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SagHip: Photocatalytic Treatment of Malathion-Contaminated Water Using Musa Biochar and Caridea Hydroxyapatite

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SagHip: Photocatalytic Treatment of Malathion-Contaminated Water Using Musa Biochar and Caridea Hydroxyapatite

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ABSTRACT

Malathion is extensively used by farmers, even in domestic households, and enormous quantities of it seep into groundwater and wastewater effluent. Human and animal life get poisoned by it. It is therefore removed from wastewater. This study aims to synthesize and analyze a composite material of Musa- biochar and Caridea-Hydroxyapatite through Photocatalytic degradation of malathion pesticide from water. This way, providing a sustainable and effective method in the removal of organophosphate pesticide from water. Musa-biochar was synthesized from banana peel waste through calcination, while Caridea-hydroxyapatite came from shrimp shell waste through carbonization. The photocatalytic degradation test under UV light revealed that the Musa-biochar/Caridea-HAp composite recorded a degradation efficiency of -1.17%, meaning minimal photocatalytic activation. The Caridea-HAp catalyst had a degradation efficiency of 22.01%, which implied its ability to degrade Malathion through UV-activated photocatalysis. The photocatalytic performance analysis revealed that Caridea-HAp recorded the highest degradation efficiency of 22.01%, followed by the composite at –1.17% and Musa-biochar at –4.23%. The findings established that Caridea-HAp acted as the dominant active photocatalyst, while biochar was mainly used as an adsorbent material. The findings are in agreement that waste-based photocatalysts are good alternatives for the remediation of pesticides and offer great potential for use in the future in sustainable water treatment and environmental management.

Keywords: *Photocatalytic Degradation, UV, Musa biochar, Caridea Hydroxyapatite, Shrimp peels, Banana peels, Malathion, organophosphate pesticide, wastewater treatment*

1. INTRODUCTION

Malathion is a non-systemic, wide-spectrum organophosphate insecticide with its chemical name Diethyl 2-[(dimethoxyphosphorothioy|)thio]butanedioate. Primarily used for agricultural purposes, public health, residential settings and mosquito control for approximately 50 years, targeting the nervous system of pests gradually killing them (Jensen and Whatling, 2010). American Cyanamid began producing malathion on a commercial basis in the United States in 1950. Chemical Company (USTC 1953), and in 1956 it was initially registered in the US (ATSDR, 2003). Its popularity stems from its effectiveness and relatively low cost, making it a common choice in both developing and developed countries. In 2023, the share of agriculture in the Philippines' gross domestic product was 9.4 percent (O'Neil, 2025). To further boost production and to prevent crop damage, pesticides are then applied. Despite the benefits it offers, consequences arise, for instance with the amount of malathion used it seeps through groundwater making it contaminated which leads to indirect harm in both animals and humans.

Surface waters contaminated by malathion has become a major concern for public health in the Philippines. Lucban River and Salasad Creek within the Pagsanjan-Lumban watershed of Laguna de Bay is being monitored wherein malathion has been found at all samples gathered. Concentrations ranged between 0.005 and 3.3 µg L-1, going beyond WHO's single-pesticide threshold of 0.1 µg L-1 in each sampling period (Varca et al., 2012). At 2008 and 2009, 22% of poisoning cases at Philippine tertiary hospitals were linked to organophosphate insecticides, such as malathion. Acute symptoms as headache, nausea, and dizziness were present in more than 50% of the patients (Lu et al., 2005). Notably, a study in Mindanao, Southern Philippines, examined farmers' self-reported symptoms of pesticide exposure and their evaluations of the effects on their health and the environment. Majority of the pesticides used by farmers were pyrethroid and organophosphate, which the WHO categorized as moderately dangerous (Class II). Symptoms of mild pyrethroid and organophosphate poisoning, such as skin irritation (33%), headache (30%), cough (23%), dry throat (15%), shortness of breath (15%), dizziness (14%), nausea (13%), and eye irritation (11%), were common health complaints following spraying (Perez et al., 2015). Such results indicate that the pervasive nature of malathion in the Philippines has indeed serious effects on human health.

To tackle these urgent water-quality issues, musa-biochar and caridea-hydroxyapatite with Photocatalytic technique is proposed. Biochar from banana peels, when activated and ground into a fine powder, has shown remarkable affinity for organophosphates: (Farias et al. 2023) found removal efficiencies of 93% for atrazine and 98% for glyphosate in water using banana peel biosorbents (adsorption capacity reaching 3.26 mg g^{-1}). However, there remains a gap in this study regarding the performance. While Musa-biochar and hydroxyapatite independently work efficiently, research is limited regarding their combined performance on malathion-contaminated wastewater treatment. This study aims to address this gap and contribute to the growing knowledge in Photocatalytic Treatment of Malathion-Contaminated Water Using Musa Biochar and Caridea Hydroxyapatite.

1.1. RESEARCH QUESTIONS

This study aims to evaluate the efficiency of utilizing Musa-biochar and Caridea-Hydroxyapatite and Photocatalytic in the removal of malathion in water. The study ought to answer the following questions:

1. How does musa-biochar, caridea-hydroxyapatite alone and both combined compare to previous water treatments in terms of cost-efficiency, removal and Eco-friendliness?
2. Does exposure to UV light significantly increase the photocatalytic degradation rate of Malathion using the Musa-biochar/Caridea-HAp composite?

1.2. OBJECTIVES

This research intends to develop and evaluate a composite material via Musa-biochar and Caridea-Hydroxyapatite through Photocatalytic degradation of malathion pesticide in water. Thereby, offering a sustainable and efficient technique in removing organophosphate pesticide from water.

1. To synthesize and characterize Musa-biochar and Caridea-hydroxyapatite for use as a photocatalyst composite.

2. To determine the photocatalytic degradation efficiency of Malathion in water using the Musa-biochar/Caridea-HAp composite under UV light.

3.To compare the individual photocatalytic performance of Musa-biochar and Caridea-HAp with their combined form.

4. To evaluate the environmental sustainability and cost-efficiency of using the Musa-biochar/Caridea-HAp composite in treating pesticide-contaminated water.

1.3. SCOPE AND DELIMITATION OF THE STUDY

The study assesses the viability of using Musa Biochar and Caridea Hydroxyapatite as photocatalysts for cost-efficiency and environmentally friendly degradation of Malathion-contaminated water with the presence of UV. Testing was limited to the effect of catalyst loading, with and without UV light irradiation, and type of variable used on the degradation of malathion. Other parameters such as optimization, material characterization and real wastewater samples were not considered for this study. The study only degrades a simulation of malathion-contaminated water and not real wastewater samples. Therefore this study focuses on simulation degradation of malathion-contaminated water while broader applications and optimization of the photocatalysts are left for future studies.

1.4. SIGNIFICANCE OF THE STUDY

This project evaluates the usage of Biochar from banana peels *Musa* and hydroxyapatite derived from shrimp *Caridea* peels as cost-efficient and eco-friendly photocatalysts for degradation of Malathion-contaminated water. The adsorption results of these degradation tests could offer a broader understanding of these catalysts and fill the gap of studies. Achieving the aims of this study could explicitly benefit:

Local Government Units. As it pertains to waste management and water quality monitoring, the research could assist local government bodies in developing and implementing ecologically sustainable policies and programs. Through the demonstration of an alternative, cost-efficient method of eliminating pesticide-contaminated water using locally available materials, the findings might serve as a scientific basis for creating eco-waste projects and also community-based water purification initiatives.

Scientific Field. Utilizing baseline data on production and photocatalytic activity of hydroxyapatite derived from shrimp peels, the present work develops our general concept of waste-based functional materials. The results can help add to the body of knowledge in environmental chemistry and sustainable materials research by serving as a guide for future studies focused on material optimisation, characterisation, and broader photocatalytic applications.

Agricultural Sector. During 2008 and 2009, 22% of poisoning in Philippine tertiary hospitals were attributed to organophosphate insecticides, including malathion (Lu et al., 2005). The article presents a viable approach to reducing malathion and other contaminants in surface water and irrigation runoff. As part of waste reduction in agriculture and aquaculture, the utilization of banana peels and shrimp shells promotes the use of a circular mechanism of managing waste in line with sustainable farming methods in Davao del Norte.

Technological and Industrial Applications. Incorporating biochar-hydroxyapatite composites in photocatalytic degradation is an innovative technique for environmental remediation. This method can be scaled up for wider uses in environmental engineering projects, community-based filtration systems, and water treatment facilities, as the study shows. Additionally, the results can stimulate new ideas for locally sustainable and adaptable pollution control and resource recovery solutions.

1.5. REVIEW OF RELATED LITERATURE

Photocatalytic Degradation

An advanced oxidation process that is both environmentally friendly is called Photocatalytic degradation. It utilizes light energy in the three electromagnetic regions: visible (vis), ultraviolet (UV) and infrared (IR) (da silva Alves,. et al, 2022).

Photocatalysis is used in most studies due to the benefits it offers, such as it being low-cost, safe to use, and low energy consumption. Photoactive NPs serve as catalysts in a variety of applications, including sustainable energy production and environmental remediation. Different photocatalysts are found to be studied for pesticide degradation such as TiO2, ZnO, as well as different semiconductors, etc. Recently greener photocatalysts visited include hydroxyapatite Ca_{10} $(PO_4)_6$ $(OH)_2$, which has now been taking the approach of photocatalysis into replacing conventional semiconducting photocatalyst. Hydroxyapatite has proven to photodegrade dyes, pharmaceuticals, and pesticides from wastewater and aqueous solutions (Credo As,. et al, 2023)

Musa-Biochar

A rich carbon substance made from biomass generated from plants is called biochar. Because of its high porosity, high surface area, high stability, high carbon content, low thermal conductivity, and high surface area, biochar is one of the best materials for a variety of applications. Evidence shows that biochar and its activated derivatives have the capacity to remove various contaminants, including synthetic and emerging organics (Cao et al., 2009, Kasozi et al., 2010, Chen et al., 2011). The study utilized bananas as Davao Region was the top banana producer with 868.19 thousand metric tons output or 38.3 percent share of the total production in this quarter (Philippine Statistics Authority, 2024). The plantations produce the majority of the trash, which includes rhizomes, pseudo-stems, and both fresh and dried leaves. Therefore, numerous scientific studies have been performed to evaluate the potential of banana wastes such as banana peel, banana peduncle and banana leaves as the feedstock to produce bio-char in various fields of application.

Caridea Hydroxyapatite

A calcium phosphate bio-material that shows tremendous potential for preventing soil, water, and air pollution is hydroxyapatite Ca_{10} $(PO_4)_6$ $(OH)_2$. Human and animal bones are composed of hydroxyapatite. Given its unique structure and appealing characteristics, including its high adsorption capacities, acid-base adaptability, ion-exchange capability, and strong thermal stability, hydroxyapatite (Hap) can be very helpful in the field of environmental management. A study shown that under UV irradiation, shrimp-based HAp-TiO_2 composites degraded malathion by more than 80% in under two hours. This strengthens the claim that Caridea- hydroxyapatite is an efficient agent in sophisticated oxidation processes for the treatment of contaminated water, in addition to being a sustainable material (Lestari et al.2022)

Synergistic Potential of Biochar, Hydroxyapatite, and Photocatalysis

Biochar derived from banana peels has a high porosity and surface functionality wherein, catalytic efficiency and adsorption increases (Cao et al., 2009, Kasozi et al., 2010, Chen et al., 2011). Caridea-hydroxyapatite sustains structural support and capability in ion exchange (Lestari et al.2022). While photocatalytic degradation is an efficient technique for the decomposition of organic and synthetic contaminants, its small surface area and quick charge recombination lacks in efficiency (Credo As,. et al, 2023). Each material works efficiently independently, yet there is limited research that explores the combination of these variables for malathion degradation. Their composite may produce a synergistic system with improved photocatalytic performance and sustainability in water treatment environmental remediation.

2. METHODOLOGY

The study extends to a total of 6 phases: (1) Collection of Materials (2) Conversion of Musa to Biochar, (3) Synthesis of Hydroxyapatite, (4) Photocatalytic Degradation, (5) Data Measurement and Analysis, (6) Waste Disposal. The materials were procured at chemvest Davao City and local suppliers within Tagum City. The study was conducted at Davao del Norte State Colleges located in Panabo City. The researcher strictly followed safety protocols to ensure a hazard free workplace. Throughout the experiment, the research was supervised and assisted by her consultant (registered chemist)

2.1. Preparation of Materials

2.1.1. Gather the Materials. The experiment commenced with purchasing one (1) bunch of Cavendish bananas at Carmen. To verify the use of Cavendish bananas, a verification from the Provincial Agricultural Office (PAGRO) Capitol was acquired. One (1) kilogram of shrimp were bought at Tagum City Wet Market. Furthermore, Potassium Hydroxide, Citric Acid, Phosphoric Acid, Sodium Hydroxide, filter paper, litmus paper and gloves were purchased at ChemVest, Davao City; Malathion 57 EC and UV lamp were sourced from City Hardware and Arellano Street, Tagum City, Davao del Norte. Laboratory apparatus needed were available at Davao del Norte State College laboratory.

2.1.2. Custom Photocatalytic Box. The plywood used for the intended box was obtained at National Irrigation Agricultural (NIA). The box dimensions are as follows: the side panels measure 15 inches by 13 inches, the top and bottom panels measure 15 inches by 10 inches, and the front and back panels measure 13 inches by 10 inches. The front panel features a square cutout with dimensions of 8 inches by 8 inches. The exterior was painted with black paint while its interior was white. Two exhaust fans measuring 120 mm by 140 mm were installed on both the left and right sides of the box. while all circuits and wiring were mounted on the rear panel

Figure 1: Custom Photocatalytic Box

2.2. Conversion of Musa to Biochar

2.2.1. Treatment of Banana Peels. After gathering banana peels, it is then sliced into small pieces for an easier procedure. Next, it is rinsed repeatedly with tap water to get rid of contaminants. 350 grams of banana peels were dried by the use of a convection oven under 70 degree Celsius for 2 hours. After initial drying, 140 grams of dried banana peels were impregnated in a 1 M KOH solution, 28 grams of KOH pellets were added to 400 mL of distilled water and is diluted to a final volume of 500 mL. Kept and covered with aluminum foil under room temperature for 10 hours.

Figure 2: Washing

Figure 3: Drying

Figure 4: Soaking

2.2.2. Pyrolysis. Then, 201 grams of banana peels were obtained after soaking it in a KOH solution. It is placed in tiny crucibles and is oven dried in a muffle furnace for 4 hours under 550 degree Celcius. After pyrolysis, its weight resulted in 36.273 grams and is grinded by the use of a mortar and pestle. The biochar is then stored in an airtight container and kept in a desiccator for further use.

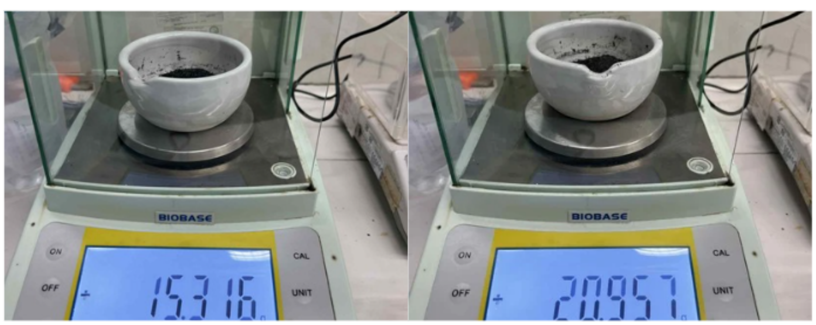


Figure 5: Weighing of Biochar

2.3. Synthesis of Caridea Hydroxypatite

2.3.1. Preparation of shrimp peels. After separating the peels of the shrimp, it is then cleaned in boiling water to get rid of biological contaminants. 42.5 grams of shrimp peels are subjected to a convection oven for drying under 70 degree celsius for 1 hour. After oven drying, the shrimp peels yielded a final weight of 16.3 grams. Then, it is placed in ceramic crucibles for incineration under 550 degree celsius for 2 hours, wherein 7.546 grams is obtained.

Figure 6: Shrimp Peels

Figure 7: Cleaning of Shrimp Peels

Figure 8: Drying

2.3.2. Acid Leaching. The 7.546 grams of shrimp peels is added to a solution of 9 grams of Citric acid diluted in 150 mL of distilled water. The solution is placed on a magnetic stirrer for equal stirring. Ash content is determined by the given formula: Weight of ash / Weight of sample × 100. Effervescence upon addition of shrimp shell ash to citric acid indicates an acid–carbonate reaction, confirming the presence of calcium carbonate in the ash. After 20 minutes, the undissolved ash subsided yet the solution is still black. One hour has passed by and the solution is still black yet transparent. The solution is then filtered using a filter paper.

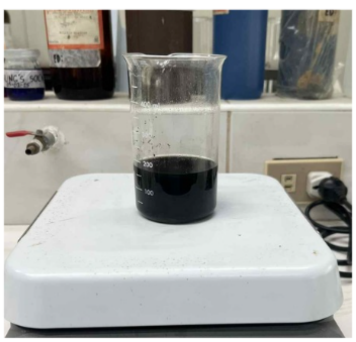


Figure 9: KOH Solution

Figure 10: Filtration

2.3.3. Adding of Phosphate Solution. 6.9 mL of phosphoric acid is diluted to 100 mL of distilled water wherein only 40.6 mL is to be used. With the filtered solution from the acid leaching, a burette is used to slowly add the phosphoric acid (1 drop per second). A pH meter is used to determine the current pH of the solution, such as its target after adding phosphate solution is a pH of 5 as the solution is currently 3. After adding 20 mL of phosphoric acid to neutralize the solution, it remains 3. The researcher decided to stop adding phosphoric acid and then proceeded with the NaOH solution.

Figure 11: Adding of Phosphoric Acid

2.3.4. pH Adjustment. 40 grams of NaOH is dissolved in 500 ml of water. A burette is used to slowly add the solution, a pH meter is used to oversee the pH wherein its target is to be a pH of 10. After adding 80 mL of the NAOH solution, it finally reached a pH of 10. The solution is then aged to 3 hours while still in the magnetic stirrer.

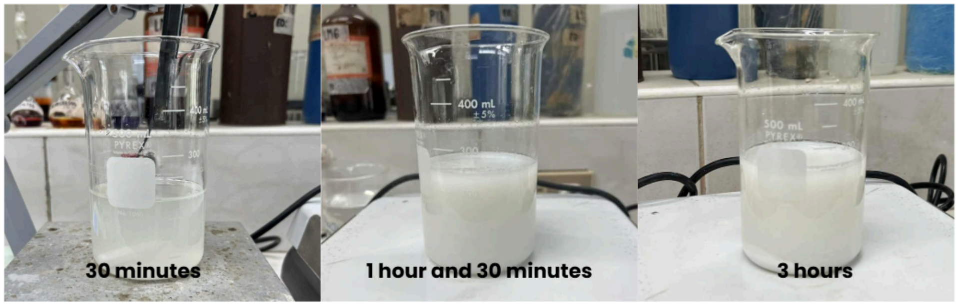


Figure 12 : Adding of NaOH solution and Aging

2.3.5. Filtration, Washing and Drying. After 3 hours, the white suspension is filtered using a filter paper. The filtered solution is left covered in the laboratory under room temperature for 3 days. It is then washed with distilled water and is oven dried under 80 degree celsius for 6 hours. The hydroxyapatite yielded to a final weight of 3.885 grams

Figure 13: Filtration

2.4. Photocatalytic Degradation

2.4.1. Malathion Handling. A simulation of a contaminated malathion-water is conducted with the addition of 1mL of malathion with a concentration of 57 EC in 100 mL of water. For every degradation, 8.8 mL of diluted malathion is added to a total of 500 mL of water, resulting in 100 ppm (570g/L). During the handling of malathion, wearing of PPE is strictly followed, windows are all open and a fan is on nearby.

2.4.2. Degradation. A custom-built photocatalytic reactor box intended for photocatalytic degradation is also used with the installation of a UV lamp. The lamp is positioned horizontally and is 10 cm above the solution. A total of six tests will be conducted. 1 gram of Musa-Biochar and 0.5 grams of Caridea Hydroxyapatite (Under UV and without UV), 0.5 grams of Musa-Biochar, 0.25 Caridea-Hydroxyapatite (Under UV and without UV) are added to the solution before the UV irradiation. The solution is irradiated for 30 minutes first without UV then 2 hours under UV with a magnetic stirrer.

The formula below is used to calculate the degradation efficiency wherein, Co= initial concentration of malathion and Ct = concentration at time (after irradiation)

Figure 14: Degradation Trials

2.5. Data Measurement and Analysis

A UV-Vis spectrophotometer is set to measure absorbance at 210 nm, the degradation efficiency of malathion is identified. Musa-biochar and Caridea Hydroxyapatite are used as photocatalysts, and the photocatalytic degradation performance will be assessed under UV exposure and without UV exposure (30 to 120 minutes) and catalyst dosages (1 g, 0.5 g, 0.25 g). The difference between the initial and residual malathion concentrations are used to compute degradation efficiency.

2.6. Waste Disposal

All experimental methods that generated waste were managed in accordance with environmental standards and the stakeholder institution's laboratory safety protocols. Excess malathion solutions and filtrates were collected in appropriately labeled hazardous waste containers and stored in a designated chemical waste storage area until disposal by a licensed hazardous waste disposal contractor. Solid wastes, such as spent hydroxyapatite–biochar composites, were dried, sealed, and labeled appropriately for disposal. Uncontaminated materials, including gloves, filter papers, and containers, were segregated and discarded according to the laboratory's standard waste segregation practices to minimize any adverse environmental effects.

3. RESULTS AND DISCUSSION

1. To synthesize and characterize Musa-biochar and Caridea-hydroxyapatite for use as a photocatalyst composite.

The removal efficiency for each treatment was calculated using:

$$\% \text{ Degradation} = \left(\frac{C_0 - C_t}{C_0}\right) \times 100$$

Table 1. Photocatalytic Degradation Efficiency and Sustainability Assessment of Musa Biochar–Caridea-HAp Composites Under UV Light

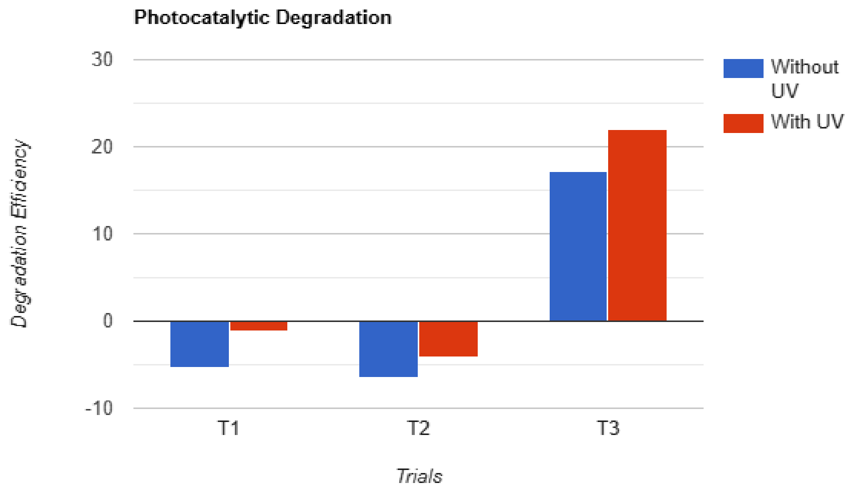
Treatment Code	Catalyst Composition	UV Condition	Absorbance (210 nm)	% Degradation	Cost Efficiency	Eco-Friendliness	Remarks / Interpretation
T1	1 g Musa biochar + 0.5 g Caridea-Hap	Without	3.229	-5.25	Moderate	Good – waste-based	No photo catalytic activity; absorbance slightly higher due to scattering.
		With	3.104	-1.17	Moderate	Good	Minimal degradation: biochar likely blocked HAp sites
T2	0.5 g Musa biochar	Without	3.266	-6.46	High (low-cost material)	Excellent – banana peel waste	No degradation observed; mainly absorptive interaction.
		With	3.198	-4.23	High	Excellent	Very limited photo response; adsorption dominant.
T3	0.25 g Caridea-Hap	Without	2.543	17.10	Moderate	Excellent – shrimp-shell waste	Moderate removal due to adsorption; UV activation needed.
		With	2.392	22.01	Moderate	Excellent	Noticeable degradation; UV-activated photocatalysis evident.
T4	1 g Musa biochar in 500 mL H_2O	-	1.470	NA	High	Excellent	Catalyst blank — control sample with no malathion added.
T5	0.5 g Car idea Hydroxyapatite in 500 mL H_2O	-	0.282	NA	Best	Excellent	Catalyst blank — reference for pure catalyst optical behavior.

2 . To determine the photocatalytic degradation efficiency of Malathion in water using the Musa-biochar/Caridea-HAp composite under UV light.

Table 2. Photocatalytic Degradation Efficiency of Malathion Using Musa-Biochar/Caridea-HAp Composite Under UV Light

Treatment Code	Catalyst Composition	UV Condition	Absorbance (210 nm)	Degradation Efficiency (%)
T1	1 g Musa-biochar +	Without	3.229	-5.25
	0.5 g Caridea-Hap	With	3.104	-1.17
T2	0.5 g Musa-biochar	Without	3.266	-6.46
		With	3.198	-4.23
T3	0.25 g Caridea-Hap	Without	2.543	17.10
		With	2.392	22.01

3.1. Visual Presentation of Results



3.2. DISCUSSION

This study investigated the synthesis and photocatalytic evaluation of Musa-biochar and Caridea-hydroxyapatite (HAp), and their composite, for Malathion-contaminated water degradation under UV illumination. The major aims were: (1) Preparation and synthesis of Musa-biochar and Caridea-HAp for use as a photocatalyst composite; (2) Determination of the efficiency of photocatalytic degradation of Malathion in water using the Musa-biochar/Caridea-HAp composite under UV light; (3) Comparison of the individual photocatalytic activities of Musa-biochar and Caridea-HAp with their combined composite; and (4) Consideration of the environmental sustainability and cost-effectiveness of the composite in cleaning pesticide-contaminated water.

Musa Biochar Performance. The Musa-biochar showed no appreciable photocatalytic activity under both UV and non-UV, with negative degradation values that were recorded. Degradation efficiency under UV (T2) -4.23%, while without UV, its efficiency is -6.46%. This trend indicates that the material was mainly acting through adsorptive interaction rather than photocatalysis, as consistent with previous studies that reported fruit-peel biochars have high porosity and large surface areas, but show few semiconductor characteristics (Lam et al., 2018; Farias et al., 2023).

Caridea Hydroxyapatite Performance. Caridea-hydroxyapatite from shrimp shell waste is responsible for semiconducting and ion-exchange behaviors, thus improving photochemical reactivity and environmental compatibility. Caridea-HAp (T3) had the best degradation efficiency at 22.01%, making it the active photocatalyst of choice. Without UV, its degradation efficiency is 17.10%. This is due to the semiconducting Ca–P lattice that efficiently produces reactive oxygen species upon exposure to UV light (Credo et al., 2023).

Composite Performance. Musa-biochar/Caridea-HAp composite (T1) had a degradation efficiency of –1.17 %, implying low photocatalytic activation. Although, in the absence of UV irradiation its efficiency is -5.25%. The negative sign could be due to experimental variation or light scattering; but it also reflects low UV absorption due to the high proportion of biochar, which most probably hindered the HAp surface.

Photocatalytic Performance. The photocatalytic performance analysis showed that Caridea-HAp had the highest degradation efficiency of 22.01%, followed by the composite at –1.17%, and Musa-biochar at –4.23%. The findings attested that Caridea-HAp was the main active photocatalyst, while biochar was mainly used as an adsorption material. The composite showed lower performance due to poor synergy between the two elements, stressing the importance to optimize the biochar-to-HAp ratio for efficient adsorption and photoactivation.

4. CONCLUSION

On the basis of the study, the following conclusions were drawn:

1. Musa-biochar and Caridea-HAp were synthesized successfully from waste banana peel and shrimp shells via carbonization and calcination, respectively. The two materials were found to be sustainable, environmentally friendly, and structurally appropriate for use in photocatalytic processes.

2. Musa-biochar/Caridea-HAp composite showed degradation efficiency of –1.17% under UV light, which is low photoactivity due to the blocking effect of biochar on the active sites of HAp. However, Caridea-HAp showed 22.01% degradation, further supporting that it possesses a strong UV-activated photocatalytic behavior. Musa-biochar mainly played a role by absorption.

3. Of the catalysts tested, Caridea-HAp was most efficient as a photocatalyst, followed by the composite and Musa-biochar. Limited activity of the composite was due to non-ideal material ratio and inadequate light penetration. Compound optimization and structure need to be achieved to improve photocatalytic performance.

4. Both the catalysts were found to be economically feasible and environmentally sustainable, obtained from waste products with negligible processing cost. Their preparation follows the waste valorization and green engineering approach, so they are likely contenders for cheap and sustainable water treatment technologies.

5. RECOMMENDATIONS

Based on the findings and conclusions of this study, the following recommendations are proposed:

On the basis of the research findings and conclusions made in this study, the following suggestions are made:

1. Tune the ratio of biochar to HAp for enhanced photocatalytic efficiency and optimized adsorption and oxidation performance of the composite.

2. Consider using advanced synthesis techniques like sol-gel or hydrothermal methods in order to improve the uniformity of the catalyst, surface reactivity, and light absorption.

3. Perform additional material characterization (e.g., XRD, FTIR, SEM, BET analysis) to relate structure and surface characteristics to photocatalytic performance.

4. Test the reusability and stability of the catalysts over several treatment cycles to establish their long-term viability and economic feasibility.

5. Expand the use of these catalysts to other pesticides or organic contaminants to assess versatility in wastewater treatment.

6. Foster community-level adoption of waste-based catalysts through collaborations with local government units and environmental departments for rural water filtration.

7. Conduct techno-economic and life-cycle assessments to confirm large-scale practicability, energy efficiency, and environmental advantages of employing Musa-biochar and Caridea-HAp composites.

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