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Utilization of *Aspergillus niger* with Sengon Powder for Integrated IoT-Based Microplastic Biodegradation in Rivers

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Keywords

Microplastic; River; Aspergillus niger; Sengon wood; IoT

Abstract

The increase in microplastic pollution has become a serious threat to ecosystems and human health. Data shoes that approximately 98% of river in Indonesia have been contaminated with microplastics. One biodegradation approach is the use of Aspergillus niger (A. niger), which is able to decompose complex organic polymers into simple compounds through depolymerization and mineralization processes into CO_2, H_2O, *or* CH_4. *Degradation efficiency can be increased by adding sengon powder (Paraserianthes falcataria) as a bulking agent to regulate porosity, humidity, and provide nutrients for fungal growth. This study aims to evaluate the combination of A. niger and sengon powder in decomposing microplastics and develop a microcontroller and IoT-based detection system. Monitoring of microplastic levels can be done through turbidity sensors and optical particle counters connected to the monitoring system. Thus, treatment interventions can be carried out in a timely manner to maintain river quality. This approach is expected to be an environmentally friendly solution to address microplastic pollution effectively and sustainably.*

INTRODUCTION

The rapidly increasing global use of plastic has become a critical environmental issue with far-reaching ecological impact. According to data from the United Nations Environment Programme (UNEP), global plastic production reached 438 million tons in 2021. However, only 12% of this total production was recycled, while 9% was released into the environment, with the remainder ending up in waste disposal sites. The widespread use of single-use plastics, composed of synthetic materials that are highly resistant to degradation, has contributed to one of the most pressing environmental concerns, namely microplastic pollution (Putra et al., 2024). Microplastics are plastic particles measuring less than five millimeters in size, generated through the physical, chemical, and biological degradation of larger plastic materials. These particles pose substantial risks to Once ingested, microplastics may accumulate within biological systems, potentially disrupting hormonal and nervous system functions and increasing the risk of metabolic disorders. Moreover, microplastics can serve as vectors for pathogens and toxic substances, thereby intensifying their adverse effects on exposed organisms (Amanu et al., 2024).

The majority of microplastic dispersion occurs in subaqueous environments, largely driven by land-based anthropogenic activities involving plastic waste, which is transported into water bodies through rainfall runoff and wind exposure. Under the influence of environmental factors such as sunlight, temperature, and wave action, larger plastic debris gradually fragments into microplastics (Aryanti et al., 2025). According to data reported by Azhary et al. (2025), approximately 98% of river

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waters in Indonesia are contaminated with microplastics, with their distribution influenced by surface currents, flow velocity, and wind dynamics. Currently, various strategies for the prevention and management of microplastics in aquatic environments have been developed, predominantly emphasizing the principles of reduction, reuse, and recycling. In practice, microplastic management is commonly supported through technological interventions, including trash barriers, as well as policy-based approaches such as the polluter pays principle. Nevertheless, a microbiologically based alternative approach utilizing herbal resources, integrated with an Internet of Things (IoT)-based monitoring and control system, is needed to complement the still-limited existing efforts in microplastic prevention and management.

Aspergillus niger is a filamentous fungus capable of producing lipase enzymes, which have been reported to contribute to microplastic degradation through the cleavage of ester bonds within polymer structures (Murni et al., 2011). In parallel, Indonesia's rich plant biodiversity offers considerable potential for the utilization of local biological resources, including Sengon (*Paraserianthes falcataria*). Sengon powder contains lignocellulosic compounds that may serve as nutrient sources, improve substrate structure, and optimize microbial activity during the biodegradation process, thereby demonstrating potential as a bulking agent (Putra et al., 2018). Accordingly, the combined application of *A. niger* and sengon powder represents a microbiologically based approach with the potential to enhance the effectiveness of microplastic biodegradation. Furthermore, the implementation of IoT-based monitoring technology is necessary to facilitate accurate and real-time assessment of the microplastic biodegradation process mediated by *A. niger* and sengon powder.

The utilization of the Internet of Things (IoT) technology presents promising opportunities to support research on microplastic degradation. This system can facilitate the acquisition of more accurate data through an initial filtration stage employing Bulk Acoustic Wave (BAW) technology, which functions to separate microplastic particle fractions for subsequent analysis (Jonai et al., 2023). Subsequently, particle monitoring is performed by adapting a laser-based Optical Particle Counter (OPC) approach, which utilizes coherent light sources to detect particles within water flow systems (Abimbola et al., 2024). In the present study, this system is further enhanced through the incorporation of a CCD TSL 1401CL sensor as a photodetector to improve detection capability. Monitoring accuracy is further strengthened through the application of a turbidity sensor, which measures water turbidity based on light-scattering properties, where the intensity of reflected light is proportional to particle concentration (Sulistyo, 2019). The integration of these IoT-based components constitutes the primary novelty of this study, enabling a more comprehensive and real-time evaluation of the microplastic biodegradation process mediated by A. niger and sengon powder. Based on this framework, the present study emphasizes the integration of biological agents, local resources, and IoT technology to develop a more effective strategy for microplastic biodegradation while strengthening the scientific novelty of the proposed approach.

RESEARCH METHOD

The research methodology employed in this study consisted of experimental methods, literature review, and prototype design (Figure 1). Experimental methods were conducted to identify the lipase enzyme activity of A. niger as a potential agent for microplastic biodegradation. The literature review involved the analysis of findings from previous studies concerning microplastic biodegradation mediated by by the lipase enzyme of A. niger, combined with sengon powder as a bulking agent, as well as the implementation of IoT-based monitoring systems. Meanwhile, prototype design was undertaken to illustrate the proposed device innovation and its operational framework.

The experimental equipment used in this study included 60 mm Petri dishes, an Olympus CX22 microscope connected to an Optilab camera, syringes, gloves, medical masks, inoculating loops, a Bunsen burner, toothpicks, conical tubes, an incubator, glass slides, cover slips, and an autoclave. The materials employed consisted of Aspergillus niger FNCC 6088, Sabouraud Dextrose Agar (SDA), Lactophenol Cotton Blue (LPCB), Luria–Bertani Agar (LBA; 1.75 g in 50 mL distilled water), 2% LBA (0.2 g in 10 mL distilled water), 1% olive oil solution (1 mL olive oil in 9 mL sterile distilled water), rhodamine solution (1 mg/mL; 10 mg in 10 mL sterile distilled water), olive oil (1 mL), rhodamine (0.5 mL), and 500 g of sengon powder. Additional components for the IoT-based monitoring prototype included a laser diode, beam dump, 10 kΩ resistor, convex lens, CCD TSL 1401CL sensor, 12 V power supply, DC–DC step-down converter, glass capillary tube, turbidity sensor, ESP32 DevKit V1, cloud platform, water pump, and a mini 3 W/8 Ω full-range speaker.The required experimental tools are 60 mm diameter petri dishes, an Olympus CX22 microscope connected to an Optilab camera, syringes, gloves, medical masks, inoculating loops, a Bunsen burner, toothpicks, conical tubes, an incubator, glass slides, cover slips, and an autoclave. Materials used include *Aspergillus niger* FNCC 6088, Sabouraud Dextrose Agar (SDA), Lactophenol Cotton Blue (LPCB), Luria Bertani Agar (LBA) (1.75 g + 50 ml distilled water), 2% LBA (0.2 g + 10 ml distilled water), 1% olive oil (1 ml olive oil + 9 ml sterile distilled water), 1mg/ml Rhodamine (10 mg + 10 ml sterile distilled water), 1 ml olive oil, 0.5 ml rhodamine. Sengon powder 500g, laser diode, beam dump, 10kΩ resistor, convex lens, CCD TSL 1401CL sensor, 12V power supply, step-down converter (DC-DC), glass capillary tube, turbidity sensor, ESP32 DevKit V1, cloud platform, water pump, mini 3W/8Ω full-range speaker.

This research was conducted over a two-week period at the Microbiology Laboratory, Faculty of Veterinary Medicine, Universitas Gadjah Mada, to isolate A. niger and extract its lipase enzyme. The A. niger FNCC 6088 strain was obtained from the Inter-University Center Laboratory (PAU) of Universitas Gadjah Mada and subsequently cultured on Sabouraud Dextrose Agar (SDA) medium. Macroscopic identification of A. niger colonies was performed through observation of colony growth characteristics. Morphological identification was subsequently conducted using Lactophenol Cotton Blue (LPCB) staining and microscopic examination. Following the establishment of a pure culture,

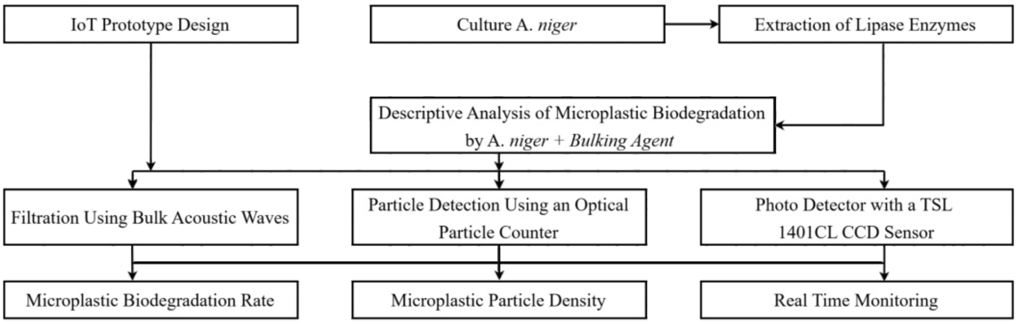

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Figure 1
Research Scheme

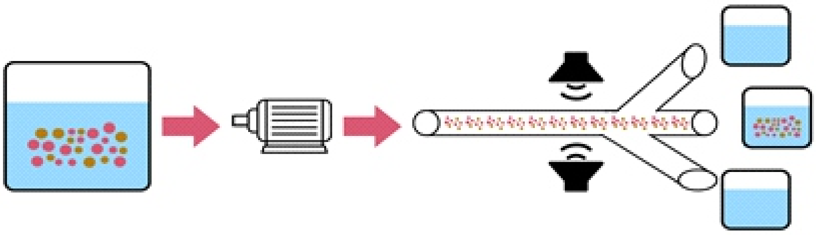

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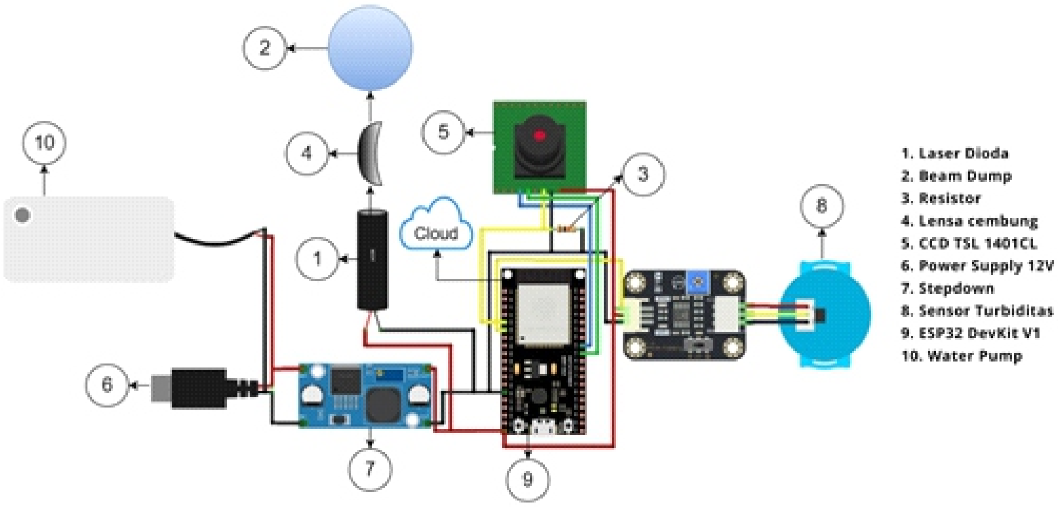
Figure 2

Filtration Mechanism using Bulk Acoustic Wave (BAW)

enzyme extraction was carried out to obtain lipase from A. niger for use as a potential agent in microplastic biodegradation. Subsequently, a descriptive analysis was performed to compare the average biodegradation rate between treatments utilizing sengon powder as a bulking agent and those without sengon powder.

The application of IoT-based biodegradation, as illustrated in Figure 2, demonstrates the operational mechanism of the Bulk Acoustic Wave (BAW) system employed as the initial filtration stage. River water is directed through an 8 mm-diameter pipe using a water pump with an approximate flow rate of 100 L/h. As the water passes through the acoustic zone, microplastic particles are driven toward the center of the channel by acoustic radiation forces, while relatively cleaner water is discharged through the lateral branches of the channel (Jonai et al., 2023). The BAW-based filtration method has been reported to exhibit high efficiency in particle separation, as it can operate across a wide frequency range, from audio to ultrasonic frequencies, thereby enhancing the effectiveness of microplastic separation (Arifianto et al., 2021).

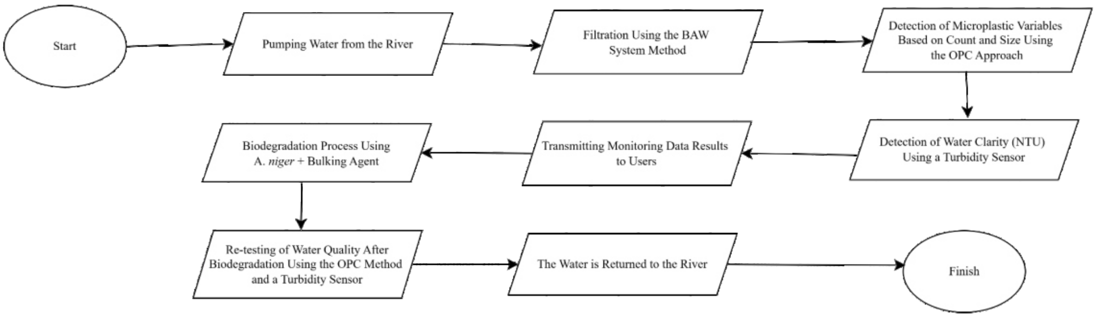
The schematic presented in Figure 3 illustrates an IoT-based water quality monitoring system integrating an Optical Particle Counter (OPC) approach and a turbidity sensor, in which all devices and sensors are configured to operate as an interconnected system. The process begins with a laser diode functioning as a coherent light source for particle detection within the water flow. A convex lens is employed to focus the laser beam, thereby improving beam concentration within the measurement channel and optimizing detection performance.



Source: Processed Primary Data, 2025

Figure 3

Schematic of the IoT-Based Biodegradation Device Prototype



Source: Processed Primary Data, 2025

Figure 4

Workflow Diagram

The primary unscattered light is subsequently directed toward a beam dump for absorption, reducing optical noise and minimizing the risk of false detection. Thereafter, scattered light generated by particle interactions is captured by a TSL 1401CL CCD sensor and converted into an analog signal. The acquired signal is transmitted to an ESP32 microcontroller for processing and subsequently delivered via Wi-Fi to a cloud platform, enabling real-time data access and monitoring by users (Masykuroh et al., 2023; Regowo, 2022). Following particle detection, the turbidity sensor measures water turbidity based on the intensity of light scattered or reflected by suspended particles, and the obtained values are expressed in Nephelometric Turbidity Units (NTU) (Regowo, 2022). The implementation of this IoT-based system enables more comprehensive water quality monitoring by providing information on both detected microplastic particle levels and water turbidity in real time.

The filtration, monitoring, and biodegradation workflow illustrated in the schematic begins with water being pumped into a filtration channel employing the Bulk Acoustic Wave (BAW) method to separate microplastic-contaminated water from relatively cleaner water (Figure 2). The filtered water is subsequently directed into the Optical Particle Counter (OPC) system through a flow restrictor and a glass capillary tube to optimize laser beam penetration and particle detection. Thereafter, the water enters a turbidity monitoring stage using a turbidity sensor to evaluate particle concentration and water turbidity. This integrated system enables the monitoring of microplastic particle size, abundance, and turbidity values, with the resulting data transmitted to users for evaluation. Following particle characterization, microplastics undergo biodegradation mediated by A. niger through the extracellular activity of lipase enzymes. Lipase facilitates the degradation of complex polymer structures into simpler compounds through mineralization processes, producing end products such as CO_2, H_2O, and methane (CH_4) (Obaid & AL-Jawhari, 2023). After biodegradation, the treated water is re-evaluated using the OPC approach and turbidity sensor to compare water quality parameters and microplastic content before and after treatment. Finally, the processed water is discharged back into the river system.

RESULTS AND DISCUSSION

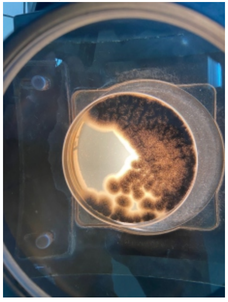
This study was conducted to optimize the utilization of A. niger in the biodegradation of microplastic polymers through the activity of lipase enzymes, with the addition of sengon powder (Paraserianthes falcataria) as a lignocellulose-rich bulking agent. To enhance process evaluation, biodegradation optimization was integrated with an IoT-based system, enabling a more comprehensive assessment of microplastic biodegradation effectiveness and facilitating real-time monitoring during data acquisition.

Aspergillus niger has been reported to produce lipase enzymes, as supported by experimental findings demonstrating their role in microplastic biodegradation. Lipase exhibits catalytic activity in hydrolysis and chemical synthesis reactions, enabling the degradation of polymeric compounds through the cleavage of ester bonds. Specifically, lipase hydrolyzes triglycerides into free fatty acids, partial glycerides, and glycerol. As substrates, triglycerides consist of long-chain fatty acids that are insoluble in water, thereby requiring enzymatic activity at the interface between the aqueous phase, in which the enzyme is dissolved, and the insoluble substrate phase (Murni et al., 2011).

The addition of sengon powder as a bulking agent may enhance bio-degradation efficiency by supplying nutrients for A. niger, improving substrate porosity, and maintaining moisture conditions favorable for microbial growth. According to Primadipta and Titah (2017), the incorporation of sengon powder promotes the growth of A. niger, thereby increasing lipase enzyme production and accelerating the biodegradation process of microplastics. Furthermore, biodegradation optimization was integrated with an IoT-based system employing Bulk Acoustic Wave (BAW) technology for the filtration and concentration of microplastic particle fractions, as well as an Optical Particle Counter (OPC) approach utilizing a laser-based optical system for particle detection. The incorporation of a CCD TSL 1401CL sensor as a photodetector, together with a turbidity sensor for turbidity measurement, further enhances monitoring performance by enabling real-time evaluation of the microplastic biodegradation process.

A. niger Characteristics

Aspergillus niger is a species belonging to the genus Aspergillus. This fungus is characterized by a filamentous morphology, black colony pigmentation, and a cream-colored reverse side. According to Markey et al. (2013), A. niger colonies initially appear white before gradually developing a black pepper-like appearance due to conidial formation, while maintaining a cream-colored reverse (Figure 5).



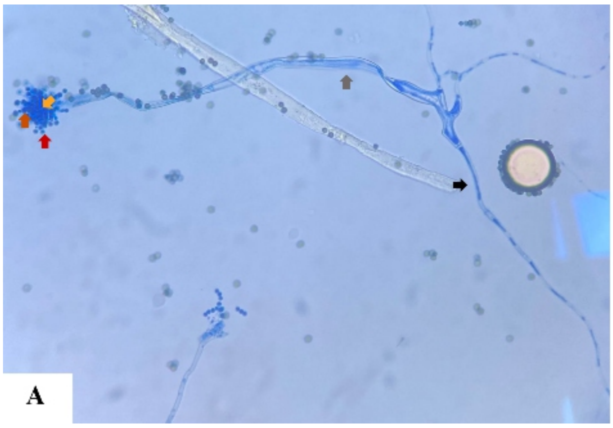
Source: Processed Primary Data, 2025

Figure 5

Macroscopic View of *Aspergillus niger* on SDA Media

Microscopically, the isolate exhibited septate hyphae and hyaline conidiophores with rounded black conidial heads. An elongated conidiophore terminating in a rounded apex forming a vesicle was also observed. Metulae were distributed across the entire surface of the vesicle, followed by the presence of darker-colored conidia. According to Hardini et al. (2025), A. niger is characterized by septate hyphae and colorless conidiophores. Consistent with the observations reported by Markey et al. (2013), A. niger exhibits large conidial heads appearing as black spherical structures under microscopic examination, with large vesicles supporting the attachment of metulae, phialides, and rough black conidia (Figure 6).

Aspergillus niger is a fungus capable of producing citric acid and at least 23 types of enzymes. Among the commercially important enzymes produced by A. niger are amylase, lipase, glucoamylase, cellulase, pectinase, glucose oxidase, and catalase (Nurhayati et al., 2020). Among these enzymes, lipase has been identified as one of the key enzymes involved in microplastic biodegradation (Table 1).



Source: Processed Primary Data, 2025

Figure 6

Microscopic *Aspergillus niger* 40x Magnification

(A) Observation Results of Isolate A. *niger* 40x Magnification Foot cell (Black Arrow), Conidiophore (Gray Arrow), Vesicle (Yellow Arrow), Mutulae (Orange Arrow), and Conidia (Red Arrow)

Based on findings reported by Mala et al. (2007), A. niger exhibited optimal lipase activity of 274.6 U/g within the first 48 h of incubation, followed by a decline in enzyme activity after 96 h. This reduction was associated with changes in water content, as excessive moisture may decrease substrate porosity, whereas insufficient moisture can result in suboptimal fungal growth and reduced substrate swelling, thereby limiting enzyme production. Therefore, the addition of a bulking agent is considered necessary to maintain favorable substrate conditions for microbial activity. The role of lipase in microplastic biodegradation involves the hydrolysis of triglycerides into free fatty acids, partial glycerides, and glycerol, while also facilitating the cleavage of ester bonds at the interface between the aqueous phase, in which the enzyme is dissolved, and the insoluble substrate phase (Murni et al., 2011).

Analysis of Biodegradation Effectiveness A. niger with Addition of Bulking Agent

The addition of sengon powder (Paraserianthes falcataria) as a bulking agent for A. niger may enhance the biodegradation rate by maintaining optimal substrate porosity, moisture content, and nutrient availability required for fungal growth and metabolic activity. Sengon powder contains lignocellulosic components, including cellulose,

Table 1

Enzymes Found in *Aspergillus niger*

Substrate(g)	Lipase activity (U/g dry substrate) [a]		
	48h	72h	96h
WB (10)	185.5 q S	271.6 q S	303.2 q S
WB (8.75)+GOC(1.25)	202.2 q S	264.1 q S	245.0 q S
WB (7.5)+GOC(2.5)	263.9 q S	384.0 q S	309.3 q S
WB (5.0)+GOC(5.0)	265.8 q S	370.4 q S	289.1 q S
WB (2.5)+GOC(7.5)	274.6 q S	371.3 q S	287.1 q S

[a] The values refer to the mean q SD of three measurement

Source: Mala et al., 2007

Table 2
Component Percentation Sengon Wood

Component (%)	Sengon Wood *(native)*	Delignification Product	
		30 30 minutes	40 30 minutes
Cellulose	41,1	75,2	77,96
Hemicellulose	22,26	10,38	8,14
Lignin	17, 51	2,58	0,93
Ash	19,13	11,74	12,97

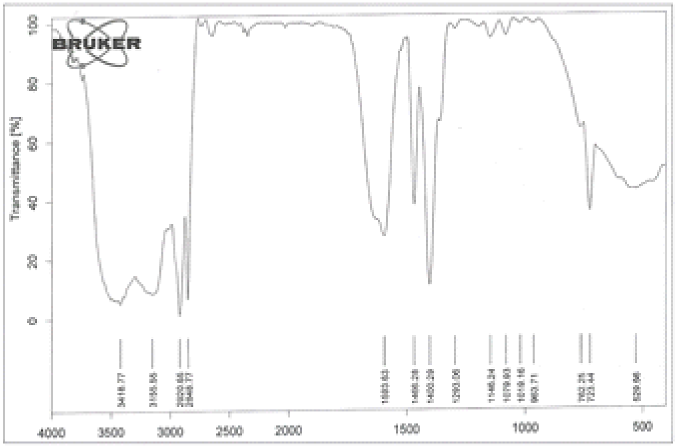
Source: Primadipta & Titah, 2017

hemicellulose, and lignin, which can support the growth and enzymatic activity of A. niger (Table 2). Cellulose, in particular, can be degraded into glucose through cellulase activity, thereby providing an additional carbon source for fungal metabolism (Primadipta & Titah, 2017; Trisanti et al., 2018).

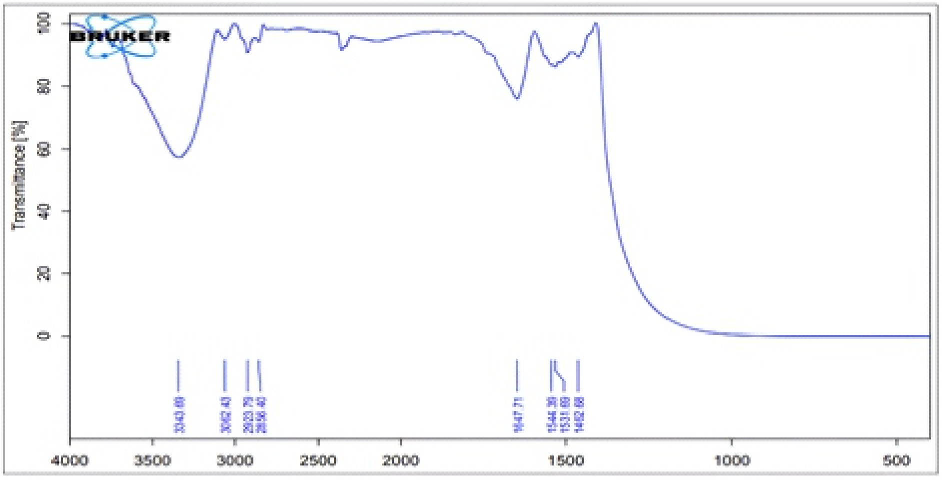
The addition of sengon powder (Paraserianthes falcataria) as a bulking agent for A. niger may enhance the biodegradation rate by maintaining optimal substrate porosity, moisture content, and nutrient availability required for fungal growth and metabolic activity. Sengon powder contains lignocellulosic components, including cellulose, hemicellulose, and lignin, which can support the growth and enzymatic activity of A. niger (Table 2). Cellulose, in particular, can be degraded into glucose through cellulase activity, thereby providing an additional carbon source for fungal metabolism (Primadipta & Titah, 2017; Trisanti et al., 2018).

The results of Fourier Transform Infrared Spectroscopy (FTIR) analysis presented in Figure 7 demonstrate the spectral profile of standard microplastics, characterized by absorption peaks at specific wavenumbers corresponding to the principal functional groups constituting the polymer structure (Obaid & AL-Jawhari, 2023). In contrast, Figure 8 illustrates spectral changes following microplastic biodegradation by A. niger, evidenced by peak shifts and reduced intensity at several absorption bands. These alterations indicate the cleavage of chemical bonds, particularly ester groups thereby confirming the enzymatic activity of A. niger in degrading the polymeric structure of microplastics (Obaid & AL-Jawhari, 2023).

As shown in Figure 9, microplastics exposed to A. niger exhibited a more rapid degradation rate, reaching a final value of 1462.68, compared with microplastics that were not treated with *A. niger*.



Source: Obaid & Al-Jawhari, 2023
Figure 7
Microplastic Degradation Without A. ***niger***



Source: Obaid & Al-Jawhari, 2023

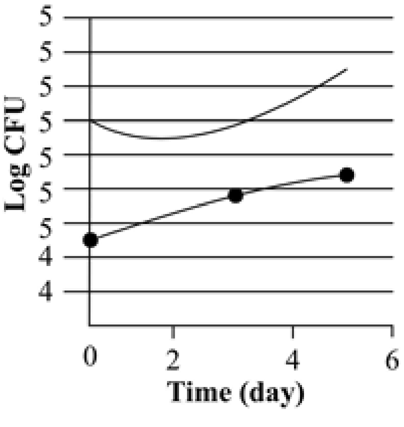
Figure 8

Microplastic Degradation With A. *niger*

The addition of a lignocellulose-rich substrate provides both nutrients and a favorable growth environment for A. niger. In treatments containing lignocellulose, the fungal population initially declined during the early stages of incubation, followed by a substantial increase from the middle to the later stages. This pattern suggests that A. niger was able to adapt effectively to the environmental conditions and subsequently proliferate. In contrast, colonies grown without lignocellulose exhibited only a slight increase in population size, indicating limited fungal growth (Primadipta & Titah, 2017). These findings demonstrate that lignocellulose serves not only as a nutrient source but also as a structural matrix that supports the growth and biodegradation activity of A. niger on microplastic substrates.

Analysis of Filtration Efficiency and Turbidity

Filtration using BAW was performed at frequencies of 5000 Hz, 7000 Hz, 9000 Hz, 11000 Hz, and 13000 Hz. The acoustophoretic force drives the microplastic particles toward the central outlet, while microplastic-free water exits through the side outlet. According to data from Nadifa & Setyawan (2021), BAW at a frequency of 13,000 Hz resulted in an 82.7% reduction in microplastics, indicating that the use of BAW with varying frequencies is quantitatively effective for microplastic filtration in water. Based on the results of the filtration effectiveness analysis using BAW,



Source: Primadipta & Titah, 2017

Figure 9

A. *niger* colonies with lignocellulose (-) and without lignocellulose (.)

Table 2
Component Percentation Sengon Wood

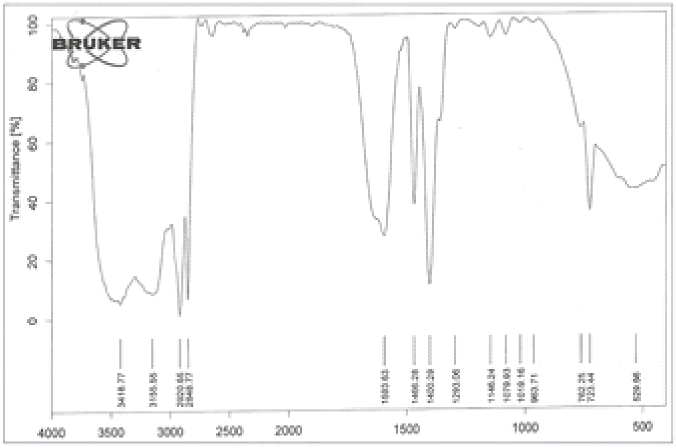
Component (%)	Sengon Wood *(native)*	Delignification Product	
		30 30 minutes	40 30 minutes
Cellulose	41,1	75,2	77,96
Hemicellulose	22,26	10,38	8,14
Lignin	17, 51	2,58	0,93
Ash	19,13	11,74	12,97

Source: Primadipta & Titah, 2017

it is evident that the application of BAW in the filtration process offers high effectiveness in separating microplastic particles from the liquid medium. The acoustic-phoretic force generated by high-frequency acoustic waves is capable of inducing the movement of microplastic particles based on their size, density, and physical properties. This process enables the selective separation of contaminated water from microplastic-free water without the use of any chemical additives.. Thus, the BAW-based filtration system has the potential to be a fast, efficient, and sustainable solution for improving water quality, particularly in mitigating microplastic pollution in aquatic environments.

Water quality parameters, including temperature, pH, dissolved oxygen (DO), total suspended solids (TSS), and salinity, were measured to characterize the environmental conditions of the study area. These parameters were evaluated to assess their potential relationship with microplastic abundance and distribution in the water samples (Table 3).

Based on the findings of Humaerah and Rasyid (2024), microplastic abundance is positively correlated with water temperature, indicating that higher temperatures are associated with greater microplastic concentrations. Temperature is considered an important physico-chemical parameter influencing the abundance and distribution of microplastics in aquatic environments (Buwono et al., 2021). Similarly, pH exhibited a positive relationship with microplastic abundance, suggesting that higher pH values are associated with increased microplastic concentrations. According to Tien et al. (2020), pH is a key water quality parameter that can be used to identify the sources and distribution patterns of microplastics in aquatic systems.



Source: Obaid & Al-Jawhari, 2023
Figure 7
Microplastic Degradation Without A. *niger*

Table 3
Result of the Analysis of Water Quality Parameters Regarding Microplastic (MP) Abundance

Correlation Test	Correlation Between Water Parameters & MP Abundance			Correlation with Correlation Level	
	Sig Value	Criteria	Conclusion	Correlation Coeficient	Strength Correlation
Temperature	0,000	<0,05	There is a correlation	0,794	Very strong
pH	0,011	<0,05	There is a correlation	0,327	Moderate
DO	0,000	<0,05	There is a correlation	-0,784	Very strong
TSS	0,000	<0,05	There is a correlation	0,722	Strong
Turbidity	0,000	<0,05	There is a correlation	0,510	Strong
Salinity	0,000	<0,05	There is a correlation	0,695	Strong

Source: Mala et al., 2007

Total suspended solids (TSS) exhibited a positive relationship with microplastic abundance, suggesting that increasing TSS concentrations are accompanied by higher levels of microplastic contamination. This association may result from the tendency of microplastic particles to adsorb onto suspended particulate matter, facilitating their accumulation in the water column. Likewise, turbidity demonstrated a positive relationship with microplastic abundance, indicating that waters with higher turbidity levels tend to contain greater concentrations of microplastics.

Salinity was also positively associated with microplastic abundance, suggesting that higher salinity levels corresponded to greater microplastic concentrations. Variations in salinity can influence the transport, buoyancy, and distribution of microplastic particles within aquatic environments. Karlsson et al. (2017) reported that differences in particle density and salinity affect the sinking behavior and distribution of microplastics, thereby influencing their accumulation patterns in aquatic ecosystems.

Based on the data analysis, the integration of filtration systems and turbidity sensors is essential for monitoring water quality, as microplastic abundance is strongly influenced by physicochemical parameters, including temperature, pH, dissolved oxygen (DO), total suspended solids (TSS), turbidity, and salinity. Monitoring these parameters enables a more comprehensive assessment of microplastic contamination and provides valuable data for evaluating the effectiveness of mitigation strategies. Consequently, the resulting information can support the development and implementation of more effective and sustainable innovations for water quality management.

CONCLUSION

This study demonstrates that the lipase enzyme produced by Aspergillus niger, in combination with sengon wood powder (Paraserianthes falcataria), has considerable potential for enhancing the biodegradation of microplastics in riverine environments. Furthermore, the integration of an Internet of Things (IoT)-based monitoring system improves the consistency, efficiency, and reliability of the biodegradation process by enabling real-time environmental monitoring and process control. Nevertheless, the present study was conducted under controlled laboratory conditions, which may not fully reflect the complexity and variability of natural aquatic ecosystems. Therefore, further research at the prototype and field scales is required to evaluate the effectiveness, scalability, and long-term performance of this approach. Such investigations will be essential for optimizing the technology, improving its overall efficiency and reliability, and facilitating its application as a sustainable strategy for microplastic mitigation and environmental management.

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