

Isolation of peat soil bacteria producing antimicrobial agents against *Escherichia coli* and *Salmonella Typhimurium*

Dede Mahdiyah¹, Putri Vidia Sari Darsono¹, Nur Hidayah¹, and Bayu Hari Mukti^{2*}

¹ Department of Pharmacology, Sari Mulia University, Banjarmasin 70238, Indonesia

² Department of Industrial Engineering, Sari Mulia University, Banjarmasin 70238, Indonesia

ABSTRACT

***Corresponding author:**
Bayu Hari Mukti
muktibh.works@gmail.com

Received: 21 September 2023

Revised: 17 December 2024

Accepted: 3 January 2025

Published: 26 November 2025

Citation:

Mahdiyah, D., Sari Darsono, P. V., Hidayah, N., & Mukti, B. H. (2025). Isolation of peat soil bacteria producing antimicrobial agents against *Escherichia coli* and *Salmonella Typhimurium*. *Science, Engineering and Health Studies*, 19, 25030002.

The global rise of antimicrobial resistance poses a severe threat to public health, demanding the discovery of novel antibacterial agents. Peat soil is an extreme environment that can be used to isolate bacteria that produce bioactive compounds. This study examined the antibacterial activity of peat soil bacteria against *Escherichia coli* and *Salmonella Typhimurium*. Peat soil bacteria were isolated using tryptone soy agar (TSA), and their morphology and characteristics were assessed (Gram staining, catalase activity). The antibacterial activity of these bacteria was examined using the well diffusion method. The minimum inhibitory concentration (MIC) of each isolated substance was determined using the dilution method, and the minimum bactericidal concentration was determined by the spread plate method. Nine bacterial isolates, termed peat soil bacteria-1–9 (PSB1–9), were obtained at dilutions of 1×10^{-7} – 1×10^{-1} on TSA. Of these, PSB-7, PSB-8, and PSB-9 exhibited potential antibacterial activity against *S. Typhimurium* and *E. coli*. These isolates were characterized as Gram-positive rods. The MICs of PSB-7–9 against *E. coli* were 4, 3, and 3 mg/mL, respectively. For *S. Typhimurium*, the MICs were 3, 4, and 4 mg/mL, respectively. However, none of the isolates exhibited bactericidal activity against either pathogen.

Keywords: peat soil bacteria; antibiotic producer; *Escherichia coli*; *Salmonella Typhimurium*

1. INTRODUCTION

Antimicrobial resistance (AMR) is a major danger to the health of both people and the environment (Galindo-Méndez, 2020; World Health Organization, 2019), and it remains the most critical global challenge to successful bacterial illness treatment and modern health (European Antimicrobial Resistance Collaborators, 2022; Nwobodo et al., 2022). It is estimated that AMR causes 700,000 deaths annually (Mancuso et al., 2021). AMR describes the ability of microbes to withstand or tolerate the effects of antibiotics (Murray et al., 2022) designed to

either kill pathogens or prevent growth (Mancuso et al., 2021). Antibiotic overuse and misuse are common global issues that significantly increase the amount of antibiotics in the environment and the spread of AMR; both issues are believed to be responsible for the significant increase in the number of pathogens carrying multidrug resistance genes (Serwecińska, 2020; World Health Organization, 2019). AMR has been confirmed for at least 12 antibiotics, including sulbactam, tazobactam, ceftriaxone, ceftazidime, cefepime, meropenem, gentamicin, amikacin, ciprofloxacin, levofloxacin, nitrofurantoin, and ampicillin (Hormozi et al., 2018).

Escherichia coli, a member of the Enterobacteriaceae family, is a highly opportunistic microbe commonly encountered in clinical settings, and it is also resistant to many drugs (Galindo-Méndez, 2020; Wang et al., 2023). Similarly, several *Salmonella* serotypes are resistant to various antibiotics (Nair et al., 2018). The emergence of AMR in *E. coli* is a matter of global concern with consequences for both human and veterinary medicine (Poirel et al., 2018). AMR is also the most common health problem in newborn babies, and treatment often fails if it is a resistant strain (Wu et al., 2021). Meanwhile, typhoid fever is a severe issue across the world (Mahdiyah et al., 2023). At least 550 million people are infected with *Salmonella* (commonly *Salmonella enterica*, subsp. *enterica*, serovar. Typhimurium [*Salmonella* Typhimurium]) annually, leading to potentially life-threatening diarrhea. By 2020, millions of cases had been confirmed in children younger than 5 years (Alenazy, 2022). A joint analysis by the European Food Safety Authority and European Center for Disease Prevention and Control reported the occurrence of AMR against six of the seven antibiotics studied in *S. Typhimurium*, including gentamicin, chloramphenicol, ampicillin, cefotaxime, ceftazidime, and tigecycline (European Food Safety Authority & European Center for Disease Prevention and Control, 2022), and infections caused by drug-resistant *Salmonella* strains have a 100% higher mortality rate than typical strains (Alenazy, 2022). Increasing AMR requires various solutions, including the identification of new potential antimicrobial targets and chemical entities (Breijyeh et al., 2020) to be used as antimicrobial drugs (Annunziato, 2019), which can be obtained from microbes living in extreme characteristic areas.

Peatlands represent an extensive and extreme environment with rich bacterial diversity, and they are among the unique ecosystems in Borneo. They offer significant potential for the discovery of natural compounds, including antibiotic-producing agents (Mukti, 2024). Peat soil is formed from organic matter and minerals in a suitable climate and topography (Wang et al., 2021). This soil contains diverse microorganisms, and it has vital uses in food, medicinal, agricultural, and livestock industries. Some of the isolated microorganisms have been found to produce enzymes that inhibit microbial growth (Mahdiyah, 2015). For example, bacteria isolated from Banjarbaru peat soil inhibited the growth of extended-spectrum beta-lactamase-producing *E. coli* and methicillin-resistant *Staphylococcus aureus* (Mahdiyah et al., 2020). The present study examined the antibacterial activity of peat soil bacteria against *E. coli* and *S. Typhimurium*.

2. METHODS AND METHODS

2.1 Peat soil sampling

In total, 50 g of peat soil obtained from a depth of 50 cm was collected using a sterile core driller to increase the possibility of isolating various bacteria (Mahdiyah et al., 2020).

2.2 Isolation of peat soil bacteria

One gram of peat soil was soaked in a 0.85% (w/v) salt solution, and a dilution series from 1×10^{-5} to 1×10^{-1} was generated. The samples were then spread onto 1/10 tryptone soy agar (TSA) and incubated at 30°C for 2 days.

After culture, the isolates were purified in Petri dishes containing TSA to obtain pure cultures. The pure cultures were grown on plates containing TSA using a scratch technique and stored for further testing (Mahdiyah et al., 2020).

2.3 Characterization of peat soil bacteria

The obtained isolates were examined to determine their morphology, and the results of Gram staining and catalase activity tests were obtained (Mahdiyah et al., 2020).

2.4 Antimicrobial activity screening using the well diffusion method

The antimicrobial activity of the supernatant (crude cell-free) of peat soil bacteria was evaluated using the well diffusion assay. The supernatant was a 2% (w/v) isolate cultured in tryptic soy broth for 48 h to permit the secretion of antimicrobial compounds. The supernatant was then centrifuged at 5000 rpm for 30 min and filtered through 0.22- μ m pore filters. The supernatant was collected and tested against *S. Typhimurium* and *E. coli* standardized to 0.5 McFarland, a turbidity equivalent to approximately 1.5×10^8 CFU/mL, ensuring uniform bacterial density. A volume of 100 μ L of the bacterial supernatant was pipetted into 6-mm wells on Mueller-Hinton agar (MHA) plates inoculated with the test bacteria. These plates were incubated at 37°C for 24 h. After incubation, the diameter of the inhibition zones around the wells, indicating antimicrobial activity, was measured to assess the potential antibacterial effects of the supernatant. MHA and the well diffusion method are widely used for standardized antimicrobial susceptibility testing (Mahdiyah et al., 2020).

2.5 Minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) testing

This study utilized the serial dilution method to test the antibacterial activity of bacterial supernatant by diluting it in Mueller-Hinton broth (MHB) to achieve concentrations of 25%, 50%, 75%, and 100% (v/v). The test bacteria were cultured in MHB and incubated at 37°C for 24 h, with the bacterial suspension adjusted to approximately 0.5 McFarland standard (1.5×10^8 cells/mL). The supernatant at each concentration was then mixed with the bacterial culture in equal parts (1:1, v/v) and incubated at 37°C for 18 h. Clarity was observed to determine the MIC, identified as the lowest concentration at which the bacterial culture appeared clear, indicating the inhibition of bacterial growth. Subsequently, the MBC was established as the lowest concentration required to completely kill the bacteria. Specifically, 100 μ L of supernatant was taken from the MIC samples that did not exhibit growth, spread over MHA, and then incubated for 18 h at 37°C (Mahdiyah et al., 2020).

3. RESULTS AND DISCUSSION

3.1 Characteristics of the peat soil bacterial isolates

Nine isolates of peat soil bacteria were obtained by the pour plate isolation technique using TSA. Bacteria were incubated for 48 h at 30°C. These isolates were labeled

peat soil bacteria-1–9 (PSB-1–9). The characteristics of the isolates are presented in Table 1.

Table 1. Characteristics of peat soil bacteria

Isolate	Shape	Gram staining	Catalase
PSB-1	Rod	–	+
PSB-2	Rod	–	+
PSB-3	Rod	–	+
PSB-4	Rod	–	+
PSB-5	Rod	–	+
PSB-6	Rod	–	+
PSB-7	Rod	+	+
PSB-8	Rod	+	+
PSB-9	Rod	+	+

The nine isolates were all rod-shaped bacteria with catalase activity. Six isolates (PSB-1, PSB-2, PSB-3, PSB-4, PSB-5, and PSB-6) were Gram-negative, whereas the remaining isolates (PSB-7, PSB-8, and PSB-9) were Gram-positive. Bacterial morphology is determined by the peptidoglycan sacculus, which is highly diverse. It affects critical biological functions (van Teeseling et al., 2017), and it is also important for proper metabolism for cell proliferation (Shiomi et al., 2009). However, its contribution to AMR is not well known (Ojkic et al., 2022). Gram-positive bacteria (actinobacteria group) have been widely used clinically as sources of antibiotics; however, Gram-negative bacteria are also known as sources of newly explored antimicrobials (Masschelein et al., 2017). Catalase is important for controlling oxidative stress and promoting the biosynthesis of secondary metabolism (Nandi et al., 2019; Yuan et al., 2021). Its main role is to convert hydrogen peroxide into water and oxygen (Yuzugullu-Karakus, 2020). Regarding antimicrobial activity, catalase can kill *E. coli* (Kono, 1995), and its antibacterial action was linked to its ability to inhibit enzymatic activity (Daniels et al., 2020; Mir et al., 2023).

3.2 Antibacterial activity of peat soil bacteria against *E. coli* and *S. Typhimurium*

Of the nine isolates identified, only three exhibited antibacterial activity: PSB-7, PSB-8, and PSB-9. These isolates exhibited antibacterial effects against both *E. coli* and *S. Typhimurium*, as evidenced by the formation of clear zones on the growth medium. The antibacterial activity results, assessed using the well diffusion method, are detailed in Table 2.

The antibacterial activity of the tested compounds, as measured by the mean diameter of the clear zones, revealed notable differences between the PSB isolates and controls. Against *E. coli*, the positive control chloramphenicol produced the largest clear zone (20.24 ± 0.21 mm), significantly greater than that of all of the

PSB isolates, demonstrating its strong antibacterial effect. Among the PSB isolates, PSB-9 exhibited the highest activity with a clear zone of 16.02 ± 0.27 mm, followed by PSB-8 (14.75 ± 0.23 mm) and PSB-7 (4.95 ± 0.09 mm). The absence of a clear zone in the Aquadest group (0 mm) confirmed its lack of inhibitory effect, validating its role as a negative control.

Similarly, against *S. Typhimurium*, chloramphenicol produced the largest inhibition zone (28.44 ± 0.50 mm), significantly larger than that of any PSB isolate. Among the isolates, PSB-9 again exhibited the greatest inhibitory activity (15.31 ± 0.84 mm), followed by PSB-8 (13.81 ± 0.27 mm) and PSB-7 (8.85 ± 0.18 mm). The clear zone sizes, which varied between 4.95 and 16.02 mm for *E. coli* and between 8.85 and 15.31 mm for *S. Typhimurium*, indicate that PSB-9 has the strongest antibacterial properties among the tested isolates, although it did not surpass the effect of the positive control.

The clear zones formed during the tests are indicative of the inhibitory effect of the compounds on bacterial growth (Ouchari et al., 2019). In the well diffusion method, the antimicrobial compound diffuses through the medium, inhibiting the growth of the tested bacterial strain (Balouiri et al., 2016). The size of the clear zone is directly proportional to the effect of the antibacterial agent (Eloff, 2019), with larger zones reflecting stronger antibacterial activity and greater inhibition of microbial growth (El Sayed et al., 2020).

These results highlighted the variability in antibacterial potency among the PSB isolates, emphasizing the superior effectiveness of PSB-9 among the isolates, although it was less potent than chloramphenicol. The clear zones observed suggest that these PSB isolates, particularly PSB-9, have potential as antibacterial agents, although factors such as compound solubility could influence their diffusion and efficacy (Eloff, 2019). The absence of inhibitory effects in the negative control further supports the antibacterial capabilities of peat soil bacteria. The clear zones representing the inhibition caused by the isolates are illustrated in Figures 1 and 2.

3.3 MIC and MBC tests of peat soil bacteria against *E. coli* and *S. Typhimurium*

To determine an effective antibiotic dose, it is crucial to assess the MIC and MBC (Rodríguez-Melcón et al., 2022). MIC defines the lowest concentration of an antibiotic that inhibits the visible growth of a bacterial strain in vitro, indicating the strain's susceptibility or resistance to the antibiotic (Kowalska-Krochmal & Dudek-Wicher, 2021). The dilution method, particularly the serial dilution technique, is the most appropriate approach for determining both MIC and MBC (Balouiri et al., 2016). Table 3 presents the MIC and MBC results for the antibiotics derived from peat soil bacteria against *E. coli* and *S. Typhimurium*, providing insights into the antibacterial effectiveness of these compounds.

Table 2. Antibacterial activity of peat soil bacteria against *E. coli* and *S. Typhimurium*

	Compound	Mean clear zone diameter (mm)	Standard error
<i>E. coli</i>	Aquadest	0 ^a	0
	Chloramphenicol	20.24 ^b ± 0.21	0.12
	PSB-7	4.95 ^c ± 0.09	0.05
	PSB-8	14.75 ^d ± 0.23	0.13
	PSB-9	16.02 ^e ± 0.27	0.15
<i>S. Typhimurium</i>	Aquadest	0 ^a	0
	Chloramphenicol	28.44 ^b ± 0.50	0.29
	PSB-7	8.85 ^c ± 0.18	0.11
	PSB-8	13.81 ^d ± 0.27	0.16
	PSB-9	15.31 ^e ± 0.84	0.49

Note: a,b,c,d,e represent statistically significant differences among the groups, as determined by ANOVA and the least significant difference test

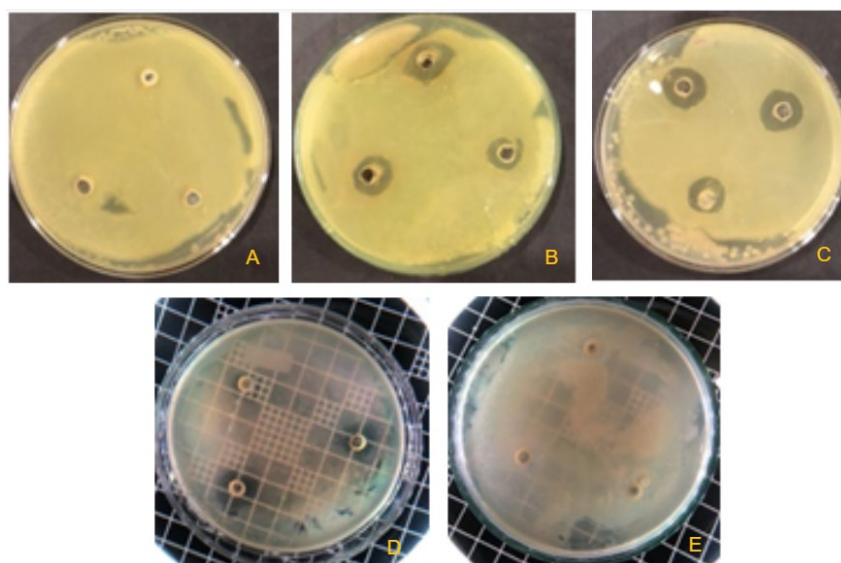
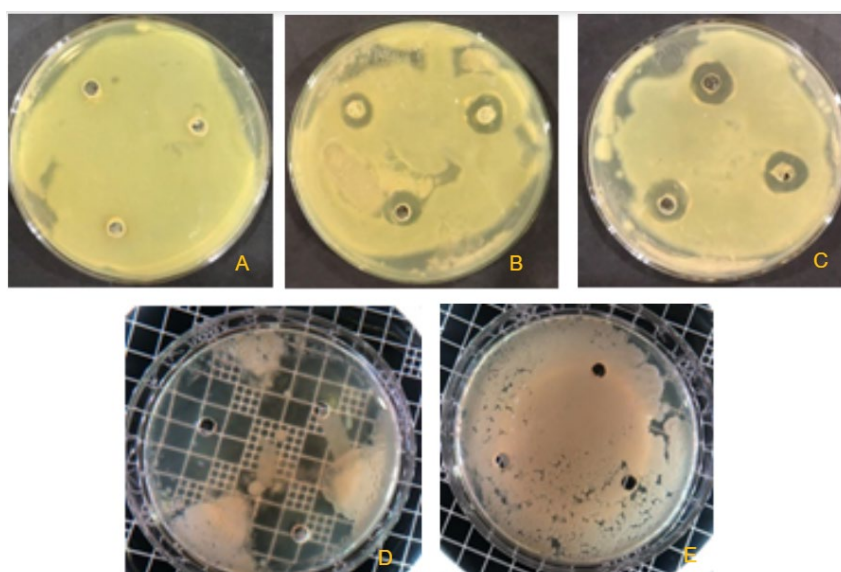

Figure 1. Appearance of clear zones for peat soil bacteria against *E. coli* using well diffusion; A) PSB-7, B) PSB-8, C) PSB-9, D) chloramphenicol, and E) Aquadest

Figure 2. Appearance of clear zones of the antibacterial activity of peat soil bacteria against *Salmonella Typhimurium* using well diffusion; A) PSB-7, B) PSB-8, C) PSB-9, D) chloramphenicol, and E) Aquadest

Table 3. MICs and MBCs of PSB-7–9 as antibacterial agents against *E. coli* and *S. Typhimurium*

	Compound	MIC	MBC
<i>E. coli</i>	PSB-7	100%	-
	PSB-8	75%	-
	PSB-9	75%	-
<i>Salmonella Typhimurium</i>	PSB-7	75%	-
	PSB-8	100%	-
	PSB-9	100%	-

The study assessed the MICs and MBCs of three peat soil bacterial isolates (PSB-7, PSB-8, and PSB-9) with noted antibacterial activity against *E. coli* and *S. Typhimurium*. The results, as presented in Table 3, demonstrate that for *E. coli*, the MIC was lowest for PSB-8 and PSB-9 at 75%, indicating that these isolates are more effective at inhibiting bacterial growth than PSB-7, which required a higher concentration (100%). Against *S. Typhimurium*, PSB-7 exhibited an MIC of 75%, suggesting it is the most effective among the isolates, whereas PSB-8 and PSB-9 both required the full concentration (100%) for inhibition.

Although these isolates exerted inhibitory effects as indicated by their MICs, none could fully eradicate the bacteria. Antimicrobial agents typically function by disrupting critical bacterial processes such as protein synthesis, cell wall formation, DNA replication, and metabolic pathways. However, exposure to sub-inhibitory antibiotic doses, as observed in this study, can lead to bacterial adaptation and potential resistance (Capita et al., 2019; Rodríguez-Melcón et al., 2019).

The discrepancy between the MIC and MBC values observed in this study, in which none of the isolates achieved bactericidal activity, highlights the importance of determining appropriate inhibitory concentrations to prevent the development of resistance (Rodríguez-Melcón et al., 2019). The findings emphasize that although the peat soil bacterial isolates possess inhibitory potential, their efficacy as antimicrobial agents remains constrained by their inability to kill the bacteria fully, suggesting the need for further optimization of their active compounds (Li et al., 2017).

Gram-positive bacteria, particularly those from the Actinobacteria group, are well known for their production of catalase and secondary metabolites with antimicrobial properties. Studies have revealed that members of this phylum, such as species from *Streptomyces*, are capable of producing potent antimicrobial compounds that inhibit Gram-negative bacteria, including *E. coli* and *Salmonella* (Alahadeb, 2022).

Bacillus spp. have been reported to produce lipopeptides and other bioactive molecules that exhibit strong antimicrobial activity against foodborne pathogens. Similarly, *Streptomyces* species, well known for its antibiotic production, including aminoglycosides and macrolides, displayed activity against both Gram-positive and Gram-negative bacteria (Alam et al., 2022). This suggests that the PSB-9 isolate could belong to a group of catalase-producing Gram-positive bacteria, with mechanisms of action related to their production of antimicrobial secondary metabolites, which could have inhibitory effects on *E. coli* and *S. Typhimurium*.

Moreover, catalase-producing bacteria have been studied for their dual role in combating oxidative stress and contributing to antimicrobial mechanisms. Catalase, which catalyzes hydrogen peroxide into water and oxygen, has been reported to play a role in the biosynthesis of secondary metabolites in several *Streptomyces* species, a mechanism that both protects the bacterial cell and potentially affects pathogen inhibition (Rasheed, 2024; Yuan et al., 2021).

4. CONCLUSION

This research succeeded in isolating rod-shaped, Gram-positive, catalase-producing bacteria with the potential to produce antibiotics from peat soil. These isolates, named PSB-7, PSB-8, and PSB-9, were characterized by the formation of a clear zone on agar plates on which *E. coli* and *S. Typhimurium* were grown using the well diffusion method. These potential bacteria have the ability to inhibit the growth of *E. coli* (MICs of 3–4 mg/mL) and *S. Typhimurium* (MICs of 3–4 mg/mL), but they did not have the ability to kill these two bacteria at the concentrations used. To expand this discovery, further research is needed, including identifying the types of bacteria and the potential antibiotic compounds they produce, as well as further testing on various types of pathogens, especially resistant ones.

ACKNOWLEDGMENTS

The researchers would like to thank the Chancellor of Sari Mulia University for funding this research through an internal grant for 2022 and the Research and Community Service Institutions (Lembaga Penelitian dan Pengabdian pada Masyarakat/LPPM) of Sari Mulia University for facilitating grant activities.

REFERENCES

- Alahadeb, J. I. (2022). Inhibitory potentials of *Streptomyces exfoliatus* strain 'MUJA10' against bacterial pathogens isolated from rural areas in Riyadh, Saudi Arabia. *PLoS ONE*, 17(4), Article e0266297. <https://doi.org/10.1371/journal.pone.0266297>
- Alam, K., Mazumder, A., Sikdar, S., Zhao, Y.-M., Hao, J., Song, C., Wang, Y., Sarkar, R., Islam, S., Zhang, Y., & Li, A. (2022). *Streptomyces*: The biofactory of secondary metabolites. *Frontiers in Microbiology*, 13, Article 968053. <https://doi.org/10.3389/fmicb.2022.968053>
- Alenazy, R. (2022). Antibiotic resistance in *Salmonella*: Targeting multidrug resistance by understanding efflux pumps, regulators and the inhibitors. *Journal of King Saud University - Science*, 34(7), Article 102275. <https://doi.org/10.1016/j.jksus.2022.102275>
- Annunziato, G. (2019). Strategies to overcome antimicrobial resistance (AMR) making use of non-essential target inhibitors: A review. *International Journal of Molecular Sciences*, 20(23), Article 5844. <https://doi.org/10.3390/ijms20235844>
- Balouiri, M., Sadiki, M., & Ibnsouda, S. K. (2016). Methods for *in vitro* evaluating antimicrobial activity: A review. *Journal of Pharmaceutical Analysis*, 6(2), 71–79. <https://doi.org/10.1016/j.jpha.2015.11.005>



- Brejijeh, Z., Jubeh, B., & Karaman, R. (2020). Resistance of Gram-negative bacteria to current antibacterial agents and approaches to resolve it. *Molecules*, 25(6), Article 1340. <https://doi.org/10.3390/molecules25061340>
- Capita, R., Vicente-Velasco, M., Rodríguez-Melcón, C., García-Fernández, C., Carballo, J., & Alonso-Calleja, C. (2019). Effect of low doses of biocides on the antimicrobial resistance and the biofilms of *Cronobacter sakazakii* and *Yersinia enterocolitica*. *Scientific Reports*, 9, Article 15905. <https://doi.org/10.1038/s41598-019-51907-1>
- Daniels, A. O., Temikotan, T., Akinkugbe, A. O., & Ibiyemi, D. (2020). Catalase activity and hydrophobicity test of bacteria susceptible to extracts of *Cleistopholis patens* and *Piliostigma reticulatum*. *European Journal of Biology and Biotechnology*, 1(3). <https://doi.org/10.24018/ejbio.2020.1.3.18>
- El Sayed, M., Ghanerad, N., Rahimi, F., Shabanpoor, M., & Shabanpour, Z. (2020). Antibacterial activity of sodium hypochlorite gel versus different types of root canal medicaments using agar diffusion test: An in vitro comparative study. *International Journal of Dentistry*, 2020(1), Article 6483026. <https://doi.org/10.1155/2020/6483026>
- Eloff, J. N. (2019). Avoiding pitfalls in determining antimicrobial activity of plant extracts and publishing the results. *BMC Complementary and Alternative Medicine*, 19(1), Article 106. <https://doi.org/10.1186/s12906-019-2519-3>
- European Antimicrobial Resistance Collaborators. (2022). The burden of bacterial antimicrobial resistance in the WHO European region in 2019: A cross-country systematic analysis. *The Lancet Public Health*, 7(11), e897–e913. [https://doi.org/10.1016/S2468-2667\(22\)00225-0](https://doi.org/10.1016/S2468-2667(22)00225-0)
- European Food Safety Authority, & European Centre for Disease Prevention and Control. (2022). The European Union summary report on antimicrobial resistance in zoonotic and indicator bacteria from humans, animals and food in 2019–2020. *EFSA Journal*, 20(3), Article e07209. <https://doi.org/10.2903/j.efsa.2022.7209>
- Galindo-Méndez, M. (2020). Antimicrobial resistance in *Escherichia coli*. In L. Rodrigo (Ed.), *E. coli infections – Importance of early diagnosis and efficient treatment* (pp. 1–15). IntechOpen. <https://doi.org/10.5772/intechopen.93115>
- Hormozi, S. F., Vasei, N., Aminianfar, M., Darvishi, M., & Saeedi, A. A. (2018). Antibiotic resistance in patients suffering from nosocomial infections in Besat hospital. *European Journal of Translational Myology*, 28(3), Article 7594. <https://doi.org/10.4081/ejtm.2018.7594>
- Kono, Y. (1995). Apparent antibacterial activity of catalase: Role of lipid hydroperoxide contamination. *The Journal of Biochemistry*, 117(1), 42–46. <https://doi.org/10.1093/oxfordjournals.jbchem.a124718>
- Kowalska-Krochmal, B., & Dudek-Wicher, R. (2021). The minimum inhibitory concentration of antibiotics: Methods, interpretation, clinical relevance. *Pathogens*, 10(2), Article 165. <https://doi.org/10.3390/pathogens10020165>
- Li, J., Xie, S., Ahmed, S., Wang, F., Gu, Y., Zhang, C., Chai, X., Wu, Y., Cai, J., & Cheng, G. (2017). Antimicrobial activity and resistance: Influencing factors. *Frontiers in Pharmacology*, 8, Article 364. <https://doi.org/10.3389/fphar.2017.00364>
- Mahdiyah, D. (2015). Isolasi bakteri dari tanah gambut penghasil enzim protease. *Jurnal Pharmascience*, 2(2), 71–79. <http://dx.doi.org/10.20527/jps.v2i2.5825> [in Indonesian]
- Mahdiyah, D., Farida, H., Riwanto, I., Mustofa, M., Wahjono, H., Laksana Nugroho, T., & Reki, W. (2020). Screening of Indonesian peat soil bacteria producing antimicrobial compounds. *Saudi Journal of Biological Sciences*, 27(10), 2604–2611. <https://doi.org/10.1016/j.sjbs.2020.05.033>
- Mahdiyah, D., Theana, M., Rahmadani, Sari, A., & Mukti, B. H. (2023). The antibacterial activity of Gambir extract (*Uncaria gambir* (hunter) Roxb) against *Salmonella typhi*. *KnE Social Sciences*, 2023, 747–757. <https://doi.org/10.18502/kss.v8i9.13389>
- Mancuso, G., Midiri, A., Gerace, E., & Biondo, C. (2021). Bacterial antibiotic resistance: The most critical pathogens. *Pathogens*, 10(10), Article 1310. <https://doi.org/10.3390/pathogens10101310>
- Masschelein, J., Jenner, M., & Challis, G. L. (2017). Antibiotics from Gram-negative bacteria: A comprehensive overview and selected biosynthetic highlights. *Natural Product Reports*, 34(7), 712–783. <https://doi.org/10.1039/C7NP00010C>
- Mir, M. A., Altuhami, S. A., Mondal, S., Bashir, N., Dera, A. A., & Alfihili, M. A. (2023). Antibacterial and antibiofilm activities of β -Lapachone by modulating the catalase enzyme. *Antibiotics*, 12(3), Article 576. <https://doi.org/10.3390/antibiotics12030576>
- Mukti, B. H. (2024). Ethnobotanical studies of medicinal plants in Borneo: Bridging tradition and pharmaceutical research. *Health Sciences International Journal*, 2(2), 154–168. <https://doi.org/10.71357/hsij.v2i2.41>
- Murray, C. J. L., Ikuta, K. S., Sharara, F., Swetschinski, L., Robles Aguilar, G., Gray, A., Han, C., Bisignano, C., Rao, P., Wool, E., Johnson, S. C., Browne, A. J., Chipeta, M. G., Fell, F., Hackett, S., Haines-Woodhouse, G., Kashef Hamadani, B. H., Kumaran, E. A. P., McManigal, B., ... Naghavi, M. (2022). Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *The Lancet*, 399(10325), 629–655. [https://doi.org/10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)
- Nair, D. V. T., Venkitanarayanan, K., & Kollanoor Johny, A. (2018). Antibiotic-resistant *Salmonella* in the food supply and the potential role of antibiotic alternatives for control. *Foods*, 7(10), Article 167. <https://doi.org/10.3390/foods7100167>
- Nandi, A., Yan, L.-J., Jana, C. K., & Das, N. (2019). Role of catalase in oxidative stress- and age-associated degenerative diseases. *Oxidative Medicine and Cellular Longevity*, 2019(1), Article 9613090. <https://doi.org/10.1155/2019/9613090>
- Nwobodo, D. C., Ugwu, M. C., Anie, C. O., Al-Ouqaili, M. T. S., Ikem, J. C., Chigozie, U. V., & Saki, M. (2022). Antibiotic resistance: The challenges and some emerging strategies for tackling a global menace. *Journal of Clinical Laboratory Analysis*, 36(9), Article e24655. <https://doi.org/10.1002/jcla.24655>
- Ojkic, N., Serbanescu, D., & Banerjee, S. (2022). Antibiotic resistance via bacterial cell shape-shifting. *mBio*, 13(3), Article e00659-22. <https://doi.org/10.1128/mbio.00659-22>
- Ouchari, L., Boukeskase, A., Bouizgarne, B., & Ouhdouch, Y. (2019). Antimicrobial potential of actinomycetes isolated from the unexplored hot Merzouga desert and

- their taxonomic diversity. *Biology Open*, 8(2), Article bio035410. <https://doi.org/10.1242/bio.035410>
- Poirel, L., Madec, J.-Y., Lupo, A., Schink, A.-K., Kieffer, N., Nordmann, P., & Schwarz, S. (2018). Antimicrobial resistance in *Escherichia coli*. *Microbiology Spectrum*, 6(4), Article ARBA-0026-2017. <https://doi.org/10.1128/microbiolspec.ARBA-0026-2017>
- Rasheed, Z. (2024). Therapeutic potentials of catalase: Mechanisms, applications, and future perspectives. *International Journal of Health Sciences*, 18(2), 1–6.
- Rodríguez-Melcón, C., Alonso-Calleja, C., García-Fernández, C., Carballo, J., & Capita, R. (2022). Minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) for twelve antimicrobials (biocides and antibiotics) in eight strains of *Listeria monocytogenes*. *Biology*, 11(1), Article 46. <https://doi.org/10.3390/biology11010046>
- Rodríguez-Melcón, C., Riesco-Peláez, F., García-Fernández, C., Alonso-Calleja, C., & Capita, R. (2019). Susceptibility of *Listeria monocytogenes* planktonic cultures and biofilms to sodium hypochlorite and benzalkonium chloride. *Food Microbiology*, 82, 533–540. <https://doi.org/10.1016/j.fm.2019.03.020>
- Serwecińska, L. (2020). Antimicrobials and antibiotic-resistant bacteria: A risk to the environment and to public health. *Water*, 12(12), Article 3313. <https://doi.org/10.3390/w12123313>
- Shiomi, D., Mori, H., & Niki, H. (2009). Genetic mechanism regulating bacterial cell shape and metabolism. *Communicative & Integrative Biology*, 2(3), 219–220. <https://doi.org/10.4161/cib.2.3.7930>
- van Teeseling, M. C. F., de Pedro, M. A., & Cava, F. (2017). Determinants of bacterial morphology: From fundamentals to possibilities for antimicrobial targeting. *Frontiers in Microbiology*, 8, Article 1264. <https://doi.org/10.3389/fmicb.2017.01264>
- Wang, S., Zhao, S., Zhou, Y., Jin, S., Ye, T., & Pan, X. (2023). Antibiotic resistance spectrum of *E. coli* strains from different samples and age-grouped patients: A 10-year retrospective study. *BMJ Open*, 13(4), Article e067490. <https://doi.org/10.1136/bmjopen-2022-067490>
- Wang, X., Cao, X., Xu, H., Zhang, S., Gao, Y., Deng, Z., & Li, J. (2021). Research on the properties of peat soil and foundation treatment technology. *E3S Web of Conferences*, 272, Article 02019. <https://doi.org/10.1051/e3sconf/202127202019>
- World Health Organization. (2019). *Health workers' education and training on antimicrobial resistance: Curricula guide*. World Health Organization. <https://apps.who.int/iris/handle/10665/329380>
- Wu, D., Ding, Y., Yao, K., Gao, W., & Wang, Y. (2021). Antimicrobial resistance analysis of clinical *Escherichia coli* isolates in neonatal ward. *Frontiers in Pediatrics*, 9, Article 670470. <https://doi.org/10.3389/fped.2021.670470>
- Yuan, F., Yin, S., Xu, Y., Xiang, L., Wang, H., Li, Z., Fan, K., & Pan, G. (2021). The richness and diversity of catalases in bacteria. *Frontiers in Microbiology*, 12, Article 645477. <https://doi.org/10.3389/fmicb.2021.645477>
- Yuzugullu-Karakus, Y. (2020). Typical catalases: Function and structure. In M. D. Bagatini (Ed.), *Glutathione system and oxidative stress in health and disease* (pp. 1–14). IntechOpen. <https://doi.org/10.5772/intechopen.90048>