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Fluid Flow Analysis on Artificial Mangrove Root Model for Marine Litter Trapping

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ABSTRACT

Plastic pollution is a pressing issue that has affected not only the oceans and rivers but also the coastal region. While studies have been conducted to determine the pollution in mangrove forests, still little can be done to reduce the pollution issue. The intricate network of mangrove root systems contributes to this issue. This study aimed to create and analyse artificial mangrove root models by using 3D-printed models and Computational Fluid Dynamics (CFD) simulations. The models, with varying porosity levels, were tested for their ability to reduce water flow and capture debris. The results showed that the model with higher porosity (94.5%) exhibited reduced flow attenuation and delayed wake formation compared to the model with lower porosity (75.1%). Tidal wave tank experiments confirmed that higher porosity consistently led to higher debris trapping percentages, regardless of debris mass, size, or type. The increased porosity reduced flow interaction and turbulence, enhancing the effectiveness of debris trapping. These findings contribute to developing more efficient artificial mangrove systems that can effectively mitigate debris transport and accumulation in aquatic environments.

1. Introduction

Plastic pollution is a pressing environmental concern known for its negative impact on the ecosystem and human health [1]. Various pathways such as improper disposal, direct dumping,

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leakages from infrastructure waste or industry, sewage discharge, surface runoff, floods, storms or landslides, transport plastic waste into the marine environment [2,3]. Rivers, especially in Asia, are major contributors to ocean plastic pollution, with Malaysia's Klang River among the top ten global culprits [4,5]. The Klang River, an essential waterway between Kuala Lumpur and Selangor, has suffered extensive pollution due to human activities. Arguably, recent research suggests that only a fraction of improperly disposed plastic waste enters the ocean, with much of it believed to be retained at riverbanks and floodplains, plants, riverbed sediments, infrastructure, lakes, and estuaries [1,5].

It is very unpredictable how floating plastic waste will move and what will happen to it in estuaries [6]. Certain river consists of bifurcation and confluence mechanisms that would affect the hydraulic system, such as the flow and bed profile of the river [7]. Many studies have proved that mangrove areas near estuaries tend to accumulate plastic waste due to their complex root system and vegetation distributions [8-12]. Mangrove forests act as a natural barrier in safeguarding the coastal populations and infrastructure from storm surges and waves, storing carbon, and trapping sediment and pollutants [13]. However, anthropogenic influences such as deforestation for land use have caused the decline of mangroves worldwide [14,15]. The survival rate of the young trees from restoration and conservation initiatives was incredibly challenging as the plastic waste pollution in the mangrove areas tends to suffocate the aerial roots of mangroves by smothering [16-18]. Investigating novel approaches to safeguard and restore mangroves and their fundamental functions is therefore critical.

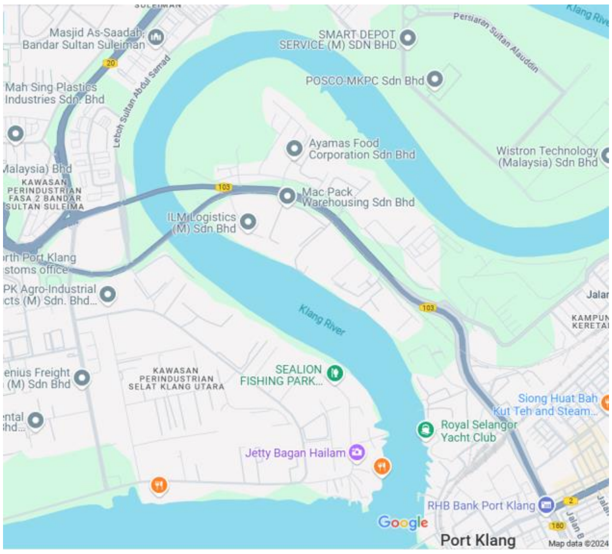
The intricate network of mangrove root structures was known for their capability to obstruct the water currents and play a major role in the formation of flow structures [19]. Few past research has been done to discover the hydrodynamics effects of artificial mangrove root systems such as water surface elevation, wave attenuation, reduction of storm surge, tsunami, tidal circulation, and flow pattern [20]. Understanding mangrove trees' unique traits and attributes is crucial in comprehending how they function and behave [21]. This study incorporated data measurements obtained from site surveys to design artificial mangrove roots which could help to simulate the performance of natural mangroves and contribute to the development of effective restoration strategies.

However, these unique features also bring negative impacts such as trapping plastic waste. The complex structure of the mangrove root system acts like a big net in trapping and subsequently accumulates in the mangrove's forest floor [8,12]. Thus, this study aims to design a lab-scale artificial mangrove root model by the root system characteristics and evaluate its debris-trapping capabilities associated with the hydrodynamic factors. The findings of this research will contribute to the development of innovative approaches to mitigate marine pollution, protect coastal habitats, and preserve essential ecosystems. Collected plastic waste could then be further processed into other products such as concrete [22].

2. Methodology

2.1 Field Survey

A field survey was conducted at Mangrove Point near Klang River (3.0210° N, 101.3790° E) to collect data on the characteristics of the mangrove's pneumatophore roots (Figure 1(a)). The mangrove species was identified as *Avicennia* sp. based on the shape and sizes of the pneumatophore's roots. At low tide, a quadrat sampling plot of 1m x 1m was established to measure the height, diameter, and number of pneumatophore roots on mature mangrove trees near the river (Figure 1(b)) [23]. The root height was measured from the exposed parts above the ground. Sampling was done during the low tidal period due to accessibility.



(a) (b)

Fig. 1. (a) Satellite image of the study site (Mangrove Point) located near Klang River; Malaysia, (b) Quadrat sampling plot of 1 m x 1 m placed on the pneumatophore roots of mature mangrove tree

2.2 Model Development

Two models of artificial mangroves were designed using Fusion 360 software to replicate the characteristics of pneumatophores roots. The models consisted of cylindrical patches in which each cylinder's diameter was known as the root diameter, while the outer diameter of the entire array of cylinders was known as the patch diameter [19,24]. Each model consisted of a circular array of cylinders with scaled dimensions based on the ratio between the diameter and height of roots. Individual cylinder with a diameter of 6 mm (minimum manufacturable diameter) and spacing ratio of 4.2 was first used to design the porosity of the model, referring to previous study of Kazemi *et al.,* [19,24]. This ratio was used as it promotes adequate drag to facilitate plastic entrapment and flow dynamics. Another model with a different variation of root diameter, 12 mm was fabricated, while patch diameter remained constant to compare the efficiency in trapping plastic waste. By altering the root diameter, the spacing ratio and porosity were affected whereas Model 1 (6 mm root diameter) has higher porosity than Model 2 (12 mm root diameter). The frontal area per volume, a and porosity, ϕ was calculated using the following formulas Eq. (1) and Eq. (2) from previous study [19]. Table 1 shows the parameters and dimensions of the experimental models and Figure 2 illustrates the fabricated models by using 3D printing.

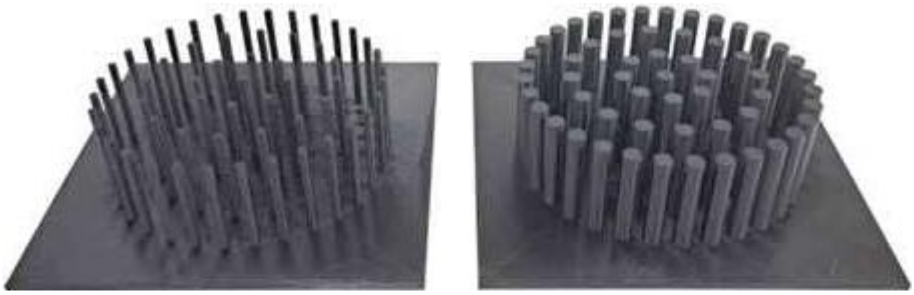
$$a = \frac{nd}{\frac{\pi}{4} \times D^2} \tag{1}$$

$$\varphi = 1 - N\left(\frac{d}{D}\right)^2 \tag{2}$$

where n is the number of roots, d is the root diameter (m), D is the patch diameter (m).

Table 1
Parameters and dimensions of the artificial mangrove root model

Model	Model 1	Model 2
No. of roots	56	56
Root diameter, d (m)	0.006	0.012
Root height, h (m)	0.063	0.063
Spacing between two adjacent cylinders, L (m)	0.025	0.018
Spacing ratio, L/D	4.2	1.5
Patch diameter, D (m)	0.192	0.192
Frontal area per volume, a (1/m)	11.61	23.21
Porosity, ϕ (%)	94.5	78.1



(a) (b)

Fig. 2. 3D-printed artificial mangrove root (a) Model 1, (b) Model 2

Then, the flow patterns around the modelled artificial mangrove roots were then examined using an unsteady-state Computational Fluid Dynamics (CFD) simulation run using Flowsquare+. The simulation employed a Cartesian uniform mesh, factoring no-slip boundary, water properties, and time steps for realistic results. The simulations considered different root diameters or porosities while maintaining root height, patch diameter, and number of cylinders.

2.3 Experimental Procedure

Experimental work was conducted in a custom-made tank with dimensions of 760 m x 260 m x 260 m and 0.005 m thick glass panel to ensure visibility and structural integrity during the experiment. JIALU EVP-102 WAVEMAKER with an output capacity of 8000 L/H was utilized to induce circular vortex movement and turbulence flow in the flume tank. The artificial mangrove root model was then submerged in the flume tank, approximately 0.5 m away from the wavemaker that was mounted at the beginning of the tank wall. A submersible pump (SOBO WP-100D) with a maximum flow rate of 560 L/H was employed to control the water levels within the flume tank during the experiment, mimicking the tidal changes of the river on-site. A damping layer was incorporated to maintain the controlled flow environment in the tank. Foam beads/balls made of polystyrene with a diameter ranging from 0.01 m to 0.05 m, thin sheets (0.03 cm x 0.03 cm) of polyethylene (PE) obtained from Ziploc bags and polypropylene (PP) from plastic bags were used as a sample to simulate marine litter in this study, due to its major contributions to plastic pollution in the river. Table 2 below shows the characteristics of debris used as a substitution for plastic waste in this experiment.

Table 2
Characteristics of debris used

Debris (plastic) type	Diameter (cm)	Shape	Area (cm^2)	Density range (g/cm^3)
Polyethylene (PE)		Square	9	0.91-0.97
Polypropylene (PP)		Square	9	0.90-0.91
Polystyrene (PS)	1	Sphere	3.14	1.01-1.04
Polystyrene (PS)	2	Sphere	12.57	1.01-1.04
Polystyrene (PS)	3	Sphere	28.27	1.01-1.04
Polystyrene (PS)	4	Sphere	50.27	1.01-1.04
Polystyrene (PS)	5	Sphere	78.54	1.01-1.04

The initial height of water in the tank was set at 0.85 m, equivalent to the height of the mangrove roots. After that, the debris was placed in front of the wavemaker and it was then activated to allow for the flow of debris towards the model. The water level was then gradually decreased (simulate the tidal change) until it reached below the base of the root model (approximately 0.02 m above the tank). The number of debris trapped by the model patch was then counted and recorded. The process was repeated on different models (Model 1 and Model 2). Three types of tests were conducted to evaluate the trapping capability of artificial mangrove root models: (1) Polystyrene (PS) balls with different diameters (1 cm to 5 cm) were used as debris; (2) varying amounts (quantity) of debris (8g to 16g of PS balls); (3) different materials of debris thin square-shaped plastic materials PP and PE. Figure 3(a) below illustrates the complete experimental setup of the tidal wave tank with the mangrove root model and Figure 3(b) portrays examples of debris that was trapped by the model to evaluate the performances.

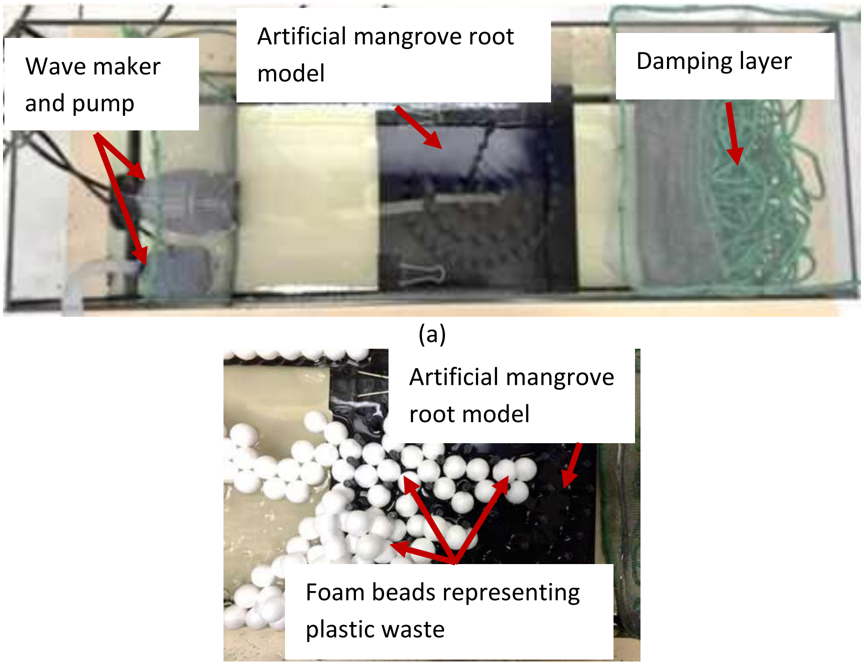
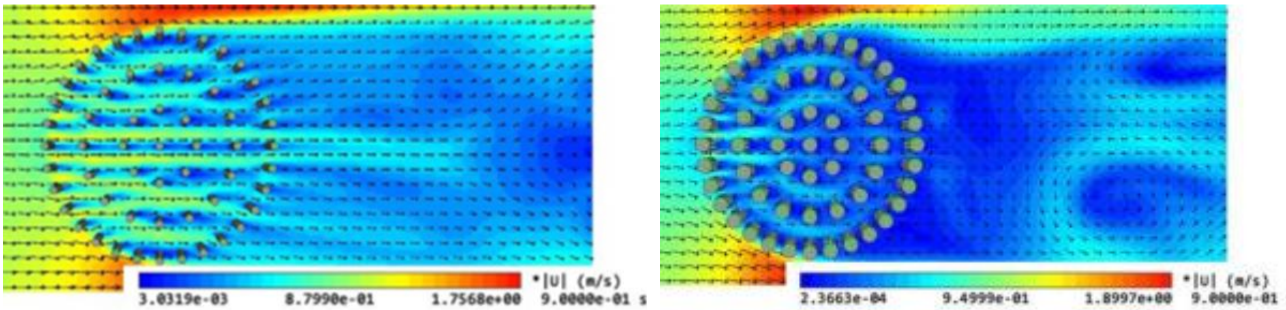


Fig. 3. Complete experimental setup of (a) tidal wave tank with artificial mangrove root model and (b) example of debris (foam beads) that were trapped by the model to evaluate the performances

3. Results

Figure 4 illustrates the CFD simulations of two different root diameters of the model with an initial velocity of 1 m/s. Flow patterns were visualized using velocity vectors, where red contours represent the jet flow and blue contours depict the turbulence stagnation area. The analysis revealed that Model 1 which has higher porosity, experienced less drag and dissipated the flow to a lesser extent as compared to Model 2 (lower porosity, higher drag).



(a) (b)

Fig. 4. CFD simulations for (a) Model 1 and (b) Model 2

The water flow velocity decreased along the roots, occasionally reaching close to 0 m/s. This decrease in velocity was attributed to the interaction between the water flow and the root edges, resulting in the formation of stagnation areas and a reduction in wave velocity. Over time, the stagnation area behind the models expanded, indicated by the growth of the blue region. Model 2, with lower porosity, exhibited a larger stagnation region compared to Model 1, which had higher porosity. Model 2 also exhibited more noticeable flow separation and changing flow directions, attributed to its lower porosity, causing it to behave more like a single cylinder in the previous work of Kazemi *et al.,* [19].

Based on Figure 5, Model 1 was able to trap debris up to a certain extent of amount which is in the range of 8g to 12g. On the contrary, Model 2 traps more debris when the amount has increased from 14g to 16 g. This result suggested that more debris would be trapped when the amount of debris that appeared in the tank was higher. This could be due to the effect of the swirling flow (Figure 4) that was produced by Model 2 after the model. The swirling flow might have caused the debris to be circulated directly behind the model. Besides, the small scale of the flume tank could have affected the flow of debris after the model as the space was not sufficient enough, the presence of a downstream boundary may lead to the accumulation of debris. Figure 6 shows the analysis of the trapping performance of the models with different sizes of debris.

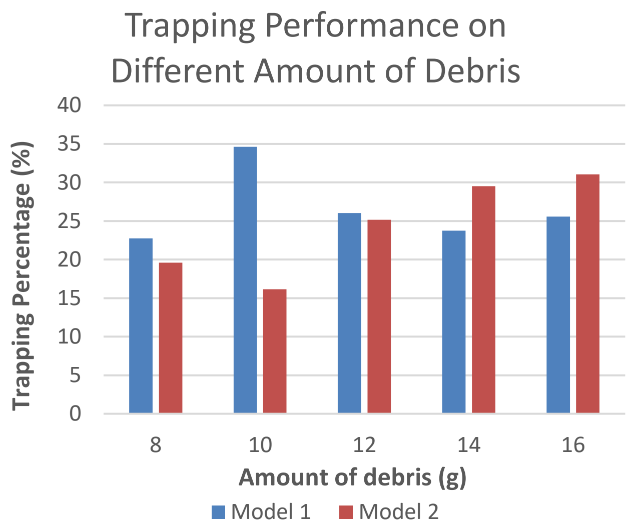


Fig. 5. The trapping performance of artificial mangrove root models with different amounts of debris

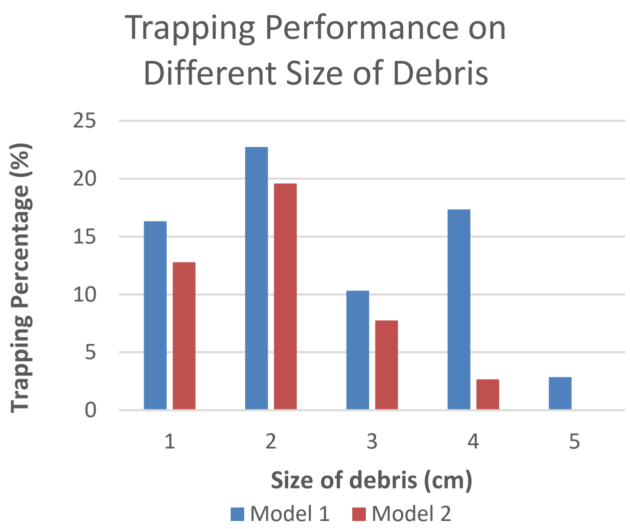


Fig. 6. The trapping performance of artificial mangrove root model with different sizes of debris

It showed that smaller debris sizes tended to have higher trapping percentages, while larger debris sizes resulted in lower trapping percentages or no trapping at all. Model 1 consistently exhibited higher trapping percentages compared to Model 2 across various debris sizes, indicating its higher efficiency at trapping debris. However, both models faced challenges in trapping larger debris particles, as indicated by decreased trapping percentages or no trapping observed for larger debris sizes (5 cm). These findings suggest that the space between each root could only trap a specific size of plastic waste. Smaller debris sizes are more easily captured by the models, while larger debris sizes require adjustments in the models, such as optimizing the porosity, to enhance trapping effectiveness.

Additionally, the trapping performance of the models with different types of debris materials was also evaluated, as shown in Figure 7. Comparing the trapping percentages between Model 1 and Model 2, we can see that Model 1 has a slightly higher trapping percentage for PE and PP plastics. However, the difference in trapping efficiency between the two models is relatively small.

Considering that the densities of PP (0.91 – 0.97 g/cm3) and PE (0.90 – 0.91 g/cm3) plastics are not significantly different, Model 1 generally shows a higher trapping percentage for both plastic types. On the other hand, the trapping performance on PS was generally lower as compared to PE and PP. This could be due to the shape of the debris used in this study where PS were a solid ball that limited the number of debris accumulated in the model. PE and PP employed a thin film which could be trapped more easily.

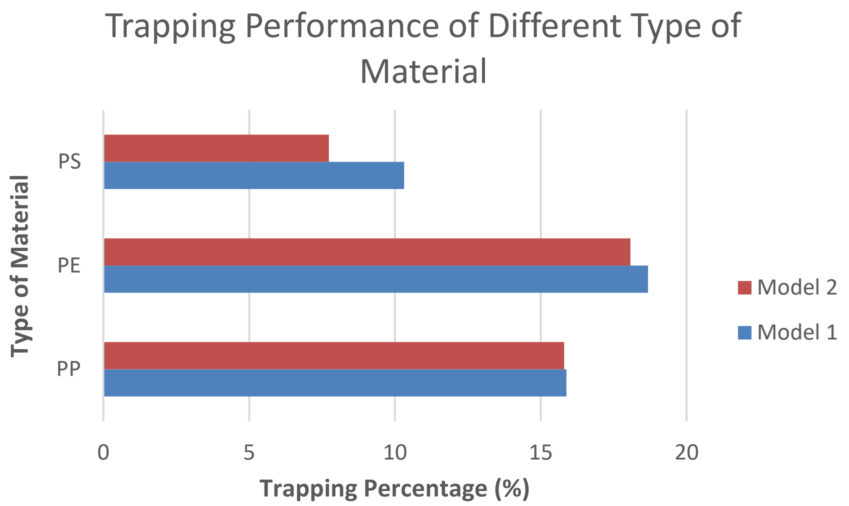


Fig. 7. The trapping performance of artificial mangrove root model with different types of material

4. Conclusions

In conclusion, this study successfully conducted a field survey to gather data on the characteristics of mangrove trees, particularly focusing on the structure of pneumatophore roots. Based on the collected data, artificial mangrove root models were designed and fabricated using 3D printing technology. Computational Fluid Dynamics (CFD) simulations provided insights into the flow patterns around the artificial mangrove roots. The higher porosity of Model 1 (94.5%) resulted in reduced flow attenuation and delayed the formation of wakes. Experimental investigations were also carried out to evaluate the debris-trapping capabilities of the artificial root models. The trapping performance experiments further supported the relationship between porosity and trapping efficiency. Model 1 consistently exhibited higher trapping percentages compared to Model 2, regardless of the mass, debris size, or type. Overall, these findings contribute to the understanding of mangrove ecosystems and provide valuable insights for the design of artificial mangrove structures that can help mitigate the pollution of debris in aquatic systems.

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References

[1] Van Emmerik, Tim, Yvette Mellink, Rahel Hauk, Kryss Waldschläger, and Louise Schreyers. "Rivers as plastic reservoirs." *Frontiers in Water* 3 (2022): 786936. https://doi.org/10.3389/frwa.2021.786936

[2] Lechthaler, Simone, Kryss Waldschläger, Georg Stauch, and Holger Schüttrumpf. "The way of macroplastic through the environment." *Environments* 7, no. 10 (2020): 73. https://doi.org/10.3390/environments7100073

[3] van Emmerik, Tim, and Anna Schwarz. "Plastic debris in rivers." *Wiley Interdisciplinary Reviews: Water* 7, no. 1 (2020): e1398. https://doi.org/10.1002/wat2.1398
[4] Ritchie, Hannah, and Max Roser. "Where does the plastic in our oceans come from?." *Our World in Data* (2024).
[5] Meijer, Lourens J. J., Tim Van Emmerik, Ruud Van Der Ent, Christian Schmidt, and Laurent Lebreton. "More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean." *Science Advances* 7, no. 18 (2021): eaaz5803. https://doi.org/10.1126/sciadv.aaz5803
[6] Tramoy, R., J. Gasperi, L. Colasse, M. Silvestre, P. Dubois, Camille Noûs, and B. Tassin. "Transfer dynamics of macroplastics in estuaries-new insights from the Seine estuary: part 2. Short-term dynamics based on GPS-trackers." *Marine Pollution Bulletin* 160 (2020): 111566. https://doi.org/10.1016/j.marpolbul.2020.111566
[7] Arifin, Muhammad Fahmi, Zulhilmi Ismail, Mazlin Jumain, Radzuan Saari, Zulkiflee Ibrahim, Deng Siti Maimunah Ishak, Erwan Hafizi Kasiman, Md Ridzuan Makhtar, and Mohd Zulkhairi Mat Salleh. "Experimental Study on Depth-Averaged Velocity and Bed Profile in a Braided Channel with a Mid-Bar." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 33, no. 2 (2024): 290-299. https://doi.org/10.37934/araset.33.2.290299
[8] Martin, Cecilia, Hanan Almahasheer, and Carlos M. Duarte. "Mangrove forests as traps for marine litter." *Environmental Pollution* 247 (2019): 499-508. https://doi.org/10.1016/j.envpol.2019.01.067
[9] Luo, Ying Y., Christelle Not, and Stefano Cannicci. "Mangroves as unique but understudied traps for anthropogenic marine debris: a review of present information and the way forward." *Environmental Pollution* 271 (2021): 116291. https://doi.org/10.1016/j.envpol.2020.116291
[10] do Sul, Juliana A. Ivar, Monica F. Costa, Jacqueline S. Silva-Cavalcanti, and Maria Christina B. Araújo. "Plastic debris retention and exportation by a mangrove forest patch." *Marine Pollution Bulletin* 78, no. 1-2 (2014): 252-257. https://doi.org/10.1016/j.marpolbul.2013.11.011
[11] Yin, Chee Su, Yee Jean Chai, Carey Danielle, Yusup Yusri, and Gallagher John Barry. "Anthropogenic marine debris accumulation in mangroves on Penang Island, Malaysia." *Journal of Sustainability Science and Management* 15, no. 6 (2020): 36-60. https://doi.org/10.46754/jssm.2020.08.004
[12] Garcés-Ordóñez, Ostin, Victoria A. Castillo-Olaya, Andrés F. Granados-Briceño, Lina M. Blandón García, and Luisa F. Espinosa Díaz. "Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta, Colombian Caribbean." *Marine Pollution Bulletin* 145 (2019): 455-462. https://doi.org/10.1016/j.marpolbul.2019.06.058
[13] Huang, Zhenhua, Yu Yao, Shawn Y. Sim, and Yao Yao. "Interaction of solitary waves with emergent, rigid vegetation." *Ocean Engineering* 38, no. 10 (2011): 1080-1088. https://doi.org/10.1016/j.oceaneng.2011.03.003
[14] Alongi, Daniel M. "Present state and future of the world's mangrove forests." *Environmental Conservation* 29, no. 3 (2002): 331-349. https://doi.org/10.1017/S0376892902000231
[15] Thomas, Nathan, Richard Lucas, Peter Bunting, Andrew Hardy, Ake Rosenqvist, and Marc Simard. "Distribution and drivers of global mangrove forest change, 1996-2010." *PloS One* 12, no. 6 (2017): e0179302. https://doi.org/10.1371/journal.pone.0179302
[16] Narayan, Siddharth, Michael W. Beck, Borja G. Reguero, Iñigo J. Losada, Bregje Van Wesenbeeck, Nigel Pontee, James N. Sanchirico, Jane Carter Ingram, Glenn-Marie Lange, and Kelly A. Burks-Copes. "The effectiveness, costs and coastal protection benefits of natural and nature-based defences." *PloS One* 11, no. 5 (2016): e0154735. https://doi.org/10.1371/journal.pone.0154735
[17] Smith, Stephen D. A. "Marine debris: a proximate threat to marine sustainability in Bootless Bay, Papua New Guinea." *Marine Pollution Bulletin* 64, no. 9 (2012): 1880-1883. https://doi.org/10.1016/j.marpolbul.2012.06.013
[18] van Bijsterveldt, Celine EJ, Bregje K. van Wesenbeeck, Sri Ramadhani, Olivier V. Raven, Fleur E. van Gool, Rudhi Pribadi, and Tjeerd J. Bouma. "Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival." *Science of the Total Environment* 756 (2021): 143826. https://doi.org/10.1016/j.scitotenv.2020.143826
[19] Kazemi, Amirkhosro, Humberto Bocanegra Evans, Keith Van de Riet, Luciano Castillo, and Oscar M. Curet. "Hydrodynamics of mangrove roots and its applications in coastal protection." In *OCEANS 2018 MTS/IEEE Charleston*, pp. 1-8. IEEE, 2018. https://doi.org/10.1109/OCEANS.2018.8604931
[20] Le Minor, Marine, Martin Zimmer, Véronique Helfer, Lucy Gwen Gillis, and Katrin Huhn. "Flow and sediment dynamics around structures in mangrove ecosystems-a modeling perspective." In *Dynamic Sedimentary Environments of Mangrove Coasts*, pp. 83-120. Elsevier, 2021. https://doi.org/10.1016/B978-0-12-816437-2.00012-4
[21] Ohira, Wataru, Kiyoshi Honda, Masahiko Nagai, and Anuchit Ratanasuwan. "Mangrove stilt root morphology modeling for estimating hydraulic drag in tsunami inundation simulation." *Trees* 27 (2013): 141-148. https://doi.org/10.1007/s00468-012-0782-8
[22] Kamarudin, Muhammad Hafiz, Mohd Yuhazri Yaakob, Mohd Sapuan Salit, Hasoloan Haery Ian Pieter, Nur Azam Badarulzaman, and Risby Mohd Sohaimi. "A review on different forms and types of waste plastic used in concrete

structure for improvement of mechanical properties." *Journal of Advanced Research in Applied Mechanics* 28, no. 1 (2016): 9-30.
[23] Kamal, Shafagh, Jan Warnken, Majid Bakhtiyari, and Shing Yip Lee. "Sediment distribution in shallow estuaries at fine scale: in situ evidence of the effects of three-dimensional structural complexity of mangrove pneumatophores." *Hydrobiologia* 803 (2017): 121-132. https://doi.org/10.1007/s10750-017-3178-3
[24] Kazemi, Amirkhosro, Keith Van de Riet, and Oscar M. Curet. "Hydrodynamics of mangrove-type root models: the effect of porosity, spacing ratio and flexibility." *Bioinspiration & Biomimetics* 12, no. 5 (2017): 056003. https://doi.org/10.1088/1748-3190/aa7ccf