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Research Article

SPIROWPLAST (Spirulina and arrowroot bioplastic): A combination of Spirulina and arrowroot to enhance the tensile strength and durability of bioplastic

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Abstract. Plastic waste that is resistant to natural degradation remains a critical environmental challenge. One promising strategy to address this issue is the development of bioplastics derived from renewable, biodegradable resources. This study investigates the potential of combining *Spirulina platensis* and arrowroot (*Maranta arundinacea*) flour to produce bioplastics with improved mechanical, chemical, and biodegradation performance. An experimental approach was employed using four formulations: bioplastics derived solely from *S. platensis*, solely from arrowroot flour, a composite of *S. platensis* and arrowroot flour, and a commercial bioplastic (ecoplast) as a positive control. Comprehensive characterization was conducted using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), tensile strength, thickness measurement, and biodegradation tests in accordance with ASTM standards. The results demonstrate that the combined *Spirulina*–arrowroot formulation exhibits more balanced and superior properties compared to single-component bioplastics. The composite bioplastic achieved a tensile strength of 4.267 MPa and an elongation at break of 105.5%, approaching the performance of commercial bioplastic. FTIR analysis confirmed the presence of key functional groups, including hydroxyl (–OH), carboxyl (–COOH), ester (C–O), and aromatic structures, indicating effective polymer network formation. SEM observations revealed a smoother and denser surface morphology, while XRD analysis indicated a semi-crystalline structure with a crystallinity of 49.6%. All bioplastic samples fully decomposed in composted soil within three days, highlighting their excellent biodegradability. Overall, the combination of *Spirulina platensis* and arrowroot flour effectively compensates for the limitations of each individual material, yielding a strong, flexible, and rapidly degradable bioplastic. These findings suggest a viable and environmentally friendly alternative to conventional plastics and provide a foundation for the future development of large-scale bioplastic products with properties comparable to commercial materials.

Keywords: bioplastic, Spirulina, arrowroot, Tensile strength

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1. Introduction

Plastic has long been widely used, particularly for packaging goods and food products. Its lightweight nature, airtightness, low cost, versatility, transparency, corrosion resistance, and durability make plastic a preferred packaging material. However, the extensive use of conventional plastics poses a significant environmental challenge because they are difficult to decompose. As the global population continues to grow, plastic consumption increases accordingly, leading to the accumulation of plastic waste in the environment and intensifying environmental pollution (Rajmohan et al., 2019).

One promising approach to addressing the limitations of conventional plastics is the development of biodegradable plastics. Biodegradable plastics, commonly referred to as bioplastics, are designed to decompose more readily under natural conditions and are therefore considered environmentally friendly alternatives (Suderman, Isa & Sarbon, 2018). The properties of bioplastics are closely related to their natural raw materials, which may include plant-derived components such as starch, cellulose, and lignin, or animal-derived components such as proteins, casein, and lipids (Ginting et al., 2017). Among these materials, starch is the most widely used for bioplastic production due to its biodegradability, low cost, and abundant availability. Starch can be sourced from various plants, including sago, cassava, corn, potatoes, and other tubers (Akter et al., 2014; Talon et al., 2017; Dome et al., 2020; Hilmi et al., 2019; Makhtar et al., 2013).

Arrowroot (*Maranta arundinacea*) is a tuber that remains underutilized despite its high starch content, making it a promising raw material for bioplastic development (Nogueira et al., 2018). Currently, arrowroot is primarily cultivated in rural areas and used as a food ingredient, with arrowroot flour being its simplest processed form and serving as an alternative carbohydrate source (Photiset & Charoenrein, 2007). Nevertheless, the application of arrowroot starch in bioplastic manufacturing is still limited. This

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limitation is mainly attributed to its low water resistance, which results from the predominance of amylopectin in arrowroot starch. Amylopectin has an amorphous structure, leading to larger free volumes and lower intermolecular density, thereby reducing the water resistance of arrowroot-based materials (Tudorachi et al., 2000).

Spirulina sp. is a microalga whose biomass contains approximately 60% protein (Ma et al., 2019). It is widely recognized for its antioxidant and antitumor properties, which has driven its large-scale cultivation. The extraction of phycobiliproteins from *Spirulina* sp. generates residual biomass rich in inorganic salts. This residue can be utilized in bioplastic production, as calcium salts present in the biomass have been reported to enhance the elongation and tensile strength of bioplastics (Li et al., 2019; Benselfelt et al., 2018).

Arrowroot and *Spirulina platensis* were selected in this study due to their complementary properties. Arrowroot-based bioplastics exhibit relatively good mechanical durability; however, the amorphous nature of amylopectin limits their water resistance. In contrast, *Spirulina* offers greater flexibility but lower mechanical strength. Therefore, this research proposes an innovative and environmentally friendly approach to bioplastic production by combining arrowroot flour and *Spirulina platensis*. The resulting bioplastic sheets are expected to exhibit improved durability, transparency, and water resistance.

The quality and characteristics of the produced bioplastics were evaluated using Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Diffraction (XRD). In addition, tensile strength, thickness, and biodegradation tests were conducted to assess the mechanical performance and biodegradability of the bioplastics. Accordingly, the objectives of this study were to evaluate the effectiveness of combining *Spirulina* and arrowroot flour in enhancing bioplastic quality and to characterize the physical, chemical, mechanical, and biodegradation properties of the resulting bioplastic materials.

2. Material and Method

2.1. Period and location of the research

The research was conducted over a three-month period, from November 2025 to January 2026, at the Integrated Laboratory of Diponegoro University, Semarang. This study employed a systematic and structured approach to data collection, which was carried out through several key stages. The initial stage involved an extensive literature review to establish the theoretical framework, identify research gaps, and support the selection of materials, methods, and relevant standards. This was followed by experimental work, including the preparation of bioplastic samples, material characterization, and performance testing using standardized laboratory procedures. In addition, field observations were conducted to support experimental findings, particularly in assessing biodegradation behavior under controlled composting conditions. The integration of literature review, laboratory experimentation, and observational analysis ensured the reliability, validity, and comprehensiveness of the data obtained in this study.

2.2. Materials

The materials used in this study comprised both natural biopolymer sources and supporting additives required for bioplastic formulation. The primary raw materials were arrowroot (*Maranta arundinacea*) starch and *Spirulina platensis* (*S. platensis*) microalgae, which served as the main biopolymer constituents. Distilled water was used as the solvent to ensure purity and consistency during solution preparation. Gelatin was incorporated as a film-forming agent to improve structural integrity, while glycerol and sorbitol were added as plasticizers to enhance flexibility and reduce brittleness of the bioplastic films. Chitosan was included to improve mechanical strength, film-forming capability, and interfacial interactions within the polymer matrix. Together, these materials were selected to promote the formation of biodegradable bioplastic films with balanced mechanical, chemical, and environmental properties.

2.3. Research design and procedure

This study employed a completely randomized design (CRD) consisting of four bioplastic formulations. Treatment B1 represented bioplastics produced solely from *Spirulina* solution without the addition of arrowroot flour, while B2 consisted of bioplastics produced exclusively from arrowroot flour without *Spirulina*. Treatment B3 involved bioplastics prepared from a combination of *Spirulina* solution and arrowroot solution, representing the composite formulation evaluated in this study. Treatment B4 served as the control and consisted of commercially produced cassava starch–based bioplastics (Ecoplas), which comply with ASTM D6400 standards and are manufactured by PT Harapan Interaksi Swadaya (Greenhope Indonesia).

The preparatory stage for raw material acquisition and processing played a critical role in the successful production of bioplastics. This stage included *Spirulina* cultivation under optimal growth conditions, the preparation of arrowroot (*Maranta arundinacea*) starch, and the formulation of *Spirulina* and arrowroot solutions prior to bioplastic casting. Proper control of these preparatory processes was essential to ensure consistency in raw material quality, homogeneity of the bioplastic matrix, and reproducibility of the experimental results.

2.3.1. Spirulina preparation

Spirulina platensis used in this study was obtained from the Center for Biorenewable Energy (C-Biore), Diponegoro University, Semarang. The *S. platensis* biomass was harvested under optimal growth conditions, as indicated by an optical density (OD) of 1.2 measured using a spectrophotometer, to ensure high biomass quality and protein content. Following harvesting, the biomass was dried using a dehydrator at 40 °C for 5 hours to preserve its biochemical properties and prevent thermal degradation. The dried spirulina was then finely ground into powder and sieved through a 100-mesh sieve to obtain a uniform particle size suitable for bioplastic formulation.

In the final preparation stage, the spirulina solution was formulated by mixing 2.25 g of spirulina powder (100 mesh) with 2.25 g of gelatin as a film-forming agent, 180 mL of a 1% (v/v) glycerol solution as a plasticizer, and 2.25 g of sorbitol to enhance flexibility.

Subsequently, 24 mL of distilled water was added, and the mixture was continuously stirred until a homogeneous solution was achieved. This spirulina-based solution was then used as a primary component in the bioplastic fabrication process.

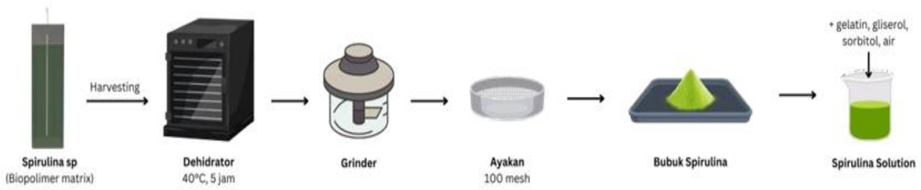

Figure 1. The process of making spirulina solution

2.3.2. Arrowroot solution preparation

The arrowroot (*Maranta arundinacea*) used in this study was obtained from mature tubers harvested at an optimal developmental stage to ensure a high starch yield. The preparation process began with the production of arrowroot starch powder. Fresh arrowroot tubers were thoroughly washed, cut into small pieces, and blended to produce a starch-rich pulp. The resulting pulp was then filtered through a cloth filter to separate the starch-containing liquid from the fibrous residue. The milky-white starch suspension was subsequently dried in an oven at 105 °C for 12 hours to remove moisture and stabilize the starch. After drying, the starch was finely ground and sieved through a 100-mesh sieve to obtain uniform arrowroot starch powder suitable for bioplastic formulation.

In the final preparation stage, 10 g of arrowroot starch powder was dispersed in 50 mL of distilled water and stirred continuously for 5 minutes to achieve uniform hydration. Subsequently, 2.5 g of glycerol was added as a plasticizer to improve flexibility, followed by the incorporation of 2 g of chitosan to enhance film-forming ability, mechanical strength, and antimicrobial properties. The resulting arrowroot starch solution was then used as a key component in the fabrication of bioplastic films.

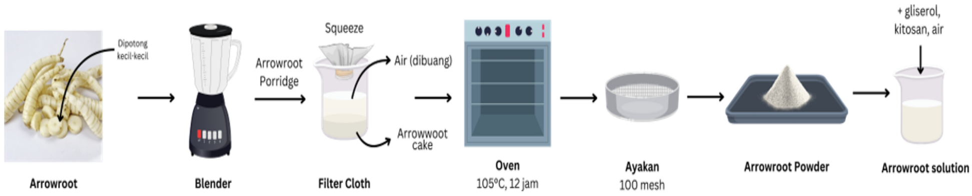

Figure 2. The process of making arrowroot solution

2.3.3. Bioplastic preparation

At this stage of bioplastic production, three types of bioplastic films were prepared. Two of these served as control samples to evaluate the quality and performance of the bioplastics produced using a consortium of *Spirulina* and arrowroot. The control bioplastics were fabricated using the same processing conditions as the composite bioplastic to ensure a valid and consistent comparison. In all formulations, the respective bioplastic solutions were heated on a hotplate at 70 °C under continuous stirring until a homogeneous gel with appropriate viscosity and consistency was formed.

The resulting gel was then carefully cast into molds with the minimum achievable thickness to produce uniform bioplastic films. Following casting, the samples were subjected to a solvent evaporation process under controlled conditions. This evaporation step is critical for removing excess solvent and promoting polymer chain interaction, thereby yielding bioplastics with sufficient rigidity while maintaining flexibility. The standardized production procedure ensured that differences in the final properties of the bioplastics could be attributed primarily to variations in raw material composition rather than processing conditions.

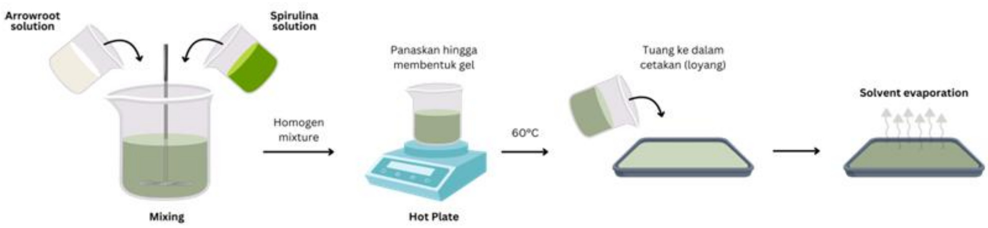

Figure 3. The process of making bioplastic from spirulina and arrowroot solution

2.3.4. Bioplastic quality characterization

To evaluate the quality of the bioplastics in accordance with ASTM standards, several analytical techniques and testing methods were employed. Fourier Transform Infrared (FTIR) spectroscopy (ASTM D6866) was used to analyze the organic molecular structure of the produced bioplastics and to confirm the formation of polymeric bonds through the identification of organic carbon functional groups. Scanning Electron Microscopy (SEM) analysis (ASTM D6400) was conducted to examine the surface morphology of the bioplastics, allowing the assessment of homogeneity, porosity, and overall morphological characteristics. X-ray Diffraction (XRD) analysis (ASTM D3039) was performed to determine the crystalline and amorphous phases of the bioplastics, which are directly related to their mechanical strength and durability. Tensile strength testing (ASTM D638) was carried out to evaluate the mechanical properties of the bioplastics, including tensile strength, flexibility, and brittleness. Thickness measurements were conducted in accordance with ASTM D1005 to determine the uniformity and thickness of the bioplastic films. Finally, biodegradation testing (ASTM D5338) was performed to assess the biodegradability of the bioplastics by microbial activity, by incubating the samples in soil and compost within a desiccator and quantifying the CO_2 evolution during the degradation process.

2.3.5. Data processing and analysis

Data processing and analysis began with the systematic compilation of all laboratory test results, which were subsequently evaluated using both qualitative and quantitative approaches. Fourier Transform Infrared (FTIR) spectroscopy was employed to identify characteristic absorption peaks at specific wavelengths, confirming the formation of polymeric structures and functional groups typical of bioplastic materials. Scanning Electron Microscopy (SEM) analysis provided detailed qualitative images of surface morphology, which were compared with the standardized morphology of biodegradable ECOPLAS plastic in accordance with ASTM D6400 to assess homogeneity, porosity, and surface uniformity. X-ray Diffraction (XRD) analysis generated diffraction patterns that were interpreted based on peak positions and intensities to distinguish between amorphous and crystalline phases, thereby providing insight into the structural organization of the bioplastics.

Mechanical properties were evaluated through tensile strength and elongation measurements, while film thickness was assessed in accordance with relevant ASTM standards to ensure consistency and reliability of the mechanical data. In the final stage of analysis, biodegradability was assessed through quantitative evaluation of time-series CO_2 evolution data, which reflects microbial activity and the extent of bioplastic degradation under controlled composting conditions. All experimental results were systematically presented in the form of tables, graphs, and microstructural images and discussed narratively to elucidate the relationships between material composition, structural characteristics, and performance. This integrated analysis highlights the synergistic effect of combining *Spirulina* and arrowroot in improving the mechanical, structural, and biodegradation properties of the developed bioplastics.

3. Result and Discussion

Bioplastics are plastics produced from raw materials that enhance their ability to undergo natural degradation (Budiman M.A. et al., 2021). In addition to their biodegradability, bioplastics are expected to retain functional properties that allow them to perform effectively as conventional plastics and meet human needs. The quality of bioplastics is evaluated through chemical and physical characterization tests, as well as biodegradability assessments, to determine their environmental performance and degradation behavior (Putri, F.A., et al., 2024). These analyses are conducted in accordance with recognized standards, such as ASTM and ISO, to provide a comprehensive evaluation of bioplastic properties and to ensure compliance with quality and environmental requirements (Folino, et al., 2023). Accordingly, this study conducted several tests following relevant ASTM standards, as described below:

3.1. Fourier Transport Infra Red (FTIR) evaluation

One of the most important analyses for determining the chemical characteristics of bioplastics is Fourier Transform Infrared (FTIR) spectroscopy. FTIR analysis is used to examine the organic molecular structure of the produced bioplastics and to confirm the formation of polymeric bonds through the identification of organic carbon–based functional groups. By utilizing infrared (IR) radiation, FTIR enables the detection of specific vibrational modes associated with functional groups in organic compounds, which serve as key indicators of successful bioplastic formation and quality (Belahcene, S., et al., 2025). In this study, the FTIR spectra of three bioplastic formulations were systematically compared with those of a commercial bioplastic (Ecoplast) that complies with established bioplastic standards.

As shown in **Figure 4**, the FTIR spectrum of the bioplastic produced using arrowroot flour and chitosan as the main components exhibits several characteristic absorption peaks associated with biopolymer structures. A broad and intense peak observed at 3289.15 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of hydroxyl groups derived from starch and chitosan. These hydroxyl groups play an essential role in forming hydrogen bonds within the polymer matrix, contributing to film cohesion and mechanical stability. Peaks at 1243 cm^{-1} and 1150 cm^{-1} are attributed to –COOH (carboxyl) functional groups, while the absorption at 1077.63 cm^{-1} is associated with C–O stretching vibrations characteristic of ester groups. In addition, the peak at 926.75 cm^{-1} corresponds to C=C stretching vibrations, which are commonly observed in polysaccharide-based bioplastics (Jung R. Melisa et al., 2018).

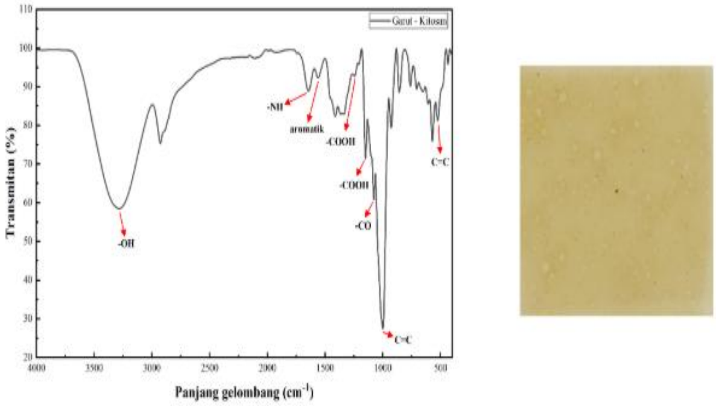

Figure 4. FTIR spectrum and visual appearance of biofilm from arrowroot

Notably, the strong intensity of the carboxyl (–COOH) absorption bands in the arrowroot-based bioplastic indicates a high degree of intermolecular interaction and crosslinking within the polymer network. This structural feature is closely related to enhanced strength and rigidity of the bioplastic film, as carboxyl groups contribute to stronger hydrogen bonding and electrostatic interactions between polymer chains. Overall, the FTIR results presented in Figure 4 confirm the successful formation of a biopolymer matrix from arrowroot flour and chitosan and demonstrate chemical characteristics that are comparable to those of commercial bioplastics, supporting the suitability of arrowroot-based materials for biodegradable plastic applications.

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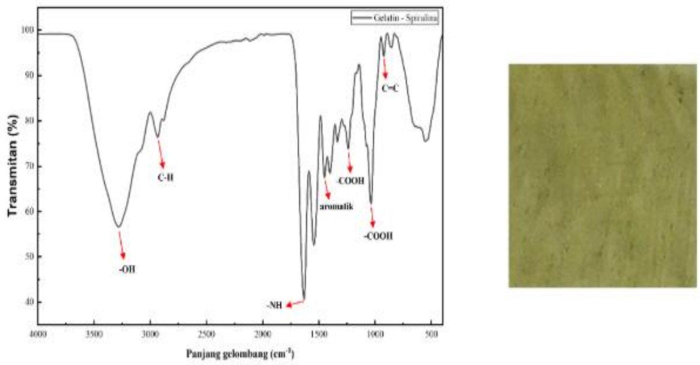

Figure 5. FTIR spectrum and visual appearance of spirulina biofilm

The FTIR analysis of bioplastics produced using *Spirulina* microalgae as the main raw material in combination with gelatin reveals spectral patterns that are generally similar to those of other bioplastics, while also exhibiting the emergence of several new peaks with higher intensity. These changes indicate modifications in the chemical structure and intermolecular interactions within the bioplastic matrix due to the incorporation of *Spirulina* and gelatin. As shown in **Figure 5**, the FTIR spectrum of the *Spirulina*-based bioplastic displays distinct absorption peaks associated with aromatic or conjugated structures at 1545.92 cm^{-1}, 1450.66 cm^{-1}, and 1402.53 cm^{-1}. The presence of these aromatic-related peaks is commonly linked to protein-derived components and conjugated systems in *Spirulina*, and their increased intensity suggests enhanced molecular mobility, which contributes to improved ductility and flexibility of the bioplastic film.

In addition to these aromatic-related peaks, several functional groups commonly observed in biopolymer-based plastics were also identified. A broad absorption band at 3281.54 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of hydroxyl groups derived from both *Spirulina* biomass and gelatin. These hydroxyl groups facilitate extensive hydrogen bonding, which plays a crucial role in film formation, cohesion, and water interaction. Furthermore, absorption peaks observed at 1239.46 cm^{-1} and 923.51 cm^{-1} are attributed to C=C stretching vibrations, which are indicative of unsaturated or conjugated structures within the biopolymer network (Jung R. Melisa et al., 2018).

Overall, the FTIR results presented in Figure 5 confirm that the incorporation of *Spirulina* and gelatin leads to the formation of a chemically complex bioplastic structure enriched with functional groups that promote flexibility and ductility. These chemical characteristics are consistent with the high elongation values observed in mechanical testing and further support the potential of *Spirulina*-based bioplastics for applications requiring flexible and biodegradable materials.

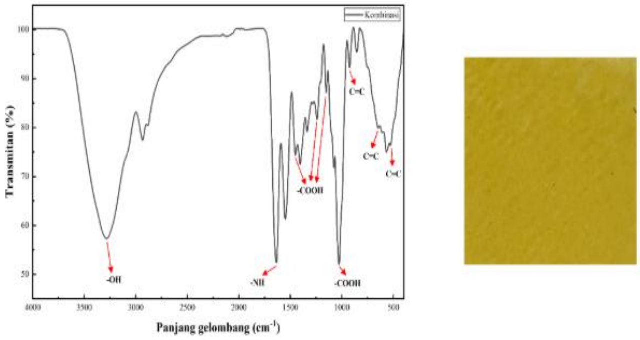

Figure 6. FTIR spectrum and visual appearance of biofilm from the combination (arrowroot – spirulina)

Furthermore, the FTIR analysis of bioplastics formulated from a combination of arrowroot flour and *Spirulina* demonstrates a clear improvement compared with bioplastics produced from single raw materials. As shown in **Figure 6**, the FTIR spectrum of the *Spirulina*-based bioplastic exhibits several characteristic absorption peaks that indicate the presence of functional groups associated with polymer flexibility and ductility. Distinct peaks observed at 1545.92 cm^{-1}, 1450.66 cm^{-1}, and 1402.53 cm^{-1} are attributed to aromatic or conjugated structures, which are commonly associated with enhanced molecular mobility and contribute to the ductile and flexible behavior of the bioplastic matrix. These functional groups are indicative of protein-derived components from *Spirulina*, which play a significant role in improving elongation properties.

In addition, several common functional groups were identified across the bioplastic formulations. A broad absorption peak at 3281.54 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of hydroxyl groups that promote hydrogen bonding within the polymer network. Peaks at 1239.46 cm^{-1} and 923.51 cm^{-1} are associated with C=C stretching vibrations, suggesting unsaturated or conjugated structures within the biopolymer matrix (Jung R. Melisa et al., 2018). The presence of these functional groups supports improved intermolecular interactions and structural cohesion.

Overall, the FTIR results presented in Figure 6 confirm that the combination of arrowroot flour and *Spirulina* enhances the chemical structure of the bioplastic by introducing complementary functional groups. This synergistic interaction contributes to improved flexibility, ductility, and overall material performance, which is consistent with the mechanical test results and supports the potential of this composite formulation as a high-quality biodegradable plastic.

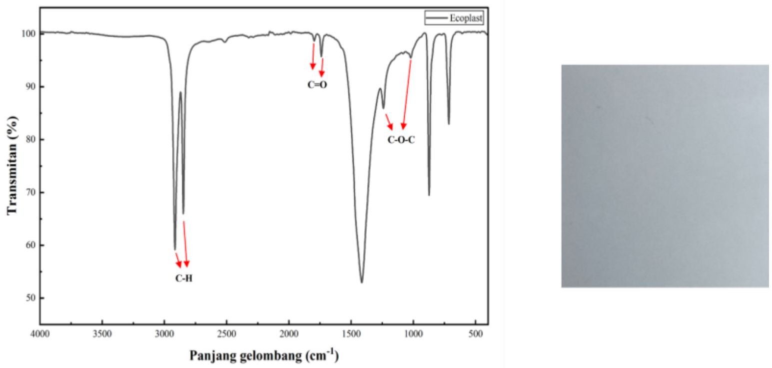

Figure 7. FTIR spectrum and visual appearance of comercial ecoplast

This study also included testing of a positive control in the form of the commercial bioplastic Ecoplast to provide a benchmark for evaluating the chemical characteristics of the bioplastics developed in this work. As shown in **Figure 7**, the FTIR spectrum of Ecoplast exhibits distinctive absorption peaks that reflect its unique chemical structure. Notably, strong peaks appear at 1796 cm^{-1} and 1739 cm^{-1}, which correspond to C=O stretching vibrations of ketone or ester carbonyl groups. These functional groups are characteristic of commercially engineered biodegradable polymers and were not observed in the bioplastics produced solely from arrowroot or *Spirulina* in this study. The presence of these carbonyl groups is commonly associated with enhanced thermal stability, mechanical strength, and controlled degradation behavior in commercial bioplastics.

Although the exact ketone-related peaks were absent in the experimental bioplastics, the combination bioplastic formulated from *Spirulina* and arrowroot exhibited absorption peaks at 1283 cm^{-1} and 1240 cm^{-1}, indicating the presence of functionally similar groups, such as C–O stretching in ester or carboxyl-related structures. These peaks suggest that the composite bioplastic possesses a polymer network with chemical functionalities that partially resemble those of Ecoplast, despite differences in raw material origin and synthesis pathways.

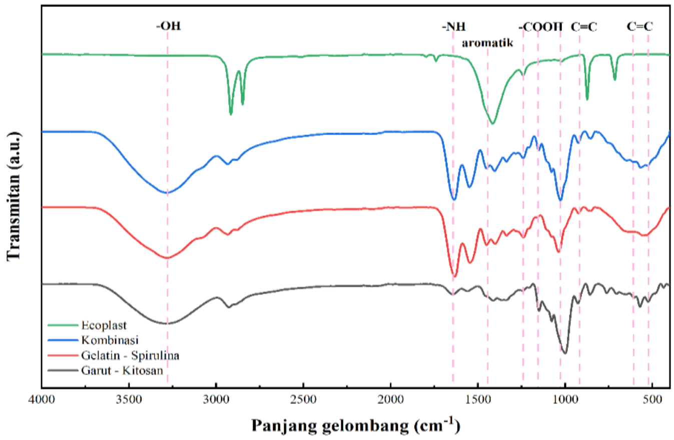

Figure 8. Comparison of FTIR spectra of biofilms.

Figure 8 presents a comparative analysis of the FTIR peaks corresponding to key functional groups across all bioplastic formulations investigated in this study. The comparison reveals that the combination bioplastic (arrowroot–*Spirulina*) exhibits noticeable improvements in several important functional groups, as reflected by increased peak intensities. In particular, the carboxylate (–COOH), ester (C–O), and aromatic functional groups appear more pronounced in the combination bioplastic than in the single-component bioplastics derived solely from arrowroot or *Spirulina*. The increased intensity of these peaks suggests stronger intermolecular interactions and a more integrated polymer network, which is indicative of improved chemical structure and enhanced material performance. Although the functional group profile of the combination bioplastic does not yet fully replicate the peak characteristics observed in the commercial bioplastic Ecoplast, the observed enhancement demonstrates a clear synergistic effect resulting from the combination of arrowroot starch and *Spirulina*.

Conversely, the hydroxyl (–OH) functional group is consistently observed in all bioplastic samples produced in this study. The presence of this group reflects the polysaccharide- and protein-based nature of the raw materials and indicates extensive hydrogen bonding within the bioplastic matrices. These hydroxyl groups play a crucial role in film formation, intermolecular cohesion, and biodegradability. Overall, the FTIR comparison shown in Figure 8 confirms that combining arrowroot and *Spirulina* leads to a more chemically complex and functionally enriched bioplastic structure, supporting the improved mechanical and structural properties observed in other characterization results.

Table 2. The results of functional group readings in FTIR analysis (Jung, R.Melisa., et al., 2018; Lubis, M., et al., 2020)

Wavelengths (cm^{-1})	Functional groups	Ecoplast (%T)	Spirulina (%T)	Arrowroot (%T)	Combination of Spirulina and arrowroot (%T)
3281.54	OH		56.60	58.53	57.30
2933.89	C-H		76.40	75.32	77.40
2915.75	C-H	59.14			
2848.68	C-H	65.94			
2115.91	Alkune	99.86	97.65	97.36	98.62
1796.78	C=O	98.70			
1739.89	C=O	95.72			
1635.07	-NH		40.71	88.88	52.33
1549,06	C=C Aromatic		52.64	92.29	61.26
1451.18	Aromatic compound		67.44		74.41
1414.87	Aromatic	52.93		82.35	
1404.77	Aromatic		68.43		72.52
1336.55	Aromatic compound		75.36	82.88	79.16
1283.30	C-O				84.86
1240.97	C-O		73.80	92.76	81.67
1142.12	-COOH			71.47	87.16
1078.50	C-O			60.76	71.85
1026.78	Aromatic CH bend	95.48	61.70		51.98
924.75	C=C		94.24	79.45	92.22
873.72	C-H	69.44			
854.15	C-CH_3		96.18	88.57	95.47
761.47	Aromatic CH			90.12	
715.25	CH2 rock	82.95		89.37	
647.56	C=C			88.73	79.92
528.82	C=C			81.24	79.63

The ester functional group plays a critical role in many bioplastic materials because it enables biodegradation through hydrolytic reactions. Ester bonds are susceptible to cleavage in the presence of water and microbial enzymes, allowing polymer chains to break down into smaller, environmentally benign molecules. In addition to ester groups, hydroxyl (–OH) functional groups are also essential in determining bioplastic properties and biodegradability. Hydroxyl groups facilitate extensive hydrogen bonding within the polymer matrix and promote interactions with water, thereby enhancing water uptake, swelling behavior, and microbial accessibility during the degradation process.

In FTIR spectroscopy, ester functional groups are primarily identified by a strong absorption band in the carbonyl (C=O) stretching region, which typically appears between 1730 and 1750 cm^{-1}. In this study, such a band is clearly observed in the commercial bioplastic Ecoplast at approximately 1739.89 cm^{-1}, indicating the presence of ester-linked polymer chains characteristic of engineered biodegradable plastics (Smith, B. C., 2022). Another characteristic absorption band of saturated esters is associated with C–O–C stretching vibrations, which generally appear in the range of 1200–1300 cm^{-1}. In this case, a peak at approximately 1240.97 cm^{-1} was detected in the *Spirulina*-, arrowroot-, and combination-based bioplastics, suggesting the formation of ester-like linkages within the natural polymer matrices.

The hydroxyl (–OH) functional group was identified by a broad absorption band around 3281.54 cm^{-1} in all bioplastic formulations produced in this study, except for Ecoplast. This broad –OH band reflects the abundance of polysaccharide- and protein-derived components and indicates strong hydrogen bonding interactions, which contribute to film formation, flexibility, and biodegradability. Furthermore, the carboxyl (–COOH) functional group, observed at approximately 1142.12 cm^{-1} in the arrowroot-based and combined bioplastics, plays an important role in enhancing interfacial adhesion within the composite structure. The presence of carboxyl groups promotes stronger intermolecular interactions and crosslinking, which in turn improves tensile strength and overall mechanical stability of the bioplastics (Rahmatullah et al., 2022). Overall, the presence and intensity of these functional groups confirm the formation of biodegradable polymer networks and help explain the improved mechanical and degradation properties observed in the composite bioplastics.

3.2. Scanning Electron Microscope (SEM) test on bioplastics

SEM (Scanning Electromagnetic Microscope) (ASTM 6400) tests were conducted on four bioplastic samples (Figure 10). This test will obtain a morphological Figureof the bioplastic surface so that its homogeneity, porosity, and morphological illustration can be determined. The results of SEM analysis on ecoplast bioplastic show that the surface is more homogeneous with a less smooth surface, while bioplastic using Spirulina shows a smooth and dense homogeneous surface. A rough and bubbly surface is significantly shown in the bioplastic made from arrowroot flour. The surface with bubbles is caused by the large amount of oxygen absorbed in the bioplastic during the manufacturing process. In addition, the surface of this Garut bioplastic is also influenced by the large amylopectin size of the flour particles (Sangian et al, 2020). Bioplastic from the combination of arrowroot flour and Spirulina shows excellent results, where the surface is smoother with a higher density and no air bubbles are found in this bioplastic.

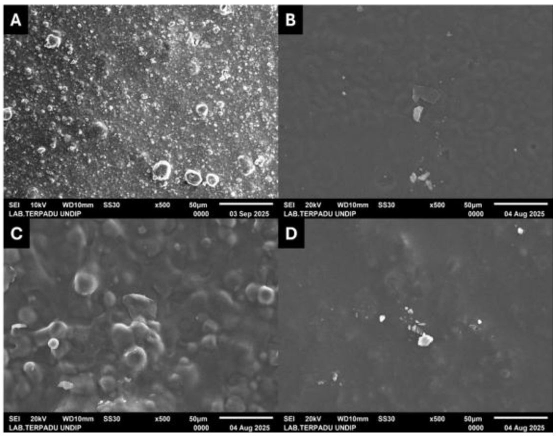

Figure 9. Biofilm morphology at x500 magnification, A) ecoplast, B) Spirulina C) Arrowroot D) combination (Arrowroot-Spirulina)

3.3. Physical Characteristics of Bioplastics with XRD (X-Ray Diffractometer) Crystallinity Test (ASTM D3039)

X-ray Diffraction (XRD) characterization was performed to evaluate the crystalline structure and degree of crystallinity of the bioplastic films. Figure 11 presents the diffraction patterns of the three bioplastics, illustrating differences in peak intensity and crystallinity that reflect their structural organization. The XRD results indicate that all bioplastic samples exhibit typical semi-crystalline behavior, characterized by the presence of a dominant diffraction peak within the 2θ range of 19–23°, which is commonly associated with the amorphous regions of biopolymer-based materials.

The arrowroot-based bioplastic film shows a primary diffraction peak at 2θ = 22.6°, with a degree of crystallinity of 46.2% calculated using the Segal method. This level of crystallinity suggests a moderate structural order, which contributes to the material's mechanical strength but also indicates a significant amorphous fraction that can facilitate water absorption and biodegradation. In contrast, the spirulina-based bioplastic exhibits a more pronounced peak at 2θ = 20.0° and a higher crystallinity value of 50.2%, indicating a slightly more ordered molecular arrangement. This increased crystallinity may be attributed to the protein-rich composition of *Spirulina*, which promotes stronger intermolecular interactions and chain alignment.

The bioplastic produced from the combination of arrowroot and *Spirulina* displays a diffraction pattern closely resembling that of the spirulina-based bioplastic, with its main peak also located at 2θ = 20.0° and a crystallinity value of 49.6%. This similarity suggests that the incorporation of *Spirulina* significantly influences the crystalline structure of the composite biofilm, leading to a more organized polymer network compared to the arrowroot-only bioplastic. The semi-crystalline nature of the composite film is particularly advantageous, as it provides a balance between mechanical strength and flexibility while maintaining sufficient amorphous regions to support biodegradation.

Overall, the XRD analysis confirms that all bioplastic films produced in this study are semi-crystalline, with amorphous phases dominating their structure. This structural characteristic is desirable for biodegradable plastics, as it supports adequate mechanical performance while facilitating environmental degradation, aligning with the intended application of sustainable and compostable bioplastic materials.

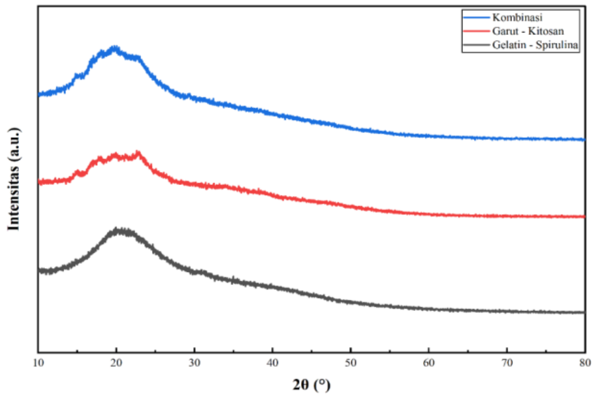

Figure 10. Diffraction comparison for bioplastic crystallinity test

3.4. Mechanical characteristics of bioplastics with thickness and tensile strength tests (ASTM D882-18)

Tensile strength and elongation tests were conducted to evaluate the mechanical performance of the bioplastics and to identify the most suitable material composition, as summarized in Table 3. These mechanical properties were measured using a Universal Testing Machine in accordance with ASTM D882-18. Tensile strength represents the material's resistance to fracture under applied tensile stress, while elongation at break reflects its flexibility and ductility. Thickness was also measured because it directly influences the cross-sectional area used in tensile strength calculations and plays an important role in determining the overall mechanical behavior of bioplastic films. All measurements were carried out using standardized methods to enable a reliable comparison with commercial bioplastics and other reported bioplastic formulations..

Table 3. Thickness and tensile strength test results

Sample	Thickness (mm)	*Tensile Strength* (Mpa)	*Elongation at break* (%)
Ecoplast	0.06	7.571	146.250
Arrowroot	0.29	5.564	48.750
Spirulina	0.24	1.872	217.750
Combination (Arrowroot-Spirulina)	0.26	4.267	105.500

Mechanical testing is a critical aspect of bioplastic development, as biopolymers derived from natural sources often exhibit lower tensile strength than conventional synthetic plastics. The bioplastic produced solely from arrowroot flour exhibited relatively high tensile strength (5.564 MPa), approaching that of the commercial bioplastic Ecoplast (7.571 MPa). This result indicates that arrowroot starch contributes significantly to the structural strength of the bioplastic matrix. However, the elongation at break of arrowroot-based bioplastics was relatively low (48.750%), suggesting limited flexibility and a tendency toward brittleness.

In contrast, bioplastics produced from *Spirulina* exhibited very high elongation at break (217.750%), indicating excellent flexibility. However, their tensile strength was considerably lower (1.872 MPa), making the material more susceptible to tearing under tensile stress. This behavior can be attributed to the protein-rich composition of *Spirulina*, which enhances elasticity but does not provide sufficient intermolecular bonding strength for high tensile resistance.

Notably, the bioplastic produced from the combination of arrowroot flour and *Spirulina* demonstrated a balanced improvement in mechanical properties. The composite bioplastic achieved moderate tensile strength (4.267 MPa) while maintaining high elongation (105.500%), resulting in a material that is both sufficiently strong and flexible. This synergistic effect suggests that arrowroot starch contributes to mechanical strength, while *Spirulina* enhances flexibility, leading to improved overall performance. Although the tensile strength of the composite bioplastic remains slightly lower than that of Ecoplast, its elongation and flexibility are comparable, indicating its strong potential as an alternative biodegradable material.

Overall, these results indicate that the combination of arrowroot flour and *Spirulina* provides the most favorable balance between tensile strength and elongation among the tested formulations. Therefore, this composite material can be considered the most suitable base material for bioplastic production in this study, offering mechanical properties that closely approach those of commercial bioplastics while maintaining biodegradability and sustainability

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3.5. Characteristics of bioplastics with biodegradability test (ASTM D5338)

To ensure that the produced bioplastics met biodegradability requirements in accordance with ASTM D5338, biodegradation tests were conducted to evaluate their ability to degrade naturally under controlled composting conditions. The bioplastics were applied to soil mixed with compost and incubated in a desiccator. All bioplastic formulations produced in this study exhibited similar biodegradation behavior. After three days of incubation, the bioplastic samples had completely disintegrated and transformed into new biomass integrated with the composted soil, leaving no visible residue. This observation indicates rapid biodegradation and compliance with the compostability criteria.

As shown in Figure 11, no residual bioplastic fragments were detected in the composted soil after the incubation period. Bioplastics in soil environments are naturally degraded as microorganisms utilize them as a carbon source. During this process, soil microorganisms secrete extracellular enzymes that cleave polymer chains into smaller molecular fragments (Withana, P.A., et al., 2025). These fragments are subsequently metabolized into simpler compounds, such as carbon dioxide, water, and microbial biomass. The rate and extent of biodegradation are strongly influenced by both the intrinsic properties of the bioplastics—such as polymer composition, crystallinity, and surface morphology—and external environmental factors, including temperature, moisture content, oxygen availability, and nutrient concentration. These results highlight the strong biodegradation potential of *Spirulina*–arrowroot-based bioplastics and their suitability for environmentally sustainable applications.

Figure 11. Testing the biodegradability of bioplastics in soil

4. Conclusion

The results of this study demonstrate that bioplastics can be successfully produced using microalgae *Spirulina* and arrowroot flour, yielding materials with properties comparable to those of commercial bioplastics such as Ecoplast. The bioplastics formulated from the combination of *Spirulina* and arrowroot flour exhibited favorable mechanical properties, including good tensile strength and elongation, which are essential for flexible bioplastics that must be easily molded and adapted to various applications. Furthermore, the synergistic interaction between *Spirulina* and arrowroot contributed to improved material characteristics, as evidenced by a semicrystalline structure, smoother surface morphology, enhanced strength, and increased density. In addition to these improved physical and mechanical properties, the resulting bioplastics retained their biodegradability, demonstrating the ability to decompose into compost under suitable conditions. These findings indicate that the combination of *Spirulina* and arrowroot flour represents a promising, sustainable alternative raw material for the development of environmentally friendly bioplastic products.

Although this study demonstrates promising results, the authors acknowledge that it has several limitations and that further research is required to refine and expand upon the findings. The combination of *Spirulina* and arrowroot flour has been shown to produce bioplastics with characteristics comparable to those of the commercial bioplastic Ecoplast, suggesting that this formulation has strong potential for large-scale and industrial bioplastic production. Future studies should therefore focus on optimizing the composition and processing conditions to achieve the best balance of mechanical strength, flexibility, water resistance, and biodegradability. In addition, further investigations into scalability, cost efficiency, and long-term environmental performance would be valuable to support the practical application and commercialization of *Spirulina*–arrowroot-based bioplastics.

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