et al. (2025). This pattern suggests that the impregnation process is governed by capillary forces and surface energy (Ramirez et al., 2019).

The significant reduction in surface area and pore volume at higher KMnO_4 loadings can be attributed to the physical occupation of the zeolite internal void space by MnO_x and K_2O species (Kar et al., 2025; Palgunadi et al., 2010). The observed textural changes suggest a pore-blocking mechanism, particularly at the pore mouth entrances, which obstructs molecular access to the internal network (Mahmoudi et al., 2017). The shift in pore size distribution at 20% loading implies that smaller pores are preferentially blocked.

These textural changes have significant implications for catalytic performance. The reduction in surface area directly correlates with a decrease in accessible acid sites within the zeolite micropores, which is expected to reduce the rates of methanol dehydration and hydrocarbon formation (Ren et al., 2019; Tavares et al., 2022). Consequently, the unmodified CZA/13X system maintains superior performance by preserving the full textural benefits of the zeolite support (Liu et al., 2018), providing a physical basis for the higher activity compared to modified counterparts (Ramirez et al., 2019).

4.1.4 Acidity Characterization

The acid site density and strength distribution of the 13X zeolite represent an optimal balance for the direct synthesis of LPG. The low-temperature sites, associated with silanol groups or weakly acidic bridging hydroxyls, provide some acidity but are generally insufficient alone for the dehydration and oligomerization required for LPG formation. In contrast, the high-temperature sites, primarily associated with bridging hydroxyl groups (Si-OH-Al) within the sodalite cages and hexagonal prisms, serve as the primary active centers for methanol dehydration.

The heterogeneity of the high-temperature peak is beneficial for LPG synthesis as it provides a range of acid strengths to catalyze different steps in the reaction network. Moderate acid strength sites are preferred for selective methanol dehydration to dimethyl ether (DME). Stronger sites facilitate C-C bond formation and chain growth.

Unlike zeolites with excessive acid strength (e.g., H-ZSM-5 or H-mordenite), which can lead to over-cracking of LPG into lighter hydrocarbons like methane and ethane, the moderate acidity of 13X minimizes these unwanted side reactions and reduces coke formation (Weber et al., 2024; Tavares et al., 2022). Furthermore, the three-dimensional pore structure combined with this balanced acidity provides shape selectivity that favors branched C_3 - C_4 hydrocarbons (Ramirez et al., 2019).

The thermal robustness indicated by the TPD profile is a decisive factor for industrial applications. Since the acid sites remain protonated at the reaction temperature of 350°C , the catalyst can maintain consistent conversion rates and selectivity during prolonged cycles (Liu et al., 2018).

4.2 Catalytic Performance Evaluation

4.2.1 CO Conversion Analysis

In contrast, the KMnO_4 -modified catalysts showed progressively decreasing CO conversions: 86.83% for CZA/10% KMnO_4 -13X and 83.14% for CZA/20% KMnO_4 -13X. From a catalytic chemistry perspective, this decrease is attributed to the disruption of the "synergistic proximity" between the methanol synthesis sites (Cu^0) and the dehydration sites (Brønsted acid sites). The introduction of MnO_2 and K_2O leads to "electronic poisoning" and "site competition". Manganese oxides, particularly β - MnO_2 , can alter the redox properties of the Cu/ZnO interface, potentially leading to the over-oxidation of active Cu^0 sites or hindering the H_2 dissociative adsorption, which is a critical step in CO hydrogenation (Palgunadi et al., 2010). Furthermore, the reduction in activity is fundamentally linked to the "methanol-intermediate inhibition." As confirmed by BET analysis, the 51% reduction in surface area for the 20% loading sample limits the diffusion of reactants to active sites. According to Le Chatelier's principle in a micro-environment, the local accumulation of methanol intermediates at the Cu surface suppresses further CO conversion rates (Ao et al., 2020). This correlates with studies on catalyst deactivation mechanisms, where pore blockage was identified as a primary cause of reduced activity.

4.2.2 Product Selectivity and Distribution

This higher selectivity of the unmodified system aligns with the mechanistic investigations by Weber et al. (2024), who emphasized that LPG formation requires a careful balance of C-C bond formation and chain growth. The acid site distribution in pristine 13X zeolite, as theoretically modeled by Tavares et al. (2022), provides the moderate acid strength necessary for selective methanol dehydration. However, the poor selectivity of the modified catalysts in this study can be rigorously explained by the "Acidity-Basicity Dualism." The decomposition of KMnO_4 releases K^+ ions that undergo ion exchange with the Brønsted acid sites (Si-OH-Al), neutralizing the sites required for the methanol-to-hydrocarbon (MTH) pathway. This reduction in "acid strength density" means the activation energy for oligomerization is no longer efficiently met, shunting the reaction towards lighter products (Weber et al. 2024). Additionally, the rod-shaped β - MnO_2 aggregates observed in SEM create a "Steric Hindrance" effect. These deposits at the zeolite pore mouths, consistent with the pore blockage model by Mahmoudi et al. (2017), create a diffusion barrier for bulky C_3 - C_4 intermediates. These molecules suffer from "restricted transition state selectivity," where increased residence time promotes secondary cracking, lowering the net LPG selectivity as documented by Ramirez et al. (2019). This further supports the findings of Liu et al. (2018), indicating that blocked acid sites lead to incomplete conversion of key intermediates.

4.2.3 Overall LPG Yield Performance

A catalytic chemistry standpoint, the drastic drop in LPG yield (nearly 50% compared to the pristine system) confirms that the "bifunctional synergy" was severely compromised by the KMnO_4 impregnation. This can be explained by the "Active Site Accessibility-Density (ASAD)" relationship. The high yield in the CZA/13X system is due to the efficient transport of methanol intermediates from the Cu-Zn-Al sites to the 13X zeolite's internal supercages. However, in the modified systems, the crystalline MnO_2 and K_2O deposits act as "diffusion bottlenecks," increasing the probability of secondary side reactions before the

intermediates can reach the critical acid sites for LPG formation (Ramirez et al., 2019). Therefore, even though syngas conversion remained relatively high, the chemical efficiency of the carbon flow toward the C₃–C₄ range was drastically reduced by the modification, highlighting that structural integrity and acid site availability are more critical than any potential alkali promotion in this specific reaction network.

4.3 Structure-Performance Relationships

The good catalytic performance of the CZA/13X system arises from the synergistic combination of several key structural factors that create suitable conditions for bifunctional catalysis, as demonstrated by comprehensive studies conducted by Liu et al. (2018). The optimal acid-metal balance represents perhaps the most critical aspect of this system's success, which aligns with theoretical frameworks developed by Weber et al. (2024). The moderate acid strength of 13X zeolite provides sufficient driving force for methanol dehydration and subsequent oligomerization reactions while avoiding excessive cracking. From a catalytic chemistry perspective, this "Acidity Tuning" is the heart of LPG selectivity; by utilizing the moderate Brønsted acidity of 13X, the reaction pathway is successfully steered toward C₃–C₄ hydrocarbons rather than lighter alkanes (CH₄, C₂H₆) which often dominate over stronger acid catalysts like H-ZSM-5 (Tavares et al., 2022).

The three-dimensional pore network of 13X zeolite contributes significantly to the observed selectivity through both geometric and diffusion effects. The supercage dimensions provide adequate space for the formation and diffusion of LPG molecules while imposing shape selectivity constraints that favor branched C₃–C₄ products over linear longer-chain hydrocarbons (Mahmoudi et al., 2017). This "Transition State Selectivity" is maintained only when the pore mouths are unobstructed, allowing for the rapid egress of bulky branched isomers before they undergo secondary cracking (Ramirez et al., 2019). The unhindered accessibility of active sites in the unmodified system ensures minimal diffusion path lengths for intermediate species (methanol/DME) while maintaining the distinct chemical environments required for each catalytic function (Kar et al., 2025).

The most critical issue is the progressive pore blockage induced by the deposition of MnO₂ and K₂O species. This 'physical shielding' creates a significant bottleneck within the reaction network, leading to the formation of a 'methanol-rich micro-environment' at the Copper (Cu) surface. Such localized concentrations thermodynamically inhibit further CO conversion, effectively stalling the reaction sequence. Furthermore, the introduction of Potassium (K) species serves as an 'alkali poison' to the zeolite's Brønsted acid sites. Through an ion-exchange process, where H⁺ ions are replaced by K⁺, the acid site density is substantially depleted. Consequently, the 'chemical pressure' necessary to drive the Methanol-to-Hydrocarbon (MTH) pathway is insufficient, as supported by the findings of Ao et al. (2020). Finally, the spatial distribution of these deposits, as observed via SEM, reveals a highly heterogeneous surface. This confirms that the deleterious effects of the modification are cumulative rather than compensatory, reinforcing the conclusions drawn by Liu et al. (2018) regarding the impact of non-uniform surface properties on catalytic efficiency.

The structure-performance relationships revealed in this study demonstrate that maintaining a "Clean Interface" between the metallic CZA and the acidic 13X is far more critical than individual

component modification. This systems-level insight suggests that for high-performance syngas-to-LPG catalysts, the design strategy must prioritize the preservation of native microporosity and acid strength over the introduction of complex transition metal promoters that may introduce unwanted steric and electronic complications (Ramirez et al., 2019).

5. Conclusion

This investigation of bifunctional catalysts for direct LPG synthesis from syngas has provided valuable insights into the importance of maintaining optimal structural properties for effective catalytic performance. The systematic comparison of unmodified and KMnO_4 -modified CZA/13X systems has revealed fundamental principles that govern the success of bifunctional catalysis. The unmodified CZA/13X catalyst demonstrated superior performance across all measured metrics, achieving 87.64% CO conversion, 38.16% LPG selectivity, and 33.47% LPG yield under the optimized conditions (350°C, 40 bar). These results represent a significant advantage over the KMnO_4 -modified alternatives, suggesting that the pristine bifunctional interface is more effective for industrial LPG production.

The structural characterization provided clear evidence for the mechanisms underlying these differences. While XRD confirmed the formation of all expected phases, it revealed that KMnO_4 decomposition produces crystalline MnO_2 and K_2O . From a catalytic chemistry perspective, these species did not act as effective promoters but rather as “catalytic poisons” that disrupted the active site architecture. SEM and BET analyses quantified a dramatic loss of surface area (up to 51%) and pore volume (47%) for the 20% KMnO_4 -loaded system. This physical degradation creates a “diffusion bottleneck” that hinders the transport of methanol intermediates from Cu sites to the zeolite acid sites, thereby breaking the “bifunctional synergy” required for continuous CO hydrogenation.

The catalytic evaluation revealed that KMnO_4 modification negatively impacts both CO conversion and LPG selectivity. The chemical evidence suggests that K^+ ions from the promoter underwent ion exchange with Brønsted acid sites (Si-OH-Al), neutralizing the sites essential for the methanol-to-hydrocarbon (MTH) pathway. This “alkali poisoning” effect, combined with the steric hindrance from rod-shaped β - MnO_2 deposits at pore mouths, shunted the reaction pathway toward lighter gaseous products and limited the formation of bulky C_3 - C_4 hydrocarbons.

The structure-performance relationships identified in this study demonstrate that the performance of the unmodified CZA/13X system results from the synergistic combination of optimal acid-metal balance, favorable pore structure characteristics, unhindered active site accessibility, and thermal stability. The moderate acid strength of 13X zeolite provides sufficient activity for methanol dehydration without causing excessive cracking. The fundamental chemical insight gained is that maintaining a “clean and accessible interface” between the metallic and acidic functions is more critical than chemical modification that introduces unwanted steric and electronic complications.

Future research should focus on exploring promoters that can enhance metal dispersion without occupying the critical internal pore volume or neutralizing the active acid sites of the zeolite. Additionally,

investigating long-term stability and resistance to poisoning under industrial conditions will further enhance the commercial viability of this technology. These fundamental insights provide a solid foundation for the continued development of bifunctional catalysis in sustainable fuel production.

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การบูรณาการ IOT บล็อกเชน และ AI เพื่อเพิ่มความสามารถในการตรวจสอบย้อนกลับและสมรรถนะ
การปฏิบัติการในห่วงโซ่อุปทานอาหาร: การทบทวนวรรณกรรมอย่างเป็นระบบ
และการวิเคราะห์ตามกรอบ TOE ในประเทศไทย

IOT, Blockchain, and AI Integration for Enhanced Traceability and Operational
Performance in Food Supply Chains: A Systematic Review and
TOE Framework Analysis in Thailand

ชนิกานต์ กมลสุข^{1*} และ วัชรพล สุขโหด¹

Chanikarn Kamonsook^{1*} and Vatcharapol Sukhotu¹

¹คณะโลจิสติกส์และดิจิทัลซัพพลายเชน มหาวิทยาลัยนเรศวร จังหวัดพิษณุโลก

¹Faculty of Logistics and Digital Supply Chain, Naresuan University, Phitsanulok Province

*Corresponding Author: chanikarnk64@nu.ac.th

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บทคัดย่อ

ห่วงโซ่อุปทานอาหารกำลังเผชิญกับแรงกดดันจากสถานการณ์ด้านความปลอดภัย การทุจริตอาหาร และความไว้วางใจ ทำให้การตรวจสอบย้อนกลับเป็นสิ่งที่จำเป็นในการเพิ่มความสามารถในแข่งขัน เนื่องจากการพึ่งพาเทคโนโลยีดิจิทัลเพียงชนิดเดียวยังคงมีข้อจำกัด ดังนั้น การบูรณาการระบบอินเทอร์เน็ตของสรรพสิ่ง (IoT) บล็อกเชน (Blockchain) และปัญญาประดิษฐ์ (AI) ร่วมกัน เพื่อให้เกิดความโปร่งใสตลอดห่วงโซ่อุปทาน ข้อมูลเชื่อถือได้ และสามารถคาดการณ์ได้ทันเวลา จึงมีความสำคัญอย่างยิ่งสำหรับประเทศไทย ซึ่งเป็นผู้ส่งออกสินค้าเกษตรและอาหารรายสำคัญ อย่างไรก็ตาม การยอมรับการใช้เทคโนโลยีดิจิทัลเหล่านี้ในกลุ่มผู้ประกอบการขนาดกลางและขนาดย่อมยังไม่มากนัก เนื่องจากเงินทุน ทักษะ และโครงสร้างพื้นฐานดิจิทัลที่ยังไม่ทั่วถึง งานทบทวนวรรณกรรมอย่างเป็นระบบนี้ยึดแนวทาง PRISMA เพื่อสังเคราะห์ผลงานวิจัยที่ผ่านการพิจารณาถ่วงดุลระหว่างปีพ.ศ. 2562-2568 ที่เป็นการบูรณาการทั้งสามเทคโนโลยี ในบริบทห่วงโซ่อุปทานอาหาร พร้อมใช้กรอบแนวคิดเทคโนโลยี-องค์กร-สิ่งแวดล้อม (TOE) วิเคราะห์ปัจจัยสนับสนุนและอุปสรรคของประเทศไทย ผลการสังเคราะห์แสดงให้เห็นว่า การบูรณาการเทคโนโลยีช่วยส่งเสริมขีดความสามารถด้านการตรวจสอบย้อนกลับ ได้แก่ การมองเห็นข้อมูลแบบเรียลไทม์จากระบบอินเทอร์เน็ตของสรรพสิ่ง การบันทึกที่ตรวจสอบได้และแก้ไขไม่ได้ด้วยระบบบล็อกเชน และการยืนยันแหล่งที่มาด้วยการวิเคราะห์ของระบบปัญญาประดิษฐ์ที่ส่งผลกับสมรรถนะการปฏิบัติการที่จับต้องได้ ไม่ว่าจะเป็นการตัดสินใจและการเรียกคืนสินค้าที่รวดเร็วขึ้น การควบคุมคุณภาพที่แม่นยำขึ้น และการลดต้นทุน ในบริบทประเทศไทย ปัจจัยสนับสนุนคือนโยบายภาครัฐ มาตรฐานอุตสาหกรรม และความร่วมมือระหว่างภาคส่วน ส่วนอุปสรรคสำคัญคือเงินทุน โครงสร้างพื้นฐานที่ไม่เหมาะสม ช่องว่างด้านทักษะ และกฎระเบียบ โดยเฉพาะกับผู้ประกอบการรายย่อย โดยสรุป งานทบทวนวรรณกรรมนี้เสนอกรอบแนวคิดที่นำการตรวจสอบย้อนกลับเป็นตัวแปรคั่นกลางเชื่อมโยงการบูรณาการเทคโนโลยีกับสมรรถนะการปฏิบัติการด้านความเร็ว คุณภาพ และต้นทุน พร้อมข้อเสนอเชิงนโยบายเพื่อยกระดับอุตสาหกรรมอาหารไทยในยุคดิจิทัล

คำสำคัญ: ระบบอินเทอร์เน็ตของสรรพสิ่ง, ระบบบล็อกเชน, ระบบปัญญาประดิษฐ์, ความสามารถในการตรวจสอบย้อนกลับ, ห่วงโซ่อุปทานอาหาร

Abstract

Food safety incidents, food fraud, and increasing trust deficits are exerting pressure on food supply chains, thereby necessitating robust traceability capabilities as a competitive advantage. Relying on a single digital technology remains insufficient in scope. Therefore, the integration of the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI) is critically important for Thailand as a major agro-food exporter to achieve comprehensive supply chain transparency, reliable data, and timely predictive insights. However, adoption rates among small and medium-sized enterprises (SMEs) remain modest due to high costs, skills gaps, and inadequate digital infrastructure coverage. This systematic literature review employs PRISMA-guided procedures to synthesize both quantitative and qualitative peer-reviewed studies published between 2019 to 2025, examining the integrated application of all three technologies, including pairwise combinations, within food supply chain contexts. It utilizes the Technology–Organization–Environment (TOE) framework to analyze Thailand-specific enablers and barriers and to interpret the connections between enhanced traceability capabilities and measurable operational performance outcomes. The synthesis reveals that technology integration strengthens traceability through three core pillars: real-time data visibility from IoT sensing and tracking systems, tamper-resistant and verifiable records through blockchain, and provenance verification through AI analytics and pattern recognition. These elements collectively translate into tangible operational benefits, including expedited decision-making and product recall processes, more precise and efficient quality control mechanisms, and cost reductions through automation, waste minimization, and comprehensive risk management. Within the Thai context, key enablers include government policy support, established industry standards, and multi-stakeholder collaborative frameworks, while significant barriers encompass high initial investment requirements, uneven digital infrastructure distribution, skill development gaps, and regulatory compliance burdens—particularly challenging for small-scale operators. In conclusion, this review proposes a conceptual framework positioning traceability as a mediating mechanism linking technology integration with operational performance improvements in speed, quality, and cost reduction dimensions, and provides actionable policy recommendations regarding infrastructure investment and capability enhancement initiatives to accelerate the responsible and inclusive advancement of Thailand’s food industry in the digital era.

Keywords: Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), Traceability, Food supply chain

1. Introduction

Complex food supply chains face critical challenges: contamination risks require rapid source identification and recalls (Zhou et al., 2022), fraud demands rigorous authentication (Stranieri et al., 2021), and consumer trust relies on transparent quality assurances (Zhou et al., 2022). Effective traceability systems have thus become essential for industry competitiveness and reliability.

Digital technologies, particularly the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI), offer powerful tools for enhancing food supply chain processes. IoT devices collect real-time data,

Blockchain ensures secure, immutable record-keeping, and AI delivers advanced analytics to optimize traceability. Recent studies by Talpur et al. (2023) and Vilas-Boas et al. (2023) highlight the growing trend of integrating these technologies to achieve more comprehensive solutions than any single technology can provide. While these three technologies offer individual benefits, their combined integration creates synergistic effects that enhance traceability capabilities beyond what any single or paired combination can achieve. The integration of all three technologies enables comprehensive traceability systems that simultaneously address transparency, data integrity, and intelligent decision-making throughout the supply chain.

Although research on IoT, Blockchain, and AI individually is extensive, there is a notable gap in systematic literature reviews examining the combined impact of all three technologies on traceability and operational performance. For example, Zhou et al. (2022) investigate traceability enhancements but do not assess quality, speed, or cost dimensions, nor do they consider the full integration of IoT, Blockchain, and AI. Tsolakis et al. (2023) evaluate AI and Blockchain integration in Thailand's tuna-industry supply chain, showing improved transparency but omitting IoT and a systematic analysis of operational outcomes. Moreover, barriers and enablers specific to the Thai context have yet to be thoroughly synthesized.

Thailand occupies a significant position in global agri-food exports, yet it still faces food safety and quality challenges that force exporters to meet increasingly stringent international standards (Holzapfel & Hampel-Milagrosa, 2020). Adoption of advanced digital tools remains limited among smallholder farmers and small and medium-sized enterprises (SMEs), primarily due to high costs, technical skills, and uneven infrastructure (Yooyativong & Kamyod, 2023).

The Technology-Organization-Environment framework, or TOE, is widely used to understand how organizations adopt new technologies (Bryan & Zuva, 2021). It considers three important areas: technology, organization, and environment (Baker, 2011). This approach is valuable for food supply chains because adopting integrated technologies like IoT, Blockchain, and AI requires coordinating across technological capabilities, organizational structures, and regulatory environments simultaneously. For Thailand's food industry, where many small and medium-sized enterprises face limited digital infrastructure, budget constraints, and unclear regulations (Yooyativong & Kamyod, 2023), the TOE framework helps identify enablers and barriers to technology adoption. This structured perspective is essential for developing practical recommendations that address all three dimensions together.

To fill these gaps, this article conducts a PRISMA-guided Systematic Literature Review and applies the Technology-Organization-Environment (TOE) framework to achieve three objectives: 1) To examine how integrating IoT, Blockchain, and AI enhances traceability capabilities in food supply chains; 2) To analyze how improved traceability drives operational performance gains in speed, quality, and cost; and 3) To identify the critical barriers and enablers for implementing such integrated technologies in Thailand's food industry. The findings will contribute a synthesized theoretical framework and offer practical guidance for entrepreneurs and government agencies to strengthen Thailand's food-sector competitiveness.

2. Materials and methods

2.1 Research Design

This study employs the Systematic Literature Review (SLR) as the primary tool for gathering, selecting, and analyzing data. This method is appropriate for addressing research objectives that require synthesizing a large body of research (Tranfield et al., 2003).

2.2 Search Strategy

2.2.1 Database

This review uses Scopus exclusively for its PRISMA-guided systematic literature review and for the TOE framework analysis because of its extensive, high-quality coverage. Searches in TCI and Google Scholar informed the background context but are not part of the SLR process or included in Figure 1.

2.2.2 Search String

To ensure comprehensive literature coverage and the ability to analyze research related to technology integration, the search strategy is designed for flexibility. Search terms are tailored to focus on articles discussing the integration of at least two technological systems within the context of food supply chains and traceability. The search comprises three groups, as follows:

2.2.2.1 Integration of Blockchain and IoT

Search string: TITLE-ABS-KEY(("Blockchain" AND ("Internet of Things" OR "IoT")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain")))

2.2.2.2 Integration of Blockchain and AI

Search string: TITLE-ABS-KEY(("Blockchain" AND ("Artificial Intelligence" OR "AI" OR "Machine Learning")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain")))

2.2.2.3 Integration of IoT and AI

Search string: TITLE-ABS-KEY(("Internet of Things" OR "IoT") AND ("Artificial Intelligence" OR "AI" OR "Machine Learning")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain"))

Articles obtained from search groups 2.2.2.1-2.2.2.3 will be combined, and duplicate records will be removed to prepare the data in accordance with PRISMA principles for the subsequent selection process.

2.3 Search Scope

There are four criteria defining the search scope within the Scopus database: 1) Articles published in peer-reviewed academic journals. 2) Studies in English. 3) Articles published from 2019 to 2025. 4) Full-text articles accessible for comprehensive review.

2.4 Screening and Selection Process

Articles were screened and selected following PRISMA guidelines. To ensure the reliability and validity of the synthesized data, a rigorous quality assessment was integrated into the selection process.

2.4.1 Inclusion Criteria

The main inclusion criteria were: 1) peer-reviewed academic articles (excluding conference abstracts and articles in press without full data); 2) published in English; 3) studies examining the integration of IoT, Blockchain, and AI, including pairwise combinations that contribute to a holistic traceability framework; 4) conducted within food or agricultural supply chain contexts; and 5) presenting measurable outcomes relevant to traceability capabilities or operational performance.

2.4.2 Exclusion Criteria

The main exclusion criteria were as follows: 1) non-research articles (e.g., reviews, editorials, book chapters); 2) studies limited to the application of a single digital technology without synergistic integration; 3) articles with inaccessible full texts; and 4) articles identified as retracted or lacking rigorous methodological standards during the quality assessment phase.

The screening process and the number of articles will be summarized in the PRISMA flow diagram for the systematic literature review as shown in Figure 1.

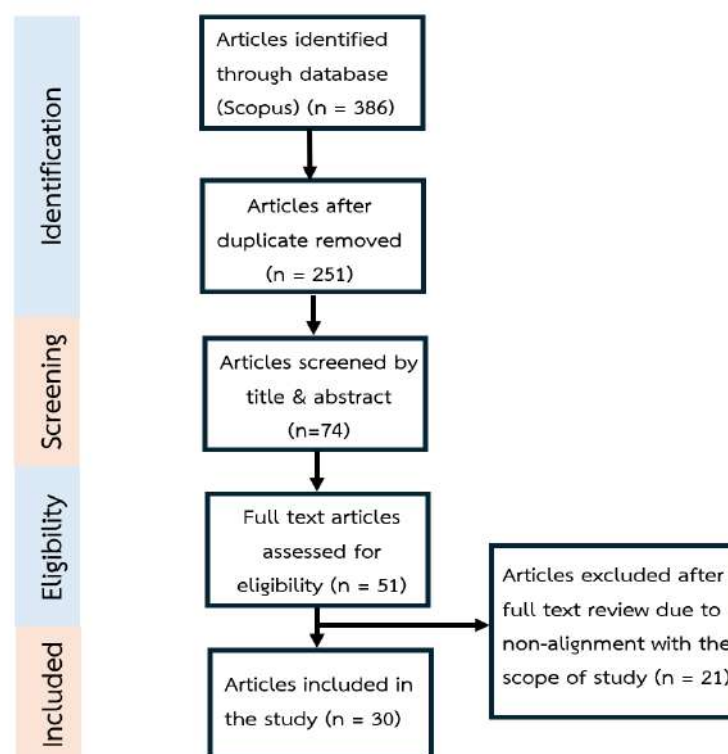


Figure 1. PRISMA Flow Diagram for Systematic Literature Review

Note: Figure 1 shows only the PRISMA flow for the systematic literature review based on Scopus. Additional TCI and Google Scholar searches supported contextual analysis but are excluded here.

2.5 Data Extraction and Analysis

Data extracted from each study comprised the author, publication year, research methodology, technology type (IoT, Blockchain, AI), implementation context, outcomes, and success factors. A standardized extraction form ensured consistency and minimized bias in data collection. The study also examined factors supporting and hindering technology integration in Thailand's food supply chain through the Technology-Organization-Environment (TOE) framework, a widely accepted model for understanding technology adoption (Bryan & Zuva, 2021). According to Baker (2011), the TOE framework classifies adoption influences into three contexts: technological, which covers existing systems, technology complexity, and compatibility with current infrastructure; organizational, which includes organizational size, resource availability, structural characteristics, and management support; and environmental, which involves industry structure, competitive pressure, and regulatory requirements. Extracted data were systematically coded by these dimensions to reveal patterns, trends, and barriers, enabling a thorough, structured analysis of technology adoption in food supply chains.

The synthesis process adopted an integrative approach, combining findings from pairwise-technology studies (such as IoT integrated with Blockchain) with triple-technology studies. Instead of separating them into distinct analysis layers, evidence was mapped to specific functional pillars, Transparency, Security, and Provenance, to demonstrate how these technologies act as complementary components of a unified digital ecosystem.

3. Results

3.1 Thematic Synthesis of Findings

3.1.1 Three Pillars of Enhanced Traceability

By synthesizing insights from both pairwise combinations and fully integrated models, the synergistic impact of IoT, Blockchain, and AI becomes evident across three core traceability pillars:

3.1.1.1 Transparency and visibility: The integration of IoT, Blockchain, and AI enhances transparency and visibility by enabling continuous, real-time monitoring of product location and condition through IoT sensors, with records stored on a shared, tamper-resistant blockchain ledger (Liberty et al., 2025; Rossi et al., 2025). AI analytics further process these data streams to generate alerts, forecasts, and decision-support dashboards, allowing stakeholders to identify disruptions and potential bottlenecks before they escalate (Vilas-Boas et al., 2023).

3.1.1.2 Data Integrity and Security: Data integrity and security are strengthened when granular observations from IoT devices are preserved as immutable blockchain transactions, reducing opportunities for unauthorized modification or data loss (Rossi et al., 2025). AI models operate as an additional validation layer by detecting anomalous patterns, sensor errors, or suspicious activities, thereby filtering out unreliable inputs and reinforcing trust in the recorded information (Femimol & Joseph, 2025; Zhang et al., 2023).

3.1.1.3 Provenance and Authenticity: Provenance and authenticity are reinforced by combining IoT-based tracking of each processing and logistics step with blockchain's verifiable chain of custody (Monteiro et al., 2021; Liu et al., 2025). AI techniques then authenticate origins and specific claims, such as geographical indication or Halal status, through pattern recognition and advanced classification methods, enabling the reliable differentiation of genuine products from counterfeits (Yang et al., 2025; Nawaz et al., 2025)

These three pillars collectively provide the conceptual foundation for examining how integrated IoT, Blockchain, and AI adoption translates into measurable improvements in speed, quality, and cost dimensions in subsequent sections.

3.1.2 Relationship Between Traceability Capabilities and Operational Performance

Technological integration does not merely enhance traceability capabilities; it translates these capabilities into tangible operational advantages. The synthesis of prior literature reveals that the synergistic collaboration of IoT, Blockchain, and AI drives measurable improvements across three strategic dimensions: speed, quality, and cost reduction. The following sections examine these impacts in detail.

3.1.2.1 Speed

Speed enhancement is the first critical dimension in which technology integration transforms operations. By combining real-time IoT data, immutable blockchain records, and AI-driven analytics, organizations accelerate responsiveness across three levels: 1) decision-making, 2) production cycles, and 3) risk management. The quantitative impact of these improvements is summarized in Table 1.

Analysis of Speed Outcomes:

1) Data Access and Decision-Making

Real-time visibility allows for instant stakeholder action. Studies indicate that animal health issues can be detected 24 hours in advance (Serrano-Torres et al., 2025), with alerts issued within 5 seconds, reducing overall response time by 30% (Halder et al., 2025). Platform efficiency is also notable, with user data requests fulfilled in just 2-5 milliseconds (Shahbazi & Byun, 2021).

2) Production and Quality Control

Automated systems leverage data integrity to operate with speed and precision. Image-based quality assessments take merely 5–60 milliseconds per unit (Femimol & Joseph, 2025; Yin et al., 2025), while pathogen identification occurs between 20 seconds and 15 minutes (Yang et al., 2025). Furthermore, blockchain transactions are verified in approximately 15 seconds (Femimol & Joseph, 2025), minimizing administrative delays.

3) Risk Management and Product Recall

Provenance capabilities drastically improve crisis response. The IBM-Walmart case demonstrates that blockchain reduces traceability lead time from 7 days to 2.2 seconds (Liberty et al., 2025; Tao et al., 2023). Additionally, AI-driven risk prediction is 80% faster than traditional methods, enabling preemptive risk mitigation (Liberty et al., 2025).

Table 1. Quantitative Metrics on Speed Enhancement from Technology Integration

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Data Access and Decision Making	AI sensors for animal health alerts.	Response Time /Early Detection	30% reduction in response time; alerts within 5 seconds; detection 24 hours in advance.	Halder et al. (2025); Serrano-Torres et al. (2025)
	Blockchain platform retrieval.	System Response Time	Data requests answered in 2–5 milliseconds.	Shahbazi and Byun (2021)
2. Production and Quality Control	AI Computer Vision for sorting/inspection.	Processing Time per Unit	Processing completed in 5–60 milliseconds/unit.	Femimol & Joseph (2025); Yin et al. (2025)
	Biotech sensors for pathogens.	Detection Time	Anomaly detection in 20 seconds (contaminants) to 15 minutes (pathogens).	Yang et al. (2025); Liberty et al. (2025)
	Blockchain transactions.	Processing Time	Transaction processing time in 15 seconds.	Femimol & Joseph (2025)
3. Risk Management and Product Recall	Blockchain traceability (IBM-Walmart)	Traceability Time	Lead time reduced from 7 days to 2.2 seconds.	Liberty et al. (2025); Tao et al. (2023); Ellahi et al. (2023)
	AI risk prediction	Processing Speed	Prediction accelerated by 80%; risk-event processing in 30 seconds.	Liberty et al. (2025); Femimol and Joseph (2025)

Note: This table synthesizes evidence of accelerated supply chain processes. Key insights indicate response times drop by up to 30%, and blockchain-enabled traceability reduces recall lead times from days to seconds, facilitating a shift from reactive to proactive management.

3.1.2.2 Quality

Quality assurance constitutes the second critical performance dimension. Integrated technology strengthens quality through multiple mechanisms, shifting the focus from reactive testing to proactive prevention. The combination of AI precision, IoT monitoring, and Blockchain verification enhances capabilities in: 1) operational quality control, 2) proactive quality management, and 3) fraud prevention. The measurable impacts of these enhancements are presented in Table 2.

Analysis of Quality Outcomes:

1) Operational Quality Control

Data integrity forms the cornerstone of high production standards. Reliable data inputs, secured by anomaly detection with up to 96% precision (Zhang et al., 2023), enable AI systems to operate at peak efficiency. Multiple studies confirm that this data foundation allows automated

classification and sorting systems to achieve accuracy rates between 84% and 98.7% (Frikha et al., 2023; Bhat et al., 2025; Yin et al., 2025).

2) Proactive Quality Management

Real-time visibility transforms quality management from inspection to prediction. Research demonstrates that IoT and AI can forecast spoilage or bacterial contamination with 85–95% accuracy (Chandran et al., 2025; Hassoun, 2025). Additionally, intelligent packaging systems leverage this data to improve the accuracy of shelf-life monitoring by 25% (Liberty et al., 2025), ensuring fresher products reach the consumer.

3) Safety Assurance and Fraud Prevention

Provenance capabilities serve as a powerful tool for consumer protection. Advanced AI techniques identify origins, adulteration, or specific certifications (such as Halal) with accuracy exceeding 94% (Liu et al., 2025; Nawaz et al., 2025). This rigorous verification leads to tangible safety outcomes, including a 30% reduction in safety incidents (Kanwal et al., 2025) and an 85% reduction in product counterfeiting (Rajan & Wani, 2025).

Table 2. Quantitative Metrics on Quality from Technology Integration

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Operational Quality Control	AI and Machine Learning for classification and sorting.	Classification/Detection Accuracy	High accuracy ranging from 84% to 98.7% across diverse contexts.	Frikha et al. (2023); Bhat et al. (2025); Jiang et al. (2025); Yin et al. (2025)
	Sensor data filtering.	Data Filtering Accuracy	96% precision in anomaly detection.	Zhang et al. (2023)
	Blockchain data verification	Data Accuracy	Data integrity maintained at 92%, with only a 3% error rate.	Femimol and Joseph (2025)
2. Proactive Quality Management	IoT and AI for spoilage prediction	Prediction Accuracy	Spoilage and contamination with 85%–95% accuracy.	Chandran et al. (2025); Hassoun (2025)
	Smart packaging to monitor shelf life	Monitoring Accuracy	Shelf-life monitoring accuracy improved by 25%.	Liberty et al. (2025)
3. Safety Assurance and Fraud Prevention	AI for adulteration/origin ID (e.g., Halal)	Identification Accuracy	Accuracy exceeding 94%, approaching nearly 100%.	Liu et al. (2025); Nawaz et al. (2025); El-tahlawy et al. (2025)
	Traceability systems.	Incident/Forgery Reduction	Safety incidents reduced by 30%; food fraud curtailed by up to 85%.	Kanwal et al. (2025); Rajan and Wani (2025)

Note: This table presents empirical evidence of quality improvements. Key insights demonstrate that AI-driven detection achieves high accuracy (up to 98.7%), while integrated systems significantly reduce food safety incidents by 30% and fraud by up to 85%.

3.1.2.3 Cost Reduction

Cost reduction is the third key performance dimension influenced by integrated IoT, Blockchain, and AI adoption in food supply chains. The literature indicates that these technologies lower costs through three main mechanisms: reducing product loss and food waste, decreasing operational and transaction costs, and mitigating risks and damage-related losses. The empirical evidence for these mechanisms is summarized in Table 3.

Analysis of Cost Reduction Outcomes:

1) Product Loss and Food Waste

Transparency and visibility capabilities enable real-time monitoring of product status and demand, shifting management from problem-solving to problem prevention. Empirical literature demonstrates that this proactive approach reduces food waste and losses by 14% to 65% (Hassoun, 2025; Kanwal et al., 2025). Furthermore, it decreases spoilage of perishable products by 20 to 30% (Liberty et al., 2025) and minimizes overstock issues by up to 25% (Sun et al., 2025).

2) Operational and Transactional Costs

Data integrity ensures that automated processes run on trusted information. When systems verify data security, smart contracts can execute transactions without human intervention. This automation directly impacts the bottom line, with research confirming overall operational cost reductions of 15% to over 23% (Kanwal et al., 2025; Sridhar et al., 2023). Specific input costs also drop significantly, including an 80% reduction in pesticide use (Liberty et al., 2025) and a 25% cut in energy consumption (Yin et al., 2025).

3) Minimizing Costs from Risks and Damages

Provenance and authenticity serve as critical risk management tools. By enabling complete traceability through immutable records, technology directly combats food fraud—a risk causing USD 10-15 billion in annual global damage. Additionally, authentic source identification limits the scope of product recalls, potentially decreasing overall supply chain damage by up to 20% (Bhat et al., 2025; Sun et al., 2025).

Table 3. Quantitative Metrics on Cost Reduction from Technology Integration.

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Product Loss and Food Waste	IoT and AI demand forecast (e.g. catering, aviation)	Food Waste/Loss Reduction	Decreases ranging from 14% to 65%	Hassoun (2025); Kanwal et al. (2025)
	IoT and digital twin technology for cold-chain monitoring of perishables.	Spoilage/Product Loss Reduction	Decreases of 20% to 30%	Liberty et al. (2025)
	Blockchain-based data management for improved forecasting.	Overstock Reduction	Reduction of 25%.	Sun et al. (2025)
2. Operational and Transaction Costs	Integrating digital technologies into manufacturing and agricultural.	Overall Operational Cost Reduction	Decreases ranging from 15% to over 23%.	Kanwal et al. (2025); Sridhar et al. (2023)
	AI-driven computer vision for precision agriculture.	Raw Material/Pesticide Cost Reduction	Reduction of 80% in pesticide costs.	Liberty et al. (2025)
	AI for environmental control in smart greenhouses.	Energy Cost Reduction	Reduction of 25% in energy costs.	Yin et al. (2025)
3. Risks and Damages-Related Costs	Technology to minimize system losses and prevent fraud.	Damage/Fraud Loss Reduction	Around 20% reduction in system damage; contributes to mitigating food-fraud losses valued at USD 10–15 billion per year.	Bhat et al. (2025); Sun et al. (2025)

Note: This table summarizes reported cost savings from integrated digital technologies. Key findings show substantial reductions in food waste (up to 65%), operational costs (up to 23%), and risk-related losses, providing a strong economic rationale for technology adoption in food supply chains.

3.2 Barriers and Enablers of Technology Adoption

The literature reveals that integrating emerging technologies into food supply chains encounters various barriers and benefits from multiple enabling factors. These factors can be classified according to the Technology–Organization–Environment (TOE) framework, as summarized in Table 4.

Table 4. Summary of Barriers and Enablers Arising from Technology Integration.

TOE	Factors	Types	Explanation	Reference
1. Technology	High investment cost	Barrier	High initial expenditures for installing, maintaining, and operating advanced technologies (such as blockchain, AI, and IoT), as well as associated data storage and analytics costs.	Dhal & Kar (2025); Hassoun (2025); Hassoun et al. (2023); Issa et al. (2024); Kanwal et al. (2025); Liberty et al. (2025); Qiao et al. (2024); Rajan & Wani (2025); Rossi et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Technological complexity	Barrier	Operation and maintenance require specialized knowledge and expertise, and certain AI models function as “black boxes,” making them difficult to understand and interpret.	Rossi et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Integration Standards	Barrier	The absence of unified integration standards, both technical and regulatory, hinders compatibility among diverse systems and platforms across supply chain organizations.	Liberty et al. (2025); Monteiro et al. (2021); Rossi et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Data security and privacy	Barrier	Concerns about safeguarding data against cyberattacks and leaks, as well as protecting business and consumer data privacy.	Dhal & Kar (2025); Issa et al. (2024); Liberty et al. (2025); Rossi et al. (2025); Sun et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Scalability & Infrastructure	Barrier	Lack of fundamental infrastructure, such as high-speed internet, to support system operations.	Hassoun (2025); Hassoun et al. (2023); Qiao et al. (2024); Rajan and Wani (2025); Sun et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
2. Organization	Organizational & Personnel Constraints	Barrier	Budget and resource constraints coupled with a shortage of personnel possessing the necessary skills, knowledge, and awareness to leverage new technologies, particularly within SMEs.	Čapla et al. (2025); Dhal & Kar (2025); Ellahi et al. (2025); Kanwal et al. (2025); Rajput et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Top Management Support	Enabler	Vision and commitment of top management serve as critical drivers for resource allocation, fostering change, and cultivating an organizational culture receptive to new technologies.	Bhat et al. (2025); Liberty et al. (2025)

Table 4. Summary of Barriers and Enablers Arising from Technology Integration (Cont.).

TOE	Factors	Types	Explanation	Reference
3.Environment	Market Acceptance & Pressure	Enabler/ Barrier	Consumer demand for transparency serves as a significant driving force, whereas consumers' willingness to pay continues to pose a notable barrier.	Bhat et al. (2025); Rajan & Wani (2025); Rossi et al. (2025)
	Regulation & Government Policy	Enabler/ Barrier	Strict safety regulations and government incentive policies are key enablers, but the absence of clear laws for new technologies remains a barrier.	Čapla et al. (2025); Hassoun, 2025; Liberty et al. (2025); Rajan & Wani (2025); Rajput et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Supply Chain Collaboration	Enabler	Effective implementation depends on collaboration, the sharing of reliable data, and support from supply chain partners.	Ellahi et al. (2025); Issa et al. (2024); Kanwal et al. (2025); Rossi et al. (2025); Sridhar et al. (2023); Yin et al. (2025)

From the table above, these factors constitute a crucial conceptual framework for discussing the challenges and opportunities in the Thai context in the following chapter.

4. Discussion

The results in Table 4 confirm that technology integration enhances traceability capabilities by delivering transparent, accurate data and verifiable provenance. This mechanism improves operational performance by accelerating processes, elevating quality, and generating tangible cost reductions across food supply chains, as illustrated in the diagram below:

**Figure 2.** Technology Integration for Enhanced Traceability and Operational Performance

However, applying these benefits to Thailand's food supply chains encounters unique challenges. When viewed through the TOE framework presented in Table 4, the most critical factors for the Thai context encompass three dimensions: 1) Technology complexity and high investment costs pose significant barriers, as inadequate infrastructure in remote areas can lead to food loss and impede traceability efficiency, while with appropriate support, these technologies enable real-time tracking and can substantially reduce waste (Surasak et al., 2019). 2) Organizational constraints, particularly among SMEs, arise from a shortage of skilled personnel and limited readiness to adopt new systems, while targeted training initiatives and cross-sector collaboration have the potential to enhance productivity and drive sustainable innovation (Kittipanya-ngam & Tan, 2020). And 3) Environmental pressures from stringent regulations and global market demands compel stakeholders to enhance transparency and adopt advanced traceability systems to ensure safety and maintain market access (Hassoun et al., 2023).

5. Conclusion and Recommendations

5.1 Conclusion

First, by integrating IoT, Blockchain, and AI, companies gain real-time visibility into every step of the supply chain, maintain tamper-proof records, and verify product origins instantly. These capabilities speed up decision-making and product recalls, improve quality control, and reduce costs through automation and better risk management. Finally, while Thailand's supportive policies, industry standards, and collaboration networks help drive adoption, high upfront investment costs, patchy digital infrastructure in rural areas, and a shortage of skilled staff still pose serious obstacles.

To overcome these challenges, entrepreneurs can kick off small-scale IoT pilots at critical sites, partner with experienced Blockchain vendors, and use open-source AI tools for focused analytics (Rui & Sundram, 2024). Government bodies should subsidize initial technology investments, fund digital skills training for SMEs, and standardize data formats across the food supply chain. Coordinated action between the public and private sectors will be key to rolling out transparent, traceable solutions that benefit all stakeholders in Thailand's food industry (Yooyativong & Kamyod, 2023).

5.2 Limitations and Future Research

This study has several limitations that suggest directions for future research: 1) Methodologically, the systematic literature review was confined to the Scopus database. Although Scopus is large, reputable, and comprehensive, this restriction may have excluded relevant studies published in other databases such as Google Scholar, Web of Science, or ScienceDirect. 2) In terms of dependent variables, the study focused on operational performance dimensions of speed, quality, and cost reduction, which may not fully capture impacts in other performance dimensions. 3) Regarding generalizability, the scope was limited to the food industry, so the findings may not be directly applicable to other industries with different contextual factors. Future research should conduct quantitative or qualitative empirical investigations by collecting primary data from food industry practitioners in Thailand to test the proposed framework and gain deeper insights into contextual barriers.

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ปัจจัยที่มีผลต่อการพัฒนาสมรรถภาพทางกายของนักศึกษาในมหาวิทยาลัยมณฑลซานซี

Factors Affecting the Development of Physical Fitness among
University Students in Shanxi Provinceโจว ชุนเหมย^{1*} และ พรชัย นุกเกื้อ¹Chunmei Zhou^{1*} and Pornchai Nookaew¹¹มหาวิทยาลัยเอเชียตะวันออกเฉียงใต้ กรุงเทพมหานคร¹Southeast Asia University, Bangkok

*Corresponding Author: chunmeizhou2025@gmail.com

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วัตถุประสงค์ของการศึกษานี้: (1) เพื่อสำรวจปัจจัยที่มีอิทธิพลต่อการออกกำลังกายของนักศึกษาระดับอุดมศึกษา (2) วิเคราะห์ปัจจัยใดที่มีผลกระทบทางตรงหรือทางอ้อมต่อการพัฒนาสมรรถภาพทางกายของนักศึกษาระดับอุดมศึกษา และ (3) เพื่อเป็นพื้นฐานในการกำหนดนโยบายส่งเสริมสมรรถภาพทางกายของนักศึกษาระดับอุดมศึกษา โดยการศึกษาความสัมพันธ์ระหว่างความเข้มข้นและความถี่ของกิจกรรมกีฬา การจัดองค์กรกิจกรรมกีฬาในสถาบันอุดมศึกษา ทรัพยากร และสภาพแวดล้อมด้านกีฬาในสถาบันอุดมศึกษา การสนับสนุนและการปฏิสัมพันธ์ทางสังคม ตลอดจนการรับรู้และแรงจูงใจ ด้านกีฬากับการพัฒนาสมรรถภาพทางกายของนักศึกษาระดับอุดมศึกษา ได้ทำการทดสอบความสอดคล้องของแบบจำลองสาเหตุที่สร้างขึ้นจากข้อมูลเชิงประจักษ์ และสำรวจผลกระทบทางตรงและทางอ้อมของตัวแปรสาเหตุต่อการพัฒนาสมรรถภาพทางกายของนักศึกษาระดับอุดมศึกษาในมณฑลซานซี การศึกษานี้ได้เลือกกลุ่มตัวอย่างนักศึกษาประมาณ 150,000 คน จาก 5 มหาวิทยาลัยในมณฑลซานซี รวมถึงมหาวิทยาลัยซานซี เครื่องมือที่ใช้ในการเก็บรวบรวมข้อมูลคือแบบสอบถาม โดยใช้วิธีการสุ่มตัวอย่างอย่างง่ายและการสุ่มตัวอย่างแบบแบ่งชั้น เลือกกลุ่มตัวอย่างจำนวน 538 คน วิเคราะห์ข้อมูลโดยใช้ซอฟต์แวร์ SPSS27 และ AMOS26 ความเที่ยงตรงของแบบสอบถามมีค่าดัชนี IOC อยู่ระหว่าง 0.6-1.0 และความเชื่อมั่นเท่ากับ 0.976 วิเคราะห์ข้อมูลโดยใช้วิธีการวิเคราะห์เส้นทาง ผลการวิจัยพบว่า ตัวแปรแต่ละตัวมีความสัมพันธ์ทางบวกอย่างมีนัยสำคัญกับการพัฒนาสมรรถภาพทางกายของนักศึกษาในระดับ 0.01 แบบจำลองปัจจัยสาเหตุที่ตั้งสมมติฐานซึ่งมีอิทธิพลต่อการพัฒนาสมรรถภาพทางกายมีความสอดคล้องกับข้อมูลเชิงประจักษ์ ($\chi^2/df=1.19$, GFI=0.844, AGFI=0.836, RMSEA=0.019, SRMR=0.07) ผลกระทบรวมของความเข้มข้นและความถี่ในการออกกำลังกายที่มีต่อการพัฒนาสมรรถภาพทางกายของนักศึกษามีค่ามากที่สุด (0.254) รองลงมาคือ สภาพแวดล้อมและทรัพยากรด้านกีฬาในสถาบันอุดมศึกษา (0.251) การสนับสนุนและการปฏิสัมพันธ์ทางสังคม (0.224) แรงจูงใจและการรับรู้ในการออกกำลังกาย (0.193) และสุดท้ายคือองค์กรกิจกรรมเชิงปฏิสัมพันธ์ในสถาบันอุดมศึกษา (0.134) ตัวแปรที่มีอิทธิพลทางตรงมากที่สุดคือการสนับสนุนและการปฏิสัมพันธ์ทางสังคม (0.224) รองลงมาคือแรงจูงใจและการรับรู้ในการออกกำลังกาย (0.193) สภาพแวดล้อมและทรัพยากรด้านกีฬาของสถาบันอุดมศึกษา (0.169) ความเข้มข้นและความถี่ในการออกกำลังกาย (0.155) และการจัดองค์กรกิจกรรมกีฬา (0.134) ตัวแปรที่มีอิทธิพลทางอ้อมมากที่สุด ได้แก่ การปฏิสัมพันธ์และการสนับสนุนทางสังคม (0.417) และแรงจูงใจและการรับรู้ในการออกกำลังกาย (0.379) ตามลำดับ

คำสำคัญ: นักศึกษามหาวิทยาลัย, สมรรถภาพทางกาย, การสนับสนุนทางสังคม, ทรัพยากรด้านกีฬา

Abstract

The objectives of this study were to: (1) explore factors influencing physical exercise among higher-education students; (2) analyze which factors have direct or indirect effects on the development of physical fitness among higher-education students; and (3) provide a basis for developing policies to promote physical fitness among higher-education students. The study examined the relationships between (a) exercise intensity and frequency, (b) the organization of sports activities in higher-education institutions, (c) sports resources and the sports environment in higher-education institutions, (d) social support and social interaction, and (e) sport-related cognition and motivation, and their effects on the development of physical fitness among higher-education students in Shanxi Province. A causal model developed from empirical data was tested for model fit, and the direct and indirect effects of the causal variables were examined. The population comprised approximately 150,000 students from five universities in Shanxi Province (including Shanxi University). Data were collected using a questionnaire. Simple random sampling and stratified sampling were used to select 538 participants. Data were analyzed using SPSS 27 and AMOS 26. The questionnaire content validity (IOC) ranged from 0.6 to 1.0, and reliability was 0.976. Path analysis showed that each variable was significantly and positively related to physical fitness development at the 0.01 level. The hypothesized causal model was consistent with the empirical data ($\chi^2/df = 1.19$, GFI = 0.844, AGFI = 0.836, RMSEA = 0.019, SRMR = 0.07). The largest total effect on physical fitness development was exercise intensity and frequency (0.254), followed by sports environment and resources in higher-education institutions (0.251), social support and interaction (0.224), exercise motivation and cognition (0.193), and the organization of sports activities in higher-education institutions (0.134). The largest direct effect was social support and interaction (0.224), followed by exercise motivation and cognition (0.193), sports environment and resources (0.169), exercise intensity and frequency (0.155), and the organization of sports activities (0.134). The largest indirect effects were social support and interaction (0.417) and exercise motivation and cognition (0.379).

Keywords: University students, Physical fitness, Social support, Sports resources.

1. Introduction

With the development of the socioeconomy and the continuous improvement of people's living standards, health has become a key focus of national attention. As the country's future, the physical fitness of university students is directly related to national development and long-term interests. In recent years, all sectors of society have paid increasing attention to the physical health of university students. The government, universities, families, and other stakeholders have participated in efforts to promote students' physical fitness. With the deepening of education reform, the role of sport and physical education in cultivating students' holistic development has become increasingly prominent. Many universities have included physical exercise as a compulsory course, increased physical education contact hours, and improved teaching quality. Improvements in campus sports facilities have also provided more opportunities

and conditions for students to engage in physical activity, promoting the formation of regular exercise habits (Xu Xiaohong, 2021). The 2014 National Physical Fitness Monitoring Bulletin reported that, among adult males aged 19–22 years, abilities such as speed, endurance, and explosive power showed a downward trend, indicating declines in these aspects of physical fitness (Wang Lin, 2015). Scholars have also noted that the future development of Chinese society depends on the overall quality of its people. In the classic article On Youth China, the importance of young people’s physical fitness is emphasized, stating that the strength of young people is related to the strength of the nation.

Research objectives. This study aimed to: (1) investigate factors influencing physical exercise among university students in Shanxi Province; (2) analyze the direct and indirect effects of these factors on students’ physical fitness improvement; and (3) provide a basis for formulating region-specific policies to promote university students’ physical fitness.

Research hypotheses. The hypotheses were as follows: H1: Exercise intensity and frequency directly improve university students’ physical fitness. H2: Exercise intensity and frequency indirectly improve physical fitness through social support and interaction. H3: Social support and interaction directly improve physical fitness. H4: University sports organization directly improves students’ physical fitness. H5: University sports resources and environment directly improve students’ physical fitness. H6: University sports resources and environment indirectly improve physical fitness through exercise motivation and cognition. H7: Exercise motivation and cognition directly improve students’ physical fitness.

Conceptual framework. This study examined factors influencing physical fitness improvement among university students in Shanxi Province. The model included three predictor variables (exercise intensity and frequency; university sports organization; and university sports resources and environment), two mediating variables (social support and interaction; and exercise motivation and cognition), and one criterion variable (physical fitness improvement among university students). The hypothesized relationships among variables are shown in Figure 1.

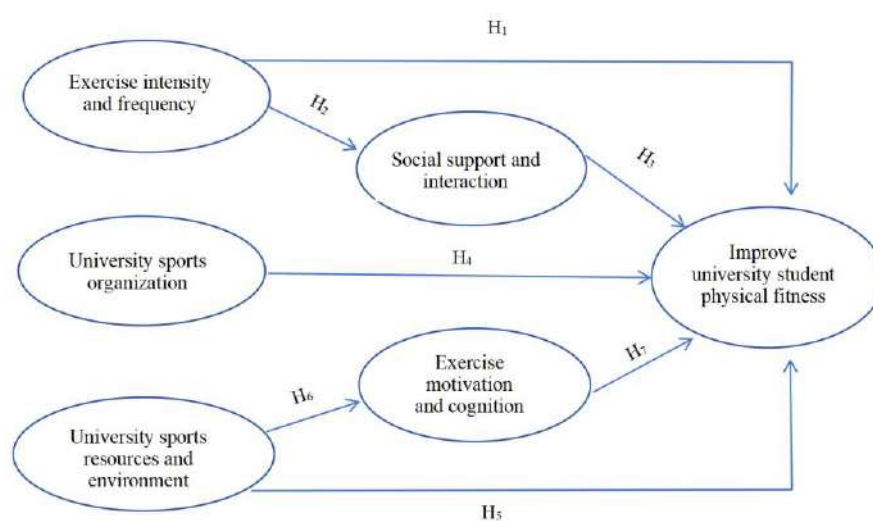


Figure 1. Research conceptual framework.

2. Materials and methods

2.1 Population and Sample

The target population comprised undergraduate and postgraduate students from five major universities in Taiyuan, Shanxi Province: Shanxi University, Taiyuan University of Technology, Shanxi Medical University, North University of China, and Shanxi Normal University, with a combined enrollment of approximately 153,000 students.

Stratified random sampling was used. First, universities were stratified by student population size. Then, within each stratum, students were randomly selected from undergraduate, master's, and doctoral programs in proportion to their numbers at each university. This procedure yielded a final sample of 538 students. The sample distribution is shown in Table 1.

Table 1. University Student Population and Sample Size

University	Student Population	Sample Size	Undergraduate	Master's	Doctoral
1	22,084	78	63	12	3
2	23,000	81	66	12	3
3	30,000	105	86	14	5
4	36,000	127	103	18	6
5	42,000	147	121	19	7
Total	153,084	538	439	75	24

Data were collected using a six-part questionnaire developed through a synthesis of established literature in sports science and health behavior. Specifically, perceived stress-related components were adapted from the Perceived Stress Scale (Cohen et al., 1983), while exercise motivation and cognition were operationalized in accordance with the self-determination theory framework (Teixeira et al., 2012). Other domains, including university sports resources and environment, social support and interaction, and physical fitness improvement, were formulated based on prior research in sport participation and health behavior. All items were rated on a 5-point Likert scale. Internal consistency reliability was assessed for each domain, with Cronbach's alpha coefficients indicating acceptable levels.

The questionnaire comprised six domains:

- 1) Exercise intensity and frequency (15 items)
- 2) Organization of university sports activities (15 items)
- 3) University sports resources and environment (17 items)
- 4) Social support and interaction (15 items)
- 5) Exercise motivation and cognition (15 items)
- 6) Physical fitness improvement among university students (15 items)

2.2 Tryout and quality of the research instruments

1) To develop the conceptual framework, formulate hypotheses, and design the sampling plan, the researchers reviewed relevant literature, concepts, theories, and prior studies on factors influencing university students' physical fitness improvement, and then defined the population and sample.

2) Based on the literature review, the researchers developed and refined the questionnaire items and overall instrument structure for data collection.

3) The draft questionnaire was submitted to the thesis supervisor to review language accuracy, clarity, and coverage consistent with the study scope and operational definitions.

4) After revision based on the supervisor's feedback, the questionnaire was sent to five experts to assess content validity. The index of item-objective congruence (IOC) was calculated, and items with IOC values of 0.60–1.00 were retained.

5) The questionnaire was revised in line with expert suggestions and resubmitted to the thesis supervisor for final review.

6) Reliability was examined using Cronbach's alpha. In general, an alpha coefficient above 0.75 indicates acceptable internal consistency.

2.3 Data collection

After the questionnaire was finalized, it was digitized and distributed via the online survey platform "Questionnaire Star." The survey link was shared through WeChat groups and by direct distribution, and paper-based questionnaires were also administered in parallel. After data collection, incomplete or invalid questionnaires were removed, and the remaining valid responses were used for descriptive statistics and subsequent analyses.

In collecting data, the researcher followed these steps:

1) Contacted the five universities in Shanxi Province to obtain permission to collect data from the participating institutions.

2) Submitted official request letters to university administrators and coordinated with relevant staff to schedule data collection.

3) Administered the questionnaire covering exercise intensity and frequency, organization of sports activities, sports resources and environment, social support and interaction, exercise motivation and cognition, and physical fitness improvement (January–February 2025). The researchers collected the data themselves.

4) Before administering the questionnaire, established rapport with participants by creating a friendly environment and encouraging them to provide accurate responses.

5) Explained the purpose of the study and the response instructions to ensure participants understood how to complete the questionnaire.

2.4 Data analysis

This article presents the data analysis results in five parts, as follows:

Part 1: Results of the examination of data distribution characteristics.

Part 2: Effects of exercise intensity and frequency, university sports organization, university sports resources and environment, social support and interaction, and exercise motivation and cognition on physical fitness improvement among university students.

Part 3: Results of the analysis of relationships among the variables (exercise intensity and frequency, university sports organization, university sports resources and environment, social support and interaction, and exercise motivation and cognition).

Part 4: Results of the examination of model fit between the empirically constructed causal model and the observed data.

Part 5: Results of the analysis of the direct and indirect effects of causal factors on physical fitness improvement among university students.

3. Results

Part 1. Descriptive statistics (mean, standard deviation, and coefficient of variation) were used to summarize each observed variable. The distribution of the data was examined using skewness and kurtosis, and the p-values of the χ^2 statistics for normality testing are reported in Table 2.

Table 2. Mean, standard deviation, distribution coefficient, skewness, kurtosis, and chisquare statistic values for testing the normal distribution of each observed variable

observable Table	min	max	$\bar{x}$	S.D.	SK	KU	C.V.	p of χ^2
EF	1.00	5.00	3.63	0.78	-1.60	-0.11	0.35	0.96
USO	1.00	5.00	3.70	0.70	-1.47	0.08	0.34	0.97
USE	1.00	5.00	3.73	0.69	-1.54	0.06	0.31	0.97
SSI	1.00	5.00	3.55	0.79	-1.38	0.03	0.30	0.98
EMC	1.00	5.00	3.65	0.78	-1.53	-0.05	0.29	0.95
IUSF	1.00	5.00	3.61	0.80	-1.43	0.07	0.32	0.98

As shown in Table 2, the minimum and maximum values for all dimensions (exercise intensity and frequency; university sports resources and environment; organization of university sports activities; social support and interaction; exercise motivation and cognition; and physical fitness improvement) were 1.00 and 5.00, respectively. Mean values ranged from 3.61 to 3.73, with standard deviations ranging from 0.69 to 0.80. The absolute values of the skewness coefficients were all below 3, with a standard error of 0.105, and the absolute values of the kurtosis coefficients were all below 10, with a standard error of 0.210. These values fall within acceptable ranges, indicating that the data were suitable for further analysis.

Part 2. The descriptive results indicate that the five hypothesized causal factors (exercise intensity and frequency; university sports organization; university sports resources and environment; social support and interaction; and exercise motivation and cognition) were all positively associated with physical fitness improvement among university students.

Table 3. The mean and standard deviation of the six variables

NO.	variables	$\bar{x}$	S.D.	level
1	Exercise intensity and frequency	3.63	0.78	agree
2	university sports organization	3.71	0.70	agree
3	university sports resources and environment	3.73	0.69	agree
4	social support and interaction	3.55	0.79	agree
5	exercise motivation and cognition	3.65	0.78	agree
6	the improvement of college students' physical fitness	3.61	0.80	agree

As shown in Table 3, the mean score for exercise intensity and frequency was 3.63 (S.D. = 0.78). The mean score for university sports organization was 3.71 (S.D. = 0.70). The mean score for university sports resources and environment was 3.73 (S.D. = 0.69). The mean score for social support and interaction was 3.55 (S.D. = 0.79). The mean score for exercise motivation and cognition was 3.65 (S.D. = 0.78). Finally, the mean score for physical fitness improvement among university students was 3.61 (S.D. = 0.80). Overall, all variables were at the “agree” level.

Part 3. This part presents the results of the relationship analysis among exercise intensity and frequency, university sports organization, university sports resources and environment, social support and interaction, and exercise motivation and cognition.

Pearson’s correlation coefficients were calculated to examine the relationships between the causal variables and physical fitness improvement among university students.

Table 4. Matrix of the correlation coefficient between the causal variables and improvement of university students' physical fitness

Variables	EF	USO	USE	SSI	EMC	IUSF
EF	1.00					
USO	.46**	1.00				
USE	.42**	.31**	1.00			
SSI	.44**	.47**	.42**	1.00		
EMC	.32**	.34**	.40**	.37**	1.00	
IUSF	.43**	.41**	.42**	.45**	.40**	1.00

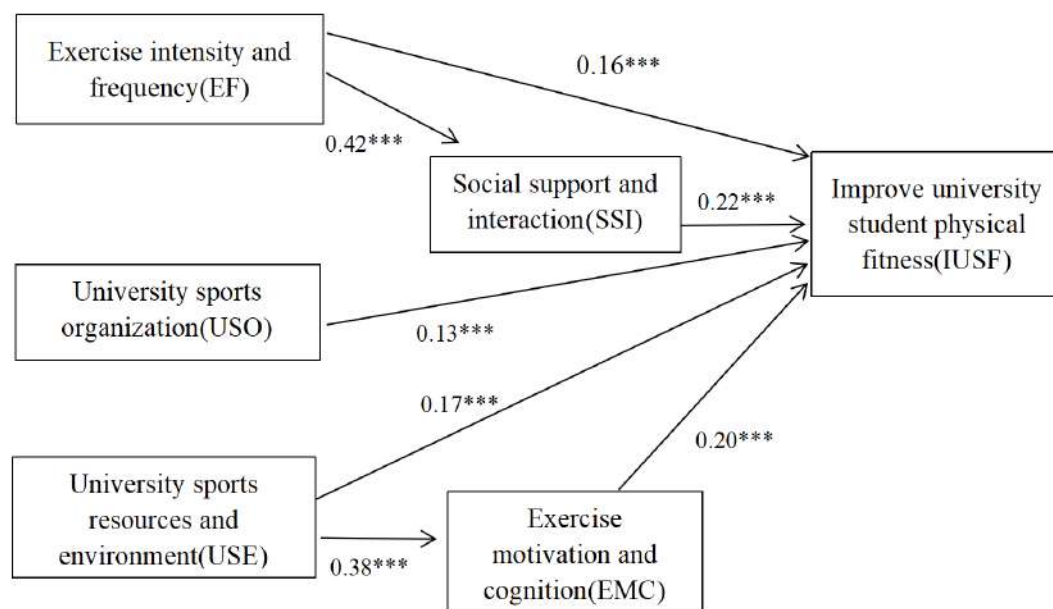
** $p < 0.01$

Pearson correlation was used to analyze the correlations among exercise intensity and frequency, school sports resources and environment, school sports activity organization, social support and interaction, exercise motivation, cognition, and physical fitness improvement. It can be seen from the table 4.

As shown in Table 4, exercise intensity and frequency were significantly and positively correlated with university sports resources and environment, university sports organization, social support and interaction, exercise motivation and cognition, and physical fitness improvement (correlation coefficients = 0.423, 0.462, 0.439, 0.324, and 0.431, respectively; all $p < 0.01$). University sports resources and environment were also significantly and positively correlated with university sports organization, social support and interaction, exercise motivation and cognition, and physical fitness improvement (correlation coefficients = 0.313, 0.415, 0.400, and 0.422, respectively; all $p < 0.01$). University sports organization was significantly and positively correlated with social support and interaction, exercise motivation and cognition, and physical fitness improvement (correlation coefficients = 0.470, 0.341, and 0.413, respectively; all $p < 0.01$). In addition, social support and interaction were significantly and positively correlated with exercise motivation and cognition and with physical fitness improvement (correlation coefficients = 0.367 and 0.452, respectively; both $p < 0.01$).

Part 4. This part reports the results of examining the fit of the empirically constructed causal model to the observed data.

Because the model fit the empirical data, the direct and indirect effects of the causal variables on physical fitness improvement were analyzed, as illustrated in Figure 2.



Note: *** indicates $p < 0.001$

Figure 2 A causal factor model affecting the improvement of university students' physical fitness

Path analysis was used to test the hypothesized relationships. As shown in Figure 2, all paths were statistically significant ($p < 0.05$), indicating that the hypothesized relationships were supported; therefore, all hypotheses were accepted.

Part 5. This part presents the results of the direct and indirect effects of the causal factors on physical fitness improvement among university students.

Table 5. Direct effects (DE), indirect effects (IE), and total effects (TE) on physical fitness improvement among university students

Effect Variable	R ²	Influence Variable	Causal Variable Effects (Standardized)				
			EF	USO	USE	SSI	EMC
SSI	0.048	DE	0.417	-	-	-	-
		IE	-	-	-	-	-
		TE	0.417	-	-	-	-
EMC	0.045	DE	-	-	0.379	-	-
		IE	-	-	-	-	-
		TE	-	-	0.379	-	-
IUSF	0.051	DE	0.155	0.134	0.169	0.224	0.193
		IE	0.099	-	0.082	-	-
		TE	0.254	0.134	0.251	0.224	0.193

As shown in Table 5, among the factors influencing physical fitness improvement among university students, exercise intensity and frequency had the largest total effect (0.254), followed by university sports resources and environment (0.251), social support and interaction (0.224), exercise motivation and cognition (0.193), and university sports organization (0.134).

The results of the data analysis to answer the research hypothesis are as follows: (1) The correlation analysis showed significant positive relationships between the causal variables and physical fitness improvement, with correlation coefficients ranging from 0.399 to 0.452 ($p < 0.01$). The strongest correlation with physical fitness improvement was social support and interaction (0.452), followed by exercise intensity and frequency (0.431), university sports resources and environment (0.422), university sports organization (0.413), and exercise motivation and cognition (0.399). (2) The path analysis results showed that exercise intensity and frequency had the greatest total effect on physical fitness improvement (0.254), followed by university sports resources and environment (0.251), social support and interaction (0.224), exercise motivation and cognition (0.193), and university sports organization (0.134). The analysis also indicated that exercise intensity and frequency affected physical fitness improvement indirectly through social support and interaction, and that university sports resources and environment affected physical fitness improvement indirectly through exercise motivation and cognition.

4. Discussion

This study developed and tested an integrated model to explain physical fitness improvement among university students in Shanxi Province, China. The findings support the multifaceted nature of physical fitness determinants, suggesting that individual exercise behaviors, institutional conditions, and social-psychological processes jointly influence fitness outcomes.

Exercise intensity and frequency showed the largest total effect, which is consistent with evidence that an adequate exercise dose is essential for improving physical fitness (World Health Organization, 2020). The significant indirect effect through social support and interaction suggests that, in this context, social dynamics may help students sustain higher-intensity or more frequent exercise. This is in line with Wang et al. (2023), who reported a mediating role of social support in the relationship between exercise intensity and cardiorespiratory fitness.

University sports resources and environment also demonstrated a strong total effect, underscoring the importance of material and spatial conditions for physical activity. The significant indirect path through exercise motivation and cognition suggests that well-designed, accessible facilities may not only enable activity but also strengthen positive exercise beliefs and motivation, as noted by Giles-Corti et al. (2005) in related environmental research.

Social support and interaction exhibited the strongest direct effect on physical fitness improvement. This highlights the potential importance of peer encouragement, guidance from instructors or coaches, and shared participation experiences in promoting fitness-related outcomes. The finding is broadly consistent with evidence that social support is associated with higher physical activity participation (Beets et al., 2010).

4.1 Theoretical and practical implications

Theoretically, the proposed model helps clarify the pathways through which behavioral, environmental, and social factors relate to students' physical fitness improvement and may complement perspectives such as Social Cognitive Theory. Practically, for university administrators and policymakers in Shanxi Province and similar settings, the results suggest that single-component interventions may be insufficient. More effective strategies are likely to combine investments in facilities with program design and social supports, for example:

- 1) Infrastructure investment: Maintain and expand high-quality, accessible sports facilities.
- 2) Social scaffolding: Establish mentorship programs, "sports buddy" systems, and inclusive club cultures to strengthen supportive networks.
- 3) Motivational design: Design sports programs and communications that emphasize mastery, enjoyment, and personal growth (intrinsic motivation), rather than focusing only on competition.

4.2 Limitations and future research

This study has several limitations. First, the cross-sectional design limits causal interpretation. Second, although the sample size was adequate, participants were drawn from a single province, which may limit generalizability. Third, physical fitness improvement was assessed via self-report and may be

subject to response bias. Future research should consider longitudinal or experimental designs, incorporate objective fitness measures, and examine additional moderators and mediators (e.g., sport type and gender differences). Replicating the model in other regional contexts would also be valuable.

5. Conclusion and suggestions

5.1 Conclusion

This study identified and quantified interrelated factors associated with physical fitness improvement among university students in Shanxi Province. The findings suggest that fitness outcomes are shaped not only by individual exercise behaviors, but also by the availability of university sports resources and the social environment that supports participation. Overall, the results provide empirical evidence that may inform integrated, multi-level policies and programs aimed at promoting university students' physical fitness.

5.2 Suggestions for future research

5.2.1 Refine exercise “dose” classifications (intensity and frequency). Future studies could classify exercise intensity (e.g., low, moderate, high) and frequency (e.g., daily, several times per week) more precisely to examine whether different combinations have distinct effects on physical fitness improvement and to support more tailored recommendations.

5.2.2 Examine specific forms of social support and interaction. Future research may analyze how different sources of support (e.g., friends, family, instructors, and sports clubs) relate to exercise persistence and effectiveness, and whether these pathways differ across student subgroups.

5.2.3 Model the combined effects of multiple factors. Building on the current findings, researchers could develop and test a more comprehensive model that incorporates exercise behavior, social support, university sports resources and environment, sports activity organization, and exercise motivation and cognition to better understand their interactions and overall effects on physical fitness improvement.

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การเพิ่มประสิทธิภาพการเผาไหม้ด้วยชุดอุปกรณ์เผาไหม้ Improving Coconut Burning Efficiency with Coconut Burning Equipment

อานวย คำบุญ¹ วรพจน์ ศิริรักษ์^{1*} พีรวัตร ลือสัก¹ อมรรัตน์ ปิ่นชัยมูล¹ และ ศุภศานต์ รักสกุล²

Aumnouy Kumboon¹, Worapot Sirirak^{1*}, Peerawat Luesak¹,

Amornrat Pinchaioon¹ and Subhasant Raksakul²

¹คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีราชมงคลล้านนา จังหวัดเชียงราย

²สถาบันการอาชีวศึกษาภาคเหนือ 2 จังหวัดพะเยา

¹Faculty of Engineering, Rajamangala University of Technology Lanna, Chaing Rai Province

²Institute of Vocational Education Northern Region 2, Phayao Province

*Corresponding Author: Worapotsirirak@rmul.ac.th

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บทคัดย่อ

งานวิจัยนี้นำเสนอการพัฒนาและประเมินประสิทธิภาพของอุปกรณ์เผาไหม้ที่ปรับปรุงขึ้นมาเพื่อเปรียบเทียบกับวิธีการคั่วแบบดั้งเดิม ผลการทดลองแสดงให้เห็นว่าอุปกรณ์ที่พัฒนาขึ้นสามารถเผาไหม้ได้ 90 ผลต่อรอบการผลิต ภายใต้สภาวะที่เหมาะสมที่กำหนดโดยวิธีทางสถิติ โดยใช้ความเร็วรอบของกลองหมุน 10 รอบต่อนาที เวลาการคั่วเฉลี่ยอยู่ที่ 140.75 นาที ซึ่งลดลงจาก 151.9 นาที ของวิธีการแบบดั้งเดิม ยิ่งไปกว่านั้น อุปกรณ์ที่ปรับปรุงนี้สามารถผลิตมะพร้าวเผาที่ปราศจากข้อบกพร่องได้ถึง 99.4% ในขณะที่วิธีการแบบดั้งเดิมผลิตมะพร้าวเผาที่ได้เฉลี่ย 91% โดยรวมแล้ว วิธีการใหม่ลดเวลาการเผาโดยเฉลี่ย 11.85 นาที เพิ่มผลผลิตได้ 8.4% อย่างมีนัยสำคัญทางสถิติ (p -value = 0.000) แม้ว่ากระบวนการที่ปรับปรุงนี้จะต้องใช้ต้นทุนเชื้อเพลิงเพิ่มขึ้น 24 บาทต่อรอบการผลิต เนื่องจากการใช้พื้นที่เพิ่มขึ้น 48 กิโลกรัม แต่ก็สามารถผลิตเปลือกมะพร้าวที่นำออกจำหน่ายได้เพิ่มขึ้น 20 ผล ส่งผลให้รายได้เพิ่มขึ้น 1,051 บาทต่อรอบการผลิต ผลการวิจัยนี้ยืนยันได้ถึงอุปกรณ์เผาไหม้ที่ปรับปรุงนี้ช่วยเพิ่มประสิทธิภาพและคุณภาพของการผลิต ทั้งด้านเวลาการเผาไหม้ที่ลดลง และผลผลิตเพิ่มขึ้น ดังนั้นอุปกรณ์นี้จึงเหมาะสมสำหรับการนำไปใช้ในระดับชุมชนและมีศักยภาพในการขยายสู่เชิงพาณิชย์ งานวิจัยในอนาคตควรศึกษาการบูรณาการวัสดุที่เก็บความร้อนและการออกแบบโครงสร้างถังใหม่ เพื่อลดการสูญเสียความร้อนและลดการใช้เชื้อเพลิง โดยไม่กระทบต่อคุณภาพการเผาไหม้ นอกจากนี้ ควรเน้นไปที่การลดการปล่อย CO₂ ผ่านแหล่งพลังงานหมุนเวียนทางเลือก การประเมินความสามารถในการปรับตัวของระบบต่อเศษวัสดุเหลือทิ้งทางการเกษตรชนิดอื่นๆ เพื่อลดต้นทุนการผลิตโดยรวม

คำสำคัญ: มะพร้าวเผา, ประสิทธิภาพการเผา, วิธีการทางสถิติ, การเผาไหม้

Abstract

This study presents the development and performance evaluation of an improved coconut roasting device, compared against the conventional roasting method. Experimental results demonstrated that the newly developed system could process 90 coconuts per batch under optimized conditions determined by the Taguchi method, with a drum rotation speed of 10 revolutions per minute. The average roasting time was 140.75 minutes, representing a reduction from 151.90 minutes observed with the traditional method. Moreover, the improved device achieved 99.4% defect-free roasted coconuts, whereas the traditional method produced an average 91% defect-free. Overall, the new method reduced burning time by an average of 11.85 minutes, increased productivity yield to 8.4%, with statistical significance (p -value = 0.000). Although the modified process required an additional fuel cost of 24 THB per batch due to higher firewood consumption (48 kilograms), it enabled the production of 20 more marketable coconuts, resulting in an increased income of 1,051 THB per batch. These findings confirm that the improved coconut roasting device enhances both efficiency and product quality in terms of decreased processing time and increased productivity. The device is therefore suitable for adoption at the community level and for potential commercial scaling. Future work should explore the integration of heat-retaining materials and redesign of the drum structure to minimize heat loss and reduce fuel consumption, without compromising roasting quality. Furthermore, focus on reducing CO₂ emissions through alternative renewable energy sources, as well as assessment of the system's adaptability to other agricultural residues is recommended to lower overall production costs.

Keywords: Coconut roasting, Combustion efficiency, Taguchi method, Process optimization

1. Introduction

Thailand's coconut industry represents a significant component of the national agricultural economy, positioning the country among the world's leading producers and exporters of coconut-based products. The sector generates a wide range of commodities, including coconut oil, coconut water, copra, and fiber-derived products, providing an essential and stable source of income for local farmers and small-scale enterprises (6Wresearch, 2022; BSAC, 2022; Aijen et al., 2022). The global market for these products continues to expand, driven by increasing consumer preference for plant-based and health-oriented foods as well as growing interest in distinctive local specialties (6Wresearch, 2022). Within this dynamic market, roasted coconut occupies a unique niche. It is highly valued by both Thai consumers and international visitors for its distinctive flavor profile and nutritional benefits, particularly in major cultivation areas such as Amphawa District in Samut Songkhram Province and Ratchaburi province (BSAC, 2022; Pokaisawan et al., 2024). Roasting is not only important for culinary purposes but also closely linked to energy utilization, as highlighted by Puchakawimo et al. (2005). Their research demonstrated that roasting significantly modifies coconut characteristics: the water content becomes sweeter and less acidic, while the flesh develops a more pronounced sweetness due to thermal effects.

Traditional roasting practices predominantly use open-fire wood combustion, which poses

environmental drawbacks and energy inefficiencies (BSAC, 2022). Additionally, such methods suffer from inconsistent heat distribution and significant products loss typically about 6 defective coconuts per batch, leading to notable economic losses. Manual supervision is necessary to maintain combustion stability and fuel regulation. Despite these limitations, traditional roasting remains vital for producing diverse food products, which effect to yeast quality improvement of product through Maillard reaction and caramelization (Eliodório et al. 2023). Previous research has addressed similar challenges by introducing engineering-based solutions. For instance, Suarbawa & Mulawarman (2021) demonstrated that mechanized roasting machines could improve work productivity by over 60% while reducing labor fatigue. Saittagaroon et al. (1984) highlighted the enhancements in aroma and flavor profile through controlled thermal treatments. Studies on biomass-powered dryers further show potential gains in energy efficiency and environmental performance (Senthil et al, 2021, Muhammad et al. 2023). Nonetheless, the adoption of such technologies in local Thai communities remains limited, with many producers still relying on uncontrolled traditional methods (Suarbawa, 2022; BSAC, 2022). This reveals a research gap in developing appropriate roasting technology tailored for community-level adoption. The need for devices that optimize yield, enhance thermal efficiency, reduce raw material losses, and align with sustainable development goals is critical. Moreover, this aligns with Thailand's Bio-Circular-Green (BCG) Economy Model, advocating for sustainable agricultural processing (Maimun et al, 2023). Hence, this study aims to design and evaluate a roasting device that maximizes yield, minimizes waste, and supports sustainable coconut processing in line with modern industrial and environmental standards. In addition, research has compared traditional and modern roasting methods in terms of yield and quality. It was found that the modern method produces higher and more consistent yields and quality than the traditional method, as well as reducing product loss in each production cycle (Nwankwo et al, 2025).

Despite these opportunities, many local producers continue to depend on traditional roasting methods characterized by limited process control, low thermal efficiency, and considerable raw material losses. Typically, one batch produces approximately 70 roasted coconuts; however, variations in maturity and non-uniform heat distribution often lead to spoilage, averaging about six defective coconuts per batch, equivalent to a financial loss of around 240 THB. The process also demands continuous manual supervision to regulate fuel input and maintain stable combustion conditions. In this context, improving coconut roasting technology has become essential to enhance efficiency, reduce product loss, and strengthen the competitiveness of community-based enterprises as well as the broader coconut industry. The adoption of engineering-based solutions and modern process optimization can increase productivity, ensure consistent product quality, and create additional revenue streams for farmers. To systematically optimize the roasting process parameters, this study employs the Taguchi design of experiments methodology, which offers significant advantages for practical industrial applications. The Taguchi method enables efficient identification of optimal operating conditions with minimal experimental runs, making it particularly suitable for resource constrained small-scale producers (Antony et al. 2024). This approach systematically evaluates multiple factors including batch size and drum rotation speed to determine the combination that maximizes yield while minimizing defects and energy consumption. Importantly, this approach is consistent with

Thailand's Bio Circular Green (BCG) Economy Model, which emphasizes sustainable practices, efficient resource utilization, and value-added processing of agricultural products (Maimun et al, 2023). Consequently, the objective of this study is to develop and evaluate a roasting device using Taguchi optimization designed to maximize yield, minimize waste, and align coconut processing with sustainable industrial development goals.

2. Materials and methods

2.1 Data Collection and Problem Analysis

To obtain a comprehensive understanding of the limitations associated with conventional coconut roasting practices, a systematic study of the entire process was conducted, as illustrated in Figure 1. On-site observations were combined with detailed data collection at each stage to identify operational bottlenecks that affected both process efficiency and product quality.

The initial survey revealed a significant production constraint. Each roasting cycle was restricted to a maximum capacity of 70 coconuts, primarily due to the limited roasting chamber area and the highly labor-intensive nature of the process. Operators were required to constantly monitor the roasting chamber, manually rotate coconuts, and replenish firewood to avoid cracking or surface burning, both of which immediately resulted in product rejection.

Baseline data were compiled from 20 roasting cycles performed under traditional conditions. Results indicated that each batch consumed between 280 and 300 kilograms of firewood. The average roasting time was measured at 151.9 minutes (approximately 2.5 hours) to achieve acceptable product characteristics. More importantly, the data summarized in Table 1 showed an average of 6.26 defective or under-roasted coconuts per cycle, corresponding to a defect rate of approximately 9%. In practice, this equated to a loss of about six coconuts per batch, thereby reducing the effective yield and lowering profitability for producers.

To further investigate the root causes of these inefficiencies, a “Why-Why” analysis was applied. The results, presented in Table 2, indicated that the primary factor contributing to low efficiency was the lack of specialized roasting equipment specifically, the absence of a dedicated kiln or oven designed to provide uniform thermal distribution. In addition, limitations associated with manual handling restricted the ability of workers to rotate coconuts evenly, particularly when the coconuts were stacked or overlapped. This resulted in non-uniform roasting conditions, leading to over-roasting, under-roasting, or cracking of coconuts, as illustrated in Figure 2.



Figure 1. Illustrates the main steps in the roasted coconut production process, including (A) roasting and turning the coconuts, (B) peeling, and (C) polishing.

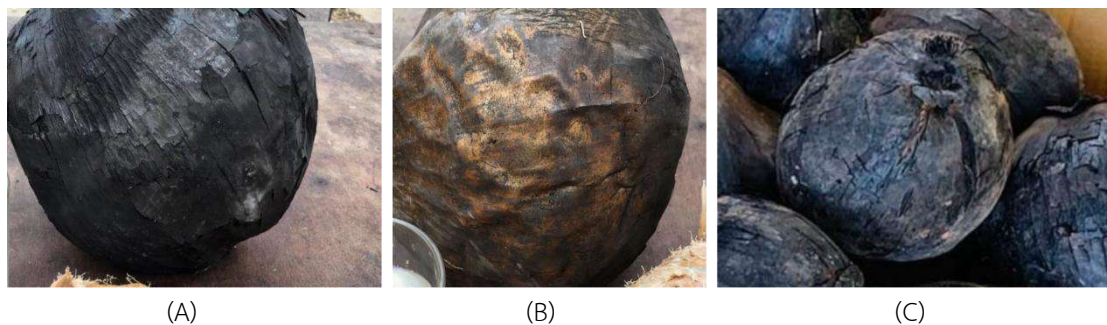


Figure 2. shows the characteristics of roasted coconuts using the traditional method, including (A) properly roasted coconut, (B) undercooked coconut, and (C) cracked or damaged roasted coconut.

2.2 Design of a Coconut Roasting Apparatus

Analysis of the baseline data presented in Table 1 indicated that the conventional roasting method produced an average yield of approximately 91% acceptable product. However, the process was highly dependent on continuous manual supervision, which required operators to rotate coconuts by hand, replenish firewood, and monitor combustion conditions. These tasks not only limited operational efficiency but also introduced potential safety hazards.

To address these shortcomings and establish a more standardized process, a coconut roasting apparatus was conceptualized and designed. The system consisted of three cylindrical roasting chambers, each fabricated from a 200-liter steel drum. These chambers were configured to operate independently and were equipped with a rotational mechanism to facilitate the turning of coconuts during roasting. This ensured uniform heat exposure across all units and minimized the risk of under-roasting, over-roasting, or surface cracking. The rotation feature was expected to reduce overall processing time while simultaneously enhancing worker safety by minimizing direct manual handling.

Table 1. Traditional coconut roasting method with 70 coconuts per batch.

No.	Roasting Time (minutes)	Defective/ Unripe roasted coconut (units)	Percentage of Good/Defective Coconuts (%)	
			Roasted Good Coconuts	Roasted Defective Coconuts
1	152	6	91.43	8.57
2	155	5	92.86	7.14
3	149	6	91.43	8.57
4	152	6	91.43	8.57
5	153	7	90.00	10.00
6	157	8	88.57	11.43
7	150	6	91.43	8.57
8	159	5	92.86	7.14
9	148	8	88.57	11.43
10	151	7	90.00	10.00
11	148	6	91.43	8.57
12	155	7	90.00	10.00
13	149	7	90.00	10.00
14	150	6	91.43	8.57
15	153	6	91.43	8.57
16	151	5	92.86	7.14
17	152	6	91.43	8.57
18	159	7	90.00	10.00
19	152	5	92.86	7.14
20	157	7	90.00	10.00
Average	151.9	6.26	91.00	9.00

Table 2. Application of Why-Why analysis for problem identification and solution guidelines.

Problem	Why 1	Why 2	Why 3	Consideration	Proposed Solution
Production is insufficient to meet demand	People	Workers are fatigued	Workers roast coconuts continuously Lack of appropriate tools for turning coconuts	Workers lack rest time	Provide a resting area and sharp-tipped iron tools for turning coconuts
	Work methods	No standardized working procedure	Visual inspection is used	Workers have over 10 years of experience	Use photo color comparisons to identify proper roasted coconut surface
	Roasting kiln	Inconsistent heat	Results in cracked or undercooked coconuts Excess firewood causes uneven heat	Workers cannot turn coconuts in time or distribute firewood evenly No method for proper heat distribution	Design a roasting device that controls heat evenly with appropriate capacity
		Roasting volume is low	Limited space	Inadequate workspace organization	Redesign layout to improve workspace for roasting more coconuts

The apparatus was specifically designed to accommodate the spatial and operational constraints of local enterprises, as illustrated in Figure 3. The system had a maximum capacity of 90 coconuts per cycle. Rotational speed could be controlled at three levels 10, 15, and 20 revolutions per minute allowing flexibility to suit varying coconut sizes and roasting conditions. By integrating these design improvements, the mechanized roasting system aimed to increase production throughput, improve product quality consistency, and reduce reliance on intensive manual labor.



Figure 3. Appearance of coconut burning equipment

2.3 Experiment and Data Collection

The experimental procedure employed coconuts with a maturity age of approximately 10–12 months, which was generally considered suitable for roasting applications. For each trial, 30 coconuts were placed into each roasting drum, resulting in a total batch size of 90 coconuts per cycle. A series of 20 experimental runs was conducted using the apparatus, with the rotational speed set at its maximum level of 20 revolutions per minute. The firewood was longan type that was more in this local area. The firewood was fulfilled an equal amount of about 30 kilograms per time for invariability of heat control. These trials were designed to evaluate the operational performance of the newly developed roasting system, identify potential technical issues, and refine the process parameters for optimal outcomes.

Prior to the full experimental campaign, preliminary tests were carried out to establish the optimal roasting parameters using the developed apparatus. The quality of roasted coconuts was subsequently assessed through sensory evaluation, focusing on shell coloration and the degree of surface cracking as primary indicators of roasting uniformity. The percentage of satisfactorily roasted coconuts was determined from these assessments, providing a benchmark for evaluating the efficiency and consistency of the roasting process.

The quality data obtained from sensory evaluations were systematically compared between coconuts processed using the newly developed roasting apparatus and those produced by the conventional method, as illustrated in Figure 4.



Figure 4. Coconut burning with equipment for burning (A) coconut filling and (B) burned coconut appearance.

This comparison was designed to evaluate the processing efficiency and quantify improvements in production capacity and cost reduction, particularly in relation to losses caused by damaged or undercooked coconuts. Prior to conducting the roasting experiments, the thermal requirements were determined in accordance with thermodynamic principles, as expressed in Equation (1). For calculation purposes, the total mass of coconuts per batch was assumed to be approximately 100 kg, with an initial temperature of 30 °C and a target final internal temperature of 140 °C (Apriyantono et al., 2002).

The effective specific heat capacity of the coconuts was estimated based on mass fraction analysis of their components: shell (10%), husk fibers (40%), flesh (30%), and coconut water (20%). According to Dirisu et al. (2020), the specific heat capacities of these constituents are approximately 1.77 kJ/kg·°C for the shell, 1.26 kJ/kg·°C for husk fibers, 3.50 kJ/kg·°C for coconut flesh, and 4.06 kJ/kg·°C for coconut water. Using these values, the overall specific heat capacity of a whole coconut was estimated at about 5.06 kJ/kg·°C.

Based on this composite value, the heat energy required to raise the temperature of a 100 kg batch of coconuts from 30 °C to 140 °C was calculated to be approximately 55.66 MJ. The corresponding firewood requirement was then estimated using Equation (2), considering the calorific value of firewood reported by the Electricity Generating Authority of Thailand (2021) as 3,820 kcal/kg (equivalent to 15,983.68 kJ/kg).

$$\text{Heat Equation} \quad Q = m \times c \times \Delta T \quad (1)$$

Where;

Q = Heat energy required (kJ)

m = Total mass of coconuts loaded into the roasting chamber (kg)

c = Specific heat capacity of coconuts (kJ/kg·°C)

ΔT = Temperature difference between the initial and final condition (°C)

$$E_{\text{input}} = m_{\text{fuel}} \times CV \quad (2)$$

Where

E_{input} = Thermal energy supplied to the system (kJ)

m_{fuel} = Mass of fuel consumed (kg)

CV = Calorific value of the fuel (kJ/kg)

To estimate the required quantity of firewood for the roasting process, heat balance calculations indicated that approximately 348.26 kg of firewood was necessary to uniformly roast a batch of 90 coconuts using the newly developed roasting apparatus. Following this estimation, 20 experimental roasting trials were carried out. The performance of each trial was recorded, and the mean roasting efficiency was subsequently determined.

For statistical validation, a Paired T-test was employed to compare the conventional roasting method with the equipment-assisted method. The hypotheses were defined as follows:

Null hypothesis (H_0): $\mu_{\text{new}} = \mu_{\text{traditional}}$ (no statistically significant difference exists between the average roasting times of the two methods).

Alternative hypothesis (H_1): $\mu_{\text{new}} \neq \mu_{\text{traditional}}$ (a statistically significant difference exists between the two methods in terms of the roasting parameter under consideration).

To identify the optimal roasting conditions achievable with the developed equipment, the experimental design was structured using the Taguchi method, incorporating two factors at three levels each. The considered factors were:

1. Batch size 70, 80, and 90 coconuts per roasting cycle. This range was selected based on: the traditional method's capacity of 70 coconuts, spatial constraints of the three drum system and maximum practical loading that maintains uniform heat distribution.
2. Rotational speed of the roasting drum adjusted to accommodate process conditions to 10, 15 and 20 round per minute. This range was determined through preliminary trials to identify speeds that: provide sufficient tumbling action for uniform heat exposure, maintain adequate contact time between coconuts and heated drum surface and prevent excessive mechanical stress that could damage coconuts.

These factors and level values arrangement resulted in a total of nine experimental runs, the details of which were presented in Table 3.

The experiment of coconut burning in each condition was repeated three times for fine burned coconut. The roasting experiments were conducted in accordance with the predefined experimental plan. The results obtained from the most effective roasting batches were selected for further analysis using the Taguchi method. The evaluation emphasized the Signal-to-Noise (S/N) ratio, applying the larger-is-better criterion as expressed in Equation (3). This analytical approach was adopted to identify the optimal operating conditions for coconut roasting when employing the developed apparatus.

Table 3. Taguchi design for experiment.

Numbers	Coconut Numbers (Coconuts)	Rotation Speeds (Rpm)
1	70	10
2	70	15
3	70	20
4	80	10
5	80	15
6	80	20
7	90	10
8	90	15
9	90	20

$$S/N \text{ ration} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n 1/y_i^2 \right) \quad (3)$$

When

y_i = The measured response obtained from the i^{th} trial in the set of n experimental runs.

n = number of replications ($n = 3$)

3. Results

The coconut roasting trials carried out using the newly developed apparatus, with a batch size of 90 coconuts, demonstrated an average roasting time of 140.75 minutes ($\approx$ 2.34 hours). The average number of defective coconuts per batch was 0.6 units, corresponding to a defect rate of 0.67%. In comparison, the conventional open-fire method required an average roasting time of 151.9 minutes (Table 4). This reflected a reduction of approximately 11.85 minutes per batch when using the improved system.

In terms of product quality, the new method yielded a substantially lower number of defective coconuts, averaging 0.6 per batch, compared with the higher defect count observed in the traditional method. Consequently, the overall success rate of the new process was 99.33%, an improvement of 8.33% over the 91% success rate achieved by the conventional method. This clearly highlights the superior performance and consistency of the newly designed equipment in minimizing product loss. The improvement in yield can be attributed to enhanced heat retention within the roasting drum, which reduces thermal losses commonly encountered in open-air roasting. The rotating drum mechanism facilitates uniform heat distribution, preventing localized overheating that typically causes surface cracking. As a result, coconuts roasted using the improved device exhibited more consistent cooking quality. Additionally, the capability to estimate and regulate fuel consumption contributed to more precise heat control, thereby improving process accuracy and repeatability.

Table 4. Comparison of results of new coconut burning methods and the old method.

No.	Burning		Time difference (minutes)	Waste		Difference between damaged coconuts (units)	Good		% difference of good
	Time			coconut			efficiency		
	(minutes)			(units)			percentage		
	New way	Old way		New way	Old way		New way	Old way	
1	140	152	-12	1	6	-5	98.89	91.43	7.46
2	141	155	-14	0	5	-5	100	92.86	7.14
3	140	149	-9	2	6	-4	97.78	91.43	6.35
4	140	152	-12	1	6	-5	98.89	91.43	7.46
5	142	153	-11	1	7	-6	98.89	90.00	8.89
6	140	157	-17	0	8	-8	100	88.57	11.43
7	141	150	-9	0	6	-6	100	91.43	8.57
8	140	159	-19	2	5	-3	97.78	92.86	4.92
9	143	148	-5	0	8	-8	100	88.57	11.43
10	140	151	-11	1	7	-6	98.89	90.00	8.89
11	140	148	-8	1	6	-5	98.89	91.43	7.46
12	141	155	-14	0	7	-7	100	90.00	10.00
13	141	149	-8	0	7	-7	100	90.00	10.00
14	140	150	-10	1	6	-5	98.89	91.43	7.46
15	140	153	-13	1	6	-5	98.89	91.43	7.46
16	141	151	-10	0	5	-5	100	92.86	7.14
17	142	152	-10	0	6	-6	100	91.43	8.57
18	142	159	-17	0	7	-7	100	90.00	10.00
19	141	152	-11	0	5	-5	100	92.86	7.14
20	140	157	-17	1	7	-6	98.89	90.00	8.89
Avg.	140.7	151.9	-11.85	0.6	6.26	-5.7	99.33	91.00	8.33

Statistical evaluation of roasting performance between the two methods confirmed a significant difference, with a p-value of 0.000 as shown in Table 5. Accordingly, the null hypothesis was rejected, and the alternative hypothesis (H_1) was accepted, verifying the superior efficiency of the new method. To further refine the roasting process, experiments were designed using the Taguchi method. The results, summarized in Table 6, showed that nearly all trials produced high-quality roasted coconuts. Analysis of the “larger-is-better” Signal-to-Noise (S/N) ratio, as illustrated in Figure 5, identified 90 coconuts per batch as the most effective operating condition for the developed apparatus. Analysis of the S/N ratios in Table 7 reveals distinct patterns in factor influence. Batch size demonstrates a clear upward trend, with S/N values increasing from 36.90 at 70 coconuts to 39.04 at 90 coconuts a delta of 2.14. This progression indicates that

larger batches yield more consistent outcomes, likely due to enhanced thermal mass stabilizing temperature fluctuations within the drum. Conversely, rotation speed shows minimal variation across the tested range to 10–20 RPM, with S/N ratios remaining essentially constant at approximately 38 at $\Delta = 0.01$. Such negligible differences suggest that heat distribution remains uniform regardless of minor speed adjustments within this operational window.

Mean response data corroborate these trends. Success rates remained exceptionally high across all batch sizes: 100% for 70 coconuts, 99.58% for 80 coconuts, and 99.51% for 90 coconuts. The Δ of 19.56 coconuts between minimum and maximum batch levels underscores the substantial effect of capacity on absolute output. In contrast, rotation speed produced nearly identical mean values at 79.67–79.78 good coconuts, with a Δ of merely 0.11 units. This consistency confirms that tumbling action within 10–20 RPM sufficiently exposes all coconuts to heating conditions. Main effects plots illustrate these relationships visually. Coconut number exhibits steep positive slopes for both mean and S/N responses, rising linearly from 70 to 89 and 37 to 39, respectively. Meanwhile, rotation speed profiles remain flat at approximately 80 of mean and 38 of S/N ratio, confirming its limited influence. Factor ranking assigns batch size as Rank 1, while rotation speed occupies Rank 2. These rankings highlight that maximizing batch capacity drives performance gains, whereas rotation speed functions as a non-critical variable adjustable for operational convenience.

Based on this analysis, optimal conditions were established at 90 coconuts per batch and 10 RPM. This configuration maximizes throughput while maintaining process stability $S/N = 39.04$ and product quality 99.51% success rate. Selecting the lowest effective rotation speed additionally reduces energy consumption and mechanical wear. Confirmation trials (Table 7) validated these parameters, consistently achieving 89–90 properly roasted coconuts per batch. The Taguchi methodology thus provided a systematic framework for process optimization, identifying batch capacity as the primary control lever while demonstrating rotation speed's flexibility within the tested range.

Table 5. Statistical results of coconut burning efficiency test using paired T-test.

Paired T-Test and CI: new method effectiveness, old method effectiveness				
Paired T for new method effectiveness - old method effectiveness				
	N	Mean	StDev	SE Mean
New method	20	99.3340	0.7554	0.1689
Old method	20	83.6425	3.4511	0.7717
Difference	20	15.6915	3.5422	0.7921
95% CI for mean difference: (14.0337, 17.3493)				
T-Test of mean difference = 0 (vs not = 0): T-Value = 19.81 P-Value = 0.000				

Table 6. Result of Taguchi design experiment.

Numbers	Factors		Good burned coconut				S/N
	Coconut numbers	rotation speeds	Replicate	Replicate	Replicate	Avg	Ratio
			1	2	3		
1	70	10	70	70	70	70	36.90
2	70	15	70	70	70	70	36.90
3	70	20	70	70	70	70	36.90
4	80	10	80	80	80	80	38.06
5	80	15	80	79	80	79.66	38.02
6	80	20	79	79	80	79.33	37.98
7	90	10	89	90	90	89.66	38.98
8	90	15	89	90	90	89.66	39.05
9	90	20	90	90	90	90	39.08

Table 7 Taguchi Analysis of Good burned coco versus Coconut Numbers, Rotation Speeds.

Response Table for Signal to Noise Ratios "Larger is better"			Response Table for Means		
Level	Coconut Numbers (Coconuts)	Rotation Speeds (Rpm)	Level	Coconut Numbers (Coconuts)	Rotation Speeds (Rpm)
1	36.90	37.98	1	70.00	79.67
2	38.03	37.99	2	79.67	79.78
3	39.04	37.99	3	89.56	79.78
Delta	2.14	0.01	Delta	19.56	0.11
Rank	1	2	Rank	1	2

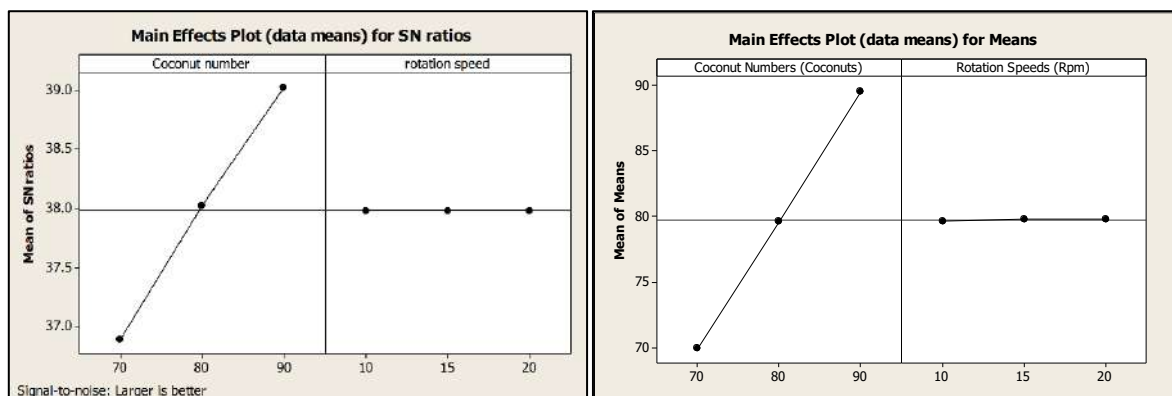


Figure 5. Main effect for S/N ratios and means analysis.

With respect to drum rotation speed, the experimental results demonstrated comparable roasting outcomes across the tested range of 10–20 revolutions per minute (RPM). This finding suggests that any speed within this interval is technically feasible. Accordingly, the optimal operating condition was determined to be 90 coconuts per batch at a drum speed of 10 RPM. Under these settings, heat distribution was effectively maintained, resulting in uniform roasting across all coconuts. When this configuration was retested (Table 8), all 90 coconuts were evenly and properly roasted, confirming the consistency of the process.

Table 8. Comparison of fuel costs of coconut burning methods.

Burn Coconut Method	Quantity of Coconut (Unit)	Firewood (Kg)	Price Per Unit (Bath)	Firewood Cost (Bath)	Good Average Yield (Unit)	Price of Roasted Coconut Per Unit	Opportunity to Sell Roasted Coconut (Bath)
New way	90	348	0.5	174	90	40	3,600
Old way	70	300		150	63.74		2,549
difference	20	48	-	24	25.66	-	1,051

In terms of fuel consumption, the improved method required approximately 348 kg of firewood per batch, which was 48 kg more than that consumed in the conventional process. This additional usage increased the fuel cost by about 24 THB per roasting cycle. However, despite the marginal rise in fuel cost, the newly developed apparatus significantly enhanced productivity by increasing the batch capacity from 70 coconuts (traditional method) to 90 coconuts.

The additional capacity of 20 coconuts per batch contributed to a substantial reduction in overall product loss. At an average market price of 40 THB per roasted coconut, this increase in yield corresponds to an additional revenue of approximately 1,051 THB per cycle. This added economic value effectively offsets the relatively small increase in fuel expenditure, thereby confirming that the newly developed roasting method represents a more efficient and economically viable improvement over conventional practices.

4. Discussion

Based on the experimental evaluation of the newly developed coconut roasting apparatus, the proposed method demonstrated superior performance compared with the conventional open-fire approach in terms of roasting time, product quality, and overall process efficiency. The average roasting duration was 140.75 minutes per batch, representing a time saving of approximately 11.85 minutes when compared with the 151.90 minutes required by the traditional method. Under the optimal conditions identified through the Taguchi method namely, roasting 90 coconuts per batch at a drum rotation speed of 10 RPM all coconuts were evenly roasted. The performance gains observed stem from fundamental improvements in heat transfer within the enclosed drum configuration. Traditional open-fire roasting relies

heavily on radiation and convection, with substantial thermal losses to ambient air. By contrast, the drum system functions as a semi-enclosed chamber that retains heat more effectively while promoting better distribution throughout the roasting volume. Hot combustion gases naturally rise and circulate along the curved interior walls due to buoyancy-driven flow, establishing organized convective patterns. Simultaneously, drum rotation ensures each coconut repeatedly cycles through different thermal zones, receiving balanced exposure to heated surfaces and gas streams. Optimization trials identified 10 RPM as the preferred rotation speed, representing an equilibrium between two competing requirements. Adequate tumbling frequency prevents coconuts from remaining stationary long enough to develop localized hot spots or charring. At the same time, sufficient contact duration with the heated drum wall allows progressive moisture removal and promotes Maillard browning reactions essential for desired color and flavor development. Preliminary tests at lower speeds resulted in scorched areas where coconuts stayed in prolonged contact with heat sources. Conversely, higher rotation rates shortened individual exposure intervals, reducing thermal energy transfer per cycle and compromising roasting uniformity. The 10 RPM setting thus emerged as a practical compromise that maintains product quality while minimizing mechanical stress and energy consumption.

Combustion characteristics also differ markedly between the two systems. Controlled airflow entering through the drum base facilitates more complete fuel oxidation, improving stoichiometric efficiency and reducing smoke emissions. Temperature stability throughout the roasting cycle benefits from this regulated combustion environment, minimizing the fluctuations typical of open-fire arrangements. Energy analysis using Equation (2) revealed an apparent paradox: while absolute firewood consumption rose by 48 kg per batch, effective energy utilization improved by approximately 28%. This efficiency gain reflects reduced thermal losses through better containment and more uniform heat distribution within the semi-enclosed chamber. Product quality metrics demonstrate the practical impact of these thermal improvements. The new system achieved 99.6% defect-free output, compared to 91% for traditional roasting. This enhancement stems from maintaining coconut surface temperatures within the 105–120°C range optimal for Maillard reactions that develop desirable browning and flavor compounds (Apriyantono et al., 2002). Simultaneously, the uniform thermal field prevents localized temperature excursions above 140°C that would cause charring and product rejection. The controlled heating environment thus ensures both chemical transformation necessary for quality and avoidance of thermal degradation that creates waste. Although the new process required an additional 48 kg of firewood per batch, corresponding to an increased fuel cost of approximately 24 THB per roasting cycle, the benefits substantially outweighed the additional expense. By increasing the roasting capacity from 70 to 90 coconuts per cycle and reducing the number of defective products, the method enabled the sale of approximately 25.66 additional coconuts per batch. At a market price of 40 THB per coconut, this translated into an average revenue gain of about 1,051 THB per roasting cycle, which clearly offset the minor increase in fuel cost.

The findings align with Suarbawa & Mulawarman (2021), who demonstrated that ergonomically designed roasting equipment improves production efficiency while reducing operator workload. Their mechanized system reduced musculoskeletal complaints by 42.21% and decreased working pulse elevation

from 54.48% to 39.00%. Similarly, the rotating drum mechanism in this study eliminates continuous manual stirring, reducing operator fatigue and heat exposure. The consistent 10 RPM rotation ensures uniform heat distribution without physical intervention, improving both product quality and worker safety, particularly important for small-scale producers working long hours. The 62.07% productivity increase reported by Suarbawa & Mulawarman (2021) supports the economic viability demonstrated in this study, where increased capacity (70 to 90 coconuts per batch) and 99.6% success rate reflect similar gains. The drum's heat-retaining properties and mechanical rotation mechanism ensure consistent quality, aligning with Sucahyo & Mustaqimah (2021), who reported that a vertically partitioned drum kiln enhances heat confinement and distribution via radiation and convection, achieving controlled carbonization temperatures (~295 °C) and improved charcoal yield.

In conclusion, the improved coconut roasting method effectively reduces roasting time, minimizes product loss, and enhances energy utilization while simultaneously generating additional economic value. These results suggest that the method is highly suitable for implementation at the community level and for small-scale industrial applications, providing both technical and economic advantages over traditional practices.

5. Conclusion and Suggestion

This study developed and evaluated the performance of a newly designed coconut roasting apparatus, benchmarked against the conventional open-fire method. Experimental results confirmed that the improved system could operate effectively under the optimal conditions identified using the Taguchi method with the larger-is-better criterion. With a batch size of 90 coconuts and a drum rotation speed of 10 RPM, the device consistently produced properly roasted coconuts in an average roasting time of 140.75 minutes. In comparison, the traditional method required 151.90 minutes and resulted in an average of 6.26 defective coconuts per batch, equivalent to a 9.00% defect rate. Thus, the new method reduced roasting time by approximately 11.85 minutes per cycle, minimized product defects, and increased the yield of quality products from 91% to 99.6%. This improvement was statistically significant ($P\text{-value} = 0.000$). Although the new process required an additional 48 kg of firewood per batch, corresponding to a fuel cost increase of about 24 THB per cycle, it enabled the roasting of 20 additional coconuts per batch while reducing waste. As a result, the potential revenue increased by approximately 1,051 THB per cycle, representing a substantial return relative to the marginal rise in fuel expense.

Overall, the findings demonstrate that the newly developed coconut roasting device significantly improves the efficiency, quality, and economic viability of the roasting process. The apparatus is therefore well-suited for adoption in community-based enterprises and holds strong potential for small-scale commercial expansion. Nevertheless, the issue of higher fuel consumption requires attention within a broader sustainability framework. Future studies should investigate strategies to reduce the environmental footprint of the roasting process, including the incorporation of thermal insulation materials or structural modifications to minimize heat loss and enhance biomass utilization efficiency. More importantly, research should focus on reducing CO₂ emissions through alternative renewable energy sources, such as biogas from

agricultural waste or solar-assisted heating systems, which would align with Thailand's Bio-Circular-Green Economy Model. Additionally, exploring the potential for utilizing coconut shell charcoal or other agricultural residues as fuel sources could simultaneously reduce operating costs, decrease dependence on firewood, and contribute to circular economic principles by converting waste into valuable energy. Life cycle assessment (LCA) studies would provide valuable insights into the overall environmental impact and guide the development of more sustainable roasting technologies that balance productivity, quality, and ecological responsibility.

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การพัฒนากรอบการพยากรณ์ด้วย LSTM สำหรับการทำนายทิศทางราคารายวัน
ของ EUR/USD ในตลาดแลกเปลี่ยนเงินตราต่างประเทศ
Developing an LSTM-Based Forecasting Framework for Predicting Daily
EUR/USD Price Direction in the Foreign Exchange Market

วรรณนะ พงษ์เสนา^{1*}

Watthana Pongsena^{1*}

¹คณะศิลปศาสตร์และวิทยาศาสตร์ มหาวิทยาลัยราชภัฏศรีสะเกษ จังหวัดศรีสะเกษ

¹Faculty of Liberal Arts and Sciences, Sisaket Rajabhat University, Sisaket Province

*Corresponding Author: w.pongsena@sskru.ac.th

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บทคัดย่อ

ตลาดแลกเปลี่ยนเงินตราต่างประเทศ (Foreign Exchange: Forex) เป็นหนึ่งในตลาดการเงินที่มีขนาดใหญ่และมีสภาพคล่องสูงที่สุดในโลก การพยากรณ์ทิศทางราคาสwapของอัตราแลกเปลี่ยนยังคงเป็นเรื่องที่ท้าทาย เนื่องจากข้อมูลอนุกรมเวลาทางการเงินมีลักษณะผันผวนสูง ไม่เป็นเชิงเส้น และไม่คงที่ตามเวลา งานวิจัยนี้พัฒนากรอบการพยากรณ์โดยใช้แบบจำลอง Long Short-Term Memory (LSTM) สำหรับการทำนายทิศทางราคารายวันของคู่เงิน EUR/USD โดยใช้ข้อมูลอัตราแลกเปลี่ยนรายวันที่ส่งออกจากแพลตฟอร์ม MetaTrader 4 ช่วง วันที่ 2 มกราคม ค.ศ. 2018 ถึง 30 เมษายน ค.ศ. 2019 จำนวน 345 ระเบียบ ข้อมูลถูกกำหนดให้อยู่ในรูปปัญหาการจำแนกสองคลาสผ่านตัวแปร Trend และสร้างข้อมูลลำดับด้วยเทคนิค sliding window สำหรับการฝึกแบบจำลอง กรอบการวิจัยนี้ศึกษาผลของพารามิเตอร์สำคัญ ได้แก่ ความยาวหน้าต่างข้อมูลนำเข้า ปริมาณข้อมูลฝึก และความรู้ในการปรับปรุงแบบจำลอง นอกจากแบบจำลอง LSTM พื้นฐานแล้วยังพัฒนาแบบจำลองปรับเหมาะและแนวทางการแบ่งกลุ่มลำดับข้อมูลตามลักษณะการเคลื่อนไหวของราคา (LSTM-CS) เพื่อให้แบบจำลองสามารถเรียนรู้รูปแบบตลาดที่แตกต่างกันได้ ผลการทดลองพบว่าแบบจำลองพื้นฐานให้ความแม่นยำร้อยละ 52.5 และเพิ่มขึ้นเป็นร้อยละ 67.5 หลังการปรับแต่งพารามิเตอร์ ขณะที่แบบจำลอง LSTM-CS ให้ผลดีที่สุดที่ร้อยละ 69.7

คำสำคัญ: หน่วยความจำระยะสั้นและระยะยาว, การพยากรณ์อนุกรมเวลา, ตลาดแลกเปลี่ยนเงินตราต่างประเทศ, การพยากรณ์ทิศทางราคา

Abstract

The foreign exchange (Forex) market is one of the largest and most liquid financial markets in the world. Predicting exchange-rate direction remains challenging because financial time-series data are highly volatile, nonlinear, and non-stationary. This study develops an LSTM-based forecasting framework for predicting the daily price direction of the EUR/USD exchange rate. The dataset consists of daily exchange-rate data exported from the MetaTrader 4 platform from 2 January 2018 to 30 April 2019, comprising 345 observations. The prediction task is formulated as a binary classification problem through a Trend variable, and sequential samples are generated using a sliding window technique for model training. The proposed

framework investigates the effects of key parameters, including input window length, training data size, and model update frequency. In addition to the baseline LSTM model, optimized models and a classification-based sequence segmentation approach based on price movement characteristics (LSTM-CS) are developed to enable the model to learn different market patterns. The experimental results show that the baseline model achieved an accuracy of 52.5%, which increased to 67.5% after parameter optimization, while the LSTM-CS model produced the best result at 69.7%.

Keywords: Long Short-Term Memory, Time-Series Forecasting, Foreign Exchange Market, Price direction prediction

1. Introduction

The foreign exchange (Forex) market is the largest and most liquid financial market in the world and plays a critical role in global trade, international investment, and monetary systems (Lyons, 2001). According to the Bank for International Settlements (BIS, 2022), the global Forex market records a multi-trillion-dollar daily trading volume, making it one of the most actively traded financial markets worldwide. Despite its high liquidity and continuous trading activity, predicting exchange-rate movements remains challenging because financial time-series data are complex, nonlinear, and non-stationary (Poon & Granger, 2003; Lim & Zohren, 2021). These characteristics make it difficult for traditional forecasting methods to capture the dynamic relationships that govern exchange-rate fluctuations.

Historically, exchange-rate forecasting has relied on two main analytical frameworks: fundamental analysis and technical analysis. Fundamental analysis evaluates macroeconomic variables such as interest rates, inflation, and monetary policy to estimate currency valuation (Rapach & Zhou, 2013). In contrast, technical analysis focuses on historical price patterns and trading indicators to identify potential future movements (Lo et al., 2000; Atsalakis & Valavanis, 2009). Although these approaches have been widely applied in financial markets, their predictive performance may be limited when market dynamics exhibit complex nonlinear behavior and rapidly changing statistical properties.

With the increasing availability of financial data and computational power, machine learning techniques have been widely explored as alternative approaches to financial time-series forecasting. Early studies demonstrated that artificial neural networks (ANNs) and support vector machines (SVMs) could improve forecasting performance under certain market conditions (Cao et al., 2003; Kamruzzaman & Sarker, 2003). These models can capture nonlinear relationships in financial data that are often difficult to model using conventional statistical techniques.

More recently, deep learning architectures have gained considerable attention in financial forecasting applications. In particular, recurrent neural networks (RNNs) are well suited to sequential data modeling because they incorporate temporal dependencies between observations. However, conventional RNN models often suffer from vanishing and exploding gradient problems when learning long-term dependencies (Hochreiter, 1998; Pascanu et al., 2013). To overcome this limitation, Hochreiter &

Schmidhuber (1997) introduced the Long Short-Term Memory (LSTM) architecture, which incorporates memory cells and gating mechanisms that regulate the flow of information across time steps. Because of these characteristics, LSTM networks have been widely applied to financial forecasting problems, including stock-price prediction, volatility forecasting, and exchange-rate modeling (Fischer & Krauss, 2018; Sezer et al., 2020; Lim & Zohren, 2021; García et al., 2024).

Recent studies have continued to explore the application of deep learning methods to exchange-rate prediction. For example, García et al. (2024) compared LSTM and bidirectional LSTM models for foreign exchange forecasting, while Nguyen et al. (2024) investigated deep learning-based predictive models for identifying Forex market trends. These studies demonstrate that deep learning approaches can capture complex nonlinear relationships in financial time-series data and may provide better predictive performance than conventional statistical methods. However, the effectiveness of such models often depends not only on network architecture but also on the configuration of important modeling parameters.

Despite the growing body of research on deep learning-based financial forecasting, many existing studies focus primarily on improving model architectures or developing hybrid neural networks. In practical forecasting environments, however, model performance can also be strongly influenced by operational parameters such as input window length, the amount of historical data used for training, and the frequency at which the predictive model is updated. These factors are particularly important in financial markets, where statistical relationships may evolve over time because of changing economic conditions, policy decisions, and market sentiment (Gu et al., 2020; Zhang et al., 2022). Systematically investigating the effects of these parameters can therefore provide valuable insights into the practical implementation of deep learning models for financial forecasting.

Another important challenge in financial time-series prediction is the heterogeneous nature of market movements. Exchange-rate sequences may contain different behavioral patterns such as persistent trends, short-term reversals, and irregular fluctuations. When a single predictive model is trained on all sequence types simultaneously, the presence of heterogeneous patterns may reduce the model's ability to learn consistent relationships between historical observations and future price movements. Segmenting sequences into more homogeneous groups may therefore improve the learning capability of forecasting models by allowing specialized models to focus on specific market behaviors.

To address these issues, this study develops an LSTM-based forecasting framework for predicting the daily directional movement of the EUR/USD exchange rate in the foreign exchange market. The EUR/USD currency pair is selected because it represents the most actively traded currency pair globally and accounts for the largest share of global Forex trading volume (Evans & Lyons, 2002; King et al., 2013; BIS, 2022). Due to its high liquidity and extensive market participation, EUR/USD is frequently used as a benchmark dataset in empirical studies of exchange-rate forecasting and algorithmic trading.

Rather than proposing a new neural network architecture, this research focuses on systematically examining how key model configuration parameters influence predictive performance in a realistic forecasting setting. The study first develops a baseline LSTM model for daily exchange-rate direction prediction using historical EUR/USD data. It then investigates the effects of three important parameters:

input window length, training dataset size, and model update frequency. In addition, a classification-based sequence segmentation approach, referred to as LSTM-CS, is introduced to partition price sequences into groups with similar movement patterns so that specialized LSTM models can learn more homogeneous market behaviors.

The main contributions of this study can be summarized as follows. First, the study develops an LSTM-based forecasting framework for predicting the daily direction of exchange rate movements using historical EUR/USD price data. Second, it systematically investigates several key model configuration parameters, including input window length, training dataset size, and model update frequency, in order to understand their influence on predictive performance. Third, the study introduces a classification-based sequence segmentation approach (LSTM-CS), which enables the model to specialize in learning different price movement patterns. Finally, comprehensive empirical evaluations are conducted to demonstrate how appropriate parameter configuration and sequence segmentation strategies can significantly improve predictive performance in Forex direction forecasting.

2. Materials and Methods

2.1 Long Short-Term Memory Networks

Long Short-Term Memory (LSTM) is a specialized recurrent neural network (RNN) architecture designed to capture temporal dependencies in sequential data (Hochreiter & Schmidhuber, 1997). RNN models process input sequences while maintaining hidden states that propagate information across time steps, allowing temporal relationships within time-series data to be modeled (Lim & Zohren, 2021). The basic structure of an RNN used for sequential processing is illustrated in Figure 1.

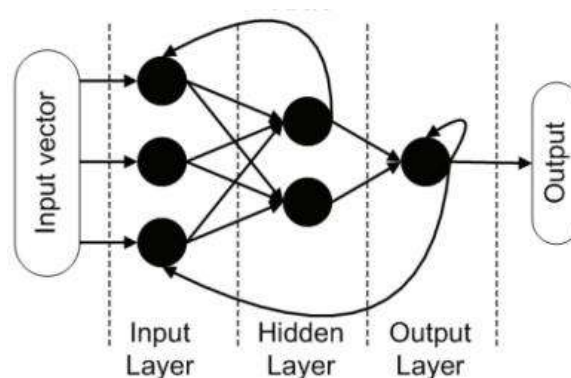


Figure 1. Structure of a recurrent neural network (RNN) for sequential data processing

However, conventional RNN models often suffer from vanishing and exploding gradient problems during backpropagation through time, making it difficult for the network to learn long-term dependencies (Hochreiter, 1998; Pascanu et al., 2013). To overcome this limitation, the LSTM architecture introduces a memory cell together with three gating mechanisms, namely the input gate, forget gate, and

output gate, which regulate the flow of information within the network. The internal structure of these gates is illustrated in Figure 2.

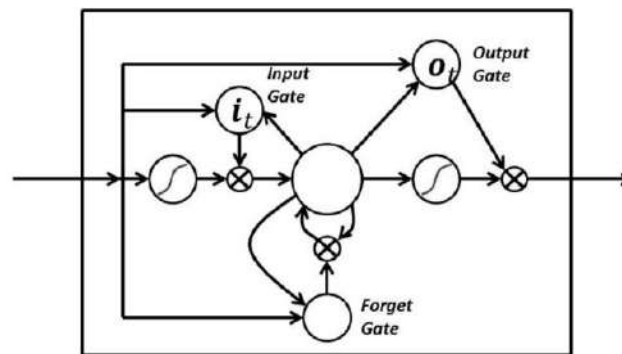


Figure 2. LSTM gating mechanisms, including the input gate, forget gate, and output gate

Because of these mechanisms, LSTM networks can retain relevant historical information over longer time horizons and have therefore been widely applied in financial time-series forecasting tasks such as stock-price prediction, volatility forecasting, and exchange-rate modeling (Fischer & Krauss, 2018; Sezer et al., 2020; Lim & Zohren, 2021).

For time-series prediction problems, LSTM models can be configured using different sequence structures. In this study, a many-to-one sequence prediction structure is employed, in which a sequence of historical observations is used to predict the direction of the next trading day. This structure is commonly used in financial forecasting applications, where past information influences future market movements, as illustrated in Figure 3.

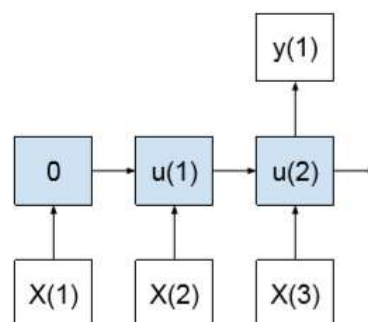


Figure 3. Many-to-one sequence prediction structure used in the LSTM forecasting model

2.2 Research Framework

The overall research framework used in this study is illustrated in Figure 4. It consists of three main stages: (1) data collection and preprocessing, (2) model development and optimization, and (3) model evaluation.

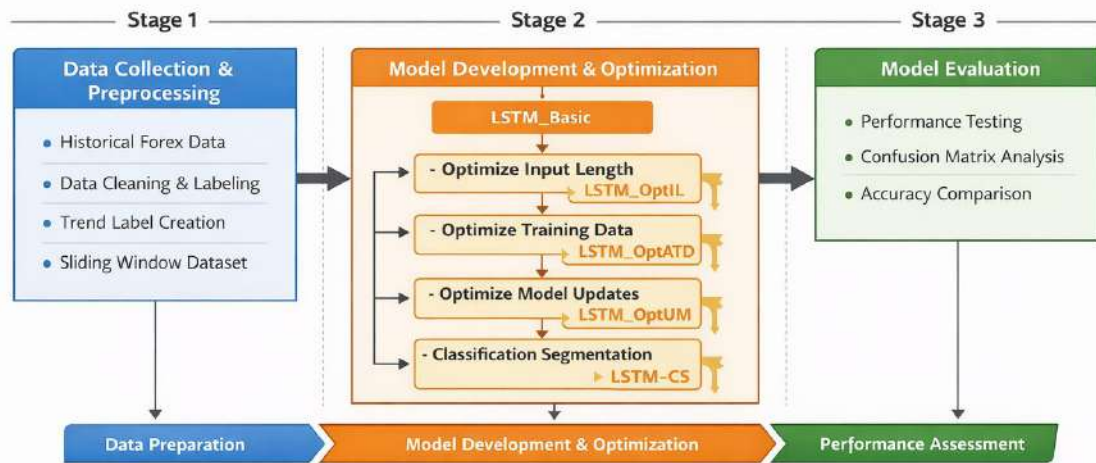


Figure 4. Research framework of the proposed LSTM-based forecasting system

In the first stage, historical Forex price data are collected and transformed into a format suitable for machine learning analysis. This stage includes data cleaning, transformation of raw price data into directional labels, and generation of sequential datasets using a sliding window technique.

In the second stage, predictive models are developed and optimized. A baseline LSTM model (LSTM_Basic) is first constructed to establish a reference model for performance comparison. Several optimized model variants are then developed by systematically adjusting important parameters that may influence predictive performance.

The models examined in this study include:

- LSTM_OptIL – Optimization of input length (window size)
- LSTM_OptATD – Optimization of the amount of training data
- LSTM_OptUM – Optimization of model update frequency
- LSTM-CS – classification-based sequence segmentation model

In the final stage, the models are evaluated using historical exchange-rate data and their predictive performance is compared using classification-based evaluation metrics derived from the confusion matrix.

2.3 Data Processing: Data Collection, Preparation, and Transformation

This section describes the procedures used for data collection, preparation, and transformation.

2.3.1 Data Collection

The dataset used in this study consists of daily historical exchange-rate data from the Forex market. The data were exported from the MetaTrader 4 trading platform provided by FXPro, which is widely used in retail algorithmic trading environments (Aldridge, 2013).

The selected currency pair is EUR/USD, covering the period from 2 January 2018 to 30 April 2019, resulting in a dataset of 345 daily observations. Although the dataset contains a limited number

of daily observations, the sliding window technique generates a large number of sequential training samples, allowing the LSTM model to learn temporal patterns effectively.

The EUR/USD pair was selected because it represents the most actively traded currency pair in the global Forex market and is commonly used as a benchmark in empirical exchange-rate research (Evans & Lyons, 2002; King et al., 2013; BIS, 2022).

The dataset follows the standard OHLC format and includes the following attributes: (1) trading date, (2) opening price, (3) highest price, (4) lowest price, (5) closing price, and (6) trading volume. An example of the exported dataset is illustrated in Figure 5.

Date	Time	Open	High	Low	Close	Volume
2018.01.02	0:00	1.2087	1.20888	1.19967	1.20004	77692
2018.01.04	0:00	1.19114	1.1953	1.18672	1.1946	6936
2018.01.05	0:00	1.19495	1.19753	1.18864	1.19366	37558
2018.01.06	0:00	1.19361	1.19683	1.18486	1.18715	38120
2018.01.07	0:00	1.1872	1.18954	1.18013	1.18327	40248
2018.01.08	0:00	1.18321	1.18466	1.17537	1.17913	36991
2018.01.09	0:00	1.17905	1.18443	1.17621	1.18387	63687
2018.01.11	0:00	1.18523	1.18691	1.18357	1.18689	4385
2018.01.12	0:00	1.18676	1.18704	1.17856	1.18312	73332
2018.01.13	0:00	1.18309	1.1859	1.17531	1.17761	79404
2018.01.14	0:00	1.17759	1.18449	1.17267	1.17832	79148
2018.01.15	0:00	1.17828	1.17892	1.15675	1.16353	100901
2018.01.16	0:00	1.16357	1.16484	1.14593	1.15632	99827
2018.01.18	0:00	1.1549	1.15724	1.15457	1.15603	3663
2018.01.19	0:00	1.15602	1.16383	1.1551	1.15939	75745
2018.01.20	0:00	1.15951	1.16139	1.15397	1.15446	76298
2018.01.21	0:00	1.1544	1.16739	1.15406	1.16137	76752

Figure 5. Example of EUR/USD historical price data exported from MetaTrader 4

2.3.2 Data Preparation

To formulate the prediction problem as a classification task, an additional variable called Trend is constructed to represent the daily price movement direction. The Trend variable is defined as follows:

$$Trend = \begin{cases} 1, & \text{if } Close_t \geq Open_t \\ 0, & \text{if } Close_t < Open_t \end{cases} \quad (1)$$

where $Close_t$ and $Open_t$ represent the closing and opening prices of trading day t .

This transformation converts the forecasting problem into a binary classification problem in which the model predicts whether the exchange rate will move upward or downward within a trading day.

Date	Time	Open	High	Low	Close	Volume	Trend
2018.01.02	0:00	1.2087	1.20888	1.19967	1.20004	77692	0
2018.01.04	0:00	1.19114	1.1953	1.18672	1.1946	6936	1
2018.01.05	0:00	1.19495	1.19753	1.18864	1.19366	37558	0
2018.01.06	0:00	1.19361	1.19683	1.18486	1.18715	38120	0
2018.01.07	0:00	1.1872	1.18954	1.18013	1.18327	40248	0
2018.01.08	0:00	1.18321	1.18466	1.17537	1.17913	36991	0
2018.01.09	0:00	1.17905	1.18443	1.17621	1.18387	63687	1
2018.01.11	0:00	1.18523	1.18691	1.18357	1.18689	4385	1
2018.01.12	0:00	1.18676	1.18704	1.17856	1.18312	73332	0
2018.01.13	0:00	1.18309	1.1859	1.17531	1.17761	79404	0
2018.01.14	0:00	1.17759	1.18449	1.17267	1.17832	79148	1
2018.01.15	0:00	1.17828	1.17892	1.15675	1.16353	100901	0
2018.01.16	0:00	1.16357	1.16484	1.14593	1.15632	99827	0
2018.01.18	0:00	1.1549	1.15724	1.15457	1.15603	3663	1
2018.01.19	0:00	1.15602	1.16383	1.1551	1.15939	75745	1
2018.01.20	0:00	1.15951	1.16139	1.15397	1.15446	76298	0
2018.01.21	0:00	1.1544	1.16739	1.15406	1.16137	76752	1

Figure 6. Example of dataset with the generated Trend variable

The distribution of upward and downward movements was examined to evaluate class balance. The dataset shows a relatively balanced distribution of both classes, and therefore no additional class-balancing techniques were applied.

2.3.3 Data Transformation

After constructing the Trend variable, the dataset is transformed into sequential samples using the sliding window technique, which is commonly used in deep learning-based time-series forecasting (Brownlee, 2018; Fischer & Krauss, 2018; Lim & Zohren, 2021).

The sliding window moves across the dataset and extracts consecutive sequences of historical observations to be used as inputs for the LSTM model, as illustrated in Figure 7.

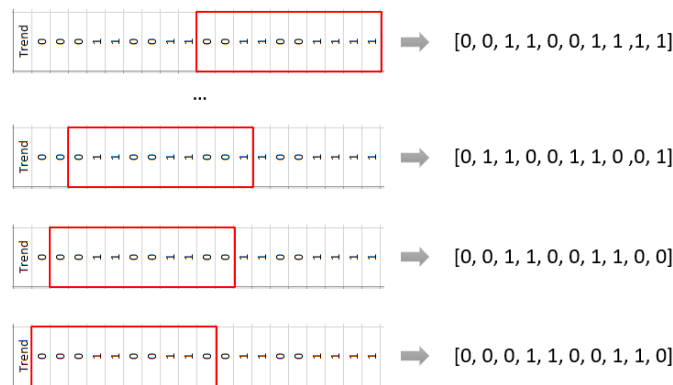


Figure 7. Sliding window technique used to generate sequential samples

Each sequence represents a set of historical directional movements used to predict the direction of the next trading day. An example of the generated sequence dataset is shown in Figure 8.

1	0	0	1	0	0	0	0	1	0	0
2	0	1	0	0	0	0	1	0	0	1
3	1	0	0	0	0	1	0	0	1	1
4	0	0	0	0	1	0	0	1	1	0
5	0	0	0	1	0	0	1	1	0	1
6	0	0	1	0	0	1	1	0	1	0
7	0	1	0	0	1	1	0	1	0	0
8	1	0	0	1	1	0	1	0	0	1
9	0	0	1	1	0	1	0	0	1	1
10	0	1	1	0	1	0	0	1	1	1
11	1	1	0	1	0	0	1	1	1	0
12	1	0	1	0	0	1	1	1	0	1
13	0	1	0	0	1	1	1	0	1	1
14	1	0	0	1	1	1	0	1	1	1
15	0	0	1	1	1	0	1	1	1	0

Figure 8. Example of binary sequence data generated from daily price movements.

2.4 Model Development and Optimization

This section describes the construction of the LSTM-based predictive models and the strategies used to improve prediction performance.

2.4.1 Problem Formulation

The forecasting task in this study is formulated as a binary classification problem. Given a sequence of historical observations:

$$X = (x_{t-n+1}, x_{t-n+2}, \dots, x_t) \quad (2)$$

the objective of the model is to predict the directional movement of the exchange rate at time $t + 1$. The conceptual prediction structure is illustrated in Figure 9.

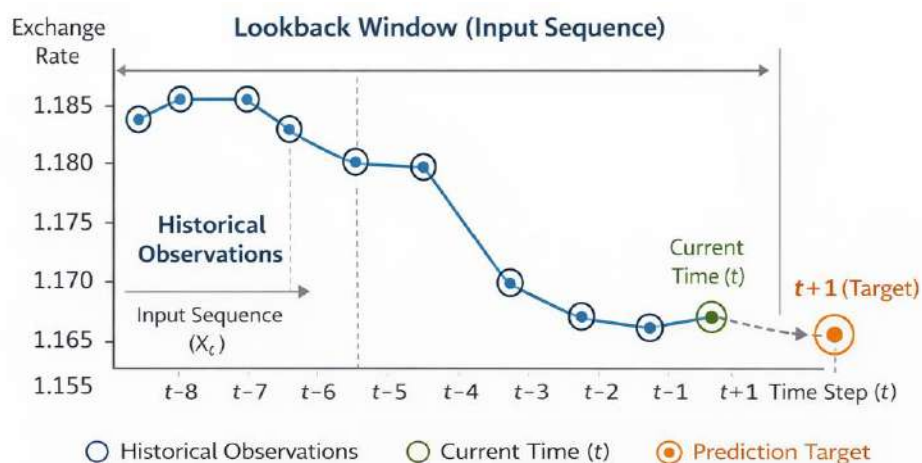


Figure 9. Conceptual illustration of daily exchange-rate direction prediction.

Three important modeling parameters are examined: (1) input window length (lookback period), (2) training dataset size, and (3) model update frequency. These parameters may influence the predictive capability of machine learning models in non-stationary financial markets (Gu et al., 2020; Sezer et al., 2020).

2.4.2 LSTM Model Architecture

The architecture consists of an input layer, an LSTM layer for temporal feature extraction, a fully connected dense layer, and a sigmoid output layer for binary classification.

The model is trained using the binary cross-entropy loss function and optimized using the Adam optimizer, which is widely applied in deep learning optimization tasks. The main hyperparameters used in the baseline model are summarized in Table 1.

Table 1. Baseline LSTM model hyperparameters

Parameter	Value
LSTM units	32
Dense units	1
Activation	Sigmoid
Optimizer	Adam
Loss function	Binary cross-entropy
Batch size	16
Epochs	50
Learning rate	0.001

2.4.3 Development of the baseline LSTM Model (LSTM_Basic)

The baseline LSTM model is first developed to establish a reference benchmark for evaluating the effectiveness of the proposed model configurations. The overall development procedure of the baseline model is illustrated in Figure 10.

The generated sequence dataset is divided into training and testing subsets following chronological order. In time-series forecasting problems, chronological data partitioning is necessary to prevent information leakage between training and testing datasets. Historical observations occurring earlier in time are therefore used for model training, while later observations are reserved for model evaluation (Lim & Zohren, 2021).

Although the sliding window technique produces overlapping sequences, the training and testing datasets are constructed independently after the chronological split. As a result, no overlapping observations exist between the two datasets, ensuring that the predictive model does not gain access to future information during training. This approach provides a more realistic evaluation framework for financial forecasting models.

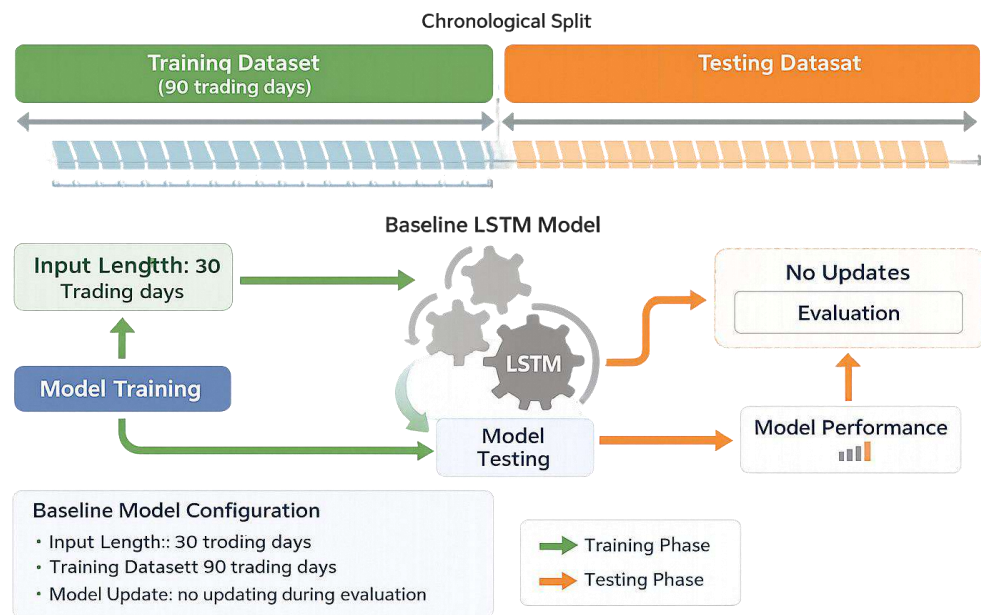


Figure 10. Development process of the baseline LSTM model

Model evaluation in this study follows a rolling chronological prediction procedure that mimics a realistic forecasting environment. At each evaluation stage, the model is trained using historical observations available up to that point and then used to generate predictions for subsequent unseen data. This procedure preserves the temporal ordering of financial time-series data and prevents information from future observations from influencing the training process. Such chronological evaluation strategies are commonly recommended for financial forecasting studies in order to avoid data leakage and ensure realistic model assessment (Sezer et al., 2020; Lim & Zohren, 2021).

The baseline model configuration uses the following parameters:

- Input length: 30 trading days
- Training dataset size: 90 trading days
- Model update: no retraining during the evaluation period

These parameter settings serve as the initial configuration for the baseline model before performing further parameter optimization in subsequent experiments.

2.4.4 Determining the Suitable Input Length (LSTM_OptIL)

To determine the most suitable input window length for daily Forex prediction, multiple configurations ranging from 5 to 30 trading days are evaluated. Shorter windows capture recent market information, while longer windows may include additional historical context. Each configuration is evaluated using the same experimental protocol to identify the window length that provides the most stable prediction performance.

The tested input lengths were selected to cover a range from short-term recent memory to longer observation windows. This range allows the experiment to examine the trade-off

between temporal relevance and the amount of historical context used by the predictive model. Similar ranges of observation windows have also been explored in previous financial time-series forecasting studies.

2.4.5 Determining the Suitable Amount of Training Data (LSTM_OptATD)

The amount of historical data used for model training may influence model performance in financial forecasting. Excessively long training datasets may introduce outdated patterns that no longer reflect current market conditions (Sezer et al., 2020).

To investigate this effect, multiple training dataset sizes are evaluated, including: 5, 7, 14, 30, 60, and 90 trading days. These experiments analyze how the amount of training data affects the predictive capability of the LSTM model.

These values were selected to represent short-, medium-, and relatively longer historical horizons commonly used in practical financial forecasting experiments. Evaluating multiple training durations allows the study to examine how the amount of historical data influences the adaptability of the model in a non-stationary financial environment.

2.4.6 Determining the Suitable Model Update Frequency (LSTM_OptUM)

Financial markets are dynamic and non-stationary environments. Prediction models trained on historical data may gradually lose predictive power if they are not updated regularly (Gu et al., 2020; Zhang et al., 2022).

To evaluate this effect, the trained model is tested over multiple consecutive trading days without retraining. The change in prediction accuracy is monitored to determine the most appropriate model update frequency.

2.4.7 Classification-Based Sequence Segmentation (LSTM-CS)

Financial time-series sequences often contain heterogeneous movement patterns, including trends, reversals, and short-term fluctuations (Sezer et al., 2020). Training a single predictive model on heterogeneous data may reduce the ability of the model to learn consistent relationships between historical observations and future price direction.

To address this issue, this study introduces a classification-based sequence segmentation approach (LSTM-CS).

The approach consists of three steps:

- 1) Generated sequences are analyzed according to the proportion of upward and downward movements within each sliding window.
- 2) Sequences are grouped into pattern categories representing different movement behaviors.
- 3) Independent LSTM models are trained for each sequence group using optimized parameter configurations.

The LSTM-CS configuration uses the following parameters:

- Input length: 10 trading days
- Training dataset size: 14 trading days
- Model update frequency: daily retraining

By training specialized models on more homogeneous subsets of data, the LSTM-CS approach aims to improve the ability of the model to capture distinct price dynamics in financial time-series data.

2.5 Performance Comparison of the LSTM Models

The predictive performance of the proposed models is evaluated using **directional prediction accuracy**, which measures the proportion of correctly predicted price movement directions relative to the total number of observations.

In financial forecasting applications, correctly predicting the **direction of price movement** is often more important than predicting the exact magnitude of price changes. Directional prediction accuracy directly influences trading decisions such as entering buy or sell positions. Therefore, directional accuracy has been widely used as an evaluation metric in financial time-series forecasting studies (Blaskowitz & Herwartz, 2011; Moosa, 2015).

The prediction accuracy is computed using Equation (3):

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (3)$$

where TP (True Positive) represents correctly predicted upward price movements, TN (True Negative) represents correctly predicted downward movements, FP (False Positive) represents incorrect upward predictions, and FN (False Negative) represents missed upward movements.

These values are obtained from the confusion matrix, which summarizes the classification results of the predictive model. The structure of the confusion matrix used in this study is presented in Table 2.

Table 2. Confusion matrix used for model evaluation

	Actual Positive	Actual Negative
Predicted Positive	TP	FP
Predicted Negative	FN	TN

The confusion matrix provides a structured representation of prediction outcomes by distinguishing between correct and incorrect directional predictions. Using these values, the overall directional accuracy of each predictive model can be computed and compared.

In financial forecasting problems, even prediction accuracies slightly above random chance may still provide practical value when incorporated into trading strategies. Traders often design trading systems with asymmetric risk–reward structures, where profitable trades generate larger gains than losing trades. Under such conditions, a trading strategy may remain profitable even when prediction accuracy is close to 50%, provided that the average payoff of winning trades exceeds that of losing trades (Tharp, 2008; Vince, 1992).

Previous studies have also emphasized that directional forecasting accuracy modestly above random benchmarks can still produce economically meaningful signals when integrated into systematic trading frameworks (Blaskowitz & Herwartz, 2011; Moosa, 2015). Therefore, the purpose of this evaluation is to determine whether the proposed LSTM-based models can achieve prediction accuracy above the random benchmark while maintaining stable performance across different parameter configurations.

This evaluation framework enables a consistent comparison between the baseline LSTM model and the optimized model variants developed in this study.

3. Results

3.1 Baseline LSTM Model Performance

The baseline LSTM model was first evaluated to establish a reference benchmark for subsequent model optimization experiments. The baseline configuration employed an input window length of 30 trading days and a training dataset size of 90 trading days, without retraining during the evaluation period.

The prediction outcomes of the baseline model are summarized using a confusion matrix, as illustrated in Figure 11.

Confusion Matrix

Output Class	Up (1)	685	584	54.0%
	Down (0)	669	702	51.2%
		50.6%	54.6%	52.5%
		Up (1)	Down (0)	
		Target Class		

Figure 11. Confusion matrix of the baseline LSTM model for daily Forex price direction prediction

During the evaluation period, the model generated predictions for 2,640 testing samples obtained from sequential rolling prediction windows. Among these predictions, 1,387 observations were correctly classified, resulting in an overall directional prediction accuracy of 52.5%.

The confusion matrix values obtained from the baseline model are presented in Table 3.

Table 3. Confusion matrix of the baseline LSTM model

	Actual Up	Actual Down
Predicted Up	685	634
Predicted Down	619	702

Based on the confusion matrix, additional classification metrics were computed to provide a more comprehensive evaluation of the baseline model performance. These metrics are summarized in Table 4.

Table 4. Classification performance of the baseline LSTM model

Metric	Value (%)
Accuracy	52.5
Precision	51.9
Recall	52.5
F1-score	52.2

The results indicate that the baseline LSTM model performs only slightly better than random guessing. This outcome is consistent with previous studies showing that short-term financial direction prediction remains challenging due to the stochastic and highly dynamic nature of financial markets (Fischer & Krauss, 2018; Sezer et al., 2020)

3.2 Effect of Input Length (Lookback Window)

To determine the most appropriate observation window for daily Forex direction prediction, multiple input lengths ranging from 5 to 30 trading days were evaluated.

The prediction accuracy obtained for each configuration during the testing period from January to April 2019 is summarized in Table 5.

Table 5. Prediction accuracy of the LSTM model with different input window lengths

Testing Period	5	7	9	10	12	15	20	25	30
JAN 2019	46.6	49.9	55.4	56.1	52.3	54.2	54.0	55.1	47.8
FEB 2019	48.4	50.0	54.1	55.2	54.0	52.0	53.8	51.8	45.9
MAR 2019	50.1	50.7	52.2	54.8	56.2	54.9	54.5	49.7	52.6
APR 2019	47.7	50.5	49.7	52.0	51.5	48.0	47.2	45.0	49.7
AVG	48.2	50.3	52.9	54.5	53.5	52.3	52.4	50.4	49.0

The results show that the 10-day input window produced the highest average prediction accuracy (54.5%). Although slightly higher accuracy was observed for the 12-day window in March 2019, the 10-day window produced the most stable performance across different testing periods. Therefore, the 10-day input window was selected for the subsequent optimization experiments.

3.3 Effect of Model Update Frequency

To evaluate the impact of model updating, prediction accuracy was monitored across consecutive trading days without retraining. The experimental results are illustrated in Figure 12.

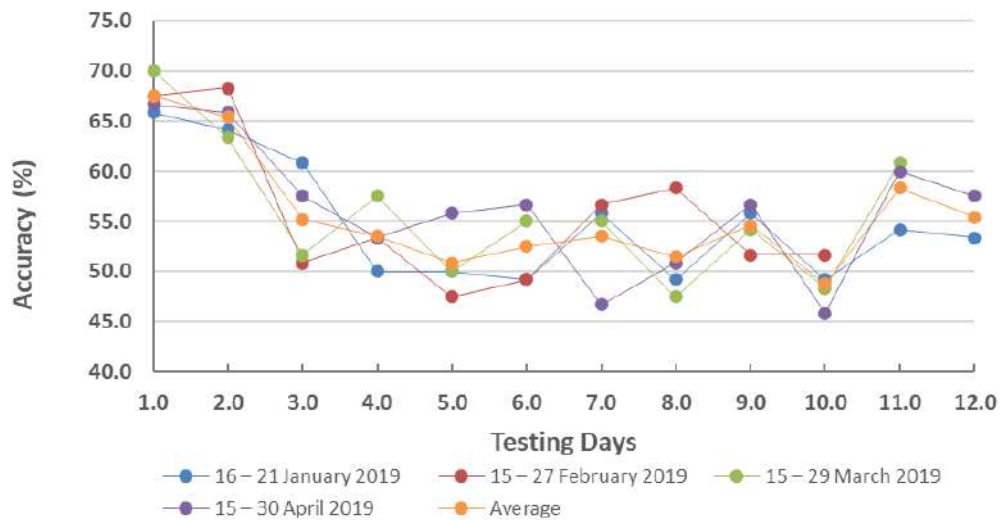


Figure 12. Prediction accuracy of the LSTM model across consecutive trading days without model retraining

The results show that prediction accuracy tends to be highest immediately after model training. In several testing periods, prediction accuracy exceeded 65% on the first evaluation day. However, prediction performance gradually declined as the model continued to generate predictions without retraining.

This decline suggests that the predictive relationships learned by the model may become less relevant as market conditions evolve over time. Therefore, frequent model updating may be necessary to maintain predictive performance in non-stationary financial environments.

3.4 Summary of Model Improvements

The overall performance of the baseline and optimized models is summarized in Table 6.

Table 6. Performance comparison of different LSTM model configurations

Model	Input Length	Training Data	Frequency Update	Accuracy (%)	Precision (%)	Recall (%)	F1-score (%)
LSTM_Basic	30	90	–	52.5	51.9	52.5	52.2
LSTM_OptIL	10	90	–	54.5	53.8	54.5	54.1
LSTM_OptATD	10	14	–	61.2	60.4	61.2	60.8
LSTM_OptUM	10	14	Daily	67.5	66.9	67.5	67.2
LSTM-CS	10	14	Daily	69.7	69.1	69.7	69.4

The results demonstrate that systematic parameter optimization significantly improves the predictive performance of the LSTM model.

First, adjusting the input window length from 30 days to 10 days improved prediction accuracy from 52.5% to 54.5%.

Second, reducing the training dataset size from 90 days to 14 days further increased prediction accuracy to 61.2%, indicating that more recent data may provide more relevant predictive signals.

Third, introducing daily model retraining increased prediction accuracy to 67.5%, suggesting that frequent model updates help maintain predictive performance under evolving market conditions.

Finally, the classification-based sequence segmentation approach (LSTM-CS) achieved the highest performance, with an accuracy of 69.7% and improved precision, recall, and F1-score values compared with the other models.

These results indicate that both model configuration and sequence segmentation strategies can contribute to improving prediction performance in daily Forex direction forecasting.

4. Discussion

4.1 Interpretation of Experimental Results

The experimental results demonstrate that predictive model configuration plays a critical role in the forecasting performance of Long Short-Term Memory (LSTM) networks for daily exchange-rate direction prediction. The baseline LSTM model achieved a directional prediction accuracy of 52.5%, which is only slightly higher than random guessing. This outcome is consistent with previous studies indicating that short-term financial direction prediction remains inherently difficult because of the stochastic and highly dynamic nature of financial markets (Fischer & Krauss, 2018; Sezer et al., 2020; García et al., 2024).

One of the key findings of this study is that reducing the input window length significantly improved predictive performance. The experimental results showed that the 10-day input window produced the most stable prediction accuracy across different testing periods. This observation suggests that excessively long observation windows may introduce outdated or irrelevant historical information into the learning process. Because financial markets evolve rapidly, older observations may no longer reflect

current market conditions. Therefore, shorter observation windows may help the predictive model focus on more recent price dynamics that contain stronger predictive signals. Similar findings have been reported in previous studies of financial time-series forecasting, in which recent data often provide more informative signals for short-horizon prediction tasks (Lim & Zohren, 2021).

Another important observation concerns the effect of training dataset size on prediction accuracy. The experimental results show that reducing the training dataset size from 90 trading days to 14 trading days improved prediction accuracy from 54.5% to 61.2%. This result suggests that incorporating large amounts of historical data does not necessarily improve predictive performance in non-stationary financial environments. When historical data span longer periods, the statistical relationships within the dataset may change because of evolving economic conditions, market sentiment, or policy changes. As a result, including excessive historical data may introduce outdated patterns that reduce the predictive capability of machine learning models. Similar conclusions have been reported in previous research on financial forecasting, where adaptive training strategies are often required to address the non-stationarity of financial time-series data (Gu et al., 2020; Sezer et al., 2020).

The experiment on model update frequency further supports this interpretation. The results show that prediction accuracy gradually declines when the trained model is applied across multiple consecutive trading days without retraining. This performance degradation indicates that predictive relationships learned from historical data may become less relevant as market conditions evolve over time. Frequent model updating therefore appears necessary to maintain forecasting performance in dynamic financial markets. Previous studies on machine learning-based financial forecasting have similarly emphasized the importance of periodic model retraining to adapt to changing market conditions (Gu et al., 2020; Zhang et al., 2022).

The highest predictive performance in this study was achieved when the classification-based sequence segmentation approach (LSTM-CS) was applied, resulting in a prediction accuracy of 69.7%. This approach partitions price sequences into groups with similar movement characteristics, allowing specialized LSTM models to learn more homogeneous patterns. Financial time-series data often exhibit heterogeneous structures, including trending periods, reversals, and irregular fluctuations. Training a single predictive model on heterogeneous sequences may reduce the model's ability to capture consistent patterns. By grouping sequences according to their directional characteristics, the LSTM-CS approach reduces pattern heterogeneity and enables each model to specialize in learning specific price movement behaviors.

In the context of financial forecasting research, achieving prediction accuracies substantially above random chance remains challenging. Previous studies commonly report directional prediction accuracies in the range of approximately 55% to 65% for short-term financial forecasting tasks (Fischer & Krauss, 2018; Sezer et al., 2020; Garcia et al., 2024). In this context, the maximum prediction accuracy of 69.7% obtained in this study suggests that combining parameter optimization with sequence segmentation strategies may be a promising direction for improving deep learning-based forecasting models. Recent research focusing specifically on EUR/USD direction prediction using machine learning methods further confirms the continued importance of this problem in quantitative finance (Guyard & Deriaz, 2024).

4.2 Limitations of the Study

Despite the promising results, several limitations should be acknowledged. First, the experiments were conducted using only the EUR/USD currency pair, and the predictive performance of the proposed framework may vary when applied to other currency pairs with different market characteristics. Second, the dataset used in this study covers a relatively limited historical period, which may restrict the generalizability of the results. Third, this study focuses on performance differences among LSTM-based configurations rather than comparisons across different model families. Therefore, the results should be interpreted as improvements within the LSTM framework rather than a claim of superiority over alternative forecasting approaches. Finally, the evaluation focused primarily on directional prediction accuracy, and the study did not examine the economic profitability of the model under realistic trading conditions such as transaction costs and market frictions.

5. Conclusion

This study developed and evaluated an LSTM-based framework for predicting the daily directional movement of exchange rates in the foreign exchange market using historical EUR/USD data. The results demonstrate that model configuration plays an important role in the predictive performance of LSTM models for financial time-series forecasting. The baseline LSTM model achieved a prediction accuracy of 52.5%, which is only slightly higher than random chance. However, systematic parameter optimization significantly improved forecasting performance.

The experimental results indicate that reducing the input window length to 10 trading days and limiting the training dataset to 14 recent trading days improved prediction accuracy, suggesting that recent market information provides more relevant predictive signals in dynamic financial environments. In addition, frequent model updating helped maintain prediction performance over time. The proposed classification-based sequence segmentation approach (LSTM-CS) further improved prediction accuracy to 69.7%, indicating that training specialized models on more homogeneous sequence groups can enhance forecasting capability.

Future research may extend this framework by evaluating multiple currency pairs, incorporating additional market features, and examining the economic profitability of the proposed forecasting approach under realistic trading conditions.

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ผลการฝึกแบบผสมผสานที่มีต่อสมรรถภาพทางกายในนักกีฬาฟุตบอลชาย

มหาวิทยาลัยราชภัฏสุรินทร์

Effects of Complex Training on Physical Fitness in Male Football Players

at Surindra Rajabhat University

ภัทรพล ทองนำ^{1*}Pattarapol Thongnum^{1*}¹สาขาวิชาวิทยาศาสตร์การกีฬา คณะครุศาสตร์ มหาวิทยาลัยราชภัฏสุรินทร์ จังหวัดสุรินทร์¹Department in Sports Science, Faculty of Education, Surindra Rajabhat University, Surin Province

*Corresponding Author: jeffyswucukku@sru.ac.th

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บทคัดย่อ

การวิจัยครั้งนี้มีวัตถุประสงค์เพื่อศึกษาผลของการฝึกแบบผสมผสานที่มีต่อสมรรถภาพทางกายในนักกีฬาฟุตบอลชายมหาวิทยาลัยราชภัฏสุรินทร์ กลุ่มตัวอย่างที่ใช้เป็นนักฟุตบอลชายมหาวิทยาลัยราชภัฏสุรินทร์ จำนวน 30 คน ได้มาโดยการเลือกแบบเจาะจง แบ่งออกเป็นกลุ่มควบคุม 15 คน และกลุ่มทดลอง 15 คน โดยกลุ่มควบคุมทำการฝึกซ้อมด้วยโปรแกรมฝึกฟุตบอลตามปกติ ส่วนกลุ่มทดลองทำการฝึกซ้อมด้วยโปรแกรมฝึกฟุตบอลตามปกติควบคู่กับโปรแกรมการฝึกแบบผสมผสาน เป็นระยะเวลา 6 สัปดาห์ 3 วันต่อสัปดาห์ วันละ 2 ชั่วโมง (16.30 – 18.30 น.) ทดสอบอัตราการเต้นของหัวใจขณะพัก ความเร็ว ความแข็งแรงของขา ความอ่อนตัว และพลังกล้ามเนื้อขา ก่อนการฝึก หลังการฝึกสัปดาห์ที่ 4 และสัปดาห์ที่ 6 วิเคราะห์ข้อมูลโดยใช้ค่าเฉลี่ย ส่วนเบี่ยงเบนมาตรฐาน วิเคราะห์ความแปรปรวนทางเดียวแบบวัดซ้ำ (One-Way Analysis of Variance with Repeated Measures) เปรียบเทียบความแตกต่างเป็นรายคู่ เมื่อพบความแตกต่างจะทำการวิเคราะห์เป็นรายคู่ด้วยวิธีของตุกี (Tukey) กำหนดนัยสำคัญทางสถิติที่ระดับ 0.05 ผลการวิจัยพบว่าหลังการฝึกสัปดาห์ที่ 6 นักฟุตบอลกลุ่มทดลอง มีอัตราการเต้นของหัวใจขณะพัก ความอ่อนตัว และพลังกล้ามเนื้อขา ดีขึ้นกว่าก่อนการฝึกอย่างมีนัยสำคัญทางสถิติที่ระดับ 0.05 จากผลการวิจัยชี้ให้เห็นว่าการฝึกแบบผสมผสานมีประสิทธิภาพในการพัฒนาอัตราการเต้นของหัวใจขณะพัก ความอ่อนตัว และพลังกล้ามเนื้อขาในนักฟุตบอลได้

คำสำคัญ: การฝึกแบบผสมผสาน, นักฟุตบอลชาย, มหาวิทยาลัยราชภัฏสุรินทร์

Abstract

This research aimed to examine the effects of complex training on physical fitness in male football players at Surindra Rajabhat University. The sample consisted of 30 male football players selected using purposive sampling and assigned to groups using matched-pair assignment: a control group (n = 15) and an experimental group (n = 15). The control group followed the regular football training program, whereas the experimental group followed the regular football training program in conjunction with a complex training program. The training lasted 6 weeks, 3 days per week, 2 hours per day (4:30 PM–6:30 PM). Resting heart rate, speed, leg strength, flexibility, and leg muscle power were assessed before training, after Week 4, and

after Week 6. Data were analyzed using means and standard deviations. One-way analysis of variance with repeated measures was used, and pairwise comparisons were performed using Tukey's method at a significance level of 0.05. The results showed that after Week 6, the experimental group demonstrated significant improvements in resting heart rate, flexibility, and leg muscle power compared with pre-training ($p < 0.05$). These findings suggest that complex training is effective for improving resting heart rate, flexibility, and leg muscle power in football players.

Keywords: Complex training, Male football players, Surindra Rajabhat University

1. Introduction

Football is a globally popular team sport that provides many benefits. Physically, it helps develop strength and overall fitness. Mentally, it helps players learn to accept defeat, acknowledge victory, and forgive others, supporting a positive life in society. This is consistent with Pokrajcic et al. (2018) and Ferrini et al. (2025), who stated that football is one of the most popular sports today. Football can also promote physical, intellectual, emotional, and social development. Similarly, Michailidis et al. (2025) and Khan & Yadav (2025) concluded that football is one of the most popular sports worldwide, with millions of male and female athletes participating. Football competitions are organized in almost every country, and the competition that every team dreams of participating in is the FIFA World Cup, held every four years. Therefore, each country organizes domestic competitions to identify skilled players for the national team. Furthermore, football is widely popular in Thailand, as evidenced by strong interest and participation whenever major competitions are held. Thailand recognizes the importance of the goal, "We want Thai football to reach the World Cup." Therefore, domestic football leagues have been established, and youth leagues have also been initiated to provide young players with experience. This lays the foundation for football development and promotes progress toward becoming future players for the Thai national team.

Basic football skills are fundamental and form the foundation of playing football. Football players should practice these skills correctly, understand the principles and methods, and train until they achieve proficiency. Each skill is important and can ultimately contribute to scoring a goal. Thongnum (2019) summarized the basic football skills as follows: stopping the ball, dribbling, passing, heading, kicking, throwing in, and shooting. This aligns with Lucas et al. (2025), who stated that football is a highly complex sport that requires the integration of physical, technical, and cognitive skills. Similarly, Tutar et al. (2024) explained that football is a popular team sport that requires a high level of tactical, technical, and physical ability to succeed. In addition to practicing the basic skills mentioned above, components of physical fitness are also essential for football players—for example, dribbling past an opponent, moving quickly and changing direction to intercept the ball, sprinting to receive the ball, and tackling to win possession. This is consistent with Turgut et al. (2025) and Shamshuddin et al. (2020), who concluded that football requires exceptional physical exertion, including jumping, pivoting/turning, tackling, high-speed running, short-distance sprinting, high power output, and rapid changes in direction. This is also consistent with Erol (2022),

who stated that the main components of soccer-specific physical fitness include acceleration, repeated anaerobic sprint ability, and explosive muscle power.

Currently, various training methods are used to enhance physical fitness, such as plyometric training followed by sprinting or hurdle jumps followed by sprinting. These methods stimulate the muscular and nervous systems and provide variety in training. Therefore, complex training can be considered an effective approach for developing football players and improving multiple components of physical fitness by incorporating diverse training methods. Debnath & Kumar (2021) explained that complex training is a highly effective form of exercise combining plyometric training and resistance training, which is especially beneficial for increasing athletes' muscular power. In addition, Choudhary et al. (2025) noted that complex training is widely used to increase strength, power, speed, agility, and jumping performance in athletes. This is also consistent with Nandakumar & Ramesh (2020), who reported that complex training is one method for developing explosive power, an essential component of athletic performance. It is widely used across many sports. Moreover, Yang et al. (2025) concluded that in modern football, the combination of technique and physical fitness is a crucial factor in developing athletic performance (Sun et al., 2025). To effectively design an exercise program that also supports psychological benefits, enjoyment is an important consideration. Exercise that is fun and satisfying can help prevent boredom (Seelamad, 2014).

For these reasons, the researcher was interested in applying a complex training model in football. Football requires the integration of various skills and physical fitness components. Currently, the football teams at Surindra Rajabhat University primarily focus on tactical patterns and playing strategies, with limited emphasis on specialized training to enhance physical fitness. The researcher believes that implementing this complex training program may positively affect resting heart rate, speed, leg strength, flexibility, and leg muscle power in football players. By using more diverse training modalities, athletes may significantly enhance their physical capabilities, providing a competitive advantage. Furthermore, the findings may serve as a valuable resource for further study and can be practically applied to benefit football athletes at all levels.

2. Materials and methods

2.1 Population

The population in this study comprised 60 male university football players from Surindra Rajabhat University.

2.2 Sample

The sample consisted of 30 male football players from Surindra Rajabhat University who participated in the 48th Thailand University Games, selected using purposive sampling.

2.3 Inclusion Criteria

2.3.1 Being a male football player at Surindra Rajabhat University who participated in the 48th Thailand University Games.

2.3.2 Having no history of, and not currently experiencing, severe or chronic injuries.

2.3.3 Voluntary participation and provision of written informed consent.

2.4 Exclusion Criteria

2.4.1 Any injury or condition that prevents participation, including injuries to the legs, ligaments, or joints sustained during training or due to accidents.

2.4.2 Having a serious communicable disease.

2.5 Research Instruments

2.5.1 The Complex Training Program (Wicharn, 2019) (Cronbach's $\alpha = 0.74$) consisted of:

- 1) 30-meter sprint.
- 2) Box jumps followed by a sprint, a slide, and another sprint.
- 3) High-knee jump run over hurdles, followed by a sprint.
- 4) High-knee run over hurdles, followed by a sprint.
- 5) High-knee jumps onto and off a box, followed by a forward-to-backward run.
- 6) Alternating step-ups on a box, followed by a lateral shuffle around cones.
- 7) High knees in place, followed by a W-drill run.
- 8) Single-leg high-knee hops in and out of a circle, followed by a square run.

2.5.2 Leg-strength dynamometer

2.5.3 Sit-and-reach test

2.5.4 Standing long jump test

2.5.5 Stethoscope

2.5.6 50-meter sprint test

2.5.7 Weighing scale

2.5.8 Stadiometer

2.5.9 Stopwatch

2.5.10 Whistle

2.5.11 Data recording form

2.6 Procedure

This study employed a quasi-experimental design with repeated measures. The study was approved by the Surindra Rajabhat University Institutional Review Board (approval no. HE 642011).

2.6.1 The researcher submitted a formal letter to the Dean of the Faculty of Education, Surindra Rajabhat University, requesting permission to conduct the study and use facilities for data collection.

2.6.2 The researcher explained the objectives, procedures, duration, complex training program, and regular football training program to the participants and emphasized strict adherence to the instructions. The researcher also explained participants' rights and benefits, including confidentiality, the right to accept or decline participation, and the freedom to decide whether to take part.

2.6.3 The participants completed a 50-meter sprint test to assess speed, and sprint times were recorded.

2.6.4 Participants were ranked from 1 to 30 based on sprint time, from the lowest (fastest) to the highest (slowest).

2.6.5 Participants were assigned to two groups ($n = 15$ each) using a matching method. Based on the recorded sprint times (seconds), participants were ordered from the lowest (fastest) to the highest (slowest). Individuals with similar times were paired (matched subjects), and each member of the pair was allocated to a different group. This process was repeated until each group had 15 participants.

2.6.6 One representative from each group drew lots to determine group assignment. Lot no. 1 was designated as the control group (regular football training program), and lot no. 2 was designated as the experimental group (regular football training program plus the complex training program).

2.6.7 After being briefed on the testing procedures, the participants completed the pre-test. Measurements included body weight, height, resting heart rate, speed, leg strength, flexibility, and leg muscle power.

2.6.8 Training was conducted on Mondays, Wednesdays, and Fridays for 6 weeks, 2 hours per day (4:30 PM–6:30 PM). The control group followed the regular football training program, whereas the experimental group followed the regular football training program combined with the complex training program. Post-tests were conducted after Week 4 and again after Week 6 using the same testing procedures as the pre-test.

2.6.9 All results were recorded for subsequent statistical analysis.

3. Results

As shown in Table 1, the control group had a mean body weight of 67.67 ± 6.70 kg and a mean height of 171.67 ± 4.75 cm. The experimental group had a mean body weight of 68.27 ± 6.86 kg and a mean height of 174.13 ± 4.47 cm.

Table 1. General characteristics of the participants

Group	Weight		Height	
	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Control Group	67.67	6.70	171.67	4.75
Experimental Group	68.27	6.86	174.13	4.47

As shown in Table 2, within the experimental group, complex training resulted in statistically significant changes ($p < 0.05$) in resting heart rate, flexibility, and power when comparing pre-training, after 4 weeks of training, and after 6 weeks of training. No statistically significant changes ($p > 0.05$) were observed for speed or leg strength.

Therefore, Tukey's post hoc test was used to conduct pairwise comparisons for resting heart rate, flexibility, and power across the three time points (pre-training, Week 4, and Week 6).

Table 2. Comparison of the effects of complex training on resting heart rate, speed, leg strength, flexibility, and power in male football players at Surindra Rajabhat University within the experimental group (pre-training, Week 4, and Week 6)

List	SS	df	MS	F	Sig
Resting heart rate					
Between Groups	336.178	2	168.089	9.337*	0.000
Within Groups	756.133	42	18.003		
Total	1092.311	44			
Speed					
Between Groups	0.250	2	0.125	0.517	0.600
Within Groups	10.174	42	0.242		
Total	10.425	44			
Legs Strength					
Between Groups	0.637	2	0.318	1.356	0.269
Within Groups	9.868	42	0.235		
Total	10.505	44			
Flexibility					
Between Groups	301.733	2	150.867	28.153*	0.000
Within Groups	225.067	42	5.359		
Total	526.800	44			
Power					
Between Groups	645.378	2	322.689	40.871*	0.000
Within Groups	331.600	42	7.895		
Total	976.978	44			

*p-value < 0.05

As shown in Table 3, Tukey's pairwise comparisons for resting heart rate within the experimental group indicated statistically significant differences ($p < 0.05$) between Week 4 and Week 6 and between pre-training and Week 6.

Table 3. Results of Tukey's pairwise comparisons for resting heart rate within the experimental group (pre-training, Week 4, and Week 6)

Testing period	Mean Difference	Sig
Pre-training and Week 4	2.800	0.180
Week 4 and Week 6	3.867*	0.043
Pre-training and Week 6	6.667*	0.000

*p-value < 0.05

As shown in Table 4, Tukey's pairwise comparisons for flexibility within the experimental group indicated statistically significant differences ($p < 0.05$) between pre-training and Week 4, between Week 4 and Week 6, and between pre-training and Week 6.

Table 4. Results of Tukey's pairwise comparisons for flexibility within the experimental group (pre-training, Week 4, and Week 6)

Testing period	Mean Difference	Sig
Pre-training and Week 4	-2.867*	0.004
Week 4 and Week 6	-3.467*	0.001
Pre-training and Week 6	-6.333*	0.000

* p -value < 0.05

As shown in Table 5, Tukey's pairwise comparisons for power within the experimental group indicated statistically significant differences ($p < 0.05$) between pre-training and Week 4, between Week 4 and Week 6, and between pre-training and Week 6.

Table 5. Results of Tukey's pairwise comparisons for power within the experimental group (pre-training, Week 4, and Week 6)

Testing period	Mean Difference	Sig
Pre-training and Week 4	-5.000*	0.000
Week 4 and Week 6	-4.267*	0.000
Pre-training and Week 6	-9.267*	0.000

* p -value < 0.05

4. Discussion

The objective of this study was to compare changes in physical performance variables within the experimental group at three points in time: pre-training, after 4 weeks of training, and after 6 weeks of training.

4.1 Resting heart rate

The results showed that within the experimental group, resting heart rate improved significantly after Week 6, indicating a time-dependent training adaptation between Week 4 and Week 6 and between pre-training and Week 6. This suggests that the complex training program influenced participants' resting heart rate. A possible explanation is that the heart muscle requires a sufficiently long period of regular exercise to adapt, leading to a lower resting heart rate. For example, the resting heart rate in the general population is typically around 70 beats per minute, whereas individuals who exercise regularly often show values around 60 beats per minute. This indicates that the heart muscle has become stronger and more efficient at pumping blood throughout the body. In the present study, the training stimulus may have

increased cardiac efficiency and supported recovery. This is supported by Moges et al. (2024), who summarized evidence that endurance athletes training at low and moderate intensity experience positive changes in blood composition and improved heart rate recovery. In addition, Lin et al. (2022) reported that higher-intensity resistance training can improve resting heart rate and heart rate variability (HRV). Similarly, Kuswoyo & Lahinda (2020). found that high-intensity training significantly improved physiological variables, including VO2max and resting heart rate, in university-level football players.

4.2 Flexibility

The findings showed that within the experimental group, flexibility improved significantly after Week 6, indicating a time-dependent training adaptation between pre-training and Week 4, between Week 4 and Week 6, and between pre-training and Week 6. This suggests that the training program contributed to improved flexibility. Flexibility refers to the ability of the body and joints to move through a full range of motion and is an important component of physical fitness. Improving flexibility typically requires regular stretching of ligaments, joint capsules, and fascia surrounding the muscles. In this study, the experimental group performed stretching exercises before and after each training session, which may explain the improvement observed. This is supported by Pranoto et al. (2025), who found that regular exercise can substantially increase flexibility, especially in athletes, and that athletes respond better to training programs than non-athletes. Similarly, Ihsan et al. (2023) reported that stretching techniques are necessary for improving flexibility and may help prevent sports injuries. Esposito et al. (2025) also concluded that resistance training may increase flexibility while simultaneously enhancing athletes' psychological and physical self-awareness more effectively than traditional stretching.

4.3 Power

The results showed that within the experimental group, leg muscle power improved significantly after Week 6, indicating a time-dependent training adaptation between pre-training and Week 4, between Week 4 and Week 6, and between pre-training and Week 6. This suggests that the training program influenced leg muscle power. A possible explanation is that the complex training program included several exercises designed to develop power (e.g., multiple forms of jumping). Leg muscle power is produced by combining strength and speed during muscle contraction and relaxation, which is essential for athletes who require fast and forceful movements. As lower-limb muscles become stronger and more explosive, power performance can improve. In addition, the program likely targeted the muscle groups commonly used in football, contributing to the observed changes. This is supported by Apriantono et al. (2023), who suggested that a 10-week sprint training program can improve athletes' physical fitness, including VO2max, agility, and vertical jump power in futsal athletes. Krzysztofik et al. (2024) summarized evidence that complex training (CT) performed at moderate to high intensity for 6 weeks can increase jumping performance, running speed, and maximal lower-body strength in football players. Likewise, Kyung & Park (2024) reported that a 6-week complex training (CPT) program was more effective than compound training (CT) in increasing strength and jump power. Xu et al. (2025) also summarized findings that an 8-week combined strength and plyometric training program is more effective than strength training alone for improving jumping ability in high-level athletes, particularly males, and suggested that plyometric formats

can be incorporated into pre-competition training cycles. Thomas et al. (2021) similarly reported that the complex training group showed a slightly better and statistically significant improvement in jump power. In addition, Hu et al. (2025) concluded that an 8-week complex training program produced greater improvements in leg muscle power, acceleration, and agility than traditional resistance training in female badminton players. Chantra (2024) also reported that the S.A.P. complex training program is effective in enhancing speed, agility, and leg power among volleyball athletes.

4.4 Speed

The results showed that within the experimental group, speed did not differ significantly across pre-training, Week 4, and Week 6. This may be because the program emphasized movements that are similar to football actions (e.g., starting, accelerating, decelerating, changing direction, and re-accelerating), which require a foundation of strength, power, and agility. Although the statistical analysis did not show a significant difference, the mean sprint time in the experimental group showed a decreasing trend (i.e., faster performance). Therefore, it is possible that a longer training duration and/or higher intensity could produce statistically significant changes. This is supported by Sun et al. (2025), who summarized evidence that SAQ training improves speed performance. Choudhary et al. (2025) also stated that complex training (CT) is an effective method for developing explosive strength, speed, and agility, especially in young athletes. Furthermore, Naveen et al. (2024) concluded that complex training can enhance several abilities in intermediate-skilled football players, including agility, speed, power, and kicking accuracy. Nugroho et al. (2024) also reported that complex training results in greater improvements in speed than plyometric training. In addition, Ceviz et al. (2025) found that a combined endurance and resistance training program lasting 12 weeks can significantly improve aerobic endurance and speed in male U-17 football players. Similarly, Purnamasari et al. (2025) summarized evidence that contrast training can significantly increase speed and lower-body strength in futsal athletes.

4.5 Leg Strength

The results showed that within the experimental group, leg strength did not differ significantly across pre-training, Week 4, and Week 6. One possible explanation is that strength refers to the ability of muscles to generate tension and exert force against external or internal resistance. Maximum strength depends on the biomechanics of the movement, the muscle groups involved, the number of muscle contractions, and the intensity of neural impulses that stimulate muscle activation. Although no statistically significant difference was observed, the mean values showed an upward trend, which may reflect that the program emphasized lower-limb training through a combination of training formats. It is possible that expanding the training methodology (e.g., increasing variety and/or adjusting the load and intensity) could produce clearer strength adaptations. This is supported by Nugroho et al. (2023), who concluded that resistance training was more effective than free-weight training for improving leg strength in athletes with high leg power, whereas free-weight training was more effective for athletes with low leg power. Therefore, strength training programs may need to consider an athlete's baseline level of leg power. In addition, Wang et al. (2023) concluded that complex training can improve maximal strength more effectively than plyometric training. Sabillah et al. (2022) also reported that Side-to-Side Box Shuffle training may be more

effective for athletes with low leg muscle strength, whereas Box Jump training may be more effective for athletes with high leg muscle strength. Finally, Zhai & Qin (2024) suggested that complex training (CT) may be valuable for developing performance variables in amateur futsal players and may offer advantages over resistance training (RT) for improving strength and muscle power.

5. Conclusion and suggestions

5.1 Conclusion

The results indicate that a complex training program can help improve resting heart rate, flexibility, and leg muscle power in football players. Therefore, complex training can be incorporated into football training to enhance these components of physical fitness.

5.2 Suggestions for future research

5.2.1 Future studies should compare complex training with other training methods to identify the most effective approach for improving football players' physical fitness.

5.2.2 Future studies should diversify complex training formats (e.g., exercise selection, intensity, and progression) to further enhance physical fitness in football players and athletes in other similar sports.

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ปัจจัยที่มีผลต่อภาวะการมีงานทำของกลุ่มอาชีพส่งเสริมสุขภาพของประเทศไทยจำแนกตามเพศ
Factors Affecting the Employment Status of Health Promotion Professionals
in Thailand, Classified by Gender

รชต ตะนาวศรี^{1*}

Rachata Tanowsri^{1*}

¹คณะวิทยาศาสตร์การกีฬาและสุขภาพ มหาวิทยาลัยการกีฬาแห่งชาติ วิทยาเขตลำปาง จังหวัดลำปาง

¹Faculty of Sports and Health Science, Thailand National Sport University, Lampang Campus, Lampang Province

*Corresponding Author: Rachatasorou7@gmail.com

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บทคัดย่อ

การเปลี่ยนแปลงต่างๆ ในสังคมส่งผลกระทบต่อการทำงานของบุคลากรด้านสุขภาพ ซึ่งในการศึกษานี้ มีวัตถุประสงค์เพื่อศึกษาปัจจัยที่มีอิทธิพลต่อสถานะการจ้างงานของกลุ่มวิชาชีพส่งเสริมสุขภาพในประเทศไทย โดยจำแนกตามเพศ ข้อมูลที่ใช้เป็นข้อมูลทุติยภูมิจากโครงการสำรวจแรงงานของสำนักงานสถิติแห่งชาติ ไตรมาสที่ 4 (ตุลาคม-ธันวาคม) ปี 2565 กลุ่มตัวอย่างในการศึกษาประกอบด้วยบุคคลอายุ 15-60 ปี ที่ทำงานในกลุ่มส่งเสริมสุขภาพและตอบแบบสอบถามครบถ้วน จำนวน 1,704 คน วิเคราะห์ข้อมูลโดยใช้ค่าเฉลี่ยและส่วนเบี่ยงเบนมาตรฐาน และศึกษาผลกระทบของตัวแปรอิสระต่อตัวแปรตามโดยใช้การวิเคราะห์การถดถอยแบบโลจิสต์ ที่ระดับนัยสำคัญ 0.05 ผลการวิเคราะห์การถดถอยพบว่าคุณพบว่า เมื่อควบคุมตัวแปรอิสระอื่น ๆ แล้ว ตัวแปรที่ยังคงมีอิทธิพลต่อการจ้างงานของกลุ่มวิชาชีพส่งเสริมสุขภาพ ได้แก่ อายุ สถานภาพสมรส และระดับการศึกษา ตัวแปรอิสระทั้งหมดสามารถอธิบายความแปรปรวนของการจ้างงานในกลุ่มวิชาชีพส่งเสริมสุขภาพได้ร้อยละ 2.8 ($R^2 = 0.028$) ที่ระดับนัยสำคัญทางสถิติ 0.05 จากผลการศึกษาพบว่า ผู้เชี่ยวชาญด้านส่งเสริมสุขภาพมีอายุระหว่าง 30-52 ปี เห็นได้ชัดว่าอายุเป็นภาพสะท้อนของสถานภาพสมรส ประสบการณ์ในการทำงาน และระดับทักษะ ปรากฏว่าบุคคลที่สมรสแล้วมีสถานะทางอารมณ์และชีวิตส่วนตัวที่มั่นคง ซึ่งส่งผลกระทบต่อความรับผิดชอบในงาน โดยเฉพาะในภาคสุขภาพที่จำเป็นต้องใช้ความละเอียดอ่อนและการจัดการความกดดัน นอกจากนี้ การจ้างงานของบุคลากรด้านสุขภาพยังได้รับอิทธิพลจากระดับการศึกษาในหลากหลายรูปแบบ ส่งผลให้เกิดการจ้างงานและค่าจ้างที่เพิ่มขึ้น ประสบการณ์ ทักษะเฉพาะทาง และการสอดคล้องกับความต้องการขององค์กรและบุคคลมักเป็นปัจจัยกำหนดสำหรับการจ้างงานในภาคสุขภาพ เพื่อเพิ่มโอกาสในการทำงานสำหรับสตรีในอุตสาหกรรมสุขภาพ สถาบันการศึกษาควรสร้างหลักสูตรที่ให้ความสำคัญกับการเรียนรู้ตลอดชีวิต ส่งเสริมการศึกษาและการฝึกอบรมด้านสุขภาพ และแก้ไขกฎหมาย รัฐบาลควรจัดตั้งโครงการเพื่อจูงใจให้แรงงานกลับภูมิลำเนา เพื่อประหยัดค่าใช้จ่ายและปรับปรุงความสัมพันธ์ในครอบครัว

คำสำคัญ: ภาวะการมีงานทำ, กลุ่มอาชีพส่งเสริมสุขภาพ, เพศ

Abstract

Various societal changes have had an impact on the employment of healthcare workers. The goal of this study was to examine factors influencing the employment status of health promotion professionals in Thailand, categorized by gender. The statistics were secondary data from the National Statistical Office's

Employment Status Survey, 4th quarter (October–December) 2022. The study sample consisted of 1,704 individuals aged 15–60 years who worked in health promotion occupations and completed the questionnaire. Data were analyzed using descriptive analysis (mean and standard deviation), and the effect of independent variables on the dependent variable were examined using Logit Regression Analysis at a significance level of 0.05. The results of multivariate logistic regression analysis showed that, after controlling for other factors, age, marital status, and educational level remained significant predictors of employment among health promotion professionals. All independent variables jointly explained 2.8% of the variation in employment status among health promotion professionals ($R^2 = 0.028$) at 0.05 statistical significance level. According to the findings, most health promotion professionals were between 30 and 52 years of age. Married individuals tend to have greater emotional and personal stability, which may influence job responsibility, particularly in the health sector where sensitivity and stress management are essential. Additionally, employment among health promotion professionals is influenced by educational attainment in a variety of ways, leading to higher employment opportunities and income. Experience, specialized skills, and alignment with organization needs are often key determinants of employment in the health sector. To enhance career prospects for women in the health industry, educational institutions should develop curricula that emphasize lifelong learning and promote health-related education and training, alongside legislation reform. The government should also implement initiatives to encourage workers to return to their home regions, thereby reducing living costs and strengthening family relationships.

Keywords: The employment status, Health promotion professional, Gender

1. Introduction

Thailand's healthcare system faces unprecedented challenges as the country navigates complex environmental changes, including economic fluctuations, evolving global trade regulations, transformative social and public health policies, and significant demographic transitions (Leerapan et al., 2021). These multifaceted pressures have fundamentally altered the landscape of healthcare employment, creating challenges for health promotion professionals, who serve as the foundation of preventive healthcare services. Despite strategic planning initiatives by the Ministry of Public Health to address workforce development needs, the intersection of these environmental changes continues to significantly impact health personnel employment patterns, necessitating a comprehensive analysis of the factors that influence career outcomes in this critical sector.

The health promotion profession encompasses a diverse range of occupations dedicated to disease prevention, lifestyle advocacy, and community health enhancement, including nutritionists, health coaches, physical education instructors, sports scientists, and organizational health consultants (World Health Organization, 2024). These professionals require advanced competencies in project planning and management, health promotion program implementation, effective communication strategies, inter-agency collaboration, data analysis, and evidence-based program evaluation (Owolabi et al., 2024). The complexity

of these roles has evolved considerably in response to Thailand's demographic transition toward an aging society, in which over 20 % of the population is projected to be elderly by 2030, fundamentally altering healthcare service demands and workforce dynamics within the Universal Health Coverage framework.

Thailand's healthcare labor market operates within a distinctive dual structure characterized by public sector positions offering job security but limited advancement opportunities, contrasted with private sector roles providing enhanced remuneration but greater employment uncertainty (Santric Milicevic et al., 2024). This structural complexity is exacerbated by persistent regional disparities, with urban centers concentrating on advanced healthcare services while rural areas experience chronic shortages of qualified health professionals. The COVID-19 pandemic has further disrupted traditional employment patterns, with health promotion professionals facing unique challenges as preventive services were deprioritized during crisis response phases (Chen et al., 2023).

Recent international research has illuminated critical dimensions of healthcare workforce dynamics that provide essential context for understanding employment patterns in health promotion. Marcus et al. (2024) demonstrated through comprehensive European network analysis that multi-age workforce management significantly influences employment outcomes in health sectors, with workers aged 30-52 years exhibiting optimal performance levels due to balanced experience and adaptability. Similarly, Hamouche & Parent-Lamarche (2023) established that age diversity affects job performance in healthcare settings, revealing complex interactions between demographic characteristics and professional effectiveness. Gender disparities in healthcare employment have been extensively documented, with Adams et al. (2022) conducting longitudinal analysis that revealed persistent gender gaps in healthcare workforce retention, particularly affecting advancement opportunities for women in health promotion roles despite their numerical predominance in the field.

Within the Thai context, empirical evidence suggests significant employment disparities between male and female health promotion graduates, with institutional data from health sciences programs indicating higher employment rates among male graduates while simultaneously revealing that over 60 % of employed male graduates work outside their specialized fields (Jackson et al., 2022). These patterns reflect broader systemic issues within Thailand's health promotion workforce, where gender differences fundamentally influence employment outcomes despite women's substantial representation in health sciences education. The intersection of educational attainment and healthcare employment has been further complicated by Thailand's rapid expansion of health sciences education programs, resulting in supply-demand mismatches across various health specialties (Fletcher et al., 2024).

Contemporary research has identified critical knowledge gaps regarding the specific mechanisms through which demographic factors influence health promotion employment in middle-income countries. Davis & Johnson (2021) revealed that health promotion professionals face unique work-life balance challenges, with marital status and family responsibilities interacting differentially with professional demands based on gender. However, comprehensive analyses using nationally representative data to examine these relationships within the Thai healthcare system remain absent from the literature. Furthermore, while international studies have examined gender effects broadly across healthcare sectors,

focused investigation of health promotion occupations within Thailand's unique socio-economic context remains limited.

This study addresses these critical knowledge gaps through innovative methodological and theoretical approaches. The research employs nationally representative data from Thailand's National Statistical Office Employment Status Survey (2022), providing unprecedented statistical power to examine post-pandemic health promotion employment patterns. The gender-disaggregated analysis represents a methodological advancement in Thai health workforce research, specifically targeting health promotion professionals whose roles are characterized by distinct demographic patterns and employment challenges. Theoretically, this investigation integrates Gender-Role Theory, Gender Equality Theory, Sex Segregation in Labor Market Theory, and Social Justice and Health Theory to provide a comprehensive analytical framework for understanding how demographic characteristics interact with labor market structures to create differential employment outcomes.

The research is positioned to contribute significantly to academic knowledge through several dimensions. First, it will provide empirical evidence on gender-employment interactions within health promotion, offering the first comprehensive analysis of how age, marital status, and educational level interact with gender to influence employment outcomes in a middle-income country context (Rodriguez et al., 2024). Second, the methodological approach establishes a template for similar analyses across ASEAN countries facing comparable healthcare workforce challenges. Third, unlike purely academic investigations, this research directly addresses workforce planning needs identified by Thai health authorities, ensuring immediate policy relevance and potential implementation impact (Turner & Clark, 2020). Finally, the synthesis of multiple theoretical frameworks provides a comprehensive analytical model adaptable for health workforce research in similar socio-economic contexts, advancing both theoretical understanding and practical applications in healthcare human resources management (Olatoye et al., 2024). Accordingly, this study examines demographic characteristics hypothesized to influence employment status among health promotion professionals in Thailand, categorized by gender, using the conceptual framework presented in Figure 1.

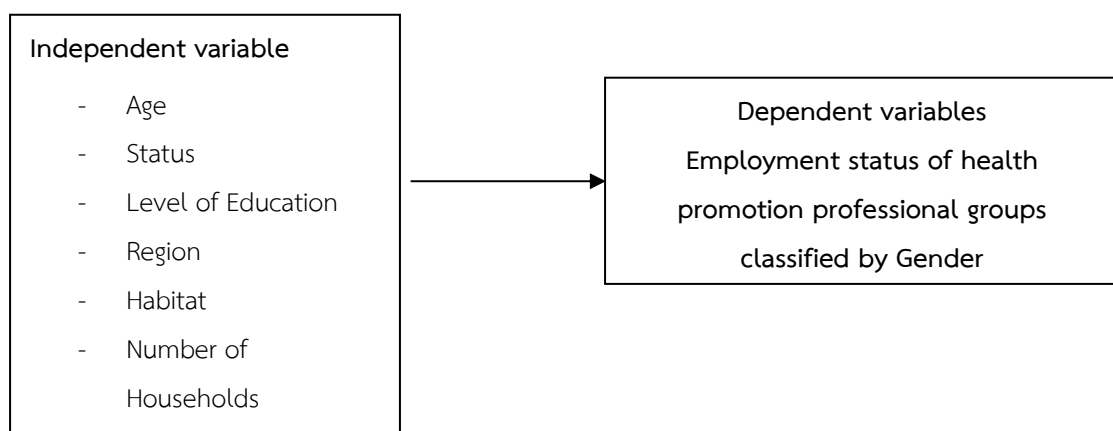


Figure 1. The conceptual framework

2. Methodology

2.1 Source of information

The National Statistical Office's "Employment Status Survey 4th Quarter (October-December) 2022" was utilized in this study to estimate the quantity and characteristics of the domestic work force.

2.2 Population and sampling

Normalized weight, a weighting technique used by the researcher to make the population size to be examined equal to the population sampled in the survey but distributed according to significant demographic features similar to the population of Thailand, was applied to the data. Thus, only individuals in the health promotion occupation group aged 15-59 years were selected. Only respondents who completed all survey items independently were included. As a result, the final analytical sample consisted of 1,704 individuals.

2.3 Methods

The research entitled "Factors Affecting Employment Status of Health Promotion Professional in Thailand Classified by Gender" has several limitations. Because the study employed secondary data from the nationwide Employment Status Survey, Fourth Quarter (October-December) 2022, collected by the National Statistical Office, the data represents a cross-sectional snapshot in time. Therefore, while these data can demonstrate associations between various factors related to employment status among health promotion professionals in Thailand by gender, they cannot establish causal relationships. Because data were obtained about two years ago, a temporal lag may exist, and current conditions may differ from those observed. Furthermore, the data used in this study was derived from an existing survey instrument; therefore, the researcher had no control over questionnaire design or variable selection. Consequently, some variables that may influence employment status among health promotion professionals by gender were not available for analysis.

This study received ethical approval for human research from Boromarajonani College of Nursing, Lampang (Approval No. E2567-046). The researcher adhered to data protection protocols, ensuring that the data were securely managed and not disclosed to third parties. In reporting the findings, only aggregated results are presented, and no personally identifiable information is disclosed.

2.4 Data Analysis

This study utilized secondary data from the National Statistical Office's Employment Status Survey, Fourth Quarter 2022, comprising 1,704 health promotion professionals aged 15-60 years. The dataset provides nationally representative post-pandemic employment dynamics within Thailand's healthcare sector, offering comprehensive demographic and employment characteristics essential for examining factors influencing career outcomes among health promotion professionals.

The selection of independent variables was grounded in established theoretical frameworks from labor economics and healthcare workforce research. Age was categorized into four theoretically meaningful groups reflecting career development stages: 15-29 years (early career establishment), 30-39 years (professional consolidation), 40-49 years (peak productivity), and 50-60 years (pre-retirement).

transition), aligning with life-course employment theories and empirical evidence from healthcare professions (Marcus et al., 2024). Marital status was operationalized as a binary variable distinguishing married individuals from unmarried persons to capture family responsibility effects on employment decisions, representing a critical demographic marker intersecting with gender roles and employment stability in healthcare contexts (Davis & Johnson, 2021). Educational attainment encompassed four hierarchical categories including below bachelor's degree, bachelor's degree, master's degree, and doctoral degree, reflecting human capital theory's emphasis on education as investment in productivity-enhancing skills particularly relevant to health promotion occupations requiring specialized knowledge and professional certification (Fletcher et al., 2024). Geographical region followed Thailand's five administrative divisions (Central, Northern, Northeastern, Southern, and Bangkok Metropolitan), capturing spatial heterogeneity in healthcare infrastructure and employment opportunities, while residential habitat distinguished urban and rural residence to reflect differential access to healthcare employment and infrastructure development. Household composition, measured as the number of household members, represented family structure complexity and potential economic dependencies influencing employment decisions.

Logistic regression analysis was employed to examine relationships between demographic characteristics and binary employment outcomes, proceeding through bivariate examination of individual effects followed by multivariate modeling estimating simultaneous effects while controlling confounding relationships. The analytical approach was selected based on the dichotomous nature of the dependent variable and the need to estimate probability relationships while controlling for multiple variables simultaneously. Data quality assessment revealed 3.7% incomplete cases with Little's Missing Completely at Random test confirming random missingness ($\chi^2 = 47.23$, $df = 52$, $p = 0.673$), supporting listwise deletion approaches. Outlier detection identified 12 cases (0.7%) with extreme residuals; however, sensitivity analyses confirmed negligible impact on parameter estimates, supporting retention of all cases to maintain representativeness and statistical power.

Multicollinearity diagnostic assessment demonstrated acceptable inter-variable relationships with Variance Inflation Factors remaining well within conventional limits: Age (1.23), Marital Status (1.18), Educational Attainment (1.45), Geographical Region (2.31), Residential Habitat (1.87), and Household Composition (1.52), all substantially below the threshold of 5.0. Tolerance values ranged from 0.43 to 0.85, exceeding the critical criterion of 0.20, while condition indices reached a maximum of 12.84, remaining well below the concerning threshold of 30. Pairwise correlation analysis revealed moderate inter-variable associations, with the strongest correlation between residential habitat and geographical region ($r = 0.34$, $p < 0.001$), reflecting expected urban-rural geographical clustering without reaching levels problematic for regression analysis. These diagnostic results collectively indicated absence of multicollinearity problems that could compromise parameter estimation or interpretation.

Model validation employed goodness-of-fit assessment through the Hosmer-Lemeshow test, which yielded $\chi^2 = 8.34$ (df = 8, $p = 0.401$), indicating adequate model fit. The non-significant result ($p > 0.05$) supports the null hypothesis that the model appropriately represents the relationship between independent variables and employment status, confirming that observed and predicted frequencies do not differ significantly across deciles of predicted probabilities. This finding provides crucial validation that model assumptions are satisfied and that parameter estimates reliably reflect the underlying relationships in the data. Robustness assessment through cross-validation using 70%-30% sample splitting demonstrated stable model performance, while bootstrap resampling with 1,000 iterations confirmed coefficient stability with variations less than 2% from original estimates. Sensitivity analyses across alternative model specifications showed parameter stability with coefficient changes below 5%, supporting the reliability and generalizability of the findings.

All statistical analyses were conducted using SPSS program with additional validation performed using R statistical software to ensure computational accuracy and result reproducibility. Statistical significance was evaluated at $\alpha = 0.05$ throughout all analyses, with effect sizes interpreted according to established conventions for logistic regression analysis in healthcare workforce research.

4.5 Limitations

The utilization of secondary data from the National Statistical Office's Employment Status Survey, while providing nationally representative scope and statistical power, imposed inherent methodological constraints on variable selection and analytical depth. As secondary data users, the researchers were unable to modify the original survey instrument design to incorporate additional variables deemed theoretically relevant to employment outcomes among health promotion professionals. This limitation is characteristic of secondary data analysis, where researchers must work within the constraints of pre-existing data collection frameworks designed for broader labor market surveillance rather than specialized healthcare workforce research.

Consequently, several potentially influential variables that could significantly impact employment status among health promotion professionals were unavailable for analysis. These omitted variables include field of study specialization, which may differentiate employment prospects between graduates of public health, nutrition, exercise science, or health education programs. Practical experience indicators such as internship completion, clinical rotations, or community-based practice exposure were not captured in the original survey design, despite their established importance in healthcare career preparation and employer preferences. Professional development factors including participation in continuing education programs, specialized certifications, short-term training workshops, or attendance at professional conferences could not be examined, limiting understanding of how ongoing skill enhancement influences career outcomes.

Language competency, particularly English proficiency and other foreign language skills increasingly valued in Thailand's globalized healthcare environment, was not measured in the dataset. Similarly, technological competencies, research experience, publication records, and professional network characteristics, all potentially significant determinants of employment success in contemporary health promotion practice, were beyond the scope of the original survey instrument. Geographic mobility preferences, salary expectations, work-life balance priorities, and career advancement aspirations, which may influence employment decisions and outcomes, were also unavailable for analysis.

These limitations inherent to secondary data analysis restrict the comprehensiveness of the explanatory model and may contribute to the moderate explanatory power observed in the study. While the available demographic variables provide valuable insights into employment patterns, the omission of profession-specific competencies, experiential factors, and individual preferences likely results in an underestimation of the true complexity of employment determination among health promotion professionals. Future research employing primary data collection specifically designed for healthcare workforce analysis could address these limitations by incorporating comprehensive measures of professional preparation, competency development, and career decision-making factors relevant to health promotion specialists in Thailand's evolving healthcare landscape.

3. Results

This section presents the study findings, which are divided into two parts: an analysis of general characteristics and an analysis of the effects of independent variables on the employment status of health promotion professionals classified by gender.

3.1 General data characteristics

The respondents' general characteristics were investigated. There were 1,704 individuals, with an average age of 41 years; 80.7% were female, while 19.3% were male. More than half of the respondents (52.2%) were married, while 39.3% were single and 8.5% were widowed, divorced, or separated. The majority of respondents (79%) held a bachelor's or higher degree, followed by secondary school (12.7%), associate degree (4.2%), elementary school (2.4%), and a lower percentage than primary school (1.7%). The Central area had the highest proportion of responders (30.8%), followed by the Northeast (28.4%), the North (21%), the South (14%), and Bangkok (5.8%). The majority of them (73.9%) lived in municipal areas, while 26.1% lived elsewhere. The typical home size is three individuals, as shown in Table 1.

Table 1. General Characteristics of Respondents (n=1,704)

General information	Numbers (percent)
1. Age (mean±SD)	41±11
2. Gender	
Male	329 (19.3%)
Female	1,375 (80.7%)
3. Status	
Single	670 (39.3%)
Married	890 (52.2%)
Widowed/Divorced/Separated	144 (8.5%)
4. Level of Education	
Less than primary school	29 (1.7%)
Primary education	41 (2.4%)
High school education	216 (12.7%)
Diploma	71 (4.2%)
Bachelor's degree or postgraduate degree	1,347 (79.0%)
5. Region	
Bangkok and surrounding areas	99 (5.8%)
Central	524 (30.8%)
Northern	359 (21.0%)
Northeast	484 (28.4%)
Southern	238 (14.0%)
6. Residential areas	
Inside the municipality	1,260 (73.9%)
Outside the municipal area	444 (26.1%)
7. Number of Households members (mean±SD)	3±1
1-2 persons	890 (52.2%)
3-4 persons	616 (36.2%)
From 5 people or more	198 (11.6%)

The effects of independent variables on the employment status of health promotion professionals classified by gender were examined using logistic regression analysis. The analysis was conducted in two stages: bivariate and multivariate analyses, as detailed below.

3.1.1 The findings of the bivariate study utilizing basic regression analysis revealed that:

1) Age: Older women had a lower likelihood of employment than younger women (odds ratio = 0.98). The connection was statistically significant at the 0.05 level. As a result, it was determined that age had an impact on employment in health promotion jobs.

2) Marital status: Married women had a lower likelihood of employment compared with single women (odds ratio = 0.89), although this association was not statistically significant. In contrast, women who were married (widowed, divorced, or separated) had a 2.19-fold higher likelihood of employment than single women, and this relationship was statistically significant at the 0.05 level. As a result, we may infer that marital status has an impact on employment in the health promotion professional category.

3) Educational level: Women with a secondary/associate degree had a 1.51-fold higher chance of being employed than women with a primary education level or lower, and women with a bachelor's degree or higher had a 2.11-fold higher chance of being employed than women with a primary education level or lower, which was statistically significant at the 0.05 level. As a result, a greater degree of education increases the likelihood of employment in the health promotion professional category compared to a lower level of education.

4) Region: Women living in the Central, Northern, and Southern regions had a higher chance of being employed than women living in Bangkok, 1.34, 1.24, and 1.50 times, respectively, whereas women living in the Northeastern region had a lower chance of being employed than women living in Bangkok, which was not statistically significant at the 0.05 level across all residential regions.

5) Residential area: Women living in municipal areas had a greater likelihood of being employed than women living outside of municipal areas, albeit this was not statistically significant at the 0.05 level. As a result, it was determined that residential areas were unrelated to employment among health promotion professionals.

6) Number of household members: Women with 1-2 household members had a 1.01-fold higher likelihood of employment than women with 5 or more household members, whereas women with 3-4 household members had a 0.89-fold lower chance of employment. The connection was not statistically significant at the 0.05 level. As a result, the number of household members had no relationship with employment among health promotion professionals.

3.1.2 After adjusting for other independent factors, the results of multivariate analysis using multiple regression demonstrated that age, marital status, and education level continued to have an impact on employment among health promotion professionals. As shown in Table 2, all independent factors explained 2.8% ($R^2 = 0.028$) of the variation in employment among health promotion professionals at a statistical significance level of 0.05, indicating that the current model captures only a modest portion of the factors determining employment outcomes in this professional category. as seen in Table 2.

Table 2. Independent variables affecting employment status of health promotion professionals classified by gender.

Variables	Univariate analysis		Multivariate analysis	
	OR (95%CI)	p-value	OR (95%CI)	p-value
1. Age	0.98 (0.97-0.99)	0.001***	0.97 (0.96-0.98)	0.001***
2. Status				
Single	1.00 (reference)		1.00 (reference)	
Married	0.89 (0.69-1.14)	0.353	1.26 (0.95-1.67)	0.108
Widowed/Divorced/Separated	2.19 (1.22-3.93)	0.008**	4.22 (2.24-7.94)	0.001***
3. Level of Education				
Less than primary school/ Primary education	1.00 (reference)		1.00 (reference)	
High school education/ Diploma	1.51 (0.85-2.67)	0.163	1.17 (0.63-2.17)	0.613
Bachelor's degree or postgraduate degree	2.11 (1.25-3.57)	0.005**	1.87 (1.06-3.29)	0.031*
4. Region				
Bangkok and surrounding areas	1.00 (reference)			
Central	1.34 (0.79-2.27)	0.272		
Northern	1.24 (0.72-2.14)	0.429		
Northeast	0.97 (0.58-1.63)	0.913		
Southern	1.50 (0.84-2.70)	0.173		
5. Residential areas				
Inside the municipality	1.01 (0.76-1.32)	0.969		
Outside the municipal area	1.00 (reference)			
6. Number of Households members				
1-2 persons	1.01 (0.68-1.49)	0.991		
3-4 persons	0.89 (0.59-1.34)	0.589		
For 5 people or more	1.00 (reference)			

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The limited explanatory power ($R^2 = 0.028$) reveals significant theoretical implications requiring expanded analytical frameworks. From Labor Market Theory perspective, the minimal variance explanation suggests that structural market forces including sectoral demand fluctuations, regional economic disparities, and institutional policies constitute primary employment determinants rather than individual demographic characteristics (Crompton, 2006; Leerapan et al., 2021). This finding indicates that

macro-economic conditions and healthcare policy transitions exert substantially greater influence on employment probability than personal attributes.

Gender-Role Theory perspectives suggest the model's limited performance reflects inadequate measurement of gendered employment processes operating beyond demographic categorization (Connell, 2005; Oakley, 2005). Traditional gender role expectations, occupational segregation patterns, and differential career socialization require sophisticated operationalization to capture their employment influence. Contemporary research demonstrates that gender disparities in healthcare employment reflect multifaceted organizational and cultural factors extending beyond demographic characteristics (Jackson et al., 2022; Olatoye et al., 2024), necessitating examination of workplace policies, organizational climates, and career development infrastructure. Social Justice and Health Theory frameworks indicate that unmeasured structural inequalities and systemic barriers significantly influence employment outcomes (World Health Organization, 2024). The minimal variance explanation suggests that institutional discrimination, unequal advancement opportunities, and differential treatment constitute significant unmeasured influences. Research by Santric Milicevic et al. (2024) demonstrates that healthcare workforce equity requires comprehensive assessment of organizational practices and systemic barriers affecting career opportunities across demographic groups.

The limited explanatory power also suggests that conventional education-based measures inadequately capture competency requirements for contemporary health promotion practice (Fletcher et al., 2024; Hamouche & Parent-Lamarche, 2023). Traditional educational categories may not reflect specialized skills, practical experience, and professional networks that increasingly determine employment success in evolving healthcare environments. Intersectionality perspectives indicate that employment determination operates through complex interactions between multiple characteristics that cannot be captured through additive demographic models (Davis & Johnson, 2021). Research by Marcus et al. (2024) demonstrates that multi-dimensional approaches reveal substantially different patterns than single-variable analyses, supporting more sophisticated analytical frameworks.

Future research should prioritize longitudinal designs examining career trajectories and mixed-methods approaches combining quantitative analysis with qualitative exploration of employment decision-making processes (Turner & Clark, 2020). Policy interventions must extend beyond demographic considerations to address structural labor market conditions, workplace equity issues, and professional development infrastructure (World Health Organization, 2023). Healthcare organizations should examine employment practices and workplace cultures to identify systemic factors influencing employment outcomes differentially across demographic groups (Owolabi et al., 2024).

4. Discussion

The demographic characteristics of respondents revealed an average age of 41 years, a predominantly female workforce, bachelor's degree or higher educational attainment, married status, central region residence, and urban municipality location, with an average household size of three persons.

These characteristics provide important context for interpreting employment patterns within Thailand's health promotion workforce and enable meaningful comparison with international healthcare workforce studies.

The finding that younger age significantly increases employment likelihood among health promotion professionals presents a complex pattern that both aligns with and diverges from established healthcare workforce research. This result supports the theoretical framework proposed by Marcus et al. (2024), who demonstrated through European network analysis that age serves as a critical determinant of employment outcomes in healthcare sectors, with optimal employment rates occurring among workers aged 30–39 years. However, our findings reveal a more pronounced age gradient, with employment probability decreasing more sharply with advancing age than reported in Marcus et al.'s multi-country analysis. The age-employment relationship observed in this study contradicts findings from Hamouche & Parent-Lamarche (2023), who identified workers aged 30–52 as demonstrating optimal employment performance due to balanced experience and adaptability. While their research suggested a plateau effect across middle-age categories, our results indicate a more linear decline in employment probability with increasing age, suggesting that Thailand's health promotion labor market may exhibit different age-related employment dynamics compared to developed country contexts examined in their telework study.

Critical interpretation of these findings suggests that the preference for younger workers in Thailand's health promotion sector may reflect several underlying mechanisms. From a Human Capital Theory perspective, the age-employment gradient could indicate rapid technological advancement and evolving practice standards that favor recent graduates with contemporary training over experienced professionals whose skills may be perceived as outdated (Fletcher et al., 2024). However, this interpretation conflicts with established evidence that experience enhances healthcare professional effectiveness, suggesting that employer preferences may be influenced by factors beyond objective competency assessment. Alternative explanations drawing from Labor Market Segmentation Theory suggest that age discrimination may operate through informal hiring practices that systematically disadvantage older applicants despite their potentially superior experience and professional networks. This interpretation aligns with international research documenting age-related employment barriers in healthcare sectors, though it contradicts policy objectives of maximizing human resource utilization in Thailand's expanding healthcare system (Leerapan et al., 2021).

The finding that widowed, divorced, or separated individuals demonstrate higher employment probability than single persons presents a counterintuitive pattern that challenges conventional assumptions about family status and employment relationships. This result contradicts expectations derived from Gender-Role Theory (Connell, 2005), which typically predicts that family responsibilities, particularly for women, create employment barriers through competing time demands and reduced workplace flexibility. Comparison with international research reveals mixed support for this finding, as Davis & Johnson (2021) found that health promotion professionals with complex family situations faced unique work-life balance challenges, which would theoretically reduce rather than enhance employment probability.

However, their research focused primarily on job satisfaction rather than employment obtainment, limiting direct comparability with our findings.

The theoretical interpretation of this paradoxical relationship may be understood through Economic Necessity Theory, whereby individuals with dissolved marriages face increased financial pressures and reduced household income support, compelling more intensive job-seeking behavior and greater willingness to accept available employment opportunities. This explanation aligns with research by Crompton (2006) on family employment reconfiguration, which demonstrated that household economic disruption often intensifies labor market participation among previously dependent family members. However, this interpretation requires critical examination of potential methodological artifacts, where the employment advantage observed among divorced/separated individuals may reflect measurement timing issues, with employment obtainment facilitating or following marital dissolution rather than resulting from it. Additionally, sample selection effects may operate if divorced/separated individuals in the dataset represent a subset with superior employment qualifications or greater career orientation compared to their married counterparts.

The positive relationship between educational level and employment probability strongly supports Human Capital Theory predictions and aligns consistently with international healthcare workforce research. This finding corroborates Fletcher et al. (2024) comparative analysis of educational requirements in public health careers, which demonstrated that advancing educational credentials significantly enhance employment prospects across multiple healthcare specialties. Convergent evidence from multiple sources reinforces this relationship, with Owolabi et al. (2024) documenting that healthcare organizations increasingly prioritize advanced educational qualifications in recruitment decisions, reflecting growing complexity in healthcare service delivery and regulatory requirements. Similarly, research by Turner and Clark (2020) demonstrated that educational attainment serves as a primary predictor of career progression and job security among healthcare professionals.

However, critical analysis of the education-employment relationship reveals important contradictions with some aspects of contemporary healthcare workforce research. While our findings support traditional Human Capital Theory predictions, they conflict with emerging evidence that employer preferences increasingly emphasize practical experience and specialized competencies over formal educational credentials (Hamouche & Parent-Lamarche, 2023). This discrepancy suggests that Thailand's health promotion labor market may retain more traditional credential-based hiring practices compared to other contexts where competency-based assessment has gained prominence. The combined effects of age, marital status, and educational attainment on employment outcomes present a complex theoretical picture that partially supports but also challenges established frameworks, with the age-employment gradient contradicting Social Justice and Health Theory expectations (World Health Organization, 2024) regarding equitable employment opportunity distribution across age groups.

Gender-Role Theory implications remain ambiguous given the predominantly female sample composition, as while the marital status findings suggest that family disruption enhances rather than impedes employment probability, this pattern may operate differently for male versus female health

promotion professionals, requiring gender-disaggregated analysis to clarify theoretical relationships (Oakley, 2005). The intersectionality of these demographic factors creates employment determination mechanisms that diverge from simple additive models predicted by traditional labor market theories, with the interaction between age and educational attainment potentially creating differential employment outcomes for various demographic subgroups that warrant further investigation (Jackson et al., 2022).

These findings have significant implications for Thailand's healthcare workforce planning and contradict some assumptions underlying current policy frameworks. The age-employment gradient suggests that policies promoting career longevity and experience retention may face implementation challenges if employer preferences systematically favor younger workers (Santric Milicevic et al., 2024). This pattern conflicts with demographic transition policies that emphasize maximizing human resource utilization across all age groups to address projected healthcare workforce shortages. Policy recommendations emerging from this analysis must acknowledge both the empirical findings and their theoretical contradictions, suggesting that while educational investment continues to demonstrate employment benefits, policies should also address potential age discrimination and examine whether employer preferences reflect objective competency requirements or systematic bias against experienced workers. Additionally, the complex relationship between marital status and employment suggests that workforce support policies should consider diverse family structures and economic circumstances rather than assuming uniform family effect patterns across different demographic groups.

5. Conclusion

This investigation examined demographic determinants of employment status among Thailand's health promotion professionals through analysis of 1,704 respondents from the National Statistical Office's Employment Status Survey. The findings reveal significant employment disparities with important theoretical and policy implications for healthcare workforce development.

Age emerged as the primary determinant of employment probability, with younger professionals experiencing substantially higher likelihood of securing employment. This age-employment gradient suggests systematic market preferences for younger workers, potentially reflecting increasing technological complexity and rapidly evolving evidence-based practices in contemporary health promotion. However, this pattern presents challenges for workforce sustainability and knowledge retention, as it underutilizes experienced professionals' accumulated clinical expertise, established community relationships, and institutional knowledge that remain valuable for effective programming.

Gender disparities persist despite women's numerical predominance in health promotion education, indicating that demographic representation in academic preparation does not translate to equitable employment opportunities. These disparities suggest structural barriers continue operating within Thailand's health promotion labor market, requiring deliberate intervention beyond increasing women's educational participation in health sciences programs.

The study supports implementing comprehensive workforce development strategies addressing both individual competency enhancement and structural barrier removal. Professional development initiatives should prioritize technological skill building and competency-based assessment frameworks enabling workers across all age groups to maintain contemporary practice standards while leveraging accumulated experience. Organizational policy reforms should examine hiring practices and workplace cultures to eliminate systematic biases disadvantaging certain demographic groups despite professional qualifications.

Policy recommendations include developing age-inclusive workforce policies preventing systematic discrimination while encouraging technological skill development across career stages. Healthcare organizations should implement competency-based hiring systems assessing actual professional capabilities rather than demographic characteristics. Mentorship programs pairing experienced professionals with technologically proficient junior colleagues could facilitate bidirectional knowledge transfer benefiting both individual development and organizational capacity.

Future research directions should address critical knowledge gaps through several approaches. Longitudinal studies tracking employment trajectories would illuminate how demographic effects evolve throughout careers and identify intervention points. Mixed-methods approaches combining quantitative analysis with qualitative exploration of employment decision-making would provide deeper understanding of mechanisms through which demographic characteristics influence outcomes. Employer perspective research examining hiring criteria and workplace culture factors would clarify whether demographic effects reflect objective competency requirements or systematic bias.

Cross-national research comparing Thailand's findings with similar middle-income countries experiencing healthcare transitions would identify best practices for workforce development and policy intervention. Methodological innovations should incorporate measures of technological competency, continuing education participation, and professional network development to better understand how these factors mediate demographic-employment relationships.

The implications extend beyond workforce planning to broader healthcare system sustainability and social equity in professional opportunity distribution. Addressing identified demographic disparities requires coordinated action across educational institutions, healthcare organizations, and policy-making bodies to ensure Thailand's health promotion workforce effectively utilizes all available human resources while providing equitable career opportunities across demographic groups. Success will significantly influence Thailand's healthcare system capacity to address evolving population health needs through comprehensive, sustainable preventive healthcare services.

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การศึกษาเปรียบเทียบฤทธิ์ด้านการอักเสบและฤทธิ์ต้านอนุมูลอิสระ
ของสารสกัดจากกระเทียมสายพันธุ์ก้านแดงและก้านขาว
Comparative Anti-Inflammatory and Antioxidant Activities of Extracted
from Red- and White-Vein *Mitragyna speciosa* (Korth.) Havil

นิชมน มุขสมบัติ^{1*}, กันตา ปรานวีระไพบูลย์², ภูริทัต กนกกังสดาล¹, มัทธน พูลเกษร³, ศุณิศา มากชูชิต⁴
สหภูมิ คูประชามิตร¹, กิรติยา แผ่นคำ¹, นริศา คำสิงห์¹ และ อรุณพร อิฐรัตน์^{1,4}
Nichamon Mukkasombut^{1*}, Kanta Pranweerapaiboon², Puritat Kanokkangsadal¹,
Mahatana Poolgesorn³, Sunita Makchuchit⁴, Sahapoom Kuprachamitr¹,
Keeratiya Pankhum¹, Narisa Kamsing¹ and Arunporn Itharat^{1,4}

¹คณะแพทยศาสตร์ มหาวิทยาลัยธรรมศาสตร์ จังหวัดปทุมธานี

²วิทยาลัยแพทยศาสตร์นานาชาติจุฬาภรณ์ มหาวิทยาลัยธรรมศาสตร์ จังหวัดปทุมธานี

³สาขาวิชาปริทัศน์วิทยา คณะทันตแพทยศาสตร์ มหาวิทยาลัยธรรมศาสตร์ จังหวัดปทุมธานี

⁴ศูนย์แห่งความเป็นเลิศทางวิชาการด้านการแพทย์แผนไทยประยุกต์ คณะแพทยศาสตร์ มหาวิทยาลัยธรรมศาสตร์ จังหวัดปทุมธานี

¹Faculty of Medicine, Thammasat University, Pathum Thani Province

²Chulabhorn International College of Medicine, Thammasat University, Pathum Thani Province

³Department of Periodontology, Faculty of Dentistry, Thammasat University, Pathum Thani Province

⁴Center of Excellence on Applied Thai Traditional Medicine Research (CEATMR), Faculty of Medicine,
Thammasat University, Pathum Thani Province

*Corresponding Author: nschamon@tu.ac.th

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บทคัดย่อ

กระเทียม (*Mitragyna speciosa* (Korth.) Havil.) ในประเทศไทยมี 2 สายพันธุ์ ที่มีการใช้บ่อยคือ พันธุ์ก้านแดง และพันธุ์ก้านขาว หมอพื้นบ้านนิยมใช้กระเทียมก้านแดงเป็นยามากกว่าก้านขาว เพื่อให้มีแรงทำงานได้นานขึ้น ทนแดด แก่ท้องร่วง ลงแดง และแก้ปวดเมื่อย ซึ่งมี 3 วิธีหลักในการบริโภคแบบดั้งเดิม ได้แก่ การแช่ในแอลกอฮอล์ การต้มใบ และการเคี้ยวใบสด ดังนั้น งานวิจัยนี้จึงมีวัตถุประสงค์เพื่อเปรียบเทียบฤทธิ์ต้านอนุมูลอิสระชนิด DPPH (DPPH assay) และฤทธิ์ด้านการอักเสบจากการยับยั้งการสร้างไนตริกออกไซด์ ของสารสกัดใบกระเทียมพันธุ์ก้านแดงและก้านขาว ที่ได้จากการแช่หมักในเอทานอล (ร้อยละ 50 และ 95) การต้ม และการคั้นน้ำ ผลการศึกษาพบว่าสารสกัดจากการแช่หมักในเอทานอล ร้อยละ 50 และ 95 ของกระเทียมพันธุ์ก้านแดงและก้านขาวมีค่า EC_{50} อยู่ในช่วงใกล้เคียงกัน (5.24–6.78 $\mu\text{g/mL}$) และค่า EC_{50} ของกลุ่มดังกล่าวยังต่ำกว่าวิธีการสกัดแบบต้มและการคั้น นอกจากนี้ยังพบว่าสารสกัดจากกระเทียมพันธุ์ก้านแดงที่ได้จากการแช่หมักในเอทานอลร้อยละ 50 แสดงร้อยละการยับยั้งการสร้างไนตริกออกไซด์ได้สูงที่สุด เมื่อเทียบกับวิธีการสกัดอื่น แม้ว่าค่า IC_{50} ของทุกตัวอย่างจะมากกว่า 100 $\mu\text{g/mL}$ โดยสรุปสารสกัดจากกระเทียมพันธุ์ก้านแดงที่ได้จากการแช่หมักในเอทานอลร้อยละ 50 แสดงศักยภาพในการต้านอนุมูลอิสระและต้านการอักเสบสูงที่สุด เมื่อพิจารณาจากการยับยั้งอนุมูลอิสระชนิด DPPH และการสร้างไนตริกออกไซด์ ตามลำดับ ผลการศึกษานี้จึงชี้ให้เห็นถึงศักยภาพของวิธีการสกัดและสายพันธุ์กระเทียมที่เหมาะสมสำหรับการพัฒนาเป็นสารออกฤทธิ์ทางชีวภาพ และสนับสนุนการเลือกใช้กระเทียมพันธุ์ก้านแดงในรูปแบบการเตรียมสารสกัดที่สอดคล้องกับการใช้ในภูมิปัญญาพื้นบ้าน

คำสำคัญ: กระเทียม, ฤทธิ์ต้านอนุมูลอิสระ, ฤทธิ์ด้านการอักเสบ, วิธีสกัด

Abstract

Mitragyna speciosa (Korth.) Havil. (kratom) in Thailand is commonly classified into two frequently used varieties: red-veined and white-veined kratom. Traditional healers more commonly use red-veined kratom than white-veined kratom for medicinal purposes, including enhancing work endurance, increasing tolerance to sunlight exposure, relieving diarrhea, alleviating withdrawal symptoms, and reducing muscle pain. Three principal traditional methods of consumption are commonly practiced, namely alcohol maceration, leaf decoction, and chewing fresh leaves. Therefore, this study aimed to compare the antioxidant activity, determined by the DPPH radical scavenging assay, and the anti-inflammatory activity, assessed by inhibition of nitric oxide production, of leaf extracts from red-veined and white-veined kratom prepared by ethanolic maceration (50% and 95%), decoction, and aqueous squeezing. The results showed that the 50% and 95% ethanolic extracts of both red-veined and white-veined kratom exhibited comparable EC_{50} values ranging from 5.24 to 6.78 $\mu\text{g/mL}$ which were lower than those obtained from decoction and aqueous squeezing. In addition, the 50% ethanolic extract of red-veined kratom showed the highest percentage inhibition of nitric oxide production among the different extraction methods, although the IC_{50} values of all samples were greater than 100 $\mu\text{g/mL}$. In conclusion, the 50% ethanolic extract of red-veined kratom demonstrated the greatest potential for antioxidant and anti-inflammatory activities, as indicated by DPPH radical scavenging activity and inhibition of nitric oxide production, respectively. These findings highlight the importance of appropriate extraction methods and kratom varieties for the development of bioactive agents and support the selection of red-veined kratom in extract preparations consistent with traditional medicinal practices.

Keywords: Kratom, Antioxidant activity, Anti-inflammatory activity, Extraction methods

1. Introduction

Kratom (*Mitragyna speciosa* Korth.) is a tropical plant belonging to the family Rubiaceae and is indigenous to Southeast Asia. In Thailand, kratom was fully removed from the list of Category 5 narcotic substances under the Narcotics Act, and the Kratom Plant Act B.E. 2565 (2022) subsequently legalized its cultivation, possession, and sale. Nevertheless, the manufacture or processing of kratom into foods, herbal preparations, pharmaceuticals, or cosmetic products remains subject to authorization under relevant regulatory frameworks. The import and export of kratom leaves remain under the supervision of the Office of the Narcotics Control Board (ONCB) (Kratom Plant Act, 2022). Following these legal changes, kratom has rapidly gained attention as an emerging economic crop in Thailand.

Previous studies have shown that medicinal plants with strong antioxidant capacity often exhibit anti-inflammatory effects or provide protection against inflammation-related cellular injury, indicating a close link between oxidative stress modulation and inflammatory responses (Arulselvan et al., 2016; Dunkhunthod et al., 2025; Klintong et al., 2024; Sittisart et al., 2020). Nitric oxide (NO) is one of the key mediators linking oxidative stress and inflammation. NO is a reactive free radical molecule with a single unpaired electron and plays a dual role in physiological regulation and pathological inflammation. It contributes to numerous physiological processes, including neurotransmission, smooth muscle relaxation, vasodilation, blood pressure regulation, gene expression, host defense, and immune regulation, and it is also implicated in pathological conditions such as neurodegenerative and cardiovascular diseases (Martemucci et al., 2022).

Traditionally, kratom leaves have been used as a folk medicine and as a stimulant, particularly among manual laborers, to alleviate fatigue, enhance physical endurance, and improve tolerance to heat. The leaves possess a bitter and astringent taste and have been used to treat abdominal pain, diarrhea, and muscle aches (Tangtrongchit, 1978). Various methods of consumption have been reported, including leaf decoction, alcoholic maceration, and chewing fresh leaves. In Thailand, kratom is commonly classified into red-, green-, and white-vein types (Srisakul, 2022). These types are reported to differ in their alkaloid profiles, which may contribute to differences in pharmacological activity (Boffa et al., 2018).

Among the identified alkaloids, mitragynine is the most abundant and is considered a major contributor to the central nervous system (CNS) depressant and analgesic effects of kratom (Kumarnsit et al., 2006, 2007). Mitragynine acts mainly as a partial agonist at μ -opioid receptors, leading to pain relief and mild sedation (Matsumoto et al., 1996). It has also been reported to inhibit the production of prostaglandin E2 (PGE2) through the suppression of cyclooxygenase-2 (COX-2) expression, indicating potential anti-inflammatory properties (Utar et al., 2011). Another major alkaloid in kratom is 7-hydroxymitragynine (7-HMG), which exhibits markedly stronger analgesic potency than mitragynine. Previous pharmacological studies have reported that 7-HMG is approximately 46 times more potent than morphine and about 13 times more potent than mitragynine in terms of analgesic activity (Kruegel & Grundmann, 2018; Matsumoto et al., 2004). This compound acts as a potent agonist at μ -opioid receptors, contributing significantly to the analgesic properties associated with kratom alkaloids (Hemby et al., 2019). Given the high pharmacological potency of 7-HMG, variations in its concentration among kratom types may influence their biological and pharmacological activities. Previous phytochemical investigations have suggested that red-vein kratom may contain relatively higher levels of 7-hydroxymitragynine compared with white-vein kratom, which could partly explain the differences in reported biological effects among kratom types (Dewatisari & Nuryandani, 2025).

Despite increasing interest, comparative studies evaluating antioxidant and anti-inflammatory activities across different kratom vein types, particularly those employing extraction methods that reflect traditional preparation, remain limited. Therefore, the present study aims to compare the anti-inflammatory and antioxidant activities of extracts from red-vein and white-vein kratom leaves, two types commonly used in both traditional and contemporary contexts. Extraction procedures were designed to mimic traditional practices to support evidence-based development of standardized kratom-based herbal products in the future.

2. Materials and methods

2.1 Sample Selection

Two kratom types commonly used by local villagers and traditional healers were selected, namely red-vein kratom collected from Chumphon Province, and white-vein kratom collected from Pattani Province, Thailand.



Figure 1. Leaves of red-vein (1a) and white-vein (1b) kratom

2.2 Plant Materials and Preparation

White-vein kratom leaves (1,729 g) were collected from Pattani Province, Thailand, and red-vein kratom leaves (1,765 g) were collected from Chumphon Province, Thailand. The leaves were thoroughly cleaned and subjected to three extraction methods: (1) maceration with ethanol (95% and 50%), (2) decoction, and (3) aqueous extraction by squeezing. The detailed procedures for each method are described below.

2.2.1 Maceration

Fresh white-vein and red-vein kratom leaves were cut into small pieces (approximately 1–1.5 cm) prior to drying. The dried white-vein and red-vein kratom leaves (198.81 g and 137 g, respectively) were macerated with 95% ethanol, while the dried white-vein and red-vein leaves (181.53 g and 142 g, respectively) were macerated with 50% ethanol at a plant material-to-solvent ratio of 1:3 (w/v) at room temperature for 3 days. The extracts were filtered, and the maceration process was repeated three times. The combined filtrates were concentrated under reduced pressure at 45 °C using a rotary evaporator (Büchi, Flawil, Switzerland) to obtain a viscous crude extract, which was further oven-dried to constant weight.

2.2.2 Decoction

Fresh white-vein and red-vein kratom leaves (324 g and 724 g, respectively) were boiled in water at a ratio of 1:3 (w/v) at 100 °C for 15 min. The extract was filtered, and the filtrate was concentrated using a freeze dryer (Lyolab, Barcelona, SPAIN), yielding dry crude powder extract.

2.2.3 Aqueous squeezing

Fresh white-vein and red-vein kratom leaves (80.65 g and 42 g, respectively) were blended with water at a ratio of 1:3 (w/v), filtered, and the filtrates were concentrated using a freeze dryer (Lyolab), yielding dry a crude powder extract. The percentage yield of each extract was calculated.

2.3 DPPH Radical Scavenging Assay

The DPPH assay is widely used for preliminary screening of antioxidant activity because it evaluates the electron- and hydrogen-donating capacity of antioxidant compounds (Brand-Williams et al., 1995). The antioxidant activity of the extracts was determined using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma-Aldrich, St. Louis, MO, USA) radical scavenging assay according to the method described by Yamazaki et al. (1994) with slight modifications. Ethanolic extracts were dissolved in absolute ethanol, whereas aqueous extracts were dissolved in sterile water. Sample solutions were prepared at various concentrations (1, 10, 50, and 100 µg/mL).

A 100 µL aliquot of each sample solution was added to 96-well microplates, followed by 100 µL of DPPH solution. Control solutions consisted of absolute ethanol or distilled water (100 µL), each mixed with 100 µL of DPPH solution. The mixtures were incubated in the dark at room temperature for 30 min.

Absorbance was measured at 520 nm using a microplate reader (The Multiskan GO, Vantaa, FINLAND). Butylated hydroxytoluene (BHT) (Sigma-Aldrich, St. Louis, MO, USA) served as a positive control. The percentage of radical scavenging activity was calculated using the following equation:

$$\text{Inhibition (\%)} = [(OD_{\text{control}} - OD_{\text{sample}}) / OD_{\text{control}}] \times 100 \quad (1)$$

where OD control is the absorbance of the control (without sample), and OD sample is the absorbance in the presence of the test sample. The half-maximal effective concentration (EC₅₀) values were calculated from the dose-response curves using nonlinear regression analysis (four-parameter logistic model) in GraphPad Prism software (GraphPad Software Inc., San Diego, CA, USA).

2.4 Cell culture

RAW264.7 macrophage cells (ATCC TIB-71TM, Virginia, USA) were cultured in RPMI-1640 medium (Gibthai, Bangkok, Thailand) supplemented with 10% heat-inactivated fetal bovine serum (FBS) (Gibco, OK, USA) and 100 U/mL penicillin–streptomycin (Gibco, OK, USA). The cells were maintained at 37 °C in a humidified incubator with 5% CO₂.

2.5 Determination of Nitric Oxide Production in LPS-Stimulated RAW 264.7 Cells

Nitric oxide (NO) production in murine macrophage-like RAW264.7 cells was evaluated following the method of Makchuchit et al., (2017). Briefly, cells were seeded into 96-well plates at a density of 1×10^5 cells/100 µL/well and allowed to adhere for 1 h. The medium was then replaced with fresh RPMI-1640 medium containing 10 ng/mL lipopolysaccharide (LPS) (Sigma-Aldrich, St. Louis, MO, USA) and the test samples (W-95E, W-50E, W-D, W-Sq, R-95E, R-50E, R-D and R-SQ) at final concentrations of 50 and 100 µg/mL and test prednisolone at a final concentrations of 0.01, 0.1, 1 and 10 µg/mL (100 µL/well). Cells were incubated for 24 h, after which NO production was assessed by measuring nitrite accumulation in the culture supernatant using Griess reagent (1% sulfanilamide and 0.1% N-(1-naphthyl) ethylenediamine dihydrochloride in 2.5% phosphoric acid) (Merck, Darmstadt, Germany).

Cytotoxicity was determined in parallel using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) (Sigma-Aldrich, St. Louis, MO, USA) colorimetric assay. After 24 h of incubation with the test samples, 10 µL of MTT solution (5 mg/mL in PBS) was added to each well. Following 2 h incubation, the medium was removed, and 100 µL of isopropanol containing 0.04 M HCl was added to dissolve the formazan crystals formed in the cells. The optical density (OD) was measured at

570 nm using a microplate reader (The Multiskan GO). Test compounds or extracts were considered cytotoxic when cell viability was less than 70% compared with the vehicle-treated control group, according to the ISO 10993-5 guideline. Prednisolone (Sigma-Aldrich, St. Louis, MO, USA) served as a positive control. Stock solutions of 50 mg/mL test samples were prepared in DMSO and diluted with RPMI-1640 medium to ensure a final DMSO concentration of <0.2%. The percentage inhibition of NO production was calculated as equation (2).

$$\text{Inhibition (\%)} = [(OD_{\text{control}} - OD_{\text{sample}}) / OD_{\text{control}}] \times 100 \quad (2)$$

Half-maximal inhibitory concentration (IC_{50}) values were calculated from dose-response curves using nonlinear regression analysis (four-parameter logistic model) in GraphPad Prism software.

2.6 Biosafety

This research project was approved by the Institutional Biosafety Committee (IBC), Thammasat University (Certificate No. 041/2568).

2.7 Statistical analysis

All experiments were conducted in triplicate, and the results are expressed as mean $\pm$ standard deviation (SD). Statistical analysis was conducted using GraphPad Prism software (GraphPad Software Inc., San Diego, CA, USA). Differences among groups were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's HSD multiple comparison test. A p-value < 0.05 was considered statistically significant.

3. Result

3.1 Extraction yield of kratom leaves obtained by different extraction methods

As shown in Table 1, the extraction yields of kratom leaf extracts ranged from 6.45% to 22.40%, depending on the extraction method and vein type. The highest yield was obtained from 50% ethanol maceration, yielding 22.40% for red-vein kratom (R-50E) and 18.60% for white-vein kratom (W-50E). In contrast, the lowest yields were observed with the decoction method, producing 6.45% for red-vein kratom (R-D) and 8.75% for white-vein kratom (W-D). Overall, ethanol maceration produced higher yields than water-based extractions (decoction and aqueous squeezing) for both vein types.

Table 1. Extraction yield (%) of kratom leaves using different extraction methods

Sample	Vein	Extraction method	Code	%yield
Dried leaves	White	Maceration with 95% ethanol	W-95E	12.50
Dried leaves	White	Maceration with 50% ethanol	W-50E	18.60
Fresh leaves	White	Kratom with Decoction	W-D	8.75
Fresh leaves	White	Kratom with Aqueous Squeezing	W-Sq	15.48
Dried leaves	Red	Maceration with 95% ethanol	R-95E	14.70
Dried leaves	Red	Maceration with 50% ethanol	R-50E	22.40
Fresh leaves	Red	Kratom with Decoction	R-D	6.45
Fresh leaves	Red	Kratom with Aqueous Squeezing	R-Sq	10.68

3.2 Antioxidant activity of kratom extracts determined by the DPPH assay

As shown in Table 2, the results indicated that extracts obtained by maceration with 50% and 95% ethanol, as well as decoction extracts from both red-vein and white-vein kratom exhibited significantly higher antioxidant activity than the standard BHT ($p < 0.05$). Among these, the 50% ethanol extract of red-vein kratom showed the lowest EC_{50} value (5.24 ± 0.30 $\mu\text{g/mL}$), compared with BHT ($EC_{50} = 16.09 \pm 2.05$ $\mu\text{g/mL}$). The decoction extracts of white- and red-vein kratom also demonstrated strong antioxidant activity, with EC_{50} value of 6.57 ± 0.12 and 8.01 ± 0.79 , respectively. In contrast, the aqueous squeezing extract of white-vein showed no significant difference compared with BHT ($EC_{50} = 11.62 \pm 3.59$ $\mu\text{g/mL}$). The aqueous squeezing extract of red-vein kratom exhibited substantially lower antioxidant activity than the other extraction methods ($EC_{50} = 50.16 \pm 2.47$ $\mu\text{g/mL}$).

Table 2. Antioxidant activity of kratom extracts determined by the DPPH assay

Sample	%Inhibition				$EC_{50} \pm SD$ ($\mu\text{g/mL}$)
	1 $\mu\text{g/mL}$	10 $\mu\text{g/mL}$	50 $\mu\text{g/mL}$	100 $\mu\text{g/mL}$	
W-95E	12.04 ± 6.37	76.04 ± 5.03	92.98 ± 0.88	94.95 ± 0.30	5.86 ± 0.56^a
R-95E	9.14 ± 4.09	71.97 ± 9.91	94.48 ± 0.40	94.19 ± 0.24	6.78 ± 0.80^a
W-50E	8.85 ± 3.38	86.96 ± 2.64	92.21 ± 0.85	92.83 ± 0.66	5.41 ± 0.29^a
R-50E	10.55 ± 6.16	87.96 ± 1.45	93.58 ± 1.07	93.17 ± 3.86	5.24 ± 0.30^a
W-D	11.37 ± 5.70	70.22 ± 1.97	81.67 ± 5.13	84.89 ± 5.09	6.57 ± 0.12^a
R-D	3.22 ± 3.83	61.48 ± 5.06	78.82 ± 8.19	84.37 ± 5.64	8.01 ± 0.79^{ab}
W-Sq	11.37 ± 3.39	47.70 ± 9.75	81.10 ± 9.95	87.20 ± 4.79	11.62 ± 3.59^{bc}
R-Sq	0.71 ± 2.04	14.48 ± 1.56	49.24 ± 2.39	73.68 ± 2.31	50.16 ± 2.47^d
BHT	4.41 ± 2.89	34.71 ± 3.96	77.85 ± 3.04	85.53 ± 0.97	16.09 ± 2.05^c

Note: Values are expressed as mean $\pm$ SD ($n = 3$). Different superscript letters (a–d) within the same column indicate statistically significant differences ($p < 0.05$), as determined by one-way ANOVA followed by Tukey's HSD multiple comparison test.

3.3 Effects of Kratom Extracts on the Viability of RAW264.7 Cells

As shown in Table 3, the viability of RAW264.7 cells treated with kratom extracts generally remained high at both tested concentrations (50 and 100 $\mu\text{g/mL}$). Most extracts exhibited cell viability values above 90%, indicating low cytotoxicity toward RAW264.7 cells under the experimental conditions. Among the tested extracts, ethanol maceration extracts (W-95E, W-50E, R-95E, and R-50E) showed the highest cell viability, with several values exceeding 110%, particularly for W-95E and W-50E. In contrast, extracts obtained by decoction and aqueous squeezing tended to show slightly lower cell viability, although the values remained close to or above 90%. When comparing kratom vein types, both white-vein and red-vein extracts showed comparable effects on cell viability at the same concentrations. The decoction extract of red-vein kratom (R-D) showed cell viability values close to 100%, while the aqueous squeezing extract of red-vein kratom (R-Sq) exhibited slightly lower viability compared with other extracts. The reference compound prednisolone showed a concentration-dependent decrease in cell viability, with values decreasing from approximately 101% at 0.01 $\mu\text{g/mL}$ to 75% at 10 $\mu\text{g/mL}$. Overall, these results suggest that most kratom extracts exhibited minimal cytotoxicity toward RAW264.7 cells at the tested concentrations.

Table 3. Cell viability of RAW264.7 cells treated with different concentrations of kratom extracts

Sample	Concentration (µg/mL)	Cell viability (%)*
W-95E	50	120.31±10.49
	100	125.65±8.48
W-50E	50	109.23±1.72
	100	122.05±6.46
W-D	50	98.72±1.84
	100	100.4±0.05
W-Sq	50	93.72±2.8
	100	95.78±6.20
R-95E	50	111.35±2.54
	100	110.85±4.45
R-50E	50	114.87±7.59
	100	115.40±10.86
R-D	50	94.95±0.34
	100	98.13±2.79
R-SQ	50	89.49±3.30
	100	93.43±1.57
Prednisolone	0.01	101±7.80
	0.1	82.79±4.39
	1	78.00±1.13
	10	75.02±1.19

*Data are presented as mean ± SD (n=3). Cell viability was assessed using the MTT assay.

3.4 Inhibitory effects of kratom extracts on LPS-Induced nitric oxide production in RAW264.7 cells

As shown in Table 4, several kratom extracts demonstrated measurable inhibitory effects on NO production in LPS-stimulated RAW264.7 macrophages. Among the extraction methods, maceration tended to yield extracts with relatively higher NO inhibitory activity. In particular, red-veined kratom extracts obtained by maceration with 50% and 95% ethanol, as well as the white-veined kratom extract obtained by maceration with 50% ethanol, showed the highest levels of NO inhibition compared with other extracts. At a concentration of 100 µg/mL, these extracts exhibited percentage inhibitions of $43.79 \pm 10.01\%$, $43.26 \pm 0.69\%$, and $41.50 \pm 10.37\%$, respectively.

Despite these observations, the overall anti-inflammatory activity of the kratom extracts remained relatively weak, as all tested extracts exhibited IC₅₀ values greater than 100 µg/mL. In contrast, the reference compound prednisolone showed strong inhibitory activity, with an IC₅₀ value of 0.20 ± 0.01 µg/mL (0.56 ± 0.03 µM). To ensure that the observed inhibition of NO production was not influenced by cytotoxic effects, cell viability was evaluated using the MTT assay (Table 3). The results indicated that all kratom extracts from both white-veined and red-veined varieties were non-cytotoxic to RAW264.7 cells, with cell viability values exceeding 80% at a concentration of 100 µg/mL. These findings suggest that the reduction in NO production observed for the extracts was not attributable to decreased cell viability. In contrast, prednisolone exhibited a strong inhibitory effect on LPS-induced NO production. However, at certain concentrations, approximately 20% reduction in cell viability was observed, which may influence the interpretation of NO inhibition. In such cases, reduced NO levels could result from decreased cell

viability rather than a direct anti-inflammatory effect.

According to ISO 10993-5 (Standard, 2009), a reduction in cell viability greater than 30% is considered cytotoxic. Therefore, to minimize potential confounding effects of cytotoxicity on NO production, only concentrations with cell viability $\geq 80\%$ (Joo et al., 2014) or $\geq 90\%$ (Pratama et al., 2024) were considered in the evaluation of NO inhibition. These criteria allowed for a more accurate assessment of the anti-inflammatory activity of kratom extracts, independent of cytotoxic effects.

Table 4. Anti-inflammatory activity of kratom extracts based on inhibition of nitric oxide (NO) production

Sample	Concentration ($\mu\text{g/mL}$)	% inhibition	IC ₅₀ ($\mu\text{g/mL}$)
W-95E	50	11.49 $\pm$ 0.88	>100
	100	41.50 $\pm$ 10.37	>100
W-50E	50	3.25 $\pm$ 9.74	>100
	100	20.99 $\pm$ 1.32	>100
W-D	50	6.92 $\pm$ 1.91	>100
	100	9.29 $\pm$ 3.30	>100
W-Sq	50	6.59 $\pm$ 1.59	>100
	100	10.85 $\pm$ 2.47	>100
R-95E	50	15.64 $\pm$ 7.72	>100
	100	43.26 $\pm$ 0.69	>100
R-50E	50	5.67 $\pm$ 10.02	>100
	100	43.79 $\pm$ 10.01	>100
R-D	50	0.08 $\pm$ 5.68	>100
	100	8.13 $\pm$ 1.48	>100
R-SQ	50	4.56 $\pm$ 4.04	>100
	100	5.35 $\pm$ 4.97	>100
Prednisolone	0.01	12.56 $\pm$ 2.70	0.20 $\pm$ 0.01
	0.1	50.06 $\pm$ 1.58	
	1	68.32 $\pm$ 0.52	
	10	74.66 $\pm$ 1.20	

*Data are presented as mean $\pm$ SD (n=3)

4. Discussion

Kratom (*Mitragyna speciosa* (Korth.) Havil) is a medicinal plant traditionally used for relieving pain and muscle soreness, as well as enhancing tolerance to heat. The most commonly used varieties are the white- vein and red -vein types. Kratom has been utilized in various preparation methods, including decoction, ethanolic maceration, and aqueous squeezing extraction. In this study, both kratom varieties were extracted using methods that closely resemble traditional practices. The obtained extracts were then evaluated for their antioxidant activity using DPPH radical scavenging assay and their anti-inflammatory activity through the inhibition of LPS-induced nitric oxide (NO) production in RAW 264.7 cells, both of which are related to inflammatory processes and pain relief. The results revealed that extraction yields were comparable across different methods, with the highest yield obtained from maceration with 50% ethanol.

The antioxidant activity evaluated by the DPPH radical scavenging assay demonstrated that extracts of both kratom types obtained by maceration with 50% ethanol, 95% ethanol, and decoction exhibited significantly stronger antioxidant activity than BHT, which served as the positive control, except for the aqueous squeezing extract. In the present study, the red-veined kratom showed lower antioxidant activity than the white-veined kratom and BHT. A previous study reported that water extraction of kratom at 100 °C for 2 hours, repeated twice, resulted in a relatively high EC₅₀ value (Parthasarathy *et al.*, 2009). In contrast, the present study demonstrated lower EC₅₀ values and stronger antioxidant activity than BHT, which may be attributed to differences in boiling time. Additionally, variations in the source and harvest season of plant materials may have influenced the concentration of bioactive compounds, leading to discrepancies in the observed results. (Kang *et al.*, 2023)

The extracts from both red-veined and white-veined kratom leaves exhibited comparable antioxidant activities across different extraction methods, including maceration with 95% ethanol, maceration with 50% ethanol, and decoction. However, in the aqueous extraction, the white-veined kratom extract demonstrated significantly stronger antioxidant activity than red-veined extract, with IC₅₀ value of 11.62±3.59 µg/mL and 51.49±4.43 µg/mL, respectively.

Regarding anti-inflammatory activity, both extracts showed comparable inhibitory effects at concentrations of 50 and 100 µg/mL across the maceration with 50% ethanol extraction, decoction, and aqueous extraction methods. Notably, in the maceration with 50%, the red-veined kratom extract exhibited greater nitric oxide inhibitory activity at 100 µg/mL than the white-veined extract, with inhibition percentages of 43.79±10.01% and 20.99±1.32%, respectively.

Previous studies have reported that high temperature or heat stress is directly associated with an increase in reactive oxygen species (ROS), leading to oxidative stress in living organisms (Zhang *et al.*, 2022). This supports the traditional use of kratom leaves to enhance tolerance to sunlight exposure. Consistently, extracts obtained through decoction, ethanolic maceration, and aqueous squeezing, commonly used in traditional practice, exhibited strong antioxidant activities in this study.

The anti-inflammatory activity of kratom extracts has previously been evaluated by measuring lipopolysaccharide (LPS)-induced nitric oxide (NO) production in RAW264.7 cells. In a previous study, Matrix 5 Step1 (M5S1), a non-alkaloid extract obtained by supercritical carbon dioxide extraction, demonstrated the highest inhibitory effect, with 60.08±10.02% inhibition at a final concentration of 100 µg/mL (Tohar, *et al.*, 2019). This inhibitory activity is comparable to that observed in the present study, in which the 50% ethanolic extract obtained by maceration exhibited anti-inflammatory activity with 43.79 ± 10.01% inhibition at the same concentration (100 µg/mL).

Based on the present findings, ethanolic extracts tended to exhibit stronger antioxidant and anti-inflammatory activity than water-based extracts obtained by aqueous squeezing or decoction. Previous studies have identified mitragynine as a major alkaloid compound with lipophilic properties and poor water solubility. A comparative study reported that the concentration of mitragynine in the water extract was 0.80 mg/g, which was markedly lower than that in the methanolic extract (4.77 mg/g) (Parthasarathy *et al.*, 2013).

However, a previous study reported that mitragynine from kratom leaves exerted anti-inflammatory effects on RAW264.7 macrophage cells by inhibiting prostaglandin E2 (PGE2) production through suppression of cyclooxygenase-2 (COX-2) expression, a key enzyme induced during inflammation, while showing no effect on COX-1 activity. These findings indicate that mitragynine possesses anti-inflammatory potential (Utar *et al.*, 2011). Furthermore, the anti-inflammatory activity of the methanolic kratom extract was demonstrated *in vivo*, where intraperitoneal administration in carrageenan-induced

paw inflammatory mediators via the arachidonic acid pathway, enhanced immune function, and promoted wound healing (Shaik *et al.*, 2009). Therefore, it is suggested that assessing only nitric oxide inhibition may not comprehensively reflect the specific anti-inflammatory mechanisms of kratom extract.

Previous studies have reported that kratom alkaloids exhibit greater biological activity than crude extracts. In silico molecular analyses demonstrated strong binding affinity of kratom alkaloids to the active sites of COX-2 and 5-LOX, supporting their potential as dual COX-2/5-LOX inhibitors. The alkaloid extract suppressed several anti-inflammation parameters, including ROS (64% reduction at 25 ppm), NO (30% reduction at 25 ppm), TNF- α (~ 50% reduction at 25 ppm), and IL-6 production (60% reduction at 6.25 ppm). Cyclooxygenase (COX) and lipoxygenase (LOX) enzymes play crucial roles in the biosynthesis of pro-inflammatory eicosanoids, including prostaglandins and leukotrienes; therefore, simultaneous inhibition of both enzymes may contribute to more effective suppression of inflammatory responses (Rahmawati *et al.*, 2024).

5. Conclusion and suggestions

Both red-veined and white-veined kratom extracts exhibited strong antioxidant activity, particularly when extracted by maceration with 50% and 95% ethanol, as well as by decoction methods, with activities greater than the standard antioxidant BHT under the tested conditions. Among the tested samples, the red-veined kratom extract showed relatively higher anti-inflammatory activity, with $43.79 \pm 10.01\%$ inhibition of nitric oxide production at a concentration of 100 $\mu\text{g/mL}$, although the IC_{50} values remained greater than 100 $\mu\text{g/mL}$. Overall, the results suggest that ethanolic extraction, particularly with 50% ethanol, may be an effective method for obtaining bioactive compounds from kratom leaves. The findings also indicate that red-veined kratom may have greater potential for applications related to pain relief and inflammatory conditions, which is consistent with its traditional use in folk medicine.

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การพัฒนาผลิตภัณฑ์วaffleฟิลกรอบผสมปูทะเล Product Development of Crispy Mud Crab Waffles

สรุเพชญ บรลือวงศ์^{1*} กฤษณะ ช่องศรี¹ และ วียรัตน์ กุมุทานาต¹
Sunpech Bunluewong^{1*}, Krisana Chongsri¹ and Wiyarat Kumutanat¹

¹คณะวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยราชภัฏราชนครินทร์ จังหวัดฉะเชิงเทรา

¹Faculty of Science and Technology, Rajabhat Rajanagarindra University, Chachoengsao Province

*Corresponding Author: sunpech.bun@gmail.com

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อพัฒนาผลิตภัณฑ์วaffleฟิลกรอบผสมปูทะเล โดยศึกษาตำรับพื้นฐานของวaffleฟิลกรอบและประเมินคุณภาพทางประสาทสัมผัส ได้แก่ ลักษณะที่ปรากฏ สี กลิ่น รสชาติ เนื้อสัมผัส และความชอบโดยรวม โดยใช้ผู้ทดสอบจำนวน 50 คน ด้วยวิธีการให้คะแนนความชอบแบบ 7 ระดับ (7-Point Hedonic Scale) ผลการศึกษาพบว่าตำรับที่ 1 ได้รับการยอมรับสูงสุด โดยมีค่าเฉลี่ยด้านสี กลิ่น รสชาติ เนื้อสัมผัส ลักษณะที่ปรากฏ และความชอบโดยรวมเท่ากับ 5.60 ± 0.99 5.70 ± 0.98 5.35 ± 0.98 5.70 ± 1.16 5.90 ± 1.10 และ 5.78 ± 0.97 ตามลำดับ จากนั้นศึกษาผลของการเติมเนื้อปูทะเลในระดับร้อยละ 5 10 และ 15 (โดยน้ำหนักแห้ง) พบว่าการเติมเนื้อปูทะเลร้อยละ 5 ให้ค่าการยอมรับสูงสุด โดยมีค่าเฉลี่ยเท่ากับ 6.33 ± 0.60 6.00 ± 0.98 6.03 ± 0.92 5.94 ± 0.91 5.78 ± 0.88 และ 6.03 ± 0.85 ตามลำดับ ผลิตภัณฑ์ที่ได้รับการยอมรับสูงสุดถูกนำไปวิเคราะห์คุณสมบัติทางกายภาพและเคมี พบว่ามีค่า water activity (a_w) เท่ากับ 0.50 ± 0.01 ค่าสี L^* 51.44 ± 0.23 a^* 6.30 ± 0.12 และ b^* 43.32 ± 0.17 และค่าความกรอบ 5.77 ± 0.24 นิวตัน ในขณะที่องค์ประกอบทางเคมีประกอบด้วยโปรตีน 12.36 ± 0.07 กรัม คาร์โบไฮเดรต 66.90 ± 0.25 กรัม ไขมัน 13.30 ± 0.17 กรัม ความชื้น 5.63 ± 0.04 กรัม เถ้า 1.98 ± 0.16 กรัม และพลังงานรวม 435.21 ± 0.34 กิโลแคลอรีต่อ 100 กรัม ผลการศึกษานี้แสดงให้เห็นว่าการเติมเนื้อปูทะเลร้อยละ 5 เป็นระดับที่เหมาะสมในการพัฒนาผลิตภัณฑ์วaffleฟิลกรอบ โดยให้คุณภาพทางประสาทสัมผัสและคุณสมบัติทางกายภาพและเคมีที่เหมาะสม

คำสำคัญ: วaffleฟิล, ปูทะเล, วaffleฟิลกรอบผสมปูทะเล

Abstract

This study aimed to develop a crispy mud crab waffle product. The study evaluated basic waffle formulations and their sensory attributes, including appearance, color, aroma, flavor, texture, and overall acceptability, using 50 participants and a 7-point hedonic scale. The results showed that Formulation 1 achieved the highest acceptability, with mean scores of 5.60 ± 0.99 , 5.70 ± 0.98 , 5.35 ± 0.98 , 5.70 ± 1.16 , 5.90 ± 1.10 , and 5.78 ± 0.97 for the respective attributes. Subsequently, the effects of mud crab meat incorporation at 5%, 10%, and 15% (w/w) were investigated. The formulation containing 5% mud crab meat demonstrated the highest acceptability, with mean scores of 6.33 ± 0.60 , 6.00 ± 0.98 , 6.03 ± 0.92 , 5.94 ± 0.91 , 5.78 ± 0.88 , and 6.03 ± 0.85 for the respective attributes. The selected formulation was further analyzed for its physicochemical properties. The results showed a water activity (a_w) of 0.50 ± 0.01 , color values of $L^* = 51.44 \pm 0.23$, $a^* = 6.30 \pm 0.12$, and $b^* = 43.32 \pm 0.17$, and a crispness value of 5.77 ± 0.24 N. The proximate composition per 100 g revealed 12.36 ± 0.07 g of protein, 66.90 ± 0.25 g of carbohydrates, 13.30 ± 0.17 g of fat, 5.63 ± 0.04 g of moisture, 1.98 ± 0.16 g of ash, and a total energy of 435.21 ± 0.34 kilocalories. These findings indicate that 5% mud crab meat is the optimal incorporation level for crispy waffle development, providing acceptable sensory quality and desirable physicochemical properties.

Keywords: Waffles, Mud crab, Crispy mud crab waffles

1. Introduction

The mud crab, *Scylla serrata* (Forsskål), is widely recognized for its unique sensory attributes and rich nutritional profile. Owing to its culinary versatility, it is widely accepted among domestic and international consumers. Additionally, *S. serrata* constitutes a significant export commodity, particularly in high-demand markets such as Hong Kong, Singapore, Malaysia, and the United States (Thotsaporn et al., 2009). In Thailand, the mud crab represents an important aquatic resource with substantial economic value, especially in Khao Din Subdistrict, Bang Pakong District, Chachoengsao Province. In this area, mud crab production provides supplementary income for local households during agricultural off-seasons, and the crabs can be processed into various value-added food products (Lalida et al., 2020).

Waffles are widely consumed bakery products produced in a variety of textures. Their main ingredients typically include wheat flour, sugar, eggs, and milk (Laddawan et al., 2022). Traditionally, waffles are produced in circular or square shapes and are characterized by a distinctive honeycomb pattern. In the commercial markets, waffle products are often developed as thin and crispy snacks (Kannika et al., 2019).

However, research on the development of value-added snack products from the mud crab, particularly crispy bakery-type products, remains limited. Due to the lack of scientific evidence, this study aims to investigate the effects of incorporating low-grade mud crab raw materials on the quality attributes of crispy waffles, thereby enhancing the value of these underutilized resources.

2. Materials and methods

This study aimed to develop a crispy waffle product incorporated with mud crab meat. The methodology involved optimizing the crab meat ratio within a classic formulation base, and conducting a comprehensive analysis of the product's physical and chemical components. The specific procedures are detailed below.

2.1 Crispy Waffle Sample Preparation

Three crispy waffle formulations, which differed in their ingredient compositions, were prepared to determine the most acceptable formulation. The samples were subjected to sensory evaluation based on appearance, aroma, taste, texture, and overall acceptability. A 7-point hedonic scale was used to evaluate the samples by 50 untrained panelists selected from Khao Din Subdistrict. The formulations are presented in Table 1, and the processing steps are illustrated in Figure 1.

The experiment was designed using a Randomized Complete Block Design (RCBD). Data were analyzed using Analysis of Variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) to determine significant differences among treatments. All statistical analyses were performed using statistical software applications.

Table 1. Recipe composition of Basic Crispy Waffle

Ingredients	Amount (%)		
	Formulation 1	Formulation 2	Formulation 3
Cake flour		25.35	17.80
All-purpose wheat flour	18.68		
Cornstarch		5.85	3.55
Chicken eggs	24.28	12.68	23.13
Salt		0.97	0.60
Sugar	12.45	9.75	11.86
Melted unsalted butter	6.23	7.79	5.95
Fresh milk	37.35	11.69	35.58
Water	-	23.39	-
Baking powder	0.38	0.58	0.35
Vanilla flavoring	0.63	1.95	1.18

Reference: Recipe 1. (Sunpech et al.,2022) 2. (Klinsukon et al.,2023) 3. (Jatupol et al.,2020)

2.2 Optimizing Amounts of Mud Crab Meat in Crispy Waffle Products

The study investigated three levels of mud crab meat to identify the optimal amount for crispy waffle production. In all experimental treatments, dried mud crab meat with a water activity (a_w) value of 0.40 was mixed into the cake flour at inclusion levels of 5%, 10%, and 15% of the flour weight. Table 2 summarizes the specific formulation used, while Figure 2 illustrates the production process for the crispy mud crab waffles. The products were subjected to sensory evaluation for appearance, color, aroma, flavor, texture, and overall acceptability using a 7-point hedonic scale. The evaluation was conducted with 50 participants selected from the population and sample group in Khao Din Subdistrict.

A randomized complete block design (RCBD) was employed for the experimental layout. Data were analyzed using Analysis of Variance (ANOVA) to determine the significance of the main effects, and Duncan's New Multiple Range Test (DMRT) was used to compare treatment means. All statistical analyses were conducted using commercial statistical software.

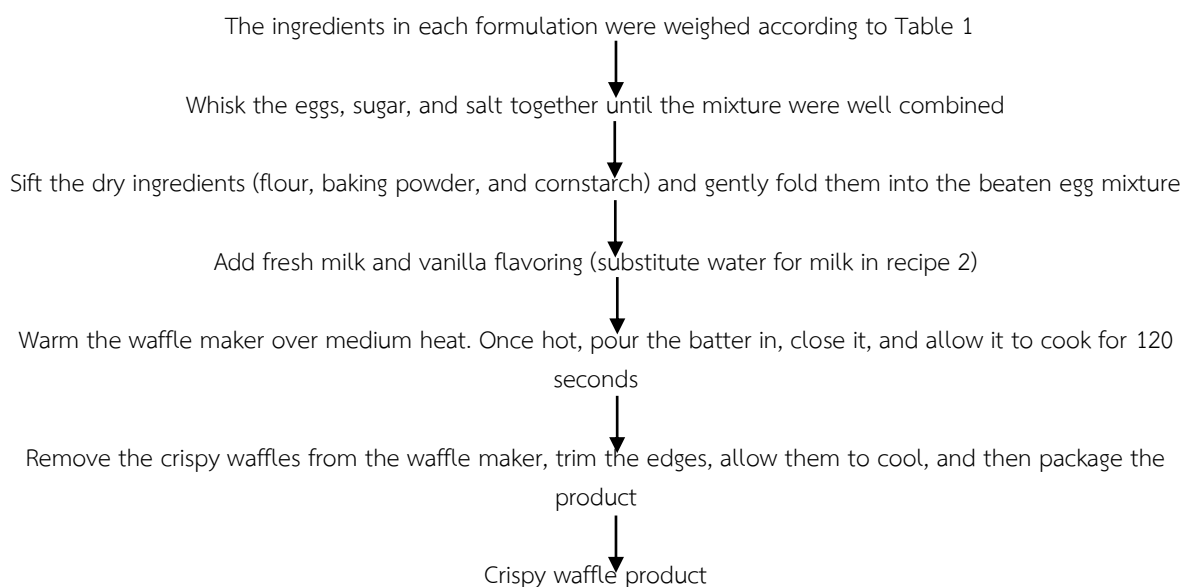


Figure 1. Crispy Waffle Processing

Table 2. Amounts of Mud Crab Meat

Formulation	Meat Proportion (%)
1	5
2	10
3	15

2.3 Analysis of Physicochemical Properties of Crispy Mud Crab Waffles

The formulation with the highest sensory acceptability was selected for further analysis of its physicochemical properties. The physical properties evaluated included water activity (a_w), color values (L^* , a^* , and b^*), and texture (crispness). The chemical composition was analyzed for its protein, carbohydrate, fat, moisture, ash, and energy contents. All analyses were performed in triplicate.

3. Results

3.1 Basic recipes of Crispy Waffles

In this experiment, three basic crispy waffle formulations with differing ingredient compositions were examined to determine the most suitable formulation. The test samples of each formulation are presented in Table 1, and the production procedure is illustrated in Figure 1. Sensory evaluations were conducted, and the mean sensory quality scores of the classic crispy waffle formulations are shown in Table 3.

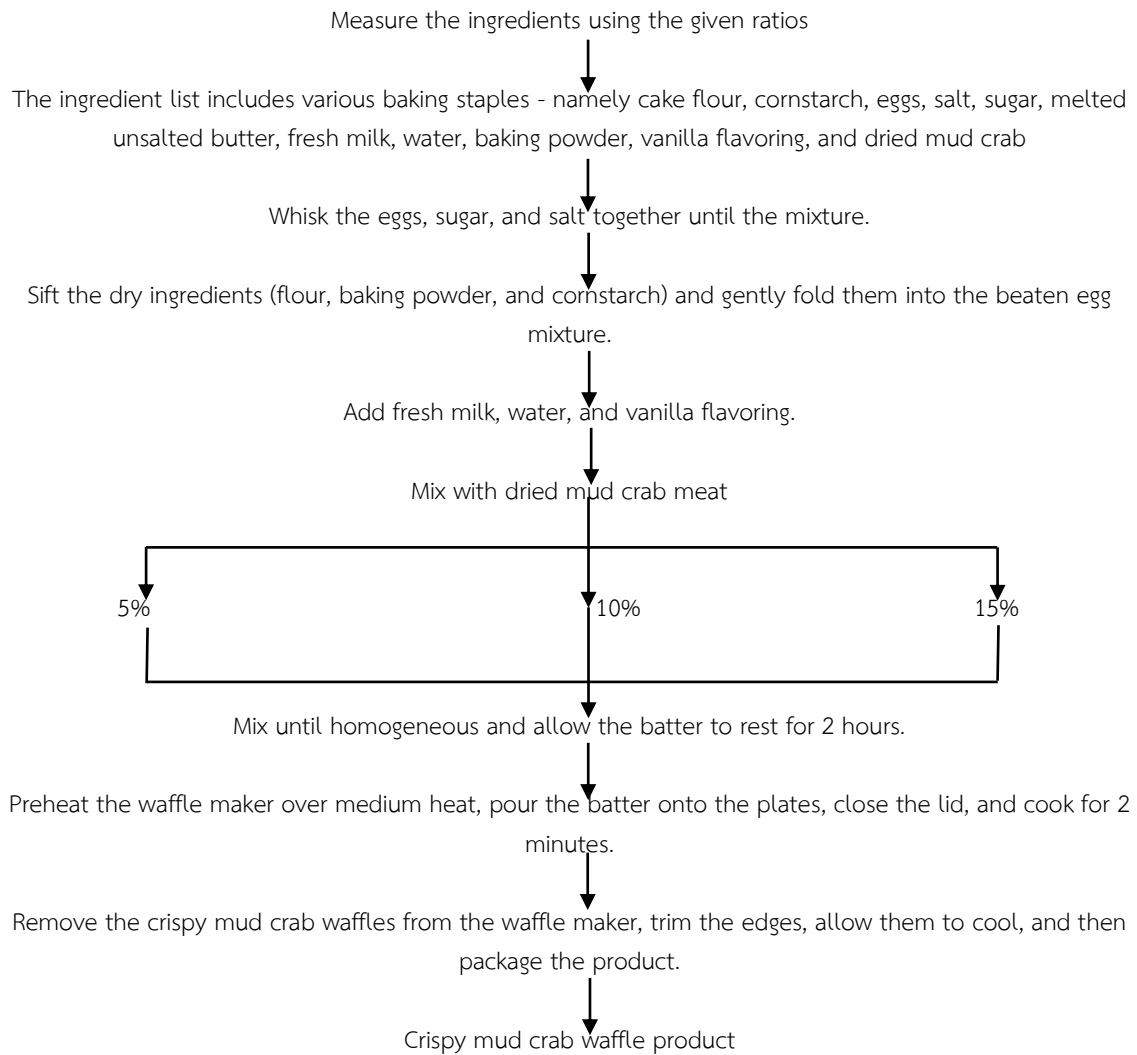


Figure 2. the production process for the crispy mud crab waffles

Table 3. Sensory Evaluation Results of the basic crispy waffle

Sensory parameters	Mean $\pm$ SD		
	Formulation 1	Formulation 2	Formulation 3
Appearance	4.60 $\pm$ 0.88 ^b	5.60 $\pm$ 0.74 ^a	3.63 $\pm$ 1.43 ^c
Color ^{ns}	5.30 $\pm$ 0.99	5.70 $\pm$ 1.16	5.33 $\pm$ 1.31
Aroma ^{ns}	5.28 $\pm$ 0.99	5.35 $\pm$ 0.98	5.18 $\pm$ 1.32
Flavor	5.40 $\pm$ 1.22 ^a	5.70 $\pm$ 0.67 ^a	4.40 $\pm$ 1.34 ^b
Texture	5.33 $\pm$ 1.14 ^b	5.90 $\pm$ 1.10 ^a	4.85 $\pm$ 1.55 ^b
Overall Acceptability	5.43 $\pm$ 1.11 ^a	5.78 $\pm$ 0.97 ^a	4.75 $\pm$ 1.46 ^b

Note: Means within the same row followed by different letters are significantly different ($p < 0.05$)

The results in Table 3 show that ingredient proportions significantly affect sensory attributes. Formulation 2 achieved the highest scores for flavor, aroma, and texture, resulting in the highest overall acceptability. In contrast, Formulation 3 showed lower scores across all sensory attributes, resulting in the lowest overall acceptability. Although Formulation 1 received the highest score for color, it was outperformed by Formulation 2 in most attributes. Overall, the results indicate that Formulation 2 was the optimal Formulation for sensory quality.

3.2 Optimal Level of Mud Crab Meat in Crispy Waffles

In this study, three levels of mud crab meat incorporation (5%, 10%, and 15% w/w) were evaluated based on flour weight. The formulations are presented in Table 2, and the production process is illustrated in Figure 2. All samples were evaluated for sensory attributes to determine the optimal level of crab meat. The mean sensory scores of crispy waffles at different levels of incorporation are summarized in Table 4.

As shown in Table 4, the results indicate that different levels of crab meat significantly affect sensory attributes. The formulation containing 5% crab meat showed the highest scores across all attributes. In contrast, the formulations containing 10% and 15% crab meat showed lower scores, with the 15% level resulting in the lowest values, particularly in texture and flavor. These results indicate that incorporating mud crab meat at 5% provides the optimal sensory quality for crispy waffle products.

Table 4. Sensory evaluation of crispy waffle with different amounts of mud crab crispy waffle products

Sensory parameters	Mean $\pm$ SD		
	5%	10%	15%
Color	6.33 $\pm$ 0.60	5.83 $\pm$ 1.01	5.26 $\pm$ 0.82
Aroma	6.00 $\pm$ 0.98	5.23 $\pm$ 1.07	5.16 $\pm$ 0.79
Flavors	6.03 $\pm$ 0.92	5.23 $\pm$ 0.67	5.81 $\pm$ 1.04
Texture	5.94 $\pm$ 0.91	5.26 $\pm$ 0.63	4.33 $\pm$ 1.06
Appearance	5.78 $\pm$ 0.88	5.36 $\pm$ 1.06	5.16 $\pm$ 0.69
Overall Acceptability	6.03 $\pm$ 0.85	5.26 $\pm$ 0.69	5.23 $\pm$ 1.04

Note: Means within the same row followed by different letters are significantly different ($p < 0.05$)

3.3 Evaluation of the Quality of Crispy Mud Crab Waffle Products

The formulation with the highest sensory acceptability, based on the sensory evaluation (Table 4), was selected for further analysis of its physicochemical properties. All analyses were performed in triplicate, and the results are presented in Table 5.

Table 5. Physicochemical Properties of Crispy Mud Crab Waffles

Parameters	Values
Physical Components	
Water Activity (a_w)	0.50 ± 0.01
Lightness (L^*)	51.44 ± 0.23
Redness (a^*)	6.30 ± 0.12
Yellowness (b^*)	43.32 ± 0.17
Textures (Crispness)	$5.77 (N) \pm 0.24$
Chemical Composition (g/100 g)	
Protein	12.36 ± 0.07
Carbohydrates	66.90 ± 0.25
Lipids (Fats)	13.30 ± 0.17
Moisture (Water)	5.63 ± 0.04
Ash (Minerals)	1.98 ± 0.16
Energy (kcal/100 g)	435.21 ± 0.34

Note: A higher L^* is a measure of greater lightness, Positive a^* is a measure of redness, while negative a^* is a measure of greenness, Positive b^* is a measure of yellowness, whereas negative b^* is a measure of blueness

Table 5 shows that the crispy mud crab waffle had a water activity (a_w) of 0.50 and a moisture content of 5.63%, indicating good product stability and a crispy texture, as supported by the texture (crispness) value (5.77 N). The L^* , a^* , and b^* values indicate that the product exhibited a yellowish color with moderate lightness.

In terms of proximate composition, the product contained 12.36% protein, 66.90% carbohydrates, and 13.30% fat, with an energy value of 435.21 kcal/100 g. The ash content (1.98%) suggests the presence of mineral components derived from the raw materials.

Overall, the crispy mud crab waffle demonstrated acceptable physicochemical properties, characterized by a crispy texture and balanced composition.

4. Discussion

As shown in Table 3, the test sample of Formulation 2 received the highest mean scores across the key sensory attributes—aroma, taste, texture, appearance, and overall acceptability. This can be attributed to the fact that Formulation 2 contained the highest proportion of corn flour, which contributed to a crispier texture. This result is supported by Sunthon et al. (2017) who reported that incorporating corn flour into snack formulations containing purple rice and corn flour enhanced product crispness.

Based on these results, the test sample of Formulation 2 was identified as the most suitable candidate for further testing aimed at establishing the optimal proportion of dried mud crab meat for the crispy waffle product.

Table 4 shows that a 5% inclusion level of mud crab meat yielded the highest mean sensory scores, indicating it to be the most appropriate amount for the crispy waffle product. As the percentage of crab meat increased, the moisture content also rose, which negatively affected the expansion of the waffle. This observation supports the work of Jeeranan et al., (2024), who found that increasing rice-field crab content in seasoned rice crackers reduced product expansion.

In addition to the increased moisture content, the higher amount of crab meat affected the dispersibility of the waffle batter. It was observed that the waffle batter containing a higher crab content spread less when placed inside the waffle iron. This result was consistent with the findings of Patcharalak et al., (2025), who developed crispy waffles enriched with pink oyster mushroom powder. Their study indicated that the fibrous structure of the powder enhanced the water-holding capacity (WHC), which limited batter spread during cooking and produced thicker waffles.

In the quality assessment of the crispy mud crab waffle that received the highest sensory acceptability, it was found that the product had a water activity (a_w) of 0.50 and a moisture content of 5.63%. These values produced a desirable crispness. According to Khanittha et al., (2025), the quality standard for dehydrated foods requires a water activity (a_w) below 0.6. As reported in their study “Characterization of Enzyme-Extracted Rice Bran Protein Powder and Its Application in Protein-Enriched Jelly,” Microbial growth is inhibited and controlled under these conditions, a process that correlates strongly with the measured crispness value of 5.77 N.

The color values (L^* , a^* , b^*) reflected moderate lightness with a dominant yellow tone, which is characteristic of dried baked products. The proximate composition showed that the product contained 66.90% carbohydrates, 12.36% protein, and 13.30% fat, providing an energy value of 435.21 kcal per 100 g, aligning with typical starch-based crispy snack formulations.

Overall, the findings indicated that the test sample of formulation 2 with the addition of 5% mud crab meat was identified as the most suitable formulation, delivering superior sensory performance and appropriate physical and chemical attributes. This outcome highlighted the product’s viability for further industrial production.

5. Conclusions and recommendations

The results of this study showed that Formulation 2 with 5% mud crab meat incorporation was the optimal formulation, demonstrating high sensory acceptability and acceptable physicochemical properties.

Future research should focus on improving the nutritional profile of the product, particularly by increasing its dietary fiber content. In addition, further studies should investigate shelf-life stability, texture changes during storage, and the effects of processing conditions on product quality. The development of standardized quality control and processing protocols is also recommended to support consistent product quality and scalability.

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การรับสัมผัสองค์ประกอบธาตุฟุมโลหะจากการเชื่อมอาร์กโลหะฐานเหล็กกล้าคาร์บอนต่ำและ
เหล็กเคลือบสังกะสีด้วยกระบวนการเชื่อมอาร์กด้วยลวดหุ้มฟลักซ์และโลหะแก๊สคลุม
Exposure to Elemental Constituents of Metal Fumes Generated from
Flux-Cored Arc Welding and Gas Metal Arc Welding
of Low-Carbon Steel and Galvanized Steel

กัญญารัตน์ เทียมแก้ว¹ อัญมณี สร้างบุญ¹ รศิกานจน์ อินธนู¹ อภิญา มณีรัตน์¹ ปิยฉัตร กลิ่นมาก¹
มนหาทิพย์ ธนาวิชิตฤกษ์¹ และ กฤษดา เพ็งอารีย์^{2*}

Kanyarat Tiamkaew¹, Unyamanee Sangboon¹, Rasikarn Inthanoo¹, Apinya Maneerat¹,
Piyachat Klinmak¹, Montatip Tanavichitlurk¹ and Kritsada Phengarree^{2*}

¹สาขาวิชาอาชีวอนามัยและความปลอดภัย สำนักวิชาสาธารณสุขศาสตร์ มหาวิทยาลัยเทคโนโลยีสุรนารี จังหวัดนครราชสีมา

²สาขาวิชาอาชีวอนามัยและความปลอดภัย ภาควิชาวิทยาศาสตร์ชีวภาพและสุขภาพ คณะวิทยาศาสตร์ มหาวิทยาลัยอุบลราชธานี จังหวัดอุบลราชธานี

¹School of Occupational Health and Safety, Institute of Public Health,

Suranaree University of Technology, Nakhon Ratchasima Province

²Occupational Health and Safety Program, Department of Biological Science,

Faculty of Science, Ubon Ratchathani University, Ubon Ratchathani Province

*Corresponding Author: kritsada.p@ubu.ac.th

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาปริมาณการรับสัมผัสฟุมโลหะ ลักษณะของฟุมโลหะ ธาตุและปริมาณธาตุองค์ประกอบของฟุมโลหะที่เป็นอันตรายจากการเชื่อมโลหะฐานเหล็กกล้าคาร์บอนต่ำ และเหล็กเคลือบสังกะสี ด้วยกระบวนการเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ และการเชื่อมอาร์กโลหะแก๊สคลุม โดยการเก็บตัวอย่างฟุมโลหะบริเวณหายใจติดตัวบุคคล และวิเคราะห์ปริมาณฟุมโลหะด้วยการชั่งน้ำหนัก การวิเคราะห์คุณสมบัติลักษณะด้วยกล้องจุลทรรศน์แบบส่องกราด (SEM) การวิเคราะห์แยกองค์ประกอบธาตุด้วยเครื่องเอกซเรย์ฟลูออเรสเซนซ์ (XRF) และการวิเคราะห์ปริมาณองค์ประกอบธาตุด้วยเครื่องวิเคราะห์ปริมาณแร่ธาตุในระดับความเข้มข้นต่ำ (ICP-MS) ผลการวิจัยพบว่า การเชื่อมแบบกระบวนการเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ด้วยเหล็กเคลือบสังกะสีมีค่าความเข้มข้นฟุมโลหะเฉลี่ยสูงสุด ($3.24 \pm 0.52 \text{ mg/m}^3$) รองลงมาคือการเชื่อมอาร์กโลหะแก๊สคลุมด้วยเหล็กเคลือบสังกะสี ($2.73 \pm 0.39 \text{ mg/m}^3$) มีขนาดสูงกว่าการเชื่อมที่ใช้เหล็กกล้าคาร์บอนเป็นโลหะฐาน ลักษณะฟุมโลหะมีลักษณะทรงกลมมีขนาดอยู่ระหว่าง $1.027\text{--}1.474 \text{ }\mu\text{m}$ ซึ่งใกล้เคียงกัน ส่วนฟุมจากเหล็กเคลือบสังกะสีมีทั้งอนุภาคขนาดไมครอน ($>1.0 \text{ }\mu\text{m}$) และนาโนเมตร ($<1.0 \text{ }\mu\text{m}$) ขนาดอยู่ระหว่าง $0.168\text{--}1.753 \text{ }\mu\text{m}$ องค์ประกอบฟุมโลหะด้วย XRF พบว่า เหล็ก (Fe) เป็นองค์ประกอบหลัก รวมทั้งพบว่ามีปริมาณความเข้มข้นจากการวิเคราะห์ด้วย ICP-MS การเชื่อมอาร์กโลหะด้วยลวดหุ้มฟลักซ์ด้วยเหล็กเคลือบสังกะสีพบฟุมโลหะรวมมากที่สุด (11.473 mg/m^3) และพบปริมาณองค์ประกอบหลัก 3 ลำดับ ได้แก่ เหล็ก (Fe) (7.968 mg/m^3) สังกะสี (Zn) (2.468 mg/m^3) และเงิน (Ag) (0.344 mg/m^3) ตามลำดับ ผลของงานวิจัยนี้ชี้ให้เห็นว่าปัจจัยที่มีผลต่อการเกิดองค์ประกอบธาตุและปริมาณของฟุมโลหะคือชนิดของโลหะฐานและกระบวนการเชื่อม

คำสำคัญ: ฟุมโลหะ, กระบวนการเชื่อมอาร์กด้วยลวดหุ้มไส้ฟลักซ์, การเชื่อมอาร์กโลหะแก๊สคลุม, การเชื่อมโลหะฐานเหล็กเคลือบสังกะสี, การเชื่อมโลหะฐานเหล็กกล้าคาร์บอนต่ำ

Abstract

This study aimed to investigate the level of metal fume exposure, the characteristics of metal fumes, and the elemental composition and concentrations of hazardous metal fumes generated from welding low-carbon steel and galvanized steel using Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW). Personal breathing zone samples were collected, and the total metal fume concentration was determined by gravimetric analysis. Fume morphology was examined using Scanning Electron Microscopy (SEM), elemental identification was performed using X-ray Fluorescence (XRF), and quantitative elemental analysis was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results indicated that FCAW on galvanized steel produced the highest average metal fume concentration ($3.24 \pm 0.52 \text{ mg/m}^3$), followed by GMAW on zinc-coated steel ($2.73 \pm 0.39 \text{ mg/m}^3$), both of which were higher than those measured during the welding of carbon steel. The metal fumes exhibited predominantly spherical particles with sizes ranging from 1.027 to 1.474 μm . Fumes generated from zinc-coated steel consisted of both micron-sized ($>1.0 \mu\text{m}$) and nanoscale ($<1.0 \mu\text{m}$) particles, with sizes ranging from 0.168 to 1.753 μm . XRF analysis showed iron (Fe) to be the principal elemental component. ICP-MS results further revealed that FCAW on galvanized steel generated the highest total metal fume concentration (11.473 mg/m^3), with the three most abundant elements being iron (Fe) (7.968 mg/m^3), zinc (Zn) (2.468 mg/m^3), and silver (Ag) (0.344 mg/m^3), respectively. These findings highlight that both the type of base metal and the welding process significantly influence the elemental composition and concentration of metal fumes.

Keywords: Metal fumes, Flux-cored arc welding (FCAW), Gas metal arc welding (GMAW), Galvanized steel, Low-carbon steel

1. Introduction

In contemporary industrial sectors, manufacturing processes have continuously advanced through the integration of modern technologies aimed at enhancing efficiency, product quality, and operational safety. Among these technologies, welding serves a crucial role as a primary process for joining or fusing metal components to achieve strong and reliable bonds. This is particularly important in welding applications for furniture structures. Commonly, two major welding processes are employed: Flux-Cored Arc Welding (FCAW), which provides high-speed and durable welds, and Gas Metal Arc Welding (GMAW), which produces cleaner welded beads with reduced fume generation. Both techniques are widely used for welding carbon steel and galvanized steel in structural work, construction, and furniture manufacturing.

Welding processes typically generate metal fumes consisting of ultrafine particles (Quémerais et al., 2015; Stanislawska et al., 2017) formed through the condensation of vaporized metals from the weld pool. These particles can be directly inhaled into the respiratory system, posing both short-term and long-term health risks (Kulkarni, 2020). Numerous studies have reported health hazards associated with exposure to metal fumes and various metal oxides, influenced by factors such as welding current or base metal composition (Phengarree et al., 2025; Hedberg et al., 2021). Metal fumes may contain a range of hazardous elements. Silver (Ag) fumes can cause argyria following prolonged exposure, characterized by a gray or bluish discoloration of the skin due to the accumulation of silver particles in the body (Cohen et al. 2004; Kim et al., 2019). Cadmium (Cd) is highly toxic and classified as a carcinogen; chronic exposure is associated with an increased risk of lung cancer (Hartwig, 2012; García-Esquinas et al., 2014). Chromium (Cr), particularly in the hexavalent form (Cr^{6+}), is a potent carcinogen capable of inducing cellular mutations and DNA damage, which may lead to lung cancer and other malignancies (Pires et al., 2006). Although copper (Cu) is

less toxic than many other metals, inhalation of copper fumes can trigger metal fume fever, presenting flu-like symptoms such as fever, chills, and fatigue within hours of exposure. High or prolonged exposure to iron (Fe) fumes can cause siderosis, characterized by the accumulation of iron particles in the lungs, chronic inflammation, and impaired respiratory function (Nemery, 2022; Banerjee et al., 2006). Nickel (Ni) is another major carcinogenic metal associated with lung and nasal cancers due to its mutagenic properties and ability to promote carcinogenesis (Genchi et al., 2020; Duda-Chodak & Blaszczyk, 2008). Manganese (Mn) exposure over extended periods may lead to manganism, a neurodegenerative disorder resembling Parkinson's disease caused by manganese deposition in the brain (Guilarte, 2010; Aschner et al., 2009). Zinc (Zn) fumes may also cause fume fever, similar to copper, but generally less severe, with recovery typically occurring within 24 hours (Schoofs, Schmit, & Rink, 2024).

Given the health impacts and hazardous composition of metal fumes, many metals commonly encountered in welding processes, such as low-carbon steel and galvanized steel (Japanese Industrial Standards Committee, 2011) pose significant health risks to welding operators. Therefore, investigating metal fume exposure during welding is essential for risk assessment and the development of effective exposure control strategies in industrial workplaces. In addition to direct health risks, welding-related illnesses may also lead to indirect impacts in industrial settings, including increased medical expenses and compensation costs, prolonged work absences that affect workers' income, and disruptions to production processes, thereby resulting in broader economic and social consequences.

Based on a systematic review of the literature, a significant knowledge gap was identified in comparative studies on the characteristics of metal fumes and their elemental composition. Currently, limited research has been conducted in this area, and no studies have yet compared the Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) processes for both low-carbon steel and galvanized steel. To address this gap, the present study aims to examine metal fume exposure generated during the welding of low-carbon steel and galvanized steel using Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) processes.

The objectives are to quantify metal fume exposure levels, characterize the morphology and particle size of welding fumes, and analyze the chemical composition and elemental concentrations within the fumes. The resulting data can be utilized to improve occupational health and safety measures for welders in the industrial sector.

2. Materials and methods

This study employed quasi-experimental research and was approved by the Human Research Ethics Committee of Suranaree University of Technology, with the ethics approval certificate number COA No. 32/2564. The approval covered metal arc welding experiments, air sampling procedures, and all related analytical methods. The research methodology was described as follows:

2.1 Welding Techniques and Base Metals

In this study, commonly used welding processes for various types of furniture production were employed. Arc welding was selected as it utilizes an electric arc as a high-temperature heat source to melt and fuse metals. Two primary welding processes were used: (1) Flux-Cored Arc Welding (FCAW) employs flux to generate shielding gas and slag that protect the weld pool from atmospheric contamination. FCAW was performed using E71T-11 flux-cored electrodes with a diameter of 1.2 mm, and (2) Gas Metal Arc Welding (GMAW), which uses an inert shielding gas to protect the weld zone from reacting with oxygen and

other atmospheric gases. In this experiment, solid welding wire with a diameter of 1.2 mm was used, along with 100% pure argon (100% Ar) as the shielding gas.

Welding was carried out on carbon steel and galvanized steel plates measuring 200 × 100 mm with a thickness of 6 mm (plates with dimensions of 200 × 100 × 6 mm). For both welding processes, bead-on-plate welding in the flat position was performed for 10 minutes and repeated three times. All welding parameters were strictly controlled to ensure the accuracy and reliability of the experimental results. The experiments were carried out in an open-type industrial welding workshop using dilution or natural ventilation. Environmental conditions were monitored, with air velocity ranging from 0.00 to 0.12 m/s, relative humidity from 49% to 57%, atmospheric pressure between 755 and 757 mmHg, and ambient temperature from 31.1 to 32.6 °C.

2.2 Collection and Quantification of Total Metal Fumes

Metal fume sampling was conducted using a calibrated personal air sampling pump (Personal Air Sampler) with a constant airflow rate of 2.0 liters per minute (L/min). The air sampling procedure was adapted from NIOSH Method #0500 for total particulates, utilizing a filter cassette equipped with a 37-mm mixed-cellulose ester (MCE) membrane filter with a pore size of 0.8 µm, as further adapted from NIOSH Method #7200. The filter cassette was positioned within the welder's breathing zone to obtain samples representative of actual exposure.

Before sampling, all filters were conditioned in a desiccator for at least 24 hours and subsequently weighed using a six-digit analytical balance. After sampling, the filters were reweighed to determine the mass of collected metal fumes. The airborne metal fume concentration (mg/m³) was calculated using Equation (1). During sampling, environmental parameters, including temperature, relative humidity, atmospheric pressure, and air velocity, were recorded to support subsequent data analysis.

$$C = \frac{(W_2 - W_1) - (B_2 - B_1) \times 10^3}{V} \quad (1)$$

where: C is the concentration of total metal fumes (mg/m³); W₁ is the weight of the filter before sampling (mg); W₂ is the weight of the filter after sampling (mg); B₁ is the weight of the blank filter before sampling (mg); B₂ is the weight of the blank filter after sampling (mg); and V is the volume of sampled air (L).

2.3 Elemental Analysis by XRF

Elemental composition was examined using X-ray fluorescence spectrometry (XRF) (Horiba, XGT-5200WR, Japan). Filter samples containing collected metal fumes from both welding processes, Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW), were analyzed by performing X-ray measurements at nine points on each filter and comparing them with blank filters. This analysis provided qualitative information to identify elemental constituents in terms of weight percentage (Wt.%). The obtained values were then averaged and subsequently used to support quantitative analysis using an ICP-MS.

2.4 Quantitative Elemental Analysis by ICP-MS

After qualitative analysis using the XRF technique, the filter samples and filter blanks were digested using a microwave digestion system (Mars 6 Microwave Digestion). Digestion was performed with 2% nitric acid (HNO₃) at 180 °C and 1,000 W for 30 minutes. The resulting solutions were subsequently analyzed using inductively coupled plasma–mass spectrometry (ICP-MS) (Agilent Technologies, model 7700,

USA) to quantify the concentrations of metallic elements in the fumes, including Ag, Cd, Cr, Cu, Fe, Ni, Mn, and Zn.

A mixed standard solution was prepared from primary standard solutions at concentrations of 1, 5, 10, 20, 50, and 100 ppb to construct calibration curves, which demonstrated correlation coefficients (R) greater than 0.995. The ICP-MS results were initially obtained in units of $\mu\text{g/mL}$ (ppb) and subsequently converted to airborne concentrations (mg/m^3) using Equation (2) to allow comparison with occupational exposure limits.

$$C = \frac{C_s V_s - C_b V_b}{V} \quad (2)$$

where C is the concentration of metal fumes in air (mg/m^3 or $\mu\text{g/L}$); C_s is the concentration in the sample solution ($\mu\text{g/mL}$); C_b is the average concentration of the blank solution ($\mu\text{g/mL}$); V_s is the volume of the sample solution (mL); V_b is the volume of the blank solution (mL); and V is the total volume of sampled air (L).

2.5 Statistical Analysis

In this study, descriptive statistics, including mean, standard deviation (SD), maximum (Max), minimum (Min), and percentages (%), were used to present the quantitative results. The analysis measured metal fume concentrations in air (mg/m^3) and quantified the elemental composition of the fumes using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), also expressed in mg/m^3 .

3. Result

3.1 Metal Fume Concentration by Gravimetric Analysis

The results of metal fume concentration determined by gravimetric analysis are presented in Table 1. For Flux-Cored Arc Welding (FCAW), welding of low-carbon steel produced an average metal fume concentration of $2.22 \pm 0.36 \text{ mg/m}^3$, while galvanized steel exhibited a higher average concentration of $3.24 \pm 0.52 \text{ mg/m}^3$. For Gas Metal Arc Welding (GMAW), welding of low-carbon steel resulted in an average metal fume concentration of $1.56 \pm 0.49 \text{ mg/m}^3$, whereas galvanized steel showed an average concentration of $2.73 \pm 0.39 \text{ mg/m}^3$. Overall, both welding processes generated higher metal fume concentrations when working with galvanized steel compared to low-carbon steel. These results demonstrate that both the welding process and the type of base metal influence metal fume generation.

Table 1. The concentration of metal fumes as determined by gravimetric analysis

Welding Process	Type of Steel	Metal fume concentration (mg/m^3)				
		n	Max	Min	SD	Mean
FCAW	Low Carbon	3	2.61	1.73	0.36	2.22
	Galvanized	3	3.92	2.94	0.52	3.24
GMAW	Low Carbon	3	2.10	1.51	0.49	1.56
	Galvanized	3	3.24	2.32	0.39	2.73

3.2 Characteristics and Particle Size of Metal Fumes Observed by SEM

Scanning Electron Microscopy (SEM) (JEOL, model JCM-5000, Japan) was used to examine the characteristics of metal fumes generated during the welding of low-carbon steel and galvanized steel using two arc welding processes: Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW). The analysis showed that in both welding processes, the metal fumes were densely packed and similarly distributed on filter paper, exhibiting spherical shapes and granular, metal-like morphology with comparable particle sizes. For FCAW, the average particle size for low-carbon steel was $1.284 \pm 0.200 \mu\text{m}$, ranging from 1.027 to 1.565 μm , while for galvanized steel, the average particle size was smaller at $0.400 \pm 0.415 \mu\text{m}$, ranging from 0.168 to 1.228 μm , with a mean below 1 μm . Particle size analysis revealed two distinct ranges: particles smaller than 1 μm (submicron-sized particles) and particles larger than 1 μm . For GMAW, the average particle size for low-carbon steel was $1.313 \pm 0.133 \mu\text{m}$, ranging from 1.139 to 1.474 μm , and for galvanized steel, it was $1.358 \pm 0.212 \mu\text{m}$, ranging from 1.139 to 1.753 μm , indicating similar particle size characteristics. Among the two welding processes, FCAW of galvanized steel produced the smallest particle sizes compared with all other conditions. In summary, the results are presented in Table 2, and the morphological characteristics of the metal fumes are shown in Figure 1 for FCAW and Figure 2 for GMAW.

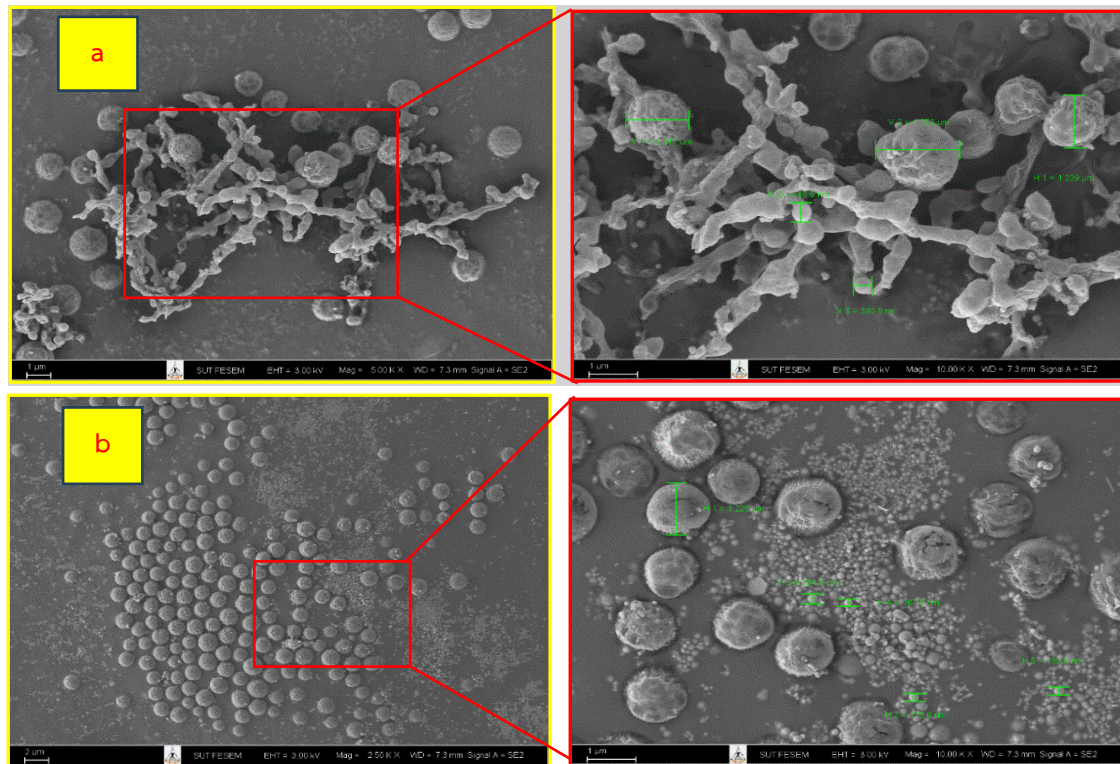


Figure 1. Morphology of metal fumes generated from Flux-Cored Arc Welding (FCAW)

(a) Low-carbon steel, and (b) Galvanized steel

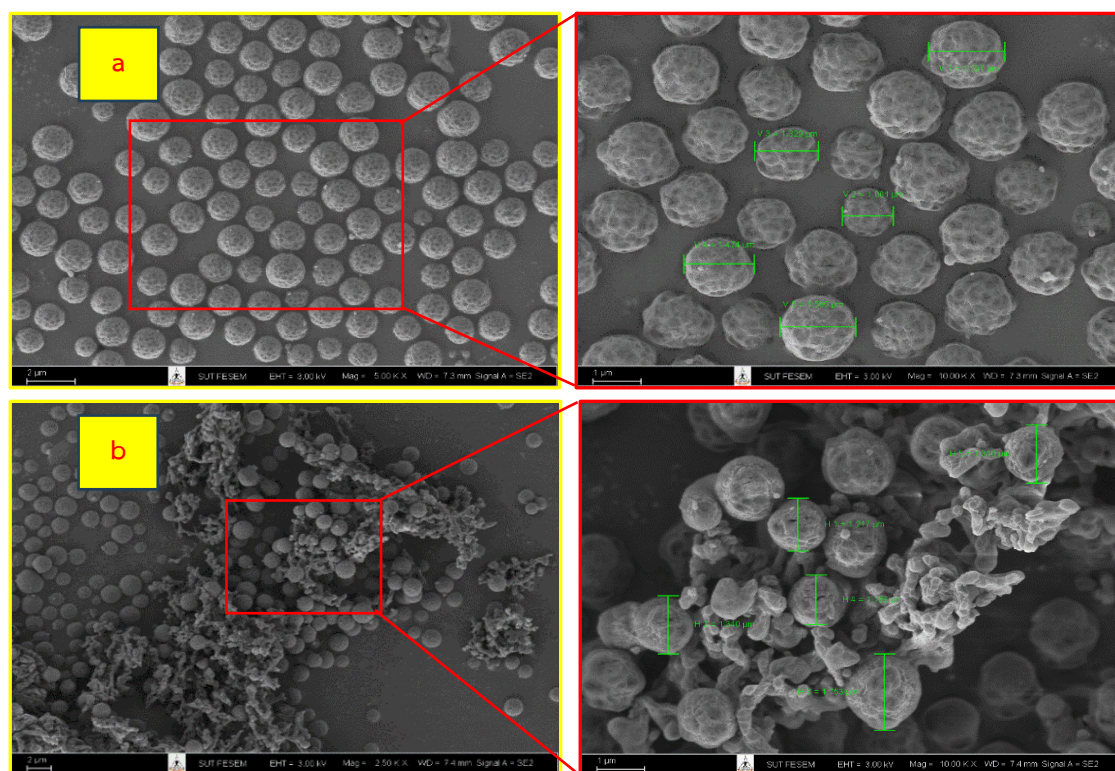


Figure 2. Morphology of metal fumes generated from Gas Metal Arc Welding (GMAW)
(a) Low-carbon steel, and (b) Galvanized steel

Table 2. Fume Particle Size from Scanning Electron Microscopy (SEM)

Welding Process	Fume particle size (μm)							
	Low Carbon Steel				Galvanized Steel			
	Min	Max	SD	Mean	Min	Max	SD	Mean
FCAW	1.027	1.565	0.200	1.284	0.168	1.228	0.415	0.400
GMAW	1.139	1.474	0.133	1.313	1.139	1.753	0.212	1.358

3.3 Elemental Composition of Metal Fumes by XRF

The elemental composition of metal fumes generated from welding varied depending on the welding process and the type of base metal. For Flux-Cored Arc Welding (FCAW) using low-carbon steel as the base metal, the five main elements in the fumes were iron (Fe, 44.37 ± 5.77 Wt.%), silver (Ag, 11.10 ± 1.64 Wt.%), manganese (Mn, 8.72 ± 0.056 Wt.%), zinc (Zn, 4.25 ± 2.24 Wt.%), and copper (Cu, 4.39 ± 3.23 Wt.%). In contrast, when galvanized steel was used as the base metal, zinc was the predominant element (Zn, 19.57 ± 13.07 Wt.%), followed by iron (Fe, 24.48 ± 16.50 Wt.%), silver (Ag, 5.51 ± 6.88 Wt.%), manganese (Mn, 4.36 ± 2.66 Wt.%), and copper (Cu, 0.31 ± 2.17 Wt.%).

For Gas Metal Arc Welding (GMAW) with low-carbon steel as the base metal, the top five elements were iron (Fe, 40.39 ± 5.06 Wt.%), silver (Ag, 17.83 ± 11.70 Wt.%), zinc (Zn, 6.65 ± 7.85 Wt.%), manganese (Mn, 6.37 ± 1.24 Wt.%), and copper (Cu, 4.38 ± 3.46 Wt.%). When galvanized steel was used as the base metal, zinc had the highest proportion, followed by iron (Fe, 35.60 ± 0.75 Wt.%), zinc (Zn,

28.77 ± 8.65 Wt.%), silver (Ag, 5.52 ± 7.27 Wt.%), manganese (Mn, 3.15 ± 0.76 Wt.%), and copper (Cu, 1.09 ± 1.39 Wt.%).

These XRF results provided qualitative information on the elemental composition of metal fumes, which served as preliminary data for subsequent quantitative analysis using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) to determine elemental concentrations at trace levels.

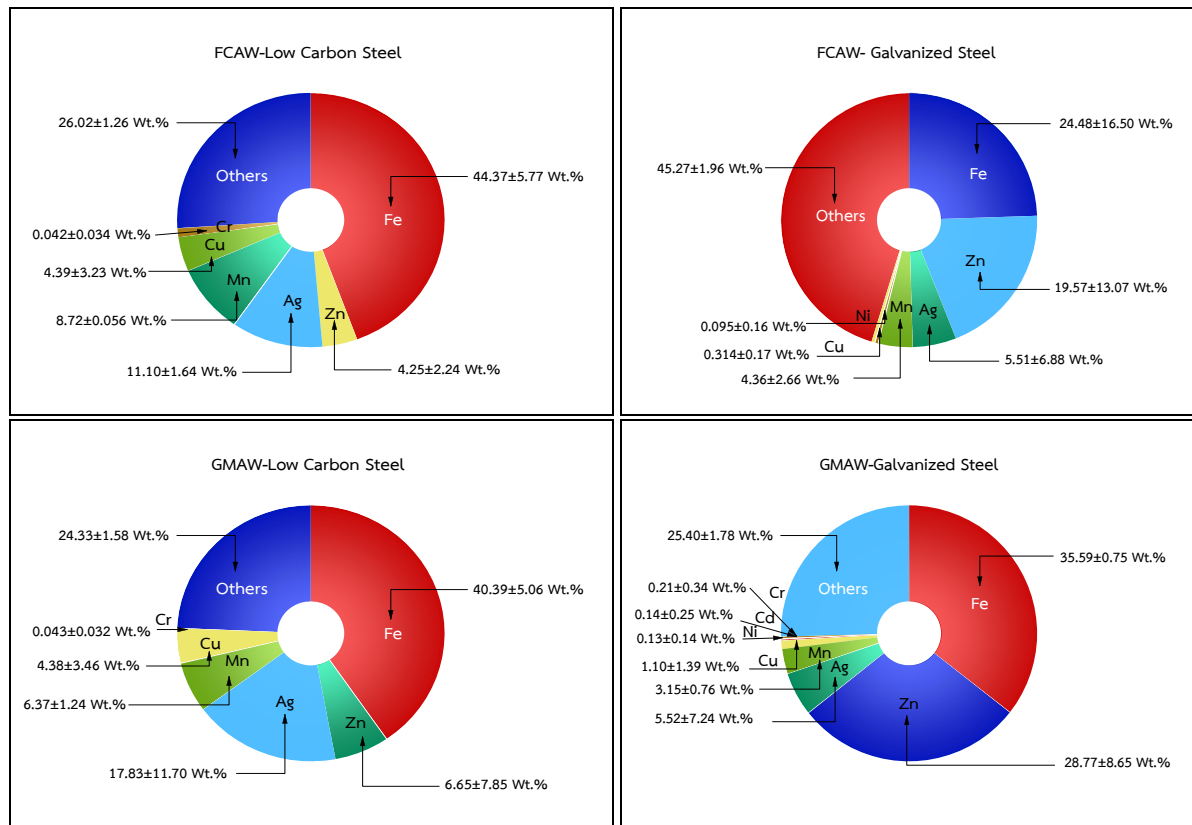


Figure 3. Weight percentage (Wt.%) of elemental composition from the welding processes

3.4 Concentrations of Elemental Components in Metal Fumes Determined by ICP-MS

When using low-carbon steel as the base metal in Flux-Cored Arc Welding (FCAW), the average concentrations of the elemental components in the metal fumes were as follows: iron (Fe) 1.235 mg/m³, zinc (Zn) 0.034 mg/m³, silver (Ag) 0.037 mg/m³, manganese (Mn) 0.130 mg/m³, copper (Cu) below 0.000 mg/m³ (below the detection limit), nickel (Ni) 0.006 mg/m³, cadmium (Cd) 0.014 mg/m³, and chromium (Cr) 0.017 mg/m³. For FCAW using galvanized steel as the base metal, the average concentrations were: Fe 7.968 mg/m³, Zn 2.468 mg/m³, Ag 0.344 mg/m³, Mn 0.677 mg/m³, Cu below 0.000 mg/m³, Ni 0.003 mg/m³, Cd 0.004 mg/m³, and Cr 0.006 mg/m³.

For Gas Metal Arc Welding (GMAW) using low-carbon steel as the base metal, the average concentrations were: Fe 0.644 mg/m³, Zn 0.017 mg/m³, Ag 0.041 mg/m³, Mn 0.059 mg/m³, Cu below 0.000 mg/m³ (below the detection limit), Ni 0.002 mg/m³, Cd 0.003 mg/m³, and Cr 0.298 mg/m³. For GMAW using galvanized steel as the base metal, the average concentrations were: Fe 1.760 mg/m³, Zn 0.641 mg/m³, Ag 0.118 mg/m³, Mn 1.185 mg/m³, Cu below 0.000 mg/m³, Ni 0.001 mg/m³, Cd 0.002 mg/m³, and Cr 0.003 mg/m³.

Figure 4 presents the results as the average concentrations of elemental components in metal fumes for each welding process using either low-carbon steel or galvanized steel as the base metal. The highest total metal fume concentration was observed in Flux-Cored Arc Welding (FCAW) with galvanized steel as the base metal (11.473 mg/m³), followed by Gas Metal Arc Welding (GMAW) with galvanized steel (2.743 mg/m³), FCAW with low-carbon steel (1.473 mg/m³), and GMAW with low-carbon steel (1.064 mg/m³), respectively.

Across both welding processes and base metals, the three most abundant elements on average were iron (Fe, 2.902 mg/m³), zinc (Zn, 0.790 mg/m³), and manganese (Mn, 0.263 mg/m³). These results indicate that FCAW using galvanized steel as the base metal produces the highest exposure to metal fumes.

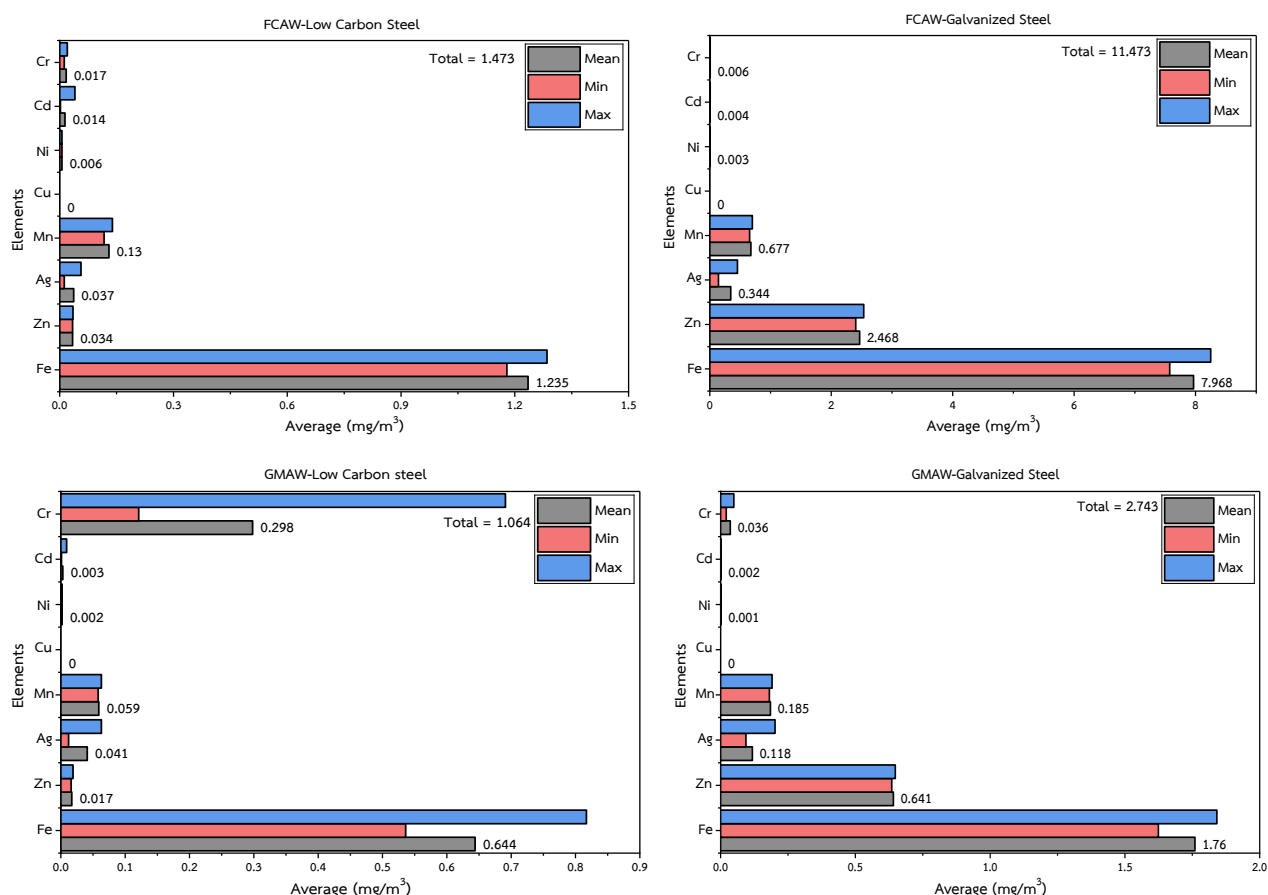


Figure 4. Concentration of elemental components in welding metal fumes (mg/m³)

4. Discussion

Analysis of Metal Fume Concentration by Gravimetric Method. The result of metal fume concentrations using the gravimetric method in the welding of low-carbon steel and galvanized steel through Flux-Cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW) is shown in Table 1, FCAW with galvanized steel as the base metal produced the highest average concentration of metal fumes (3.24 ± 0.52 mg/m³), followed by GMAW with galvanized steel (2.73 ± 0.39 mg/m³). These concentrations were higher than those observed when low-carbon steel was used as the base metal. This finding is

consistent with previous studies by Cao et al. (2018) and Hartmann et al. (2019), which reported that welding galvanized steel leads to increased evaporation of metals and oxides under arc heating.

Morphology of Metal Fumes by Electron Microscopy. Scanning Electron Microscopy (SEM) analysis showed that metal fumes from low-carbon steel in both welding processes were densely packed and deposited on the filter in a similar pattern, exhibiting spherical shapes and metallic granules. This observation is consistent with Wycislik-Sosnierz et al. (2024), Sowards et al. (2008) and Phengarree et al. (2025), who reported that metal fumes from FCAW and GMAW form spherical particles that tend to agglomerate into micron-sized clusters. In the case of galvanized steel, metal fumes exhibited mixed particle sizes, including micron-sized particles ($>1.0\ \mu\text{m}$) and submicron-sized particles ($<1.0\ \mu\text{m}$), as shown in Figures 1A and 2B. Notably, welding with galvanized steel showed zinc volatilization, likely due to oxidation reactions in the arc atmosphere, leading to the formation of fine particles through condensation of evaporated metals (Lipton, 2025; Yang et al., 2018).

The elemental composition of metal fumes was analyzed by X-ray fluorescence (XRF), and the results are presented in Figure 3. The result showed that iron (Fe), the main component of both the welding wire and the base metal, was the predominant element in all welding processes. In FCAW using low-carbon steel, the major elements were Fe (44.37 Wt.%), Ag (11.10 Wt.%), and Mn (8.72 Wt.%). When galvanized steel was used as the base metal, Fe (24.48 Wt.%), Zn (19.57 Wt.%), and Ag (5.51 Wt.%) were the dominant elements. For GMAW, low-carbon steel exhibited Fe (40.39 Wt.%), Ag (17.83 Wt.%), and Zn (6.65 Wt.%), whereas galvanized steel showed Fe (35.59 Wt.%), Zn (28.77 Wt.%), and Ag (5.52 Wt.%). These findings are consistent with Guney (2021), confirming that Fe is the primary component of welding fumes. Other potentially hazardous elements, including Mn, Zn, and Ni, were also detected. The elemental composition varied depending on the base metal, welding process, and the presence or absence of ventilation. The results obtained from XRF analysis provided preliminary compositional information and were subsequently used for quantitative analysis using the ICP–MS technique.

ICP–MS analysis confirmed that Fe remained the predominant component of metal fumes. Welding of galvanized steel produced the highest total metal fume concentrations in both welding processes, with FCAW generating the highest levels (total metal fumes: $11.473\ \text{mg}/\text{m}^3$). In FCAW with galvanized steel, the average concentrations of elements were Fe $7.968\ \text{mg}/\text{m}^3$, Zn $2.468\ \text{mg}/\text{m}^3$, Ag $0.344\ \text{mg}/\text{m}^3$, Mn $0.677\ \text{mg}/\text{m}^3$, Ni $0.003\ \text{mg}/\text{m}^3$, Cd $0.004\ \text{mg}/\text{m}^3$, and Cr $0.006\ \text{mg}/\text{m}^3$, as shown in Figure 4. These metal fumes pose significant health risks. Hexavalent chromium (Cr^{6+}) is a potent carcinogen associated with lung and other cancers (Kouokam et al., 2022; DesMarias & Costa, 2019). Iron (Fe) exposure can lead to siderosis, resulting in chronic inflammation and impaired respiratory function (Nemery, 2022; Marques et al., 2022). Silver (Ag), identified as the third most abundant elemental component in zinc-coated, iron-based alloys, poses potential health risks following prolonged exposure. Chronic exposure to silver may result in argyria, a condition characterized by gray or bluish discoloration of the skin caused by the accumulation of silver particles within the body (Kim et al., 2019). Nickel (Ni) is a carcinogen linked to lung and nasal cancers (Genchi et al., 2020; Duda-Chodak & Blaszczyk, 2008). Manganese (Mn) exposure may induce neurotoxicity and Parkinson-like symptoms (Lu et al, 2023; Gonzalez-Alvarez et al., 2022; Khindri & Maj, 2025).

5. Conclusion and suggestions

The findings of this study indicate that Flux-Cored Arc Welding (FCAW) carries a higher risk of metal fume exposure compared to other welding processes, primarily due to the flux in the welding wire, which stabilizes the arc but also increases fume generation. Welding with galvanized steel further elevates

exposure because of zinc volatilization. Moreover, the smaller average particle sizes increase the likelihood of deep respiratory deposition and associated toxicity. Hazardous elements such as hexavalent chromium (Cr^{6+}), cadmium (Cd), silver (Ag), and iron (Fe) pose significant risks for respiratory diseases and cancer, emphasizing the need for effective exposure control measures. Overall, the factors influencing the generation and dispersion of metal fumes include the type of base metal, flux content in the welding wire, and arc intensity between the wire and base metal. For occupational safety, local exhaust ventilation (LEV) should be implemented, processes that minimize metal fume generation should be selected, and respiratory protective equipment in accordance with NIOSH 42 CFR Part 84 should be used.

5.1 Suggestions for Practical Application

The findings of this study can guide the enhancement of occupational safety standards in welding, particularly for tasks involving galvanized steel and Flux-Cored Arc Welding (FCAW), which were found to produce higher levels of metal fumes than Gas Metal Arc Welding (GMAW). Consequently, the results can inform the implementation of engineering controls, such as local exhaust ventilation systems, and the selection of welding processes that reduce metal evaporation. Moreover, knowledge of the composition of metal fumes can assist in choosing suitable respiratory protective equipment based on the level of risk. These findings can also support the development of safety manuals or best-practice guidelines for welders to ensure compliance with occupational health standards. Additionally, the data can be applied to improve training programs and workplace risk assessments, helping to minimize exposure to metal fumes and effectively safeguard workers' health.

5.2 Suggestions for future research

1) The study should be extended to examine metal fume generation from other types of metals, such as stainless steel or metal alloys, to compare the composition, particle size, and concentration of fumes under different welding conditions. In addition, long-term, systematic investigations on the health effects on workers are recommended.

2) Further research is needed to evaluate the influence of welding parameters and the effectiveness of ventilation systems in reducing metal fume concentrations. Real-time monitoring technology can be utilized to track changes in fume concentrations under actual working conditions and to develop control measures tailored to specific welding environments. In addition, welding activities should be investigated in real workplace settings, and the measured exposure levels should be compared with established occupational exposure limits, such as OEL–TLVs or other relevant standards, in order to identify hazards and assess health risks among welders.

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การพัฒนากรอบการจัดการแบบบูรณาการสินค้าซีฟิชมาและแบบจำลองอ้างอิง
การดำเนินงานของซีฟฟลายเซนปลานิลในจังหวัดอุบลราชธานี
Development of an Integrated Lean–Six Sigma–SCOR Framework for Enhancing
Tilapia Supply Chain Performance in Ubon Ratchathani

ปวิณยุดา บุญรมย์¹ จุรีรัตน์ บุตรเหลา¹ ธนัฐดา แก้วสุข¹ อายุพร ชาวฟอง¹
พนิดา ยิ่งยืน¹ จริยา พันธา^{1*} และ นัทธพงศ์ นันทสำเรือง¹

Pawinyada Boonrom¹, Chureerat Butlao¹, Tanadda Kaewsuk¹, Aryuporn Khaofong¹,
Panida Yingyuen¹, Jariya Panta^{1*} and Natthapong Nanthasamrong¹

¹คณะเทคโนโลยีอุตสาหกรรม มหาวิทยาลัยราชภัฏอุบลราชธานี จังหวัดอุบลราชธานี

¹Faculty of Industrial Technology, Ubon Ratchathani Rajabhat University, Ubon Ratchathani province

*Corresponding Author: jariya.p@ubru.ac.th

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อวิเคราะห์โครงสร้างและประสิทธิภาพของซีฟฟลายเซนปลานิลในจังหวัดอุบลราชธานี และพัฒนากรอบการปรับปรุงแบบบูรณาการที่ผสานแบบจำลองอ้างอิงการดำเนินงานซีฟฟลายเซน แนวคิดลีน และกระบวนการของซีฟิชมา แม้ว่าพื้นที่จะมีผลผลิตปลานิลประมาณ 11,601 ตันต่อปี คิดเป็นมูลค่า 670.9 ล้านบาท แต่ระบบซีฟฟลายเซนยังคงเผชิญกับความไม่มีประสิทธิภาพเชิงโครงสร้าง การประสานงานที่อ่อนแอ และการกระจายมูลค่าที่ไม่เป็นธรรมระหว่างผู้มีส่วนได้ส่วนเสีย การวิจัยนี้ใช้การออกแบบเชิงคุณภาพแบบกรณีศึกษาเดียว โดยเก็บรวบรวมข้อมูลผ่านการสัมภาษณ์เชิงลึกและการสังเกตภาคสนามจากผู้ให้ข้อมูลจำนวน 20 ราย ครอบคลุม 4 กลุ่ม ได้แก่ ฟาร์มเพาะพันธุ์ ฟาร์มเลี้ยงแบบกระชัง ผู้ขนส่ง/ผู้ค้าส่ง และผู้ค้าปลีก จากนั้นใช้ SCOR ในการวิเคราะห์กระบวนการซีฟฟลายเซน ใช้แนวคิดลีนในการระบุความสูญเสีย และใช้ DMAIC เป็นกรอบในการวิเคราะห์ปัญหาและออกแบบแนวทางปรับปรุงอย่างเป็นระบบ ผลการศึกษาพบว่ากระบวนการวางแผนเป็นคอขวดสำคัญที่สุดของซีฟฟลายเซน เนื่องจากขาดการพยากรณ์ความต้องการและการแบ่งปันข้อมูล ส่งผลให้เกิดการจัดหาแบบตอบสนอง การผลิตไม่สอดคล้องกับความต้องการ และกระบวนการขนส่งที่กระจัดกระจาย การวิเคราะห์ด้วยแนวคิดลีนพบว่าความสูญเสียประเภทการขนส่งและการรอคอยเป็นปัญหาหลัก จากการประเมินตัวชี้วัดด้วยมาตรวัดแบบลิเคิร์ต 5 ระดับ พบว่าประสิทธิภาพด้านระยะเวลาการส่งมอบ (2/5) ต้นทุนการขนส่ง (2/5) และการประสานงานระหว่างผู้มีส่วนได้ส่วนเสีย (1/5) อยู่ในระดับต่ำ ขณะที่ความเชื่อถือได้ของการส่งมอบคำสั่งซื้ออยู่ในระดับปานกลาง (3/5) จากผลการศึกษาได้เสนอแนวทางปรับปรุงจำนวน 7 แนวทาง ครอบคลุมระยะสั้น กลาง และยาว ได้แก่ การสร้างกลไกแบ่งปันข้อมูลความต้องการ การรวมเส้นทางขนส่ง การรับรองมาตรฐานการปฏิบัติทางการเกษตรที่ดี การจัดตั้งสหกรณ์เกษตรกร และการพัฒนาแพลตฟอร์มดิจิทัลเพื่อเพิ่มประสิทธิภาพ ความโปร่งใส และการประสานงาน โดยแสดงให้เห็นว่ากรอบการทำงานแบบบูรณาการ SCOR–Lean–DMAIC สามารถใช้ในการวิเคราะห์และแก้ไขปัญหาเชิงโครงสร้างเชิงปฏิบัติการ และเชิงระบบของซีฟฟลายเซนเกษตรกรรมแบบรายย่อยได้อย่างเป็นระบบ

คำสำคัญ: ซีฟฟลายเซนปลานิล, แบบจำลองอ้างอิงการดำเนินงานซีฟฟลายเซน, สินค้าซีฟิชมา, กรอบการจัดการซีฟฟลายเซนแบบบูรณาการ, ซีฟฟลายเซนการเพาะเลี้ยงสัตว์น้ำ

Abstract

This study analyzes the structure and performance of the tilapia supply chain in Ubon Ratchathani, Thailand, and develops an integrated improvement framework combining the Supply Chain Operations Reference (SCOR) model, Lean principles, and the Six Sigma DMAIC methodology. Despite producing 11,601 tons annually with a value of 670.9 million baht, the provincial supply chain continues to face structural

inefficiencies, weak coordination, and unequal value distribution among stakeholders. A qualitative single-case study design was employed, with primary data collected through in-depth, semi-structured interviews and field observations involving 20 informants across four stakeholder groups: breeding farms, cage-based grow-out farms, transporters/wholesalers, and retailers. SCOR was used to map and evaluate supply chain processes, Lean analysis identified non-value-added activities, and DMAIC guided systematic problem analysis and improvement design. The results reveal that the Plan process is the most critical bottleneck across all actors due to the absence of demand forecasting and information sharing, leading to reactive sourcing, poorly timed production, and fragmented delivery processes. Lean analysis further identifies Transportation and Waiting as the dominant waste categories, driven by uncoordinated routing and repeated handling of live fish. Performance evaluation using a structured five-point Likert scoring procedure indicates low efficiency in delivery lead time (2/5), transportation cost efficiency (2/5), and stakeholder coordination (1/5), while order fulfillment reliability is moderate (3/5). Based on these findings, the study proposes seven improvement strategies across short-, medium-, and long-term horizons, including demand information-sharing mechanisms, route consolidation, Good Agricultural Practices (GAP) certification, farmer cooperative development, and a conceptual digital supply chain platform to enhance coordination, transparency, and efficiency. The study demonstrates how an integrated SCOR–Lean–DMAIC framework can systematically diagnose and address structural, operational, and systemic challenges in smallholder-based aquaculture supply chains.

Keywords: Tilapia supply chain, SCOR model, Lean Six Sigma, integrated supply chain framework, aquaculture supply chain

1. Introduction

Thailand's freshwater aquaculture sector produced approximately 466,953 tons in 2023, generating a market value of around 28,517 million baht. Among cultured species, Nile tilapia (*Oreochromis niloticus*) holds the highest economic value. In 2024, national tilapia production reached 275,958 tons, accounting for 27.63% of freshwater aquaculture output, with a farm-gate value of approximately 13,686 million baht. Ubon Ratchathani Province ranks 8th nationally, producing 11,601 tons valued at 670,867,000 baht across 17,420 farms. Despite this scale, economic benefits remain disproportionately captured by intermediaries rather than primary producers, reflecting broader patterns in Southeast Asian small-scale aquaculture systems (Department of Fisheries, 2024).

The tilapia supply chain in Ubon Ratchathani faces persistent structural and operational challenges. Farmers have low bargaining power due to information asymmetry and heavy dependence on transporter–wholesalers. Inter-stakeholder coordination is weak, and live fish transportation is inefficient. Mortality rates during transport can reach 10–18%, representing significant revenue losses under retail prices of 50–65 THB per kilogram (Colt & Fornshell, 2014). The absence of demand forecasting forces farmers to accept farm-gate prices significantly below downstream value, with margin gaps estimated at 30–50% in comparable aquaculture systems (Bjorndal et al., 2014; Kruijssen et al., 2020). These vulnerabilities are further compounded by limited access to financial services, price volatility, and slow adoption of production and information technologies (Gao & Wongleedee, 2025).

Existing research on aquaculture value chains in South and Southeast Asia has largely emphasized descriptive mapping of actors and relationships. Although recent studies increasingly address resilience and sustainability, systematic, process-oriented improvement frameworks remain limited (Mahmud et al., 2026).

Post-harvest losses in regional fish supply chains are estimated at approximately 25%, driven by inadequate handling, lack of cold chain infrastructure, and inefficient logistics (Kruijssen et al., 2020). Studies applying structured frameworks demonstrate their value in related contexts: SCOR analysis has identified planning failures as key sources of inefficiency in agri-food logistics (Mulyadi et al., 2025), while Lean Six Sigma applications consistently highlight Transportation and Waiting as dominant waste categories (Costa et al., 2018). In fisheries, VSM–DMAIC approaches have proven effective in identifying operational bottlenecks even in qualitative settings (Thamke, 2020), and Lean Six Sigma adoption has been linked to improved financial performance (Tortorella et al., 2020). These frameworks are inherently complementary: SCOR identifies where performance gaps occur, Lean explains what drives inefficiency, and DMAIC provides a structured pathway for improvement (Gomaa, 2025).

However, prior studies typically apply these frameworks in isolation or at a single organizational level. SCOR alone lacks mechanisms for cross-actor coordination (Supply Chain Council, 2012; Mulyadi et al., 2025), Lean lacks system-wide mapping capabilities (Costa et al., 2018), and DMAIC lacks the diagnostic breadth needed for multi-tier supply chains (Gomaa, 2025). In the Ubon Ratchathani case, inefficiencies are simultaneously structural, operational, and systemic, requiring an integrated analytical approach that can address coordination failure, logistics inefficiency, and root-cause persistence across multiple stakeholders.

To address this gap, this study develops and applies an integrated Lean–Six Sigma–SCOR framework to analyze and improve the tilapia supply chain in Ubon Ratchathani. The study maps the supply chain using SCOR, identifies inefficiencies through Lean analysis, and applies DMAIC to examine root causes and propose targeted improvements. The DMAIC cycle is operationalized through the Define, Measure, Analyze, and Improve phases, while the Control phase is considered a future implementation stage. Theoretically, this study extends the application of integrated management frameworks to smallholder aquaculture in developing economies. Practically, the findings provide actionable insights for farmers, supply chain actors, and policymakers seeking to enhance efficiency, coordination, and competitiveness in the tilapia supply chain.

2. Materials and methods

2.1 Research Design

This study adopts a qualitative single-case study design combined with a framework development approach to analyze and improve the tilapia supply chain in Ubon Ratchathani, Thailand. The case is defined as a province-level supply chain encompassing four stakeholder tiers: breeding farms, cage - farming operations, transporters/wholesalers, and retailers. This design is appropriate for examining how and why structural and operational inefficiencies arise within a real-world context (Yin, 2018; Creswell, 2013). The study aims for analytic generalization by developing context-specific insights and a transferable improvement framework. Data were collected from multiple sources, including interviews, field observations, and secondary documents.

The analysis applies an integrated framework combining the SCOR model, Lean principles, and the Six Sigma DMAIC methodology to systematically evaluate performance, identify waste, and guide process improvement.

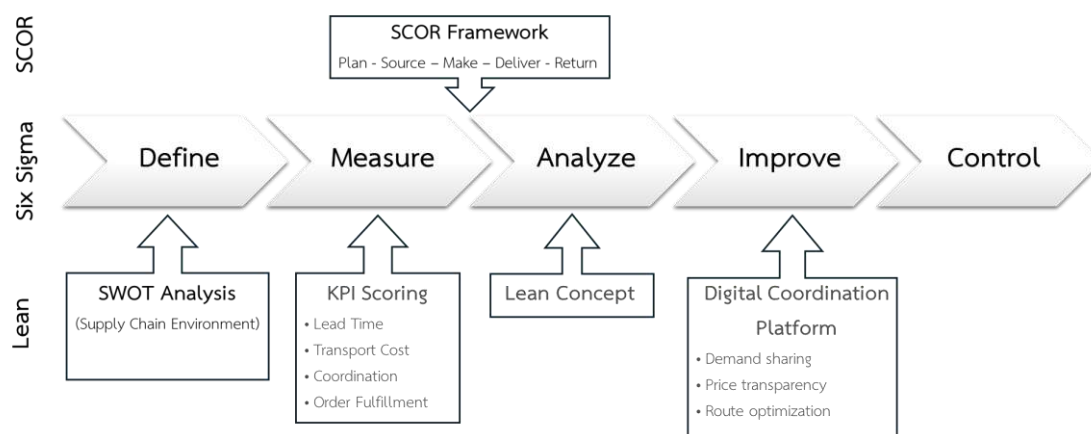


Figure 1. Integrated Lean–Six Sigma–SCOR framework for tilapia supply chain analysis and improvement

As illustrated in Figure 1, the integrated framework adapts the SCOR–Lean–DMAIC model of Nanthasamroeng et al. (2021) with four key extensions. First, SCOR mapping is applied across all stakeholder groups, breeding farms, cage farms, transporters/wholesalers, and retailers, to enable cross-actor performance diagnosis. Second, SWOT analysis is incorporated into the Define phase to capture contextual factors. Third, a five-point expert scoring approach is embedded in the Measure phase to establish KPI baselines for lead time, transportation cost, coordination efficiency, and order fulfillment reliability in a qualitative setting. Fourth, the Improve phase introduces a conceptual digital coordination platform to address planning inefficiencies, bargaining power imbalance, and transportation waste. These extensions constitute the study’s methodological contribution. Table 1 summarizes the alignment between SCOR and DMAIC.

Table 1. Mapping of SCOR processes to DMAIC phases and Lean perspective in the integrated framework

SCOR process	Role in the tilapia supply chain (Ubon Ratchathani)	DMAIC in this study	Lean perspective (waste focus)	Key outputs in this study
Plan	Informal, experience-based planning at all actor levels with no demand forecasting or shared information platform; strong dependence on transporter–wholesalers for price and volume decisions.	Define–Measure–Analyze–Improve: Define planning as a system-level problem; Measure current planning practices and qualitative SCOR KPIs; Analyze root causes (information asymmetry, lack of shared platform); Improve via shared demand information mechanisms and standardized planning routines.	Waiting, overproduction, excess processing caused by missing demand signals and independent planning by each actor.	Identification of Plan as the primary bottleneck across all actors; proposal of weekly demand-sharing reports and coordinated planning mechanisms.

Table 1. Mapping of SCOR processes to DMAIC phases and Lean perspective in the integrated framework (Cont.)

SCOR process	Role in the tilapia supply chain (Ubon Ratchathani)	DMAIC in this study	Lean perspective (waste focus)	Key outputs in this study
Source	Decentralized input procurement (broodstock, feed, equipment) by individual farmers and breeders, limiting bargaining power and economies of scale.	Define–Measure–Analyze–Improve: Define sourcing fragmentation; Measure input channels and sourcing practices; Analyze effects on cost and supply security; Improve via cooperative or coordinated procurement options.	Inventory and transportation waste due to duplicated and uncoordinated purchasing.	Recognition of fragmented sourcing as a contributor to high input cost; suggestion of cooperative structures for input procurement.
Make	Breeding and grow-out operations at farms; biologically sound husbandry but exposed to climate variability and poorly synchronized with downstream demand.	Define–Measure–Analyze–Improve: Define production-stage issues (e.g., unsynchronized stocking/harvesting); Measure current Make processes against SCOR reliability and cost attributes; Analyze process variability and vulnerability; Improve via basic standardization and better scheduling.	Defects, over-processing, waiting (e.g., stress-induced mortality, non-standardized handling, idle capacity).	Clarification that Make is technically sound but its value is eroded by upstream Plan and downstream Deliver failures; identification of simple process-level improvements.
Deliver	Live-fish transportation and distribution dominated by transporter–wholesalers; fragmented routing, high transport cost, and high in-transit mortality.	Define–Measure–Analyze–Improve: Define Deliver as a critical bottleneck; Measure lead time, transportation cost, coordination efficiency, and order fulfillment reliability using SCOR metrics; Analyze causes using Lean waste mapping; Improve via route consolidation, coordinated scheduling, and a conceptual digital logistics platform.	Transportation and Waiting identified as dominant wastes (redundant trips, non-optimized routes, repeated handling of live fish).	Evidence of low responsiveness and cost performance; proposal of consolidated routing, digital coordination, and improved handling protocols.

Table 1. Mapping of SCOR processes to DMAIC phases and Lean perspective in the integrated framework (Cont.)

SCOR process	Role in the tilapia supply chain (Ubon Ratchathani)	DMAIC in this study	Lean perspective (waste focus)	Key outputs in this study
Return	No formal Return processes; unsold or rejected fish handled in ad hoc ways, if at all.	Define–Measure–Analyze (conceptual): Acknowledge the absence of structured Return processes; qualitatively consider their implications for waste and quality.	Potential defects and inventory waste associated with unmanaged returns.	Identification of Return as a prospective area for future system design and KPI development rather than a current focus of empirical implementation.

Note: The Control phase is included conceptually in the framework but is not empirically executed in the present study.

2.2 Data Collection

Primary data were collected through in-depth, semi-structured interviews with key stakeholders across four tiers of the tilapia supply chain: breeding farms, grow-out farms, transport operators/wholesalers, and retailers. Participants were selected using purposive and snowball sampling based on their operational roles. Purposive criteria were defined separately for each stakeholder group to ensure sufficient operational experience. Tilapia breeding farms were eligible if they had operated continuously for at least three years and actively supplied juvenile fish to cage farms within Ubon Ratchathani Province. Cage- farming operations required a minimum of three years of grow-out experience along the Mun River and at least one floating cage unit. Fish transport operators/wholesalers were included if they had at least three years of experience purchasing and distributing live tilapia within the province and operated at least one dedicated live-fish transport vehicle. Retailers were selected based on a minimum of two years of selling live or fresh tilapia at a fixed market location. Across all groups, willingness, and ability to describe operational processes, cost structures, and coordination practices in detail were additional inclusion criteria. Snowball sampling was applied in midstream and downstream tiers to identify further informants through practitioner referrals.

Table 2. Informant Profile by Supply Chain Tier

Stakeholder Group	Supply Chain Tier	Number of Informants	Sampling Method	Average Interview Duration
Tilapia breeding farms	Upstream	5	Purposive	45–90 min
Cage farming operations	Midstream	6	Purposive + Snowball	45–90 min
Fish transporters / wholesalers	Midstream–Downstream	4	Snowball	45–90 min
Retailers	Downstream	5	Snowball	45–90 min
Total		20		

As shown in Table 2, total of 20 informants across four stakeholder tiers aligns with a purposive, depth-oriented sampling strategy appropriate for qualitative single-case study research (Creswell, 2013). Data collection continued until thematic saturation was reached, with no substantively new themes emerging from additional interviews. Given the relatively small and geographically concentrated population of tilapia supply chain operators in the Mun River basin, the sample is considered representative of key operational perspectives. The study aims for transferability rather than statistical generalizability, consistent with case study methodology (Yin, 2018).

Interviews were conducted at participants' operating locations, lasting approximately 45–90 minutes, using a semi-structured guide covering operational processes, logistics activities, cost structures, information flow, and coordination. All interviews were conducted in Thai and subsequently transcribed and translated. Non-participant observation and secondary data from fisheries statistics and related reports were used to support the analysis. Triangulation across multiple data sources enhanced the credibility of the findings, and all participants provided informed consent and were assured of confidentiality.

2.3 Analytical Framework

The analytical framework integrates three complementary components in a sequential structure. First, the SCOR model is used to map and evaluate supply chain processes across the Plan, Source, Make, Deliver, and Return domains, with performance assessed in terms of reliability, responsiveness, and cost efficiency. Second, Lean principles are applied to identify non-value-added activities, particularly in transportation, waiting, over-processing, and excess inventory, using value stream concepts. Third, the Six Sigma DMAIC methodology serves as the overarching problem-solving framework, guiding the study through the Define, Measure, Analyze, Improve, and Control phases to systematically analyze inefficiencies and develop improvement strategies.

Although Six Sigma is conventionally associated with quantitative defect reduction and statistical process control, its application here is interpreted in a qualitative dimension. Variation reduction is operationalized as the identification and mitigation of recurring process inconsistencies across supply chain actors. Three forms of qualitative variation are examined: price volatility resulting from transporter-dominated price setting; inconsistent product quality and handling due to the absence of live-fish handling standards; and coordination variability arising from the lack of shared planning routines

and information platforms. The DMAIC cycle is used to identify these variation sources (Define–Analyze), assess their severity through expert-scored KPI evaluations (Measure), and design targeted interventions to reduce their occurrence and impact (Improve), with Control treated as a prospective implementation stage.

2.4 Performance Measurement

Supply chain performance was evaluated using four key performance indicators (KPIs) derived from SCOR attributes and operational considerations: lead time, transportation cost, coordination efficiency, and order -fulfillment reliability. KPI assessment followed a structured two-round expert scoring procedure using a five-point Likert scale (1 = very poor, 5 = excellent). In the first round, informants from the four supply chain tiers independently rated current-state performance on each KPI based on their operational experience, and scores were aggregated using arithmetic means, with numerical values and corresponding descriptive levels (High, Moderate, Low) reported side by side in Table 6 to support transparency and enable future pre/post comparison. In the second round, aggregated scores were presented to a panel of five academic and industry experts; where panel assessments differed from informant means by more than one scale point, scores were revised through structured discussion until consensus was reached, and the final KPI values in Table 6 represent these consensus-validated ratings. A comparative assessment was also conducted between current-state performance and projected performance under the proposed improvement framework using the same scoring procedure applied to stakeholder-informed estimates of expected improvement.

2.5 SWOT-Based Contextual Analysis

To complement the process-level diagnosis and support problem prioritization in the Define phase of the DMAIC cycle, a SWOT analysis was incorporated into the analytical framework. Macro-level opportunities and threats were identified by synthesizing evidence from in-depth interviews, non-participant observations, and secondary data on production, market trends, and policy conditions for freshwater aquaculture in Ubon Ratchathani. Interview transcripts were reviewed to extract statements on external drivers (market demand, policy support, climate variability, competitive pressure), which were coded and grouped into opportunity and threat factors through iterative researcher consensus. The resulting SWOT matrix (Table 3) highlights four key opportunities, fast biological growth of tilapia, relatively low feed cost, strong domestic demand, and supportive government policy, and four key threats, high export taxes and costs, climate variability and flooding, intense inter-regional price competition, and structurally low bargaining power of cage -farm operators. These factors did not serve as performance indicators but framed the interpretation of SCOR and Lean findings and guided the design of improvement strategies.

Table 3 Opportunities and Threats in Tilapia Supply Chain of Ubon Ratchathani

Dimension	Factor	Implication for Supply Chain
Opportunity	Fast biological growth rate of tilapia	Short production cycles; potential for high throughput if coordination improves
	Relatively low feed cost compared to other aquaculture species	Moderate cost base; margin improvement possible through supply chain efficiency gains
	Strong and growing consumer demand for tilapia in Thai cuisine	Stable downstream demand; market pull exists for improved supply reliability
	Government policy support for freshwater aquaculture	Access to extension services, subsidized broodstock from Inland Fisheries Center
Threat	High export taxes and associated export costs	Limits international market development; traps supply chain in domestic low-margin markets
	Climate variability and seasonal flooding	Disrupts cage operations on the Mun River; increases production uncertainty
	Intense price competition from other tilapia producing regions	Downward pressure on farm-gate prices; exacerbates farmers' low bargaining power
	Low bargaining power of cage farm operators	Structural dependency on wholesalers; suppresses farm profitability and reinvestment capacity

2.6 Research Procedure

The research procedure is structured around the DMAIC methodology, with the Define, Measure, Analyze, and Improve phases executed and the Control phase specified conceptually as a later implementation stage. In the Define phase, key supply chain problems were identified using stakeholder interviews, SIPOC analysis, and process mapping. In the Measure phase, the current-state supply chain was mapped with the SCOR framework and baseline performance was assessed against defined KPIs, supported by value stream visualization. In the Analyze phase, root causes were examined using Fishbone diagrams and the 5-Why technique, with Lean waste categories mapped to identify critical inefficiencies. In the Improve phase, an integrated improvement framework was developed, including process redesign and a conceptual digital coordination platform, with feasibility assessed through stakeholder consultation. The Control phase is outlined conceptually, proposing KPI tracking and role assignment as guidance for future implementation rather than empirically tested interventions.

2.7 Conceptual Evaluation of the Proposed Model

The proposed integrated framework was evaluated through a two-stage expert validation process to assess operational feasibility and the credibility of the KPI scoring procedure. In both stages, a structured five-point Likert scale was used so that expert judgments could be linked directly to the KPI scores reported in Table 6.

In Stage 1, five supply chain practitioners were purposively selected: two cage farm operators with at least five years of commercial tilapia farming experience, one fish transport operator/wholesaler active on the Mun River basin route, and two retail vendors handling live freshwater fish. They reviewed the proposed improvement strategies and assessed their feasibility using a five-point checklist covering implementability under current resource constraints, expected impact on operational efficiency, and barriers to adoption. Practitioners also rated current-state and projected post-improvement performance for the four KPIs: lead time, transportation cost, coordination efficiency, and order fulfillment reliability.

These individual ratings were averaged to form initial KPI scores and improvement estimates.

In Stage 2, three experts (two academics in supply chain or agricultural logistics and one industry consultant with food or aquaculture experience) evaluated the framework using a rubric covering: logical consistency of the SCOR–Lean–DMAIC sequence, methodological completeness, alignment between root causes and interventions, and transferability to comparable smallholder aquaculture contexts. Each criterion was rated on a five-point scale, with qualitative comments requested for ratings below 4. The expert panel also reviewed Stage-1 KPI scores. When any expert's view differed from practitioners' means by more than one scale point, discrepancies were discussed until a consensus value was reached. The final KPI scores in Table 6 reflect these consensus-validated ratings and the feedback incorporated into the refined framework.

3. Results

3.1 Current Structure of the Tilapia Supply Chain

The tilapia supply chain in Ubon Ratchathani consists of four main stakeholder groups across upstream, midstream, and downstream stages, as illustrated in Figure 2. The upstream stage is led by breeding farms that source broodstock, procure feed from commercial suppliers, and utilize basic transport equipment to distribute tilapia fry to farmers. These inputs form the foundation for subsequent production activities. The midstream stage comprises both subsistence and commercial farmers. Subsistence farmers typically raise fish in ponds or rice paddies for household consumption, while commercial operators, particularly cage-based farms along major water bodies, rear fish to market size for sale. This stage represents the primary production segment of the supply chain. The downstream stage is dominated by fish transporters who also function as wholesalers. These actors collect fish directly from farms, determine purchase prices, and distribute products to retailers and food service operators. This structure results in strong farmer dependency on wholesalers, who act as the primary interface between production and market distribution.

In addition to the structural configuration, three key flows characterize the supply chain. Product flow moves downstream from breeding farms to farmers, then to transporters, retailers, and ultimately consumers. Financial flow operates in the reverse direction, with transporters–wholesalers capturing a significant share of the margin at the midstream–downstream interface. Information flow, however, is highly centralized at the transporter level, with limited upstream sharing of demand and price data, resulting in information asymmetry that disadvantages farmers.

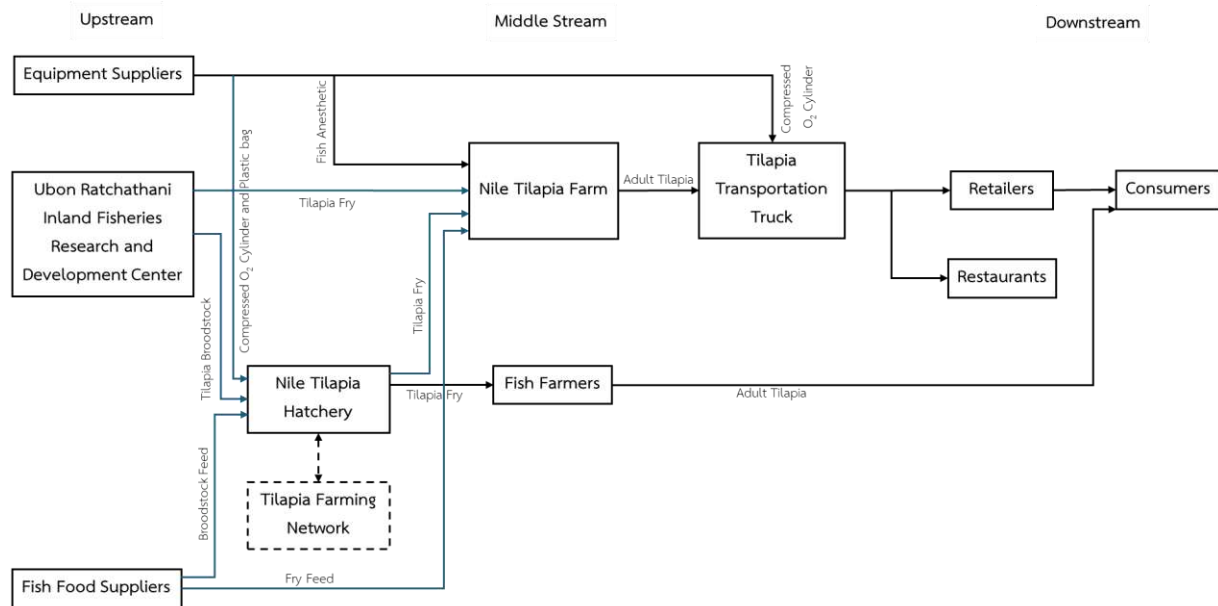


Figure 2. Current structure of the tilapia supply chain in Ubon Ratchathani

3.2 SCOR-Based Process Analysis by Supply Chain Actor

Supply chain processes were analyzed using the SCOR model framework, applied independently to each of the four key actors: (1) tilapia breeding farms, (2) cage farming operations, (3) fish transporters/wholesalers, and (4) retailers. The analysis focused on the Plan, Source, Make, and Deliver processes for each actor and examined how weaknesses in these processes contribute to overall supply chain underperformance. Table 4 summarizes the main issues identified across all segments, organized by SCOR process category.

Table 4. Summary of key issues by supply chain segment and SCOR process

Supply chain segment	SCOR process	Main issues identified	Performance implication
Upstream – Tilapia breeding farms	Plan	Informal, experience-based planning of juvenile output; no demand forecasting or structured communication with cage farms.	Systematic mismatches between fry supply and downstream demand; risk of chronic over- or under-supply.
	Source	Inputs (broodstock, feed, equipment) procured individually from limited suppliers.	Weak bargaining power; limited economies of scale and higher unit input costs.
	Make	Biologically sound breeding cycle but exposed to climate variability and poorly synchronized with cage-farm stocking schedules.	Production variability and timing mismatches that propagate downstream.
	Deliver	Basic live-fish delivery to cage farms using simple equipment; no coordinated scheduling.	Localized transport inefficiencies and stress-induced fry losses.

Table 4. Summary of key issues by supply chain segment and SCOR process (Cont.)

Supply chain segment	SCOR process	Main issues identified	Performance implication
Midstream – Cage farming operations	Plan	Stocking and harvesting based on personal experience; no access to formal demand data from downstream buyers.	Reactive production planning, recurrent supply–demand imbalances, and dependence on transporter-wholesalers.
	Source	Juveniles sourced exclusively from breeding farms; feed from a small number of commercial distributors.	Limited supplier choice and weak price-negotiating position for key inputs.
	Make	Technically sound grow-out operations along the Mun River but not synchronized with market demand and vulnerable to climate variation.	Biological performance is undermined by planning failures; heightened exposure to price volatility.
	Deliver	Farmers sell only at farm-gate to transporter-wholesalers, who set both price and quantity.	Very low bargaining power; farm-gate prices substantially below consumer-end value.
Midstream– Downstream – Fish transporters / wholesalers	Plan	Route planning based on informal knowledge; no integrated routing or demand aggregation system.	Fragmented trips, excess fuel consumption, and extended delivery lead times.
	Source	Product sourced directly from cage farms at prices determined unilaterally by transporters.	Structural monopsony power and persistent margin capture at the midstream–downstream interface.
	Make (Handle)	Live-fish handling during loading and in-vehicle holding with limited standardization and constrained tank capacity.	Elevated stress and mortality risk; inconsistent product condition on arrival.
	Deliver	Fragmented distribution to retailers and restaurants; no cold chain and no route optimization.	High transportation cost and prolonged lead times; mortality and shrinkage that can reach 10–18% in extreme cases.

Table 4. Summary of key issues by supply chain segment and SCOR process (Cont.)

Supply chain segment	SCOR process	Main issues identified	Performance implication
Downstream – Retailers	Plan	Purchase volumes based on daily experience and intuition; no formal demand forecasting or sales recording.	Demand variability not captured systematically, reinforcing upstream planning uncertainty.
	Source	Exclusive sourcing from transporter-wholesalers through a single procurement channel.	Limited ability to compare prices or secure alternative supply; dependency on transporter pricing.
	Make (Process)	Live-to-fresh conversion and display without standardized handling or temperature control.	Handling losses and shrinkage of approximately 10–18% of daily throughput under typical conditions.
	Deliver	Direct sale to end consumers and restaurants with no formal order management or feedback system.	Absence of structured demand information flowing upstream; missed opportunity for coordinated planning and performance feedback.

Across all four actors, the Plan process was consistently the weakest link, with no actor operating a structured demand forecasting or information-sharing mechanism. When the Plan is dysfunctional, Source becomes reactive, Make becomes poorly timed, and Deliver becomes fragmented, a cascading failure pattern that is most acutely expressed in the Deliver process of the transporter-wholesaler tier, where fragmented routing, the absence of cold chain, and unilateral price-setting converge to suppress both operational efficiency and farmers' bargaining power.

3.3 Problem Identification: Lean Waste Analysis

Applying a Lean perspective to the cross-actor SCOR process findings, five categories of operational problems were identified, each corresponding to specific non-value-added activities (waste types) as defined in the TIMWOOD framework.

The absence of integrated information systems is the root structural cause underlying most of the problems identified in Table 5. When demand signals from retailers fail to reach breeding farms, mismatches between supply and actual market demand systematically arise across all SCOR processes.

3.4 Integrated KPI Assessment

Based on the cross-actor SCOR analysis and Lean waste mapping, four key performance dimensions were assessed. Given the qualitative nature of the data collection (in-depth interviews and field observation), performance levels are reported using a descriptive scale (High / Moderate / Low) referenced directly to stakeholder testimony and observed conditions.

Table 5. Lean Waste Mapping of the Tilapia Supply Chain, Ubon Ratchathani

Problem	Lean Waste Type	SCOR Process Affected	Evidence Source
Low bargaining power of farmers due to transporter price-setting	Overproduction / Waiting	Source (Farm), Deliver (Farm)	In-depth interviews
Lack of coordination among supply chain stakeholders	Defects / Waiting	Plan (all actors)	Observation; no shared planning platform
Limited information sharing; no demand visibility	Waiting / Excess processing	Plan (all actors)	No demand data shared upstream
Inefficient transportation routes; no route optimization	Transportation	Deliver (Transporter)	Fragmented logistics; no routing system
Exposure to climate variability (temperature, seasonal flood)	Defects	Make (Cage Farm)	Climate change identified as key threat
Decentralized, uncoordinated input procurement	Inventory / Transportation	Source (all actors)	Separate procurement by each actor

Table 6. KPI Performance Assessment

KPI Dimension	SCOR Metric Category	KPI Score (1–5)	Descriptive Level	Primary Contributing Factor
Delivery lead time (farm to retailer)	Responsiveness	2	Low	Multiple uncoordinated handling stages; no scheduling system
Transportation cost efficiency	Cost	2	Low	Fragmented routing; no route optimization, each transporter operates independently
Stakeholder coordination	Reliability	1	Low	No shared information platform; each actor plans independently
Order fulfillment reliability	Reliability	3	Moderate	Demand is relatively stable domestically but subject to seasonal and climate-induced disruption
Farmer bargaining power / margin capture	Cost / Supply chain equity	2	Low	Structural dependence on transporter-wholesaler as sole buyer

The convergence of low scores across responsiveness, cost, and coordination metrics indicates that the current tilapia supply chain in Ubon Ratchathani operates significantly below its potential. The Make process at the cage farm level is biologically sound, but its value is systematically eroded by Plan and Deliver failures at every actor interface. This pattern is consistent with what Lean–Six Sigma literature describes as a systemic coordination failure rather than a localized operational defect.

4. Discussion

The most consequential finding of this study is structural rather than operational. The tilapia supply chain in Ubon Ratchathani is misaligned in a way that systematically transfers value from producers to intermediaries. Transporter-wholesalers simultaneously act as the sole buyer, price setter, and logistics provider, eliminating competitive pricing conditions. Farmers, lacking harvesting equipment and market knowledge, remain dependent on these actors. This pattern is consistent with Gao & Wongleedee (2025) and Bjorndal et al. (2014), who identify intermediary dominance and power asymmetry as key drivers of income suppression in smallholder systems. From a SCOR perspective, this imbalance is most evident in the Deliver process, where farm-gate prices are determined unilaterally (Supply Chain Council, 2012). The absence of price discovery mechanisms further destabilizes the Plan process, reinforcing a known systemic failure in aquaculture supply chains where limited information visibility degrades performance across all SCOR domains (Kruijsen et al., 2020).

SCOR-based analysis across all stakeholder tiers reveals that the Plan process is the weakest link throughout the system. Planning relies primarily on experience rather than structured demand data, resulting in weak demand signal transmission from downstream actors. This dysfunction propagates across subsequent processes: Source becomes reactive, Make poorly timed, and Deliver fragmented. Consequently, key performance indicators including lead time, coordination efficiency, and transportation cost, were assessed as low, despite technically sound grow-out practices. This systemic pattern aligns with findings by Mulyadi et al. (2025), who show that planning deficiencies are a primary source of downstream inefficiencies in agri-food logistics systems.

Lean analysis further clarifies how these inefficiencies manifest. Transportation and Waiting emerge as dominant waste types due to fragmented logistics controlled by individual transporters operating without shared routing or scheduling information. Repeated fish handling introduces both waiting-time waste and quality risks, including mortality and stress-induced weight loss, further reducing farmers' margins. Costa et al. (2018) similarly identify Transportation and Waiting as the most prevalent waste types in food supply chains. Evidence from DMAIC-based logistics studies in Thailand indicates that route standardization and improved coordination can reduce distribution costs by approximately 9% (Nanthasamroeng et al., 2021), suggesting that meaningful efficiency gains are achievable under coordinated interventions.

The primary methodological contribution of this study lies in integrating SCOR, Lean, and DMAIC within a single analytical framework for smallholder aquaculture. SCOR identifies where inefficiencies occur, Lean specifies the types of waste involved, and DMAIC structures the improvement process (Gomaa, 2025). This integration allows qualitative insights from interviews and observations to be organized within a systematic problem-solving framework, even in the absence of complete quantitative datasets. Importantly, standardizing the Plan process through shared demand information would enable measurable baselines for continuous improvement, something not possible under current informal practices.

The proposed digital supply chain platform operationalizes this integrated framework by addressing three core deficiencies. First, shared demand data and simple forecasting tools aim to correct planning

failures by improving upstream visibility. Second, transparent price discovery mechanisms—such as reference pricing or recorded transaction data, seek to rebalance bargaining power and reduce dependence on unilateral pricing. Third, coordinated routing and scheduling functions aim to reduce transportation waste by consolidating delivery routes and minimizing redundant handling. These proposals align with Thailand's broader digital agriculture agenda, including the Thailand 4.0 and Agriculture 4.0 initiatives (Board of Investment, 2020; Ministry of Agriculture and Cooperatives, 2022), as well as ongoing aquaculture development programs (Department of Fisheries, 2024). However, successful implementation requires prior capacity-building, as digital readiness among smallholder farmers remains uneven.

The findings also align with broader sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs) and Thailand's Bio-Circular-Green (BCG) Economy Model. Addressing intermediary dominance supports SDG 1 (No Poverty) and SDG 2 (Zero Hunger), particularly by improving smallholder income and productivity. Efficiency gains in logistics contribute to SDG 8 (Decent Work and Economic Growth), while reducing post-harvest losses supports SDG 12.3 on minimizing food loss. Within the BCG framework (NESDC, 2023), improved production practices align with the Bio economy, logistics optimization supports circular principles, and reduced resource utilization contributes to green economy goals. Future integration of Life Cycle Assessment metrics could further align the supply chain with national carbon reduction targets.

Despite these contributions, several limitations must be acknowledged. The study relies on purposive and snowball sampling from a sample of 20 key informants across stakeholder tiers, which supports analytical depth but limits statistical generalization. KPI assessment is based on expert-informed subjective scoring rather than direct measurement; therefore future research should establish quantitative baselines for rigorous evaluation. Furthermore, this study reaches only the Improve phase of DMAIC; the Control phase remains untested and represents an important direction for future work, including pilot implementation of routing optimization, the establishment of cooperative models, and the development of digital platform prototypes. Incorporating environmental performance indicators, such as greenhouse gas emissions, would also strengthen the framework's relevance to sustainability policy.

5. Conclusions and recommendations

5.1 Conclusions

This study analyzed the tilapia supply chain in Ubon Ratchathani using an integrated Lean–Six Sigma–SCOR framework and proposed improvement strategies supported by digital technologies. The chain follows a four-actor linear configuration dominated by transporter-wholesalers, who control pricing, purchase volume, and logistics, leaving cage farms with no effective alternative market access. Despite producing 11,601 tonnes valued at 670,867,000 baht annually and ranking 8th nationally, the sector operates significantly below its economic potential. SCOR analysis revealed dysfunctional Plan processes at all actor levels, characterized by a lack of demand forecasting, inter-actor coordination, or a shared information platform. Lean waste mapping identified Transportation and Waiting as the dominant non-value-added activities, arising from fragmented logistics and the absence of coordinated scheduling—with key performance indicators (lead time, transportation cost, and coordination efficiency) all assessed as Low. The integrated SCOR–Lean–DMAIC sequence provides a transferable analytical model extending industrial engineering methodologies to smallholder aquaculture supply chains.

5.2 Recommendations

In the short term (0–12 months), a weekly demand-sharing report circulated among transporters and cage farms via LINE or WhatsApp would reduce the information vacuum at the Plan level; standardizing juvenile fish grading and delivery scheduling between breeding and cage farms would cut waiting time and improve grow-out planning; and introducing GAP certification for cage farms, supported by the Inland Fisheries Research and Development Center, would establish a quality baseline for domestic and export markets. In the medium term (12–36 months), a consolidated transport-routing pilot among several transporters would lower delivery costs and generate necessary performance data, while forming a farmer cooperative would restructure bargaining power and allowing cage farms to negotiate directly with buyers and access higher-value channels. In the long term (36+ months), a phased digital platform integrating demand forecasting, price transparency, and route optimization should be implemented with Thai ag-tech partners, with carbon footprint metrics incorporated into performance monitoring given the emission intensity of tilapia and tightening export disclosure requirements.

5.3 Theoretical Contributions

This study contributes three advances to the supply chain management literature: (1) methodological integration-demonstrating a structured sequence that unifies the SCOR, Lean TIMWOOD, and DMAIC frameworks, applied here for the first time to smallholder aquaculture; (2) contextual extension-applying industrial supply chain frameworks to a live-product logistics context governed by biological production cycles and structural market power imbalances; and (3) empirical baseline- providing the first systematic, SCOR-based performance assessment of the Ubon Ratchathani tilapia supply chain, against which future interventions can be evaluated.

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การจัดการความรู้การใช้สมุนไพรในครัวเรือนเพื่อการดูแลสุขภาพของผู้สูงอายุจังหวัดลำปาง
Knowledge Management of Household Herb Use for
Older Adults' Health Care in Lampang Province

สุขุมาล ทองดี^{1*}

Sukhuman Thongdee^{1*}

¹คณะศิลปศาสตร์ มหาวิทยาลัยการกีฬาแห่งชาติ วิทยาเขตลำปาง จังหวัดลำปาง

¹Faculty of Arts, Thailand National Sport University Lampang Campus, Lampang Province

*Corresponding Author: sukhuman.13@gmail.com

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บทคัดย่อ

การวิจัยผสมผสานครั้งนี้มีวัตถุประสงค์เพื่อศึกษาพฤติกรรมการใช้สมุนไพรในครัวเรือนและถอดบทเรียนองค์ความรู้การใช้สมุนไพรในครัวเรือนในการดูแลสุขภาพของผู้สูงอายุในจังหวัดลำปาง กลุ่มตัวอย่าง คือ ผู้สูงอายุที่มีอายุ 60-75 ปี จำนวน 397 คน และสัมภาษณ์เชิงลึกและสนทนากลุ่ม จำนวน 15 ราย เครื่องมือที่ใช้ในการเก็บรวบรวมข้อมูล ได้แก่ แบบสอบถามการจัดการความรู้การใช้สมุนไพรในครัวเรือนเพื่อการดูแลสุขภาพของผู้สูงอายุในจังหวัดลำปาง จำนวน 44 ข้อ ตรวจสอบความเที่ยงตรงเชิงเนื้อหาโดยหาค่า IOC มีค่าตั้งแต่ 0.84-1.00 และมีค่าความเชื่อมั่น (α) เท่ากับ 0.92 และแบบสัมภาษณ์การจัดการความรู้การใช้สมุนไพรในครัวเรือนเพื่อการดูแลสุขภาพของผู้สูงอายุในจังหวัดลำปาง สถิติที่ใช้ในการวิเคราะห์ข้อมูล ได้แก่ ค่าร้อยละ ค่าเฉลี่ย ส่วนเบี่ยงเบนมาตรฐาน และข้อมูลเชิงคุณภาพใช้การวิเคราะห์เชิงเนื้อหา ผลการศึกษา พบว่า กลุ่มตัวอย่างส่วนใหญ่ (ร้อยละ 76.83) เคยใช้สมุนไพรในการดูแลสุขภาพ มากกว่าครึ่งหนึ่ง (ร้อยละ 69.52) มีความรู้เรื่องการใช้สมุนไพรอยู่ในระดับสูง และมากกว่าครึ่ง (ร้อยละ 67.51) มีการใช้สมุนไพรโดยรับประทานสดหรือนำมาปรุงอาหาร เกือบครึ่งหนึ่ง (ร้อยละ 49.12) มีพฤติกรรมการใช้สมุนไพรอยู่ในระดับปานกลาง นอกจากนี้ ข้อมูลเชิงคุณภาพพบว่า ผู้สูงอายุมีความรู้เกี่ยวกับสมุนไพรในระดับดีมาก โดยสามารถระบุสรรพคุณและวิธีการใช้สมุนไพรได้อย่างถูกต้อง ส่วนผู้สูงอายุทั่วไปมีความรู้พื้นฐานในการใช้สมุนไพรที่พบได้ในครัวเรือน เช่น ขิง ฟาทะลายโจร ขมิ้นชัน และกระเทียม แสดงให้เห็นถึงภูมิปัญญาท้องถิ่นที่สามารถดูแลสุขภาพผู้สูงอายุได้อย่างเหมาะสม สะท้อนความเข้าใจในการใช้สมุนไพรพื้นบ้านผสมผสานกับข้อมูลทางวิทยาศาสตร์ยุคใหม่

คำสำคัญ: การจัดการความรู้, การใช้สมุนไพรในครัวเรือน, การดูแลสุขภาพ, ผู้สูงอายุ, จังหวัดลำปาง

Abstract

This mixed-methods research aimed to examine household herb use behaviors and to extract lessons learned regarding knowledge of household herb use for older adults' health care in Lampang Province. The sample consisted of 397 older adults aged 60-75 years for the quantitative study, and 15 participants for in-depth interviews and focus group discussions. The research instruments included (1) a 44-item questionnaire on knowledge management of household herb use for older adults' health care in Lampang Province, with content validity verified through IOC values ranging from 0.84 to 1.00 and reliability (α) of 0.92, and (2) an interview guide on knowledge management of household herb use for older adults' health care in Lampang Province. Data were analyzed using percentages, means, and standard deviations; qualitative data were analyzed using content analysis. The findings showed that most participants (76.83%) had used herbs for health care. More than half (69.52%) had a high level of knowledge about herb use, and more than half (67.51%) used herbs by consuming them fresh or incorporating them into food. Nearly half (49.12%) demonstrated a moderate level of herb-use behavior. Qualitative findings indicated that the

older adult participants had very good knowledge of herbs and could accurately describe their properties and how to use them. In addition, older adult participants demonstrated basic knowledge of common household herbs, such as ginger, *Andrographis paniculata*, turmeric, and garlic, reflecting local wisdom that can appropriately support older adults' health. These findings reflect an understanding of traditional herbal medicine integrated with modern scientific information.

Keywords: Knowledge management, Household herb use, Health care, Older adults, Lampang Province

1. Introduction

Knowledge management (KM) is a systematic approach to capturing, organizing, sharing, and using an organization's knowledge to improve efficiency and competitiveness (Heisig et al., 2020). In the context of health development and Thai traditional medicine (KM) is crucial for preserving and transmitting Thai herbal wisdom as cultural heritage. KM also facilitates the delivery of information and knowledge to the right people at the right time (APQC, 2025). Organizational knowledge is commonly classified into two types: explicit knowledge, which can be recorded and easily shared, and tacit knowledge, which is embedded in personal experience, intuition, and skills and is difficult to articulate (Venkitachalam & Busch, 2012).

Thai herbs have a long history dating back to the Sukhothai period and continuing to the present day. Knowledge from Indian Ayurvedic medicine has been integrated with local wisdom (Tungkwampian et al., 2015; Fakkham et al., 2012). Thai herbs are used in many areas, including food, medicine, health care, and beauty products. However, managing Thai herbal knowledge remains challenging, particularly in safeguarding local experts' tacit knowledge, which is often transmitted across generations through practice and direct experience (Ruangsan et al., 2021). Without appropriate management, such knowledge may be lost with the older generation. Tungkwampian et al. (2015) developed a Thai herbal knowledge base using ontology techniques and proposed ten core concepts: product combinations, finished product forms, herbal substances, clinical warnings, flavor, triads, health problems, and consumption methods. This system helps link scientific information with language that the general public can understand.

Thailand has entered an aging society, leading to growing interest in the use of herbal medicines as complementary approaches for illness management and health promotion among older adults. Evidence from a primary care setting in Thailand indicates a high prevalence of herbal medicine use among elderly patients, although many users did not adequately consider principles of safe herbal medicine use, highlighting the need for greater attention from healthcare providers (Ananchaisarp et al., 2021). Demand for herbs in Thailand is also growing rapidly, with a domestic market value of approximately 42.4 billion baht in 2018 and an 11% increase from the previous year (Thai Embassy Maputo, 2020). The Thai government has emphasized the role of Thai herbs in health security and economic sustainability through the First National Master Plan on Thai Herbal Development, 2017–2021. Strategy 3 aims to increase the use of herbs for illness treatment and health promotion and to strengthen their integration within the national health system (Ministry of Public Health, 2017). The Ministry of Public Health has also set a target to increase the use of herbal medicines in the National Health Security System to at least 1.5 billion baht by the end of 2025 and 3 billion baht by 2026 (Nation Thailand, 2025). These targets demonstrate the government's commitment to incorporating Thai traditional medicine into mainstream healthcare.

Kanjanahattakij et al. (2019) reported that 32.6% of a Thai worker population used herbal or traditional medicine, and that herbal and traditional medicine use was more common among individuals with self-reported chronic diseases. This finding underscores the continuing importance of herbs and

traditional medicine within Thailand's health system. Although Thai people have long used household herbs for self-care and primary treatment, systematic household-level promotion and knowledge management remain limited. Jungsomjatepaisal (2019) developed a prototype for promoting the use of herbal medicine in Thai households and found that, after implementation, household practice in using herbal medicine for illness treatment increased substantially. This evidence suggests that household herbal use can be strengthened when community-based mechanisms, practical guidance, and systematic monitoring are integrated into local health promotion. However, as Thailand transitions into an aging society with increasing demand for herbal medicine, there remains a critical gap in systematic knowledge management of household herbal use among older adults, especially at the community level. The key challenge is preserving tacit knowledge embedded in older adults' practices before this wisdom is lost (Ruangsang et al., 2021). While previous research has developed ontology-based Thai herbal knowledge systems that incorporate scientific information (Tungkwampian et al., 2015) and explored AI-driven approaches for collecting herbal knowledge (Yaiprasert & Yusakul, 2022), these efforts have largely focused on formal healthcare settings rather than community-based household practices. The Northern Research and Development Institute's preliminary research indicated that Lampang residents use herbs for various purposes; however, it did not comprehensively examine behavioral patterns or establish a knowledge management framework tailored to older adults in this region.

Thai herbal knowledge management faces several challenges. First, it involves conserving and transmitting tacit knowledge held by older generations with extensive experience. Second, it requires integrating traditional knowledge into modern healthcare systems. Third, it requires ensuring the quality and safety of herbal products. One possible approach is to apply artificial intelligence (AI) to support herbal knowledge management. Yaiprasert & Yusakul (2022) demonstrated the use of web-scraping techniques combined with machine learning to collect and classify Thai herbal knowledge from online sources, thereby improving access and processing efficiency. In addition, Sukparseart et al. (2024) developed a semantic Thai herb knowledge mining system for treatment, showing that semantic processing and knowledge mining can be applied to organize Thai herbal information in a more systematic and retrievable form. These approaches could be applied to Thai herbal information systems to integrate knowledge from multiple sources and support more accessible, evidence-informed, and systematic use of herbal knowledge.

Nevertheless, there has been no comprehensive mixed-methods study that systematically investigates both (1) quantitative patterns of household herbal use behaviors and (2) qualitative dimensions of knowledge management practices among older adults in Lampang Province. Empirical evidence is still limited regarding how older adults use, preserve, and transmit herbal knowledge within households. Therefore, this study addresses these gaps by examining: (1) the extent and patterns of household herbal use among older adults in Lampang Province; (2) their knowledge levels regarding herbal properties and applications; (3) the ways this tacit knowledge is managed and transmitted within households; and (4) best practices that can be extracted and systematized to support intergenerational knowledge transfer. Understanding these behavioral and knowledge management dimensions is essential for designing community-based interventions that preserve local herbal wisdom, support health security objectives, reduce healthcare costs, and ensure sustainable transmission of this cultural heritage.

Knowledge management is essential for the long-term preservation and development of Thai herbal wisdom, particularly in an aging society that requires effective and affordable healthcare options. Integrating tacit and explicit knowledge through KM supports intergenerational transfer and strengthens Thailand's herbal sector. Research on household herbal use among older adults in Lampang Province highlights the need for community-level KM to sustain knowledge transmission and promote appropriate

use of Thai herbs in health care. Such efforts can reduce healthcare expenditure, increase public understanding of safe herbal use in daily life, and enhance the value of Thai herbs, creating future economic opportunities for local producers. Government support, appropriate use of modern technology, and collaboration among local experts and academics will be important in advancing Thai herbs as a sustainable sector and strengthening competitiveness in the global market.

2. Methodology

Primary data were collected through a survey, and secondary data were obtained from research articles, theses, and online sources.

Population and Sample: The study population consisted of older adults residing in Mueang District, Lampang Province. The sample size was determined using Yamane's (1973) formula.

$$\frac{N}{1+Ne^2} \quad (1)$$

Based on the calculation, the required sample size was 397, using a 95% confidence level and a 5% margin of error. The inclusion criteria were older men and women aged 60–75 years who were able to communicate effectively and had no major physical limitations. A simple random sampling method was used to select 397 participants from 14 subdistricts (Table 1).

This study used a questionnaire on household herbal use behavior among older adults in Mueang District, Lampang Province, adapted from Tasnakon's (Inthajak, 2021) research instrument. The questionnaire comprised three sections: (1) general information, (2) knowledge of household herbal use, and (3) household herbal use behavior. Content validity was assessed using IOC values of 0.84–1.00; item discrimination (R_{xy}) ranged from 0.539 to 0.861; and reliability (α) was 0.92. An interview guide on knowledge management of household herbal use for older adults' health care in Lampang Province was also evaluated: IOC values were 0.88–1.00; item discrimination (R_{xy}) ranged from 0.622 to 0.845; and reliability (α) was 0.94. The questionnaire was pilot-tested with 30 older adults.

Table 1. presents the proportion of older adults aged 60–75 years in Mueang District, Lampang Province, who were selected through simple random sampling from 14 subdistricts

Subdistrict	Number of Population (Persons)	Samples (Persons)
Tumbon Suandok	1,426	11
Tumbon WieangNuae	3,340	25
Tumbon Klouyprae	2,858	22
Tumbon Soptui	3,737	28
Tumbon Chompoo	7,839	59
Tumbon Pongsanthong	5,059	38
Tumbon Huawieang	1,774	13
Tumbon Thungphai	1,996	15
Tumbon Prabat	5,621	43
Tumbon Bansadet	2,673	20
Tumbon Pichai	5,483	41
Tumbon Nikhompattana	1,304	10

Table 1. presents the proportion of older adults aged 60–75 years in Mueang District, Lampang Province, who were selected through simple random sampling from 14 subdistricts (Cont.)

Subdistrict	Number of Population (Persons)	Samples (Persons)
Tumbon Bohaew	5,076	38
Tumbon Tonthongchai	4,289	32
Total	52,475	397

Source: Lampang District Office, Lampang Province

For data collection, the researcher conducted fieldwork in person. An official request letter from Thailand National Sport University, Lampang Campus, was submitted to village headmen and community leaders to seek support for data collection. The researcher visited the study area to introduce themselves, explain the research objectives to participants, and request their cooperation in completing the questionnaire. Data collection lasted 75 days. The completed questionnaires were then checked for completeness and accuracy prior to statistical analysis. After the study was completed, the researcher returned the results to the community.

Quantitative data were analyzed using a statistical software package. Descriptive statistics (percentages, means, and standard deviations) were used to describe participant characteristics and household herbal use behaviors among older adults in Mueang District, Lampang Province. For the qualitative component, content analysis was used to categorize responses according to the study objectives, compare patterns of herbal use across contexts, and extract key lessons learned. To enhance trustworthiness, data credibility was established through triangulation by comparing information from multiple sources and member-checking with key informants to confirm the accuracy of interpretations.

3. Results

This section presents the study findings according to the research objectives and is divided into two parts: (1) household herbal-use behaviors among older adults in Lampang Province, and (2) extracted lessons learned regarding knowledge management of household herb use for older adults' health care. To establish the context for interpreting household herbal-use behaviors, the general characteristics of the respondents and their recent use of herbs are first presented in Table 2, followed by the patterns of herbal use by health condition in Table 3.

The study sample comprised 397 respondents, most of whom were female (272 respondents, 68.51%). The respondents' average age was 72.5 years, and many reported underlying conditions such as hypertension, diabetes, osteoarthritis, and gout. Regarding education, 152 respondents (38.29%) had completed primary school or lower, and 104 respondents (26.20%) had completed lower secondary school. Most respondents (283; 71.28%) reported a monthly income of 5,001–10,000 baht. In terms of occupation, 142 respondents (35.77%) were farmers and 81 (20.40%) were general laborers. Within this demographic context, household herbal use remained common among the respondents. In the past 1–2 months, 305 respondents (76.83%) reported using herbs for health care, whereas 92 respondents (23.17%) reported never using herbs. This information provides the descriptive context for understanding the specific herbal-use practices presented by health condition.

For gastrointestinal problems, the five herbal-use practices with the highest mean scores included consuming tamarind dipped in salt or drinking tamarind juice to relieve constipation ($\bar{x}$ = 2.71), consuming turmeric to relieve bloating, flatulence, indigestion, or gastritis ($\bar{x}$ = 2.56), consuming senna for constipation

($\bar{x}$ = 2.45), consuming raw bananas to relieve gastritis or mild diarrhea ($\bar{x}$ = 2.34), and consuming basil to relieve bloating, flatulence, and indigestion ($\bar{x}$ = 2.25). Overall, these findings indicate the continued use of local wisdom in supporting digestive health among older adults in the study area.

Table 2. General information about the sample (n = 397)

Characteristics	Number	Percentage
Sex		
- Male	125	31.49
- Female	272	68.51
Level of Education		
- Upper or Primary education	152	38.29
- Lower secondary school	104	26.20
- High school/Vocational Certificate	89	22.42
- Associate degree/Vocational Certificate level	43	10.83
- Bachelor's degree	8	2.02
- Upper Bachelor's degree	1	0.25
Average monthly income		
- Less than 5,000 baht/month	68	17.13
- 5,001 – 10,000 baht/month	283	71.28
- 10,001 – 15,000 baht/month	34	8.56
- More than 15,001 baht/month	12	3.02
Occupation		
- Retired civil servants	56	14.11
- Trader	79	19.90
- Agriculturist	142	35.77
- General employee	81	20.40
- Construction contractor	3	0.76
- Housewife/househusband or unemployed	36	9.07
In the past 1-2 months, have you used herbs to take care of your health?		
- ever	305	76.83
- never	92	23.17

Table 3 shows that household herbal use behaviors among older adults in Lampang Province varied by health condition. Herbs used for respiratory problems had the highest mean scores ($\bar{x}$ = 2.39–2.85). Using Indian gooseberry to relieve sore throat, cough, and phlegm had the highest mean score ($\bar{x}$ = 2.85, S.D. = 0.64). For digestive problems, commonly used herbs included tamarind dipped in salt for constipation ($\bar{x}$ = 2.71, S.D. = 0.64) and turmeric for stomach disorders ($\bar{x}$ = 2.56, S.D. = 0.63). Herb use for other conditions had the lowest mean scores ($\bar{x}$ = 1.75–1.94). Overall, these findings suggest that older adults selectively apply local knowledge in health care, focusing on familiar and effective herbs for common, everyday symptoms.

Table 3. The level of herbal use behavior in households of older adults in Lampung Province (n = 397)

information	Regularly (Percentage)	Sometimes (Percentage)	Never (Percentage)	Mean	S.D.
1. Gastrointestinal illnesses					
1.1 Herbs used to treat stomach diseases					
1.1.1 You can eat turmeric when you have symptoms of bloating, flatulence, tightness, colic, and stomach ailments.	86 (21.66)	235 (59.19)	76 (19.14)	2.56	0.63
1.1.2 You can eat raw bananas to treat stomach problems or mild diarrhea.	95 (23.93)	212 (53.40)	90 (22.67)	2.34	0.68
1.2 Herbs used to relieve symptoms of bloating, flatulence, and indigestion.					
1.2.1 You eat basil when you have symptoms of bloating, flatulence, and indigestion.	31 (7.81)	202 (50.88)	164 (41.31)	2.25	0.67
1.3 Herbs used to relieve constipation					
1.3.1 Do you eat tamarind with salt or tamarind juice when you are constipated?	43 (10.83)	248 (62.47)	106 (26.70)	2.71	0.64
1.3.2 You eat senna when you are constipated.	51 (12.85)	231 (58.19)	115 (28.97)	2.45	0.69
1.4 Herbs used to relieve diarrhea					
1.4.1 You eat raw guava when you have diarrhea.	32 (8.06)	131 (33.00)	234 (58.94)	1.38	0.58
1.4.2 You eat mangosteen peel when you have diarrhea.	6 (1.51)	165 (41.56)	226 (56.93)	1.27	0.57
2. Respiratory illnesses					
2.1 You can drink lemon juice when you have a sore throat, cough, or phlegm.	87 (21.91)	226 (56.93)	84 (21.16)	2.39	0.65
2.2 You eat Indian gooseberry when you have a sore throat, cough, or phlegm.	92 (23.17)	253 (63.73)	52 (13.10)	2.85	0.64
2.3 You take <i>Andrographis paniculata</i> when you have a sore throat, cough, or phlegm.	94 (23.68)	211 (53.15)	92 (23.17)	2.31	0.68

Table 3. The level of herbal use behavior in households of older adults in Lampang Province (n = 397)
(Cont.)

information	Regularly (Percentage)	Sometimes (Percentage)	Never (Percentage)	Mean	S.D.
3. Urinary tract illnesses					
3.1 You can drink lemongrass water when you have difficulty urinating or urinating.	42 (10.58)	193 (48.61)	162 (40.81)	2.17	0.69
3.2 You can eat roselle when you have urinary retention or difficulty urinating.	45 (11.34)	209 (52.64)	143 (36.02)	2.24	0.62
3.3 You eat thatch when you have difficulty urinating or difficulty urinating.	34 (8.56)	196 (49.37)	167 (42.07)	2.18	0.70
4. Skin-related illnesses					
4.1 You use aloe vera to treat burns and scalds.	89 (22.42)	231 (58.19)	77 (19.40)	2.52	0.69
4.2 You use Mahakan herb when you have boils or blisters.	54 (13.60)	182 (45.84)	161 (40.55)	2.01	0.69
4.3 You can use fresh garlic when you have a rash from insect bites.	48 (12.09)	171 (43.07)	178 (44.84)	1.98	0.66
4.4 You use Phaya Yo when you have herpes/shingles.	41 (10.33)	197 (49.62)	159 (40.05)	2.18	0.69
5. Other illnesses					
5.1 You ate bitter melon to cure and help with appetite.	32 (8.06)	167 (42.07)	198 (49.87)	1.75	0.61
5.2 You eat Cassia alata when you have insomnia.	34 (8.56)	156 (39.29)	207 (52.14)	1.94	0.59
5.3 You can use turmeric when you have pain, sprains, strains, or bruises.	43 (10.83)	165 (41.56)	189 (47.61)	1.86	0.63

This study extracted lessons learned from household herbal use among older adults in Lampang Province across four main dimensions. For gastrointestinal care, older adults demonstrated wisdom in selecting highly effective herbs that are readily available locally, particularly tamarind in various forms. The most common remedies for constipation were tamarind dipped in salt or tamarind juice ($\bar{x}$ = 2.71) and senna ($\bar{x}$ = 2.45), reflecting awareness of laxative components such as tartaric acid and malic acid. Turmeric was also used for gastrointestinal disorders ($\bar{x}$ = 2.56). For respiratory symptoms, older adults commonly used Indian gooseberry ($\bar{x}$ = 2.85), lemon juice ($\bar{x}$ = 2.39), and *Andrographis paniculata* ($\bar{x}$ = 2.31), consistent with Thai traditional medicine principles that classify and select herbs based on symptom severity. In urinary tract and skin care, specialized herbs were used selectively, such as roselle for urinary symptoms ($\bar{x}$ = 2.24) and aloe vera for burns ($\bar{x}$ = 2.52). Although most participants reported using herbs (76.83%), lower mean scores in some symptom groups ($\bar{x}$ = 1.75–1.94) suggest a transition between the persistence and possible loss of local wisdom. Overall, these findings highlight the importance of systematically recording and

preserving knowledge by developing a local herbal database, promoting intergenerational knowledge transfer, and integrating traditional wisdom with modern health systems

4. Discussion

The findings on household herbal use among older adults in Lampung Province revealed distinct patterns of local knowledge application that are consistent with knowledge management theories and traditional medicine frameworks. The integration of tacit and explicit knowledge in everyday herbal practices suggests that these indigenous health systems operate in a systematic and transferable way.

4.1 Behavioral Patterns and Knowledge Management Theory

The high mean score for herbal use in respiratory care, particularly Indian gooseberry ($\bar{x} = 2.85$), reflects the application of tacit knowledge embedded in community practice. This finding aligns with Nonaka and Takeuchi's SECI model (socialization, externalization, combination, and internalization), as discussed in contemporary knowledge management literature (Martínez-Martínez et al., 2021). The relatively low standard deviation (S.D. = 0.64) indicates consistent knowledge application across the study group, suggesting effective socialization processes through which tacit knowledge has been transmitted via observation and repeated practice. This consistency supports the view that, when tacit knowledge is reinforced through routine use and intergenerational transmission, it can remain stable even without formal documentation (Vrontis et al., 2022).

Similarly, the pattern of herbal use for gastrointestinal problems—particularly tamarind in various forms ($\bar{x} = 2.45$ – 2.71) and turmeric ($\bar{x} = 2.56$)—suggests nuanced decision-making based on symptom severity and preparation complexity. This adaptive use reflects what Lave & Wenger (2020) describe as “situated learning” within communities of practice, in which knowledge develops through contextual experience. The ability to adjust preparations according to the clinical presentation also reflects internalization in the SECI model, whereby explicit knowledge becomes tacit through practice (Martínez-Martínez et al., 2021). The relatively high mean score for turmeric may further indicate integration of traditional wisdom with scientific evidence regarding curcumin's anti-inflammatory properties (Amalraj et al., 2017; Kocaadam & Şanlıer, 2017), representing an evidence-informed traditional practice.

4.2 Knowledge System Complexity and Traditional Ecological Knowledge

The identification of four main dimensions of herbal knowledge, gastrointestinal, respiratory, urinary, and dermatological applications, illustrates the holistic and systematic nature of traditional medicine systems. This multidimensional structure aligns with Berkes (2017), who conceptualizes Traditional Ecological Knowledge (TEK) as a complex adaptive system integrating empirical observations, customary practices, and worldviews accumulated over generations. Participants' ability to classify herbs by target organ systems and therapeutic properties also reflects what Langeder et al. (2020) describe as “folk taxonomy”: systematic classification approaches that parallel biomedical categories while remaining grounded in experiential learning and cultural transmission.

The use of specific herbs for urinary and skin-related conditions, such as roselle ($\bar{x} = 2.24$) and aloe vera ($\bar{x} = 2.52$), reflects organ-specific therapeutic knowledge consistent with ethnopharmacological principles. This selective use also supports the concept of medical pluralism in health-seeking behavior, in which traditional and biomedical systems coexist and are chosen based on perceived appropriateness for specific conditions (Napier et al., 2014). In addition, practices related to seasonal availability and household preservation, observed in respiratory herb use, including Indian gooseberry, lemon juice ($\bar{x} = 2.39$), and *Andrographis paniculata* ($\bar{x} = 2.31$), suggest adaptive household resource management consistent with

sustainability-oriented approaches to medicinal plant production and utilization in Asian traditional medicine systems (Astutik et al., 2019).

4.3 Knowledge Erosion and Transmission Vulnerability

The notably lower mean scores in some symptom categories ($\bar{x} = 1.75\text{--}1.94$), particularly for urinary tract and skin-related care, raise concerns about knowledge erosion despite the overall high use rate (76.83%). This pattern is consistent with what Reyes-García et al. (2021) describe as erosion of traditional knowledge in local communities under modernization, urbanization, and declining intergenerational transmission. The selective loss also suggests that more specialized or less frequently used remedies are particularly vulnerable, consistent with the “use it or lose it” principle in cultural transmission theory (Koster et al., 2020).

This vulnerability can be interpreted through social learning theory, which emphasizes that cultural transmission requires not only exposure but also motivation, opportunity, and perceived relevance (Reyes-García et al., 2021). The shift toward modern healthcare may reduce opportunities for younger generations to observe and practice traditional herbal treatments, particularly for conditions perceived to require specialized care. In addition, the complexity of preparation methods for certain remedies may create barriers to learning, especially when expert knowledge is not readily accessible within households or community networks.

4.4 Integration with Health System Frameworks

The findings underscore the importance of integrating traditional herbal knowledge into formal health systems, consistent with the World Health Organization’s (2019) WHO Traditional Medicine Strategy 2014–2023, which emphasizes harnessing traditional medicine through evidence-based policy and practice. The demonstrated knowledge of herbal properties and appropriate applications provides a foundation for systematic documentation; however, such efforts must be carefully managed to prevent the risks of biopiracy and to protect the intellectual property rights of knowledge holders (Nordin et al., 2012).

The systematic patterns observed in this study also support the development of community-based knowledge management interventions. Such initiatives can draw on hybrid strategies that combine traditional oral transmission with modern documentation tools, ensuring both cultural authenticity and accessibility (Martínez-Martínez et al., 2021). For example, community-owned digital repositories, video documentation, and community herbal gardens may function as externalization mechanisms that help convert tacit knowledge into explicit forms while maintaining local ownership and control (Vrontis et al., 2022).

4.5 Implications for Sustainable Knowledge Preservation

Evidence of both knowledge retention and erosion highlights the need for systematic documentation and revitalization programs. In line with UNESCO frameworks for safeguarding intangible cultural heritage, such programs should prioritize active transmission over passive preservation, ensuring that knowledge remains a living practice rather than an archived artifact (Kurin, 2007). This approach also aligns with the concept of biocultural heritage, which recognizes the close relationship between biological diversity and cultural knowledge systems (Gavin et al., 2020).

The findings also suggest that effective knowledge management in traditional medicine requires attention to the social, cultural, and economic contexts that shape knowledge transmission. Interventions may focus on strengthening communities of practice, creating incentives for knowledge sharing, and incorporating traditional herbal knowledge into primary health care education. As recommended by Wanjohi et al. (2020), such multifaceted approaches can help ensure that Thailand’s

herbal heritage continues to contribute to health security while adapting to contemporary healthcare challenges.

In summary, household herbal knowledge among older adults in Lampang Province represents a sophisticated form of traditional ecological knowledge that shows both resilience and vulnerability. Systematic documentation, together with theory-informed interpretation of use patterns, provides a basis for culturally appropriate and scientifically informed knowledge management strategies that can preserve this heritage for future generations while supporting Thailand's health security objectives.

5. Conclusion

This mixed-methods study achieved its objectives by examining household herbal use behaviors and extracting lessons learned regarding knowledge management for older adults' health care in Lampang Province. The findings indicate clear patterns of herb use across health conditions and suggest that older adults possess substantial tacit knowledge embedded in everyday health practices.

The behavioral patterns observed indicate that household herb use among older adults in Lampang Province is condition-specific and adapted to symptom severity. For gastrointestinal problems, participants frequently used tamarind in various forms ($\bar{x}$ = 2.45–2.71) and turmeric ($\bar{x}$ = 2.56), reflecting the ability to select remedies for specific symptoms. Respiratory treatments also showed diverse local options, including Indian gooseberry ($\bar{x}$ = 2.85), lemon juice ($\bar{x}$ = 2.39), and *Andrographis paniculata* ($\bar{x}$ = 2.31), demonstrating a locally grounded repertoire for common respiratory symptoms.

The lessons learned highlight both strengths and vulnerabilities in local knowledge management. Although 76.83% of participants reported using herbs, lower mean scores in some symptom categories ($\bar{x}$ = 1.75–1.94), particularly for urinary tract and skin-related care, may indicate reduced use, shifting health practices, or gradual knowledge loss in these domains. This finding underscores the need for systematic documentation and strengthened intergenerational knowledge transfer.

The extracted knowledge suggests that older adults in Lampang Province retain practical herbal wisdom that supports day-to-day health care. Participants could identify medicinal properties, preparation methods, and appropriate uses of common household herbs such as ginger, *Andrographis paniculata*, turmeric, and garlic. However, differences in the level of use across health conditions also suggest that tacit knowledge transmission may be fragile in an aging society.

Overall, the findings support establishing systematic knowledge management frameworks to preserve household herbal knowledge as cultural heritage. Documenting patterns of herbal use and related knowledge provides a basis for interventions that strengthen intergenerational transfer, integrate traditional wisdom with modern health systems, and promote safe and accessible herbal practices. These efforts can contribute to Thailand's health security goals and help reduce healthcare costs among older adults.

6. Ethical Approval Statement

This study received ethical approval for research involving human participants from Sirindhorn College of Public Health. Approval was granted under research ethics code SCPHYLIRB-2567/316. The researcher ensured confidentiality and data protection throughout the study, including secure data management and restricted access to study records. Findings are reported in aggregate, and no personally identifiable information (e.g., names or other identifying details) is disclosed.

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**319 THAI PHANTHA ROAD, PHO SUB-DISTRICT,
MUEANG DISTRICT, SISAKET PROVINCE 33000**

