

Comparative Study of Physical Components and Degradability of Natural Fibers as Alternative Biofilm Media for Wastewater Treatment Systems

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Abstract

This study supports the Sustainable Development Goals (SDGs) on clean water and sustainable production by evaluating the potential of natural fibers as biofilm media for wastewater treatment. Seven types of media were assessed and evaluated, including polyurethane sponge as a control, straw, coconut fiber, sugar palm fiber, sphagnum moss, oil palm empty fruit bunches (EFB), and tree fern board. The evaluation was conducted over a 30-day period based on physical characteristics (pore size and porosity) and water quality parameters (pH, TDS, TSS, and COD), complemented by organoleptic observations. Media performance was ranked using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The results indicated that tree fern board (TOPSIS score = 0.833) and sugar palm fiber (TOPSIS score = 0.778) were the most promising natural biofilm media, exhibiting porous structures, high physical stability, and characteristics favorable for biofilm development, with performance approaching that of polyurethane sponge. In contrast, straw, EFB, coconut fiber, and sphagnum moss showed lower performance due to rapid degradation or insufficient structural stability, which adversely affected water quality. Overall, this study demonstrates that tree fern board and sugar palm fiber are promising, sustainable alternatives to synthetic biofilm media, with potential for use in environmentally friendly wastewater treatment systems.

Keywords

Biofilm Media, Natural Fibers, Wastewater Treatment, Biological Degradation, TOPSIS Method, Sustainable Development Goals (SDGs)

Received: 28 February 2026, Accepted: 9 July 2026

<https://doi.org/10.26554/ijems.2026.10.4.290-299>

1. INTRODUCTION

Rapid population growth, urbanization, and economic development have substantially increased wastewater volume and pollution load globally, creating an urgent need for effective, sustainable, and environmentally friendly treatment systems (United Nations-Water, 2025). Biofilm-based systems, in which microorganisms attach to media surfaces to degrade pollutants biologically, are increasingly adopted (Saini et al., 2023). Their performance depends strongly on biofilm media characteristics, as physical properties such as shape, porosity, and surface area directly influence biofilm structure and treatment efficiency (Deena et al., 2022).

Previous studies have highlighted the importance of carrier physical characteristics in determining biofilm performance. Ahmad et al. (2017) demonstrated that carrier size influenced biofilm development, microbial distribution, and nitrogen removal performance, while Hu et al. (2020) reported that carrier internal diameter affected biofilm characteristics and biomass accumulation. Similarly, Tong et al.

(2021) developed a novel porous carrier with a reported porosity of 57.93% that supported biofilm cultivation. In practical applications, polyurethane sponge media have been widely employed in Downflow Hanging Sponge (DHS) systems because their highly porous structure provides favorable conditions for biomass retention and stable reactor performance (Onodera et al., 2014). These findings collectively indicate that physical media characteristics are critical factors influencing biofilm carrier performance.

Synthetic polymers, including polyethylene and polypropylene, dominate as biofilm media due to their durability and stability; however, their non-biodegradability contributes to plastic pollution, underscoring the need for renewable, biodegradable alternatives (Acarer, 2023). Indonesia offers substantial potential, with abundant natural biomass, including straw, coconut fiber, sugar palm fiber, sphagnum moss, oil palm empty fruit bunches (EFB), and tree fern board (Erdiwansyah et al., 2024; Lestiani et al., 2021; Prasani et al., 2021; Lempang, 2012).

Natural fibers are considered promising due to their

biodegradability, availability, and low cost (Lago et al., 2024). Coconut, kenaf, abaca, and jute fibers provide structures conducive to microbial attachment and growth while maintaining sufficient mechanical resistance (Derakhshan et al., 2018). Their microporous nature increases surface area, promoting biofilm formation and improving treatment efficiency (Low et al., 2021). Utilizing natural fibers aligns with SDG 6 by supporting sustainable wastewater treatment and SDG 8 by fostering local resource utilization and green industry development (Ministry of National Development Planning/National Development Planning Agency (Bappenas), 2023).

However, variations in fiber chemical composition influence their suitability as biofilm media. Cellulose, hemicellulose, and lignin proportions determine mechanical strength, hydrophobicity, and biodegradation rates (Rocha et al., 2022). While cellulose enhances strength, lignin increases resistance to degradation but may inhibit microbial adhesion (Zhao et al., 2019). Biofilm media must balance operational stability with post-use biodegradability, with degradation influenced by environmental factors including pH, temperature, microbial activity, and enzymes (Mgbemena and Mgbemena, 2017; Munimathan et al., 2024). Fibers with higher hemicellulose degrade faster, whereas high lignin content slows degradation (Rajeshkumar et al., 2023).

Previous studies on natural fiber biofilm media have primarily focused on biofilm formation and treatment performance, often evaluating individual materials under specific operating conditions. Comparative assessments of multiple natural fibers under identical experimental conditions remain limited. In addition, information regarding material degradation, long-term stability, and contaminant release characteristics is rarely reported, despite their importance for practical biofilm media applications. Furthermore, the application of multi-criteria decision analysis (MCDA) for objective material ranking and selection remains limited. Therefore, this study combines experimental evaluation with TOPSIS-based analysis to comparatively assess the physical characteristics and degradation-related behavior of various natural fibers as potential biofilm media. The findings are expected to provide a scientific basis for environmentally sustainable material selection and support the transition toward a circular economy.

2. EXPERIMENTAL SECTION

2.1 Biofilm Media Preparation and Pretreatment

The biofilm media used in this study consisted of polyurethane sponge as a comparison medium, straw (*Oryza sativa* L.), coconut fiber (*Cocos nucifera* L.), sugar palm fiber (*Arenga pinnata* Merr.), sphagnum moss (*Sphagnum* spp.), oil palm empty fruit bunches (EFB; *Elaeis guineensis* Jacq.), and tree fern board (*Dicksonia squarrosa* (G.Forst.) Sw.). All materials were cleaned, cut to a uniform size, and stabilized in net tubes with a fixed volume of 29.53 cm³ to ensure dimensional consistency. The media were characterized in

terms of pore size and porosity, then immersed in 500 mL of distilled water for 30 days. During the soaking period, pH and Total Dissolved Solids (TDS) were monitored daily, while organoleptic parameters (odor and color scores) and Total Suspended Solids (TSS) and Chemical Oxygen Demand (COD) were measured on days 10, 20, and 30 to assess material degradation, indicated by changes in suspended solids and organic matter concentrations. Distilled water was used to isolate the intrinsic degradation behavior of each material under controlled conditions, minimizing interference from complex constituents typically present in wastewater. This approach enables a clearer assessment of material-induced effects and potential contaminant release from the tested media, rather than evaluating pollutant removal performance.

2.2 Pore Size Measurement of Biofilm Media

Pore size measurements were performed to characterize the physical properties of biofilm media related to microbial attachment and growth using a calibrated digital microscope equipped with a CMOS sensor (maximum resolution 1920 × 1440 pixels; magnification up to 1600×). Prior to measurement, the microscope scale was calibrated using the built-in calibration standard to ensure dimensional accuracy. Microscopic images were captured for each sample, and pore dimensions were determined based on the calibrated scale displayed in the imaging system. Four representative pore locations were analyzed for each medium, selected to reflect the material's overall structure. The measured pore sizes were subsequently averaged, and the results are presented as mean ± standard deviation to account for material heterogeneity.

2.3 Porosity Measurement of Biofilm Media

Porosity of the biofilm media was determined using a volume-based method by comparing pore volume to total media volume. The media were placed in a cylindrical net tube with a fixed total volume of 29.53 cm³ and immersed in water until fully saturated. Pore volume was calculated as the difference between the total volume and the solid material volume. Porosity was then expressed as the percentage ratio of pore volume to total volume (Ganat, 2020).

2.4 Measurement of pH, TDS, Odor, and Color in Biofilm

pH and total dissolved solids (TDS) were measured daily using a multifunction pH-TDS-EC-temperature meter (EZ-9908, China) following SNI 6989.11:2019 (National Standardization Agency of Indonesia, 2019a), with routine calibration using standard buffer solutions (pH 4.01, 7.00, and 10.00) and a 1413 µS/cm standard solution, producing results consistent with SNI-based methods (Chuzaini et al., 2022). The odor and color of the biofilm media soaking water were evaluated organoleptically on days 10, 20, and 30 via direct inhalation and visual observation under standardized light-

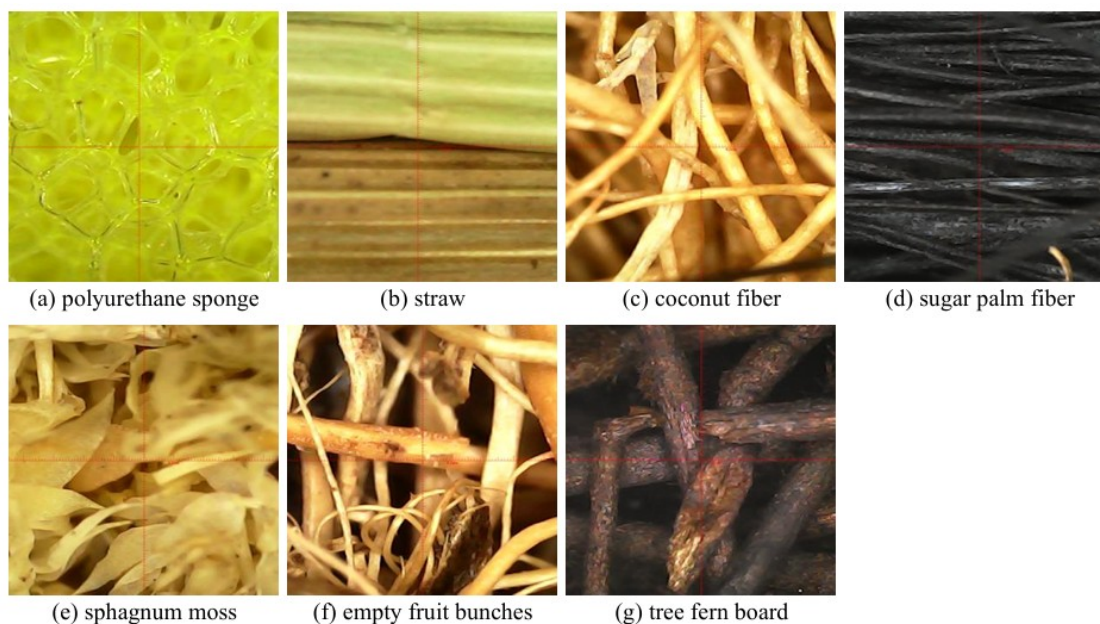


Figure 1. Microscopic Image of Biofilm Media Before Examination

ing, respectively (Moheman et al., 2014). Observations were recorded using a descriptive scoring scale ranging from 0 (no noticeable odor or color change) to 4 (very strong odor or highly concentrated color) (Sukardi, 2018). As organoleptic assessments are inherently qualitative, the scoring results were used as supportive indicators rather than definitive analytical measurements.

2.5 TSS and COD Measurement

TSS and COD were measured on days 10, 20, and 30 during the biofilm media soaking period to evaluate changes in water quality. TSS analysis followed SNI 6989.3:2019 using the gravimetric method with filtration, oven drying at 103–105 °C (Yamato DKN 401, Japan), and weighing to constant mass using an analytical balance (Shimadzu ATX224R, Japan) (National Standardization Agency of Indonesia, 2019b). COD was determined according to SNI 6989.02:2019 using the closed reflux spectrophotometric method with potassium dichromate oxidation under acidic conditions, followed by UV–Vis spectrophotometric measurement (Shimadzu UV-2600, Japan) to obtain COD concentrations (National Standardization Agency of Indonesia, 2019c). Due to the limited sample volume and the destructive nature of COD and TSS analyses, measurements were performed once for each medium at each sampling interval (days 10, 20, and 30). This approach was considered sufficient for tracking temporal changes in material degradation during the soaking period.

2.6 Multi-Criteria Decision Analysis (MCDA) TOPSIS Method

Multi-Criteria Decision Analysis (MCDA) was applied using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank alternatives based on multiple evaluation criteria. In this study, TOPSIS was applied as a ranking-based decision analysis method to identify the most suitable biofilm media by integrating multiple physical and degradation-related parameters into a single comparative evaluation. The TOPSIS method ranks alternatives by identifying the option closest to the positive ideal solution and farthest from the negative ideal solution. The analysis procedure, following the framework proposed by Łatuszyńska (2014), involved constructing a decision matrix comprising alternatives and criteria, normalizing the matrix to eliminate unit differences, and assigning weights to each criterion with the total weight equal to one. Equal weighting was applied to all criteria to minimize subjective bias in the absence of established priority levels among the evaluated parameters. This approach provides an objective baseline comparison in this preliminary material screening, although alternative weighting methods, such as the Analytic Hierarchy Process (AHP), may be considered in future studies. A weighted normalized decision matrix was then generated, followed by the determination of positive and negative ideal solutions based on benefit and cost criteria. The distance of each alternative from both ideal solutions was calculated to obtain a preference index (C_i), with higher values indicating better overall performance (Łatuszyńska, 2014). This study was designed as a preliminary comparative assessment focusing on material screening and ranking under controlled laboratory conditions. Therefore, the results were inter-

preted descriptively to identify relative performance trends among the tested media rather than to establish definitive statistical differences.

3. RESULTS AND DISCUSSION

3.1 Pore Size of Biofilm Media

The physical characteristics of biofilm media affects ability of microorganisms to attach and grow. Table 1 shows the average pore size of several natural materials tested as biofilm media, and their physical forms are shown in Figure 1.

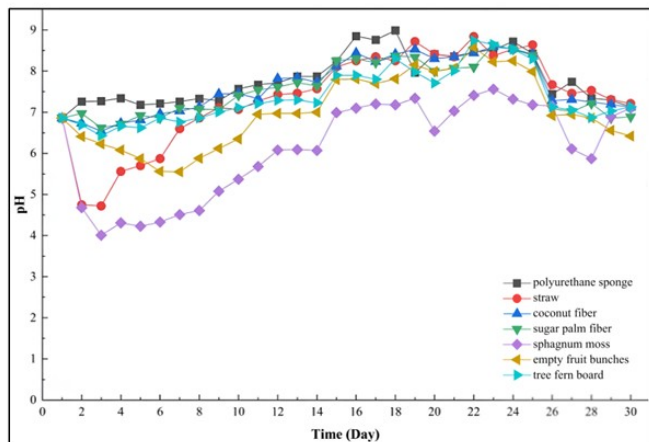


Figure 2. Measurement of pH in the Biofilm Media Soaking Water

Figure 2 presents microscopic images of the seven biofilm media, while Table 1 summarizes their average pore size and porosity values. Tree fern board exhibited the largest pore size (0.4085 ± 0.0950 mm) with high porosity (87.81%), indicating potentially favorable physical characteristics for biofilm support by facilitating oxygen and nutrient diffusion. In contrast, sugar palm fiber showed the smallest pore size (0.1068 ± 0.0274 mm), which increased surface area but potentially restricted mass transfer within pores. The polyurethane sponge exhibited the highest porosity (94.24%) and a moderate pore size (0.2390 ± 0.0178 mm), consistent with its common application as a biofilm carrier. These variations suggest that biofilm performance is strongly influenced by the balance between pore size and porosity. Consistent with previous studies, excessively small pores may inhibit initial microbial attachment due to increased electrostatic repulsion and promote clogging under rapid biofilm growth (Feng et al., 2015; Coyte et al., 2017), whereas substrates with suitable pore structures may enhance nutrient diffusion and biofilm expansion (Asp et al., 2022). Accordingly, media such as tree fern board with large pore size and high porosity may support more uniform biofilm distribution and improve microbial access to substrate surfaces.

3.2 Condition of pH and TDS in Biofilm Media

Biofilm media play a critical role in wastewater treatment systems by providing surfaces for microbial attachment and biofilm formation. The performance of natural and synthetic biofilm media was evaluated by monitoring pH and Total Dissolved Solids (TDS) in soaking water during a 30-day incubation period, with temporal variations presented in Figure 2 and Figure 3. Figure 2 illustrates the pH fluctuations of the soaking water over 30 days. All media exhibited an identical initial pH of 6.86, followed by an increase during the mid-incubation period. Polyurethane sponge, straw, coconut fiber, sugar palm fiber, EFB, and tree fern board reached peak pH values between days 18 and 23, then gradually returned to near-neutral conditions by day 30. Sphagnum moss showed a distinct pattern, with a sharp decrease in pH during the early incubation phase, followed by a gradual increase to neutral conditions. The temporary pH elevation observed in most media may be associated with microbial activity and the degradation of alkaline organic compounds, while the final stabilization near neutral pH may indicate the development of a more balanced system.

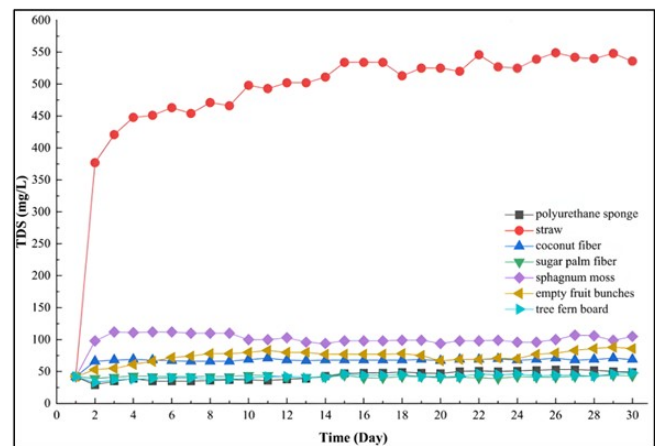


Figure 3. TDS Measurement of Biofilm Media Soaking Water

Figure 3 shows variations of TDS concentrations among the tested media. Straw exhibited the greatest increase in TDS during the soaking period, indicating substantial solute release from the material. Sphagnum moss and EFB also showed moderate increases in TDS, reflecting the release of soluble components during degradation. In contrast, polyurethane sponge, sugar palm fiber, and tree fern board displayed relatively low and stable TDS values over time. These results suggest that easily degradable materials tend to release higher concentrations of dissolved solids, whereas polyurethane sponge and tree fern board demonstrated better stability. These trends may also indicate microbial activity developing on the media surface, which contributes to the transformation of organic and dissolved matter.

Table 1. Pore Size and Porosity of Biofilm Media

Materials	Pore Size (mm)	Porosity
Polyurethane sponge (comparison media)	0.2390 ± 0.0178	94.24%
Straw	0.2420 ± 0.0724	51.24%
Coconut fiber	0.1858 ± 0.0618	77.99%
Sugar palm fiber	0.1068 ± 0.0274	73.92%
Sphagnum moss	0.1742 ± 0.0560	68.51%
EFB	0.2417 ± 0.0819	78.33%
Tree fern board	0.4085 ± 0.0950	87.81%

3.3 Organoleptic Odor Score and Color Score

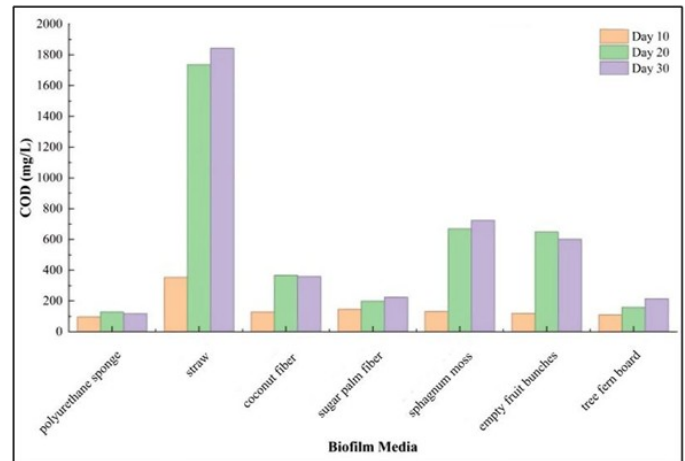
Odor and color examinations of biofilm media-soaked water were conducted on the 10th, 20th, and 30th days to observe changes over time. The results are shown in Table 2, which presents the odor and color scores based on the intensity of odor and color changes in each medium. Scores were assigned on a scale of 0-4, with 0 indicating no odor or color, and 4 indicating a very strong odor or color.

Based on Table 2, polyurethane sponge consistently showed the best organoleptic performance, with odor and color scores of 0 on all observation days, indicating stable and clear soaking water throughout the incubation period. In contrast, straw exhibited the strongest and most persistent odor and color development, reaching the maximum score of 4 by days 20 and 30. Coconut fiber, sugar palm fiber, and tree fern board demonstrated generally mild odor and low color intensity, while sphagnum moss and EFB showed progressive increases, particularly toward the end of the observation period. Overall, the results indicate that the polyurethane sponge exhibited the highest organoleptic stability, whereas straw and EFB showed more pronounced changes in odor and color during soaking. Organoleptic observations are qualitative and may involve subjective interpretation; therefore, they are used as supportive indicators rather than definitive measurements. Further studies can incorporate instrumental techniques (e.g., spectrophotometry and GC-MS) to improve the objectivity of this analysis.

3.4 COD and TSS in Biofilm Media

The concentrations of Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) in the soaking water of various biofilm media were evaluated to assess the extent to which each material affected water quality during soaking. The measurements were conducted on days 10, 20, and 30, and the variations in COD and TSS values for each biofilm medium are presented in Figure 4 and Figure 5, respectively.

As shown in Figure 4, straw media exhibited the highest COD concentration throughout the observation period, reaching a peak of 1,842.84 mg/L on day 30, indicating a substantial release of organic compounds into the soaking water. Sphagnum moss and EFB also showed pronounced increases in COD, with maximum values of 723.41 mg/L and 601.19 mg/L, respectively, suggesting that these materials

**Figure 4.** Result of COD Measurement in Biofilm Media Soaking Water

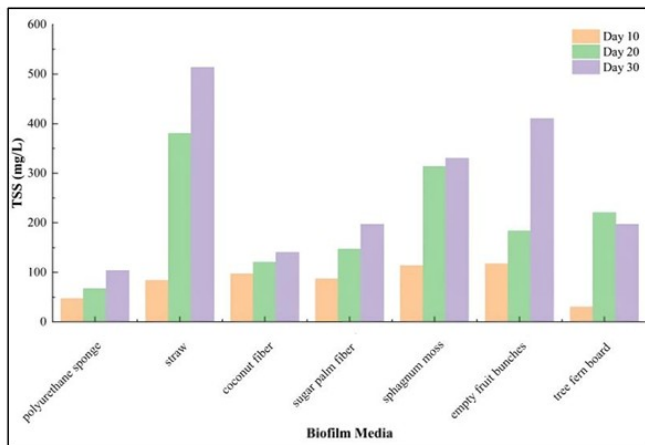
were readily degradable and released considerable amounts of organic matter. In contrast, coconut fiber, sugar palm fiber, and tree fern board showed a more controlled increase in COD, with values remaining relatively lower than those in the highly degradable media. Polyurethane sponge showed the lowest and most stable COD profile during the soaking period, with a value of 118.00 mg/L on day 30, indicating minimal organic release and greater suitability as biofilm media for maintaining water quality.

The TSS trends illustrated in Figure 5 indicate that straw media experienced the highest increase in suspended solids, reaching 513.33 mg/L on day 30, reflecting the release of a large quantity of particulate matter during soaking. EFB and sphagnum moss also showed substantial increases in TSS, reaching 410.00 mg/L and 330.00 mg/L, respectively, indicating that these materials were prone to physical decomposition and particle release. Sugar palm fiber and coconut fiber exhibited moderate TSS levels, with gradual increases over time. Meanwhile, polyurethane sponge and tree fern board consistently showed the lowest TSS concentrations and relatively stable trends from day 10 to day 30, suggesting that these media contributed minimal suspended solids to the soaking water and were more favorable for biofilm application. Overall, material degradation in this

Table 2. Measurement Result of Odor and Color Scores of the Biofilm Media Soaking Water

Biofilm Media	Odor Score Day-			Color Score Day-		
	10	20	30	10	20	30
Polyurethane sponge (comparison media)	0	0	0	0	0	0
Straw	3	4	4	2	4	4
Coconut fiber	1	1	1	2	2	2
Sugar palm fiber	1	1	1	0	0	1
Sphagnum moss	1	1	2	1	1	2
EFB	1	3	3	2	2	4
Tree fern board	1	1	1	0	1	1

study was assessed using indirect indicators (COD, TSS, and TDS), which reflect the release of organic and particulate matter. Additional approaches, such as high-resolution surface observation using SEM and mass loss analysis, may further support the evaluation of material degradation characteristics.

**Figure 5.** Result of TSS Measurement in Biofilm Media Soaking Water

3.5 Best Biofilm Media Based on TOPSIS Method

The performance of seven biofilm media was evaluated using the TOPSIS method based on 20 criteria, including water quality parameters (COD, TSS, TDS, odor score, color score, and pH measured on days 10, 20, and 30) and physical characteristics of the media (pore size and porosity). These parameters reflect each medium's ability to maintain a stable aquatic environment while supporting optimal biofilm growth. The ideal biofilm medium was defined as one that minimized increases in pollutant-related parameters (COD, TSS, TDS, odor, and color), maintained pH close to neutral (7), and exhibited a large pore size and high porosity.

All criteria were normalized to ensure comparability among parameters with different units, and the normalized results were visualized using a radar chart (Figure 6). For water quality and organoleptic parameters, normalized val-

ues closer to zero indicate better performance, reflecting lower pollutant levels. In contrast, for physical parameters (pore size and porosity), values closer to one represent better media characteristics.

Figure 6 shows that the polyurethane sponge performed best at maintaining soaking water quality, with consistently low values of COD, TSS, odor score, and color score, and a pH close to neutral, although its pore size and porosity were relatively limited. The tree fern board also demonstrated strong overall performance, combining stable water quality with a relatively large pore size. Straw, despite its favorable physical characteristics, performed poorly in terms of water quality due to high pollutant release. Coconut fiber and sugar palm fiber exhibited balanced but moderate performance, while sphagnum moss and EFB were less favorable because of higher contaminant levels and pH instability.

Each criterion was assigned an equal weight of 0.05, resulting in a total weight of 1. The weighted normalized matrix was then used to determine positive and negative ideal solutions, followed by the calculation of separation distances and preference indices. This equal-weight approach ensures that all parameters contribute proportionally without emphasizing any single criterion, providing a balanced basis for comparison. The preference index reflects the relative closeness of each alternative to the ideal solution, where higher values indicate better overall performance. The results are presented in Table 3. Based on the TOPSIS preference index, polyurethane sponge ranked first (0.852), followed by tree fern board (0.833), with sugar palm fiber identified as the second-best natural biofilm medium (0.778) and coconut fiber (0.696), while sphagnum moss, EFB, and straw exhibited lower performance due to poorer water quality stability. Overall, polyurethane sponge and tree fern board were the most suitable media, with tree fern board representing the highest-performing natural alternative. This performance may be associated with the coarse, porous, and mechanically robust structure of tree fern board, which potentially supports nutrient diffusion and microbial attachment while maintaining structural stability under aqueous conditions.

Similarly, sugar palm fiber has demonstrated effective biofilter performance by supporting biofilm growth capable of degrading pollutants in domestic wastewater, although

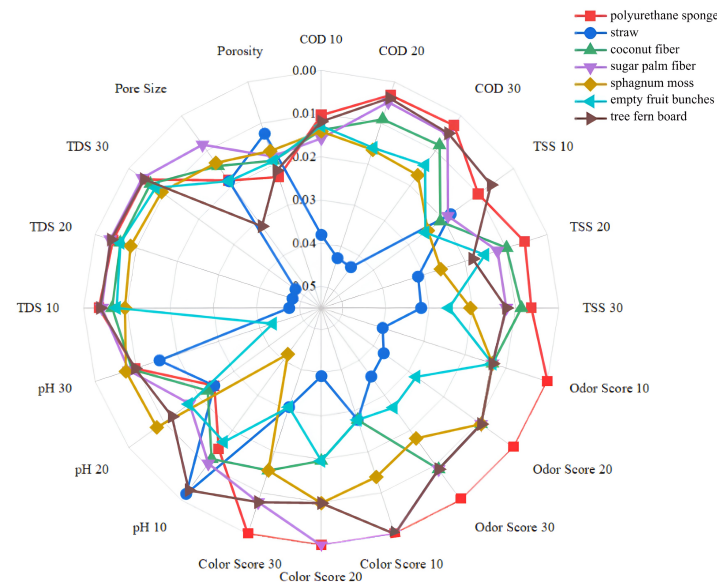


Figure 6. Radar Chart of Normalized Criteria Result Data on Biofilm Media

Table 3. Preference Index of TOPSIS Method

Alternative	Preference Index	Best Solution
Polyurethane sponge (comparison media)	0.852	1
Tree fern board	0.833	2
Sugar palm fiber	0.778	3
Coconut fiber	0.696	4
Sphagnum moss	0.613	5
EFB	0.545	6
Straw	0.265	7

media density remains critical, as overly dense configurations limit water flow and oxygen transfer, whereas excessively loose arrangements reduce microbial contact and treatment efficiency (Putra and Purnama, 2021). The large pore size and high porosity of tree fern board enable uniform nutrient and water distribution without clogging, achieving performance comparable to that of synthetic media, while media with small pore sizes may hinder initial biofilm attachment due to electrostatic repulsion (Feng et al., 2015) and are more prone to clogging from rapid microbial growth (Coyle et al., 2017). In contrast, appropriately porous media such as tree fern board promote nutrient diffusion and lateral biofilm expansion (Asp et al., 2022), and its rough, cavity-rich structure has been shown to support uniform biofilm development and effective BOD and COD reduction in chicken slaughterhouse wastewater, confirming its efficiency and environmental suitability as a biofilter medium (Juherah and Mangiri, 2017).

3.6 Exploring the Potential of Natural Fibers for Biofilm Formation in Wastewater Treatment Systems

Natural fibers such as sugar palm fiber and tree fern board exhibit considerable potential as alternative biofilm media for wastewater treatment, as biofilm-based systems such as trickling filters (TF) and rotating biological contactors (RBC) require coarse, porous substrates to maintain stable biomass under continuous flow, similar to mesh rotating biological reactors (MRBR) that employ high-porosity synthetic fibers to enhance biomass retention and nitrification–denitrification (Onodera et al., 2014; Fuchigami et al., 2021). Based on TOPSIS analysis, polyurethane sponge (control) showed the highest preference index (0.852), followed by tree fern board (0.833) and sugar palm fiber (0.778), demonstrating that these natural materials perform comparably to synthetic media and outperform other natural alternatives, including straw, coconut fiber, sphagnum moss, and empty fruit bunch (EFB).

To further highlight the contribution of the present study, Table 4 compares selected biofilm media reported in previous studies with those evaluated in this work. Particu-

Table 4. Comparison of Previous Studies and the Present Study

Media Type	Physical Characteristics Evaluated	Degradation Assessment	Main Focus	Reference
Kenaf fiber	Limited	No	Biofilm carrier evaluation	(Derakhshan et al., 2018)
Cellulosic fiber	Limited	No	Biofilm development	(Low et al., 2021)
Porous polymer carrier	Porosity reported	No	Biofilm cultivation	(Tong et al., 2021)
DHS sponge	Sponge structure reported	No	Reactor performance	(Onodera et al., 2014)
Natural fibers and sponge	Pore size and porosity	Yes	Media selection and stability	This study

lar attention is given to pore characteristics, porosity, and degradation-related information, as these parameters may influence both biofilm development and the long-term stability of biofilm media.

As shown in Table 4, previous studies have investigated both natural and synthetic biofilm media, primarily focusing on biofilm development, microbial attachment, and treatment performance. However, quantitative information regarding pore size, porosity, and especially material degradation remains limited or was not reported in most studies. This limitation is particularly important for natural fiber media because biodegradation may compromise long-term performance and operational stability. In contrast, the present study evaluates both physical characteristics (pore size and porosity) and degradation-related indicators under identical experimental conditions. Therefore, this study provides a more comprehensive assessment of natural biofilm media by considering not only their suitability for microbial attachment but also their material stability during prolonged immersion.

Beyond technical performance, the use of tree fern board and sugar palm fiber offers a sustainable substitute for synthetic media, supports domestic resource utilization and small-scale enterprises, promotes circular economy practices, and reduces reliance on plastic-based materials in wastewater treatment systems. Although these results demonstrate promising material characteristics, their performance in practical systems such as trickling filters (TF), rotating biological contactors (RBC), and mesh rotating biological reactors (MRBR) has not been directly validated in this study. Therefore, further investigations at pilot or full scale are required to confirm their applicability under real operating conditions.

The use of distilled water in this study enabled the evaluation of material-induced effects under controlled conditions without interference from complex constituents commonly present in wastewater. This approach provides a clearer assessment of the intrinsic degradation behavior of the tested materials. Future studies using actual wastewater are recommended to further evaluate the applicability of these materials under practical operating conditions. In addition, biofilm

formation was not directly quantified and was inferred from water quality parameters. However, these parameters may provide indirect indications of microbial activity and material degradation occurring on the media surface. Therefore, future studies should include direct biofilm characterization, such as biomass attachment measurements, biofilm thickness analysis, or microbial community assessment, to provide a more comprehensive evaluation of biofilm media performance.

4. CONCLUSIONS

Based on the evaluation of seven biofilm media, polyurethane sponge exhibited the best overall performance, while tree fern board was identified as the most promising natural biofilm medium, followed by sugar palm fiber. Tree fern board combined a large pore size (0.4085 ± 0.0950 mm), high porosity (87.81%), and good physical stability, whereas straw and oil palm empty fruit bunch (EFB) showed rapid degradation and poor water quality performance. TOPSIS analysis confirmed these findings, ranking polyurethane sponge first (0.852), tree fern board second (0.833), and sugar palm fiber third (0.778). Overall, this study demonstrates that tree fern board and sugar palm fiber are promising sustainable alternatives to synthetic biofilm media. By integrating the evaluation of physical characteristics and degradation-related behavior with TOPSIS analysis, this study provides a more comprehensive basis for selecting environmentally sustainable biofilm media. Further studies using actual wastewater in practical treatment units under both laboratory-scale and onsite conditions, together with direct biofilm characterization, are recommended to validate the applicability and long-term performance of these biofilm media.

5. ACKNOWLEDGEMENT

This research was funded by the Institute for Research and Community Service (LPPM), Universitas Andalas under the Penelitian Skripsi Sarjana (PSS) grant scheme, Contract Number 193/UN16.19/PT.01.03/PSS/2025. The authors would also like to express their sincere gratitude to the Department of Environmental Engineering, Universitas An-

dalas, for providing research facilities, laboratory support, and technical assistance throughout the study.

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