A Model System to Assess the Effect to Planktonic Predator-Prey Dynamics Under Varying Microplastic Concentrations

Sarina Mae Bien Arciga[1*] and David Montagnes[2]

ABSTRACT

Microplastics, small plastic debris known to affect a wide range of organisms, may affect the growth rate of prey populations and subsequently influence predator populations. However, the mechanisms underlying their effects on predator and prey population dynamics have not been fully explored. This study aimed to evaluate these effects in planktonic organisms employing a modeling approach with parameters derived from the ciliates, *Paramecium* and *Didinium*. The Independent Response model was parameterized to include a function describing the prey growth rate's response to increasing microplastic concentrations. By varying the rate (a) at which prey growth responded to different microplastic concentrations and running the model to steady states, the study revealed significant shifts in predator-prey dynamics. Low microplastic levels maintained constant predator and prey populations, while intermediate levels caused a gradual decline in predators, leading to extinction at high microplastic concentrations. Consequently, prey populations increased to their carrying capacity. This phase shift, from top-down control by predators to prey populations reaching carrying capacity, could have profound implications for food web dynamics. The existence of alternative steady states in the population was influenced by both the rate (a) of prey response and microplastic concentration. Furthermore, the sigmoidal relationship between prey growth rate and microplastic levels also had a substantial influence on the modeled dynamics of the predator-prey system. The model suggests that in the natural ecosystems, the removal of predators from the system due to perturbations can cause a decrease in top-down control, thereby causing an increase in prey populations to carrying capacity and an alteration of the overall food web dynamics.

Keywords: Carrying capacity, Growth rate, Parameterize, Steady States

INTRODUCTION

Microplastics, defined as plastic particles smaller than 5 mm, are widespread pollutants that significantly affect ecosystems, particularly zooplankton, which may ingest them. Microplastics interfere with natural feeding processes by competing with food particles and occupying gut space (Baum and Worm, 2009), thereby reducing energy available for essential biological functions like growth and reproduction (Critchell and Hoogenboom, 2018). This leads to diminished reproductive output in zooplankton populations (Ziajahromi *et al*., 2018). Such ingestion not only hampers zooplankton growth and survival but also impacts higher trophic levels, as zooplankton are key prey species (Montagnes and Fenton, 2012; Cole *et al*., 2013; Prata *et al*., 2019; Sun *et al*., 2019). The adverse effects of microplastics on both zooplankton and their predators make it crucial to understand these impacts at the predator-prey level, which forms the basis of food web dynamics.

[1]Bicol University Tabaco, Albay, Philippines
[2]University of Liverpool, Liverpool, UK
[*]Corresponding author. E-mail address: smbarciga@bicol-u.edu.ph
Received 11 July 2024 / Accepted 21 January 2025

Predator-prey systems provide a valuable framework for exploring how environmental factors influence broader community interactions. These dynamics can be examined empirically or through population modeling, which allows for the observation of long-term trends that empirical studies might not capture. Predator-prey interactions typically settle into one of three steady states: oscillating population sizes, stable populations, or predator extinction with prey reaching carrying capacity (Rosenzweig and MacArthur, 1963; Allen, 1976; Turchin, 2003; Allesina and Pascual, 2008). Understanding these dynamics under perturbations like microplastics is crucial, as such factors can shift the balance of predator-prey interactions (Galloway and Lewis, 2016). Microplastics can reduce prey growth rates, which is a key factor in predator-prey dynamics. While it is challenging to empirically observe these dynamics over extended periods, modeling allows for the examination of how reduced prey growth rates affect the system over time.

The Independent Response Model introduced by Fenton *et al*. (2010) suggests that predator growth declines when prey numbers fall below a critical threshold. This model is particularly relevant when assessing the impacts of microplastics on prey populations and the resulting implications for predator abundance at steady states. In this study, the Independent Response Model was adapted and parameterized to account for the effects of microplastics on prey growth rates, and the resulting predator-prey dynamics were explored.

A sigmoid response function can be introduced into the Independent Response Model to describe the impact of microplastics on prey growth rates. This function captures how the inhibitory effects of microplastics increase with concentration, eventually reaching a maximum where further increases in microplastic levels have minimal additional effects on growth (Carrillo and González, 2002). By varying microplastic concentrations, the response of the predator-prey system can be modeled, focusing on how these perturbations influence population abundance at steady state.

The *Paramecium-Didinium* predator-prey system is a well-studied model for examining population dynamics under various environmental conditions (Gause *et al*., 1936; Veilleux, 1979). The model system has been useful because these ciliates can easily be manipulated under controlled conditions with both *Paramecium* and *Didinium* having rapid generation times. This system is inherently unstable, with *Didinium* often driving *Paramecium* to extinction unless conditions are altered, such as by increasing the medium's viscosity to reduce predator-prey encounters (Gause *et al*., 1936; Luckinbill, 1973). Past studies have demonstrated that under controlled conditions, this system can exhibit oscillations or stabilize at a steady state, making it an ideal framework for testing the effects of environmental perturbations like microplastics (Li and Montagnes, 2015).

Objectives of the Study

The threat of the increasing of microplastics in the environment warrants assessment of their long-term impacts on organisms; however, it is impractical to observe their populations in the natural environment over extended time periods. This study attempted to address this challenge with the following objectives: introduce a function to describe the effect of microplastics on the growth rate of prey, and assess the direct impact of microplastics on prey and their indirect effects on planktonic predator-prey dynamics, particularly in relation to steady-state population levels. To achieve this, a mechanistic model based on the classic predator-prey system involving the ciliates *Paramecium* (prey) and *Didinium* (predator) (Salt, 1974; Veilleux, 1979; Li and Montagnes, 2015) was adapted. This model was employed to investigate how the introduction of microplastics as perturbations affects predator and prey populations, as well as the potential risk of species extinction.

MATERIALS AND METHODS

This section details the methods, encompassing the function utilized to elucidate how prey growth rate responds to microplastic concentrations, along with the modeling procedure employing parameters derived from the Independent Response Model.

Study site and study organisms

The study was conducted at the Institute of Integrative Biology, University of Liverpool, UK utilizing computer programs that simulate changes in populations of predator and prey over time. Population parameters from the ciliates, *Paramecium* and *Didinium* were used in the Independent Response Model (Fenton *et al*., 2010). The Independent Response Model is a mechanistic model that represents ecological processes and relationships particularly between prey and predators. This model was parameterized to include a function describing the effect of microplastics to prey population growth rate. The parameterized model assumed that particle sizes correspond to a range between 0.2 to 2 µm, which are sizes that *Paramecium* can ingest; however, the types of microplastics were generalized, as the model assumed that all types would affect the growth rate, without consideration of the effect's magnitude.

The response function

A sigmoid function is a biologically plausible response pattern that has been empirically observed in growth rate responses to other types of perturbations (e.g., Baas Becking, 1937; Turchin, 2003; Winship *et al*., 2017). To evaluate the impact of microplastics on predator-prey dynamics, the specific growth rate of prey (r, d^{-1}) was modeled to vary and decrease with microplastic concentration using a phenomenological sigmoid function (Equation 1),

$$f(m) = r\left(1 - \frac{1}{1+\exp\left((-am+ab)\right)}\right) \qquad (1)$$

Here, f(m) represents the realized growth rate, r is the prey growth rate in the absence of perturbation, m ($\times10^3$ mL^{-1}) denotes the microplastic concentration, a (d^{-1}) determines the rate of decline in growth rate and shapes the response, and b ($\times10^3$ mL^{-1}) indicates the microplastic concentration at which 0.5 r occurs. The curvature of the response was adjusted by varying *a*-values (Figure 1). Changing a from 0.01 to 0.05

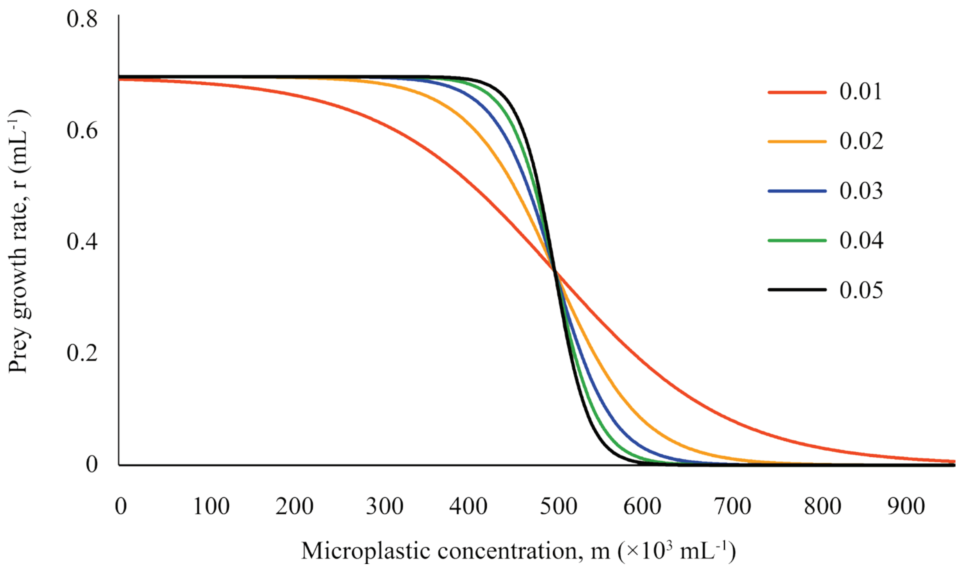

Figure 1. An illustration of how different values of a (from Equation 1) influence the growth rate in response to rising microplastic concentrations ($\times10^3$ mL^{-1}). The choice of b (500×10^3 mL^{-1}) parallels dose-response curves, where this value represents the concentration at which half of the maximum effect is observed.

resulted in a function describing how the effect varies with increasing microplastic concentration (m). A lower a enhances the visibility of the effect, as prey growth rate begins declining at lower microplastic concentrations; although this decline is gradual until higher concentrations of m. Setting b at 500 ($\times 10^3$ microplastics·mL^{-1}) establishes a standard inflection point for the sigmoid response, ensuring comparability across all *a* values.

Modelling the dynamics and the effect of changing a and microplastic concentration

The adjusted growth rate function (Equation 1) was incorporated into the Independent Response model (Equations 2 and 3, Fenton *et al*., 2010). This model was then employed to evaluate the impact of microplastics on predator-prey dynamics.

$$\frac{dV}{dt} = f(m)V\left(1 - \frac{V}{K}\right) - \frac{I_{max}CV}{k_1 + V} \quad (2)$$

$$\frac{dC}{dt} = \frac{C\mu_{max}(V-V')}{k_2 + V-V'} \quad (3)$$

Here V represents prey abundance; C represents predator abundance; K denotes the prey carrying capacity; I_{MAX} is the predator's asymptotic ingestion rate; k_1 is the half-saturation constant for ingestion; μ_{MAX} signifies the predator's maximum growth rate; V' is the threshold prey concentration at which predator's growth rate becomes zero; and k_2 is a constant. Parameter values were sourced from existing literature (Table 1). The model was designed to consider predators extinct when their numbers drop below 10^{-3}.

Without the influence of microplastics, the parameter values (Table 1) led to constant abundances of the prey (~13 mL^{-1}) and predator (~5 mL^{-1}) at steady state. These values were used as a baseline to identify deviations in dynamics under the influence of microplastics. We ran simulations across a range of *a*-values and *m*, with *m* values starting with the estimated environmental concentration of 1 ($\times 10^3$) particles·mL^{-1} (Lenz *et al*., 2016), for the lowest concentration and 1,000 ($\times 10^3$ mL^{-1}) for the maximum concentration that would result in zero growth rate of the prey. The maximum concentration was estimated based on the assumption that microplastics would continue to increase given the present exponential input of plastic pollutants in the environment (Everaert *et al*., 2018). Simulations, initiated at 13 *Paramecium* and 5 *Didinium*, were continued until a steady state was reached, and the abundances of both populations were measured. The steady state abundance was then explored across the given parameter space to identify the pattern of dynamics at varying *a*-values and *m*.

RESULTS AND DISCUSSION

As the concentration of microplastics (m, mL^{-1}) increased, the final steady state abundances of the predator and prey populations were affected. Initially, *Paramecium* maintained a density of ~13 mL^{-1}, while *Didinium* gradually decreased from their stable numbers of ~5 mL^{-1} (Figure 2a, 2b). At high m levels, *Didinium* populations went extinct, allowing *Paramecium* to reach its carrying capacity (Figure 2c).

Table 1. Parameter values for the independent response model of predator-prey dynamics (Li and Montagnes, 2015).

Parameter	Values	Units
r	0.69	d^{-1}
K	109	mL^{-1}
I_{MAX}	28.5	d^{-1}
k_1	200	mL^{-1}
μ_{MAX}	1.43	d^{-1}
V'	13	mL^{-1}
k_2	50	mL^{-1}

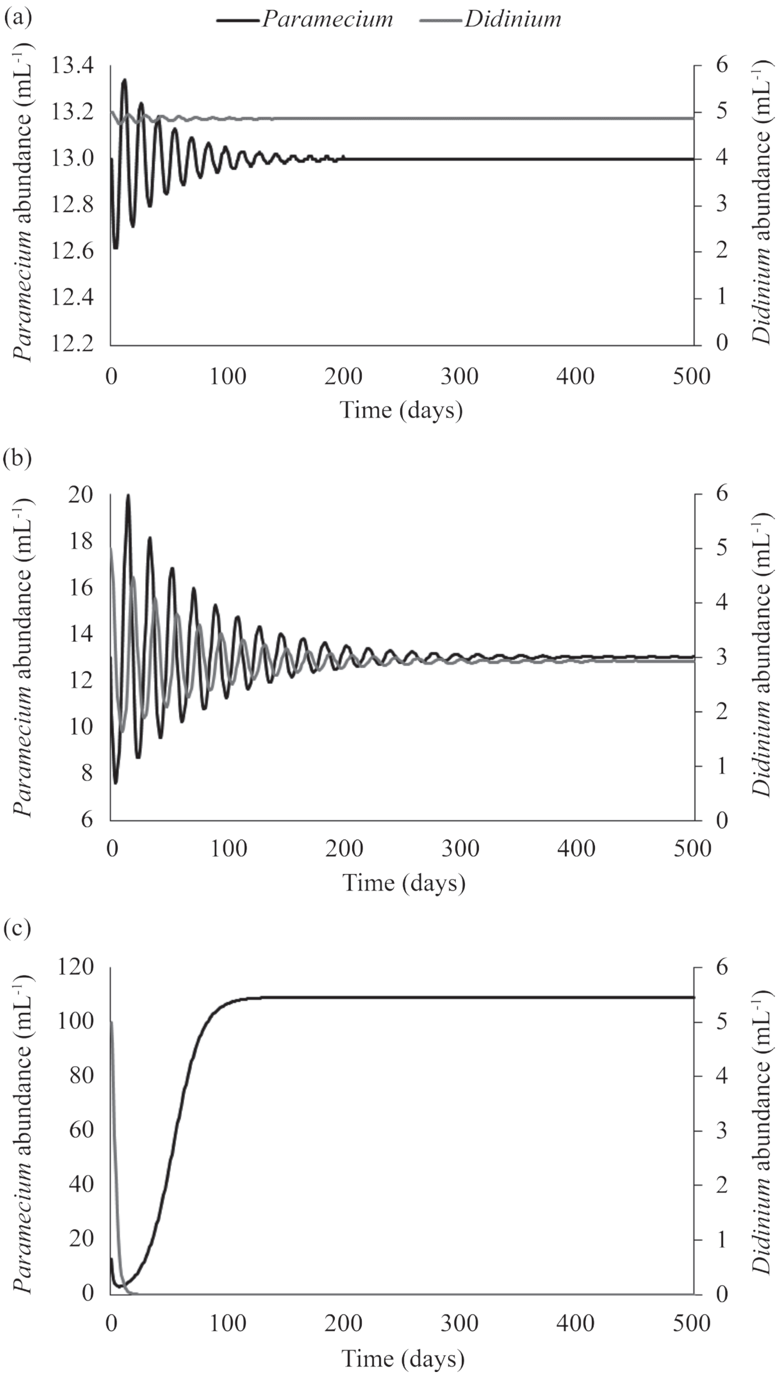

Figure 2. Simulations tracking the abundance changes of *Paramecium* and *Didinium* over 500 d (a = 0.01 d^{-1}) were conducted until the populations reached steady states, revealing a phase shift of the prey dynamics from (b) to (c). (a) At low microplastic concentrations, both *Paramecium* and *Didinium* maintained constant numbers; (b) At intermediate microplastic levels, *Paramecium* remained constant, while the *Didinium* population gradually decreased; (c) When microplastic concentrations exceed intermediate levels, the *Didinium* population went extinct, allowing the *Paramecium* population to reach its carrying capacity.

The impact of microplastics on the steady state abundances of predator and prey was influenced by how microplastic concentration influenced growth rate (*a*-value) (Figure 3a, 3b). This indicates that there was an interaction between microplastic concentration and *a*-values. At all *a*-values, a phase shift in population dynamics was observed, with *Paramecium* abundance shifting from constant numbers (13 mL^{-1}) to carrying capacity at high microplastic concentrations (Figure 3a). Notably, as a increased, the shift occurred at a comparably lower microplastic concentration.

The *Didinium* population at steady-state was similarly affected by changes in both *a*-values and microplastic concentration. At low microplastic levels, the population remained stable at ~5 mL^{-1}; however, as microplastic concentration increased, the *Didinium* population exhibited a gradual funnel-shaped decline due to varying a-values (Figure 3b). This gradual decrease was more pronounced and occurred at lower m and lower a, though *Didinium* did not become extinct until microplastic levels were high. As a increased, the gradual decline happened at relatively higher m values; however, *Didinium* extinction occurred at lower concentrations compared to when a was smaller. This explains why carrying capacity of *Paramecium* was reached at lower m when a was 0.05 compared to when it was 0.01.

In natural predator-prey systems, predators exert top-down control on prey populations, maintaining them at constant levels. Under normal conditions, this top-down control results in balanced food webs and stable community dynamics (Leroux and Loreau, 2015). For example, in marine environments, certain planktivorous fish species regulate algae populations through grazing; without this control, algae would proliferate uncontrollably (Lynam *et al*., 2017).

Using parameters obtained by Li and Montagnes (2015) in the Independent Response model for this study illustrated systems with top-down mechanisms in a model predator-prey system, where prey abundance at steady state was determined by the threshold prey concentration (See Methods, Equation 3). The model indicated that at low levels of perturbation, such as microplastics, top-down control persists, keeping prey at threshold levels. However, as microplastic concentration increases, prey numbers fall below the threshold level required for predator survival. This shift in steady-state dynamics allows prey populations to escape predator control and reach their carrying capacity. These findings have significant implications for broader community and food web dynamics.

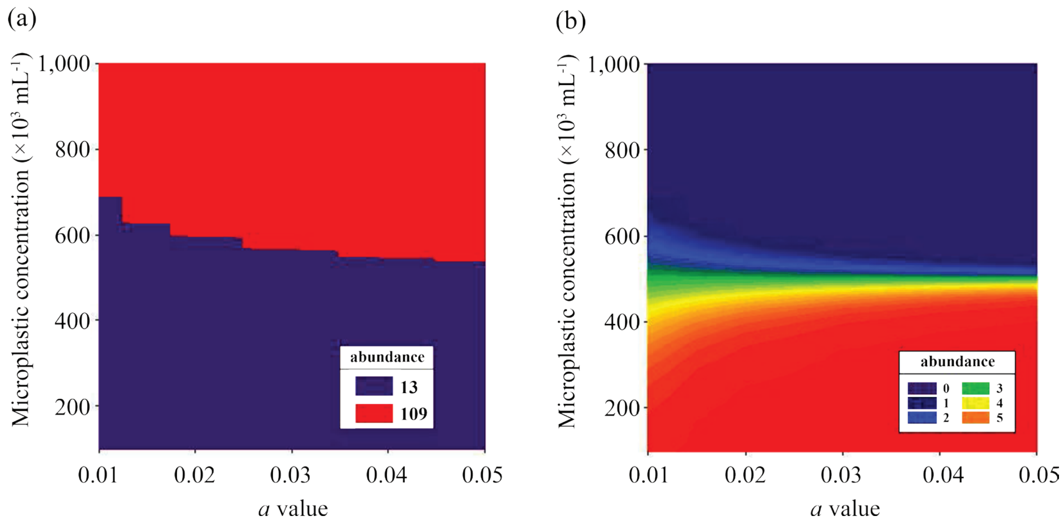

Figure 3. The abundance of (a) *Paramecium* and; (b) *Didinium* population at varying combinations of a and microplastic concentrations.

Microplastics affect population abundance at steady states

The bistability of predator-prey systems has been recognized as a common response to environmental perturbations (Beisner, 2012; Huang *et al*., 2015). This bistability involves a phase shift from top-down control, where prey numbers are constant, to prey reaching their carrying capacity, influenced by the threshold concentration in the Independent Response model. Since prey serve as a resource for predators, disturbances affecting the prey can impact the predators, leading to two steady-state scenarios.

First, at low microplastic concentrations, prey reproduction and population replenishment slow down as they biologically respond to microplastics. At this stage, prey populations stabilize at threshold levels due to the constant grazing pressure from predators (Chakraborty *et al*., 2012). The predator population thus has enough resources to survive without increasing in number (Fenton *et al*., 2010). Second, at intermediate and high microplastic levels, prey growth rates are significantly reduced more by microplastics than by predator ingestion. The model predicts that in the absence of perturbations, prey growth rates are primarily affected by the grazing pressure from predators, but when microplastics are introduced prey growth rates become more affected by the presence of microplastics than by predator grazing pressure. Consequently, prey populations can no longer reach the threshold concentration. This leads to a decline in predator populations as their resources diminish, eventually causing predator extinction. Without the suppressive effects of predators, prey populations then reach their carrying capacity (Rao and Larsen, 2010).

The dynamics of the predator-prey model indicate broader ecological implications of increasing microplastics, posing risks to biodiversity, productivity, and ecosystem services. Sustained impacts on prey growth rates can lead to predator extinction, and the removal of top-down control can affect larger food web and ecosystem dynamics (Huang *et al*., 2020). In systems where predators have been eliminated due to natural or human-induced disturbances, prey populations tend to grow until they surpass the availability of food in the environment (Prata *et al*., 2019). Additionally, other predator species may increase in density, altering the natural dynamics of the system (Ritchie and Johnson, 2009). This is implied in the results of the model when natural predators of a prey population become extinct due to the cascading effect of microplastics on the upper trophic level. This rise in so-called mesopredators occurs in ecosystems where mammal and fish populations have been significantly reduced due to overexploitation (Baum and Worm, 2009). While current environmental levels of microplastics (Lenz *et al*., 2016) still allow for top-down control by predators, the model suggests that a sustained increase in microplastics can shift these dynamics.

Sigmoidal function for growth rate affects the model results

The sigmoidal response of growth rate to increasing microplastics had a substantial effect on the modeled population dynamics. The extent to which the predator population began to decline and eventually went extinct (Figure 3b) was influenced by the specific shape of the growth response curve. This explains the non-uniform pattern of the gradual decrease in predator numbers leading to extinction. Consequently, the shape of the growth response to perturbations, such as microplastics, can determine the dynamics of both predator and prey populations. With a constant model inflection point (b), it was relatively simple to observe and compare shifts in dynamics across various rates of growth rate decrease (a). If the growth rate response to perturbations were modeled with different types of sigmoid curves (e.g., hyperbolic, Hendriks *et al*., 2005), or if the inflection point were altered, the dynamics could differ significantly. Exploring such non-linear functions that describe growth rate responses to perturbations could provide valuable insights into predator-prey dynamics under varying microplastic concentrations.

CONCLUSIONS

This model demonstrates that microplastics, acting as perturbations in prey populations, can have cascading effects on predator populations. In natural ecosystems where top-down control persists, high levels of perturbations can lead to the extirpation of predators, contributing to the bistability of the predator-prey system. The model indicates that the response of prey growth rate to increased microplastics affects the patterns in which the two steady states are achieved. This suggests that investigating other types of response curves could provide additional insights. Moreover, adjusting the growth curve horizontally (by changing the value of b) without altering its shape could also significantly impact the model's dynamics. Furthermore, the sustained increase in microplastics (Cole *et al*., 2013; Duis and Coors, 2016) calls for further assessment of their effects on other population dynamics parameters, such as carrying capacity, which also influence the stability of predator-prey systems. Results further imply that microplastics as pollutants not only affect the individual organism but may cascade to the population level. Future research may focus on understanding the long-term ecological effects such as survival rates across different species, and explore how these may scale up to affect trophic interactions and community compositions. On the policy side, stricter regulations on plastic production, usage, and disposal should be implemented to mitigate the cascading effects of microplastics.

ACKNOWLEDGEMENTS

We acknowledge the British Council, the Philippine's Commission on Higher Education (CHED), Bicol University and University of Liverpool for forging partnerships that supported the authors in this research endeavor. We would also like to thank all the people who provided assistance and support in the conduct of this study.

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