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Morphological Degradation of Sago Starch (*Metroxylon* sp.) Bioplastic of Palopo, South Sulawesi

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Abstract. *The growing concern over non-organic plastic waste has driven the development of bioplastics from renewable sources, such as sago starch (Metroxylon sp.), as an environmentally friendly alternative. This study aims to analyze the morphological structural changes of sago starch bioplastics exposed to UV radiation using Scanning Electron Microscopy (SEM). The bioplastics were prepared from sago starch, subjected to controlled UV irradiation, and subsequently examined with SEM to observe microstructural modifications. The results demonstrate that UV radiation significantly induces degradation and structural alterations, characterized by increased surface roughness, and changes in the fracture structure and cross-section of the bioplastic. SEM images show the progression of structural damage at various UV exposure times (24, 48, and 72 hours), illustrating the formation of cracks, micro-cavities, and increased porosity. These findings underscore the importance of understanding UV degradation for developing more environmentally resistant sago bioplastics.*

Keywords: *sago starch; Metroxylon sp; UV radiation; morphology; SEM.*

Type of the Paper: Regular Article.

1. Introduction

The global environmental pollution caused by synthetic plastic waste has driven the development of more sustainable alternative materials. Nearly 95-99% of plastic materials come from non-renewable sources, “Synthetic Plastics” [1]. Conventional plastics, derived from fossil-based resources, exhibit very low biodegradation rates, leading to significant accumulation in various ecosystems and posing serious threats to the environment and human health [2]. As global plastic production continues to increase, the development of bioplastics has emerged as a promising solution to reduce reliance on synthetic plastics and minimize their negative environmental impact. Biodegradable materials play an important role in environmental sustainability because they participate in the natural cycle of “from nature to nature” by maintaining an ecological balance that allows waste to decompose naturally without leaving harmful residues [3]. Bioplastics, or biodegradable plastics, are produced from environmentally friendly agricultural plant materials [4]. Biodegradable packaging made from biodegradable materials can replace synthetic plastics because they readily decompose, like starch, a cheap and

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readily available polysaccharide, and can be derived from both conventional and non-conventional sources and their waste [5,6].

The demand for these sustainable materials has sparked research into the development of starch-based bioplastics as an alternative to difficult-to-degrade petrochemical plastics [7]. Bioplastics are defined as polymers derived from renewable resources, such as starch, cellulose, proteins, and lipids. Among these, sago starch (*Metroxylon* sp.) is a promising material due to its abundance, biodegradable properties, and significant potential as a raw material for thermoplastic starch (TPS) [8]. Sago starch *(Metroxylon sp.)* is readily available in South Sulawesi, where large-scale production of sago occurs [7]. This makes it an ideal candidate for bioplastic production, as it can be sourced sustainably and in large quantities [8]. The sago palm is abundant in the region and can be harvested without significantly affecting local ecosystems. The potential for large-scale sago starch production for bioplastic manufacturing aligns with the need for renewable and abundant resources in the growing bioplastics industry. Thermoplastic starch (TPS) is considered one of the substitutes for synthetic polymers [9]. Current research trends focus on the development of biocomposites, which are fully degradable 'green' materials, through the combination of biodegradable polymers with natural fibers that are also easily degradable.

However, bioplastics derived from biological sources generally possess lower mechanical properties and durability compared to conventional plastics, thus limiting their applications. Although bioplastics made from renewable natural materials exhibit airtight and watertight properties and are readily degraded by microorganisms upon environmental disposal, their generally inferior mechanical properties and resistance compared to conventional plastics remain a challenge [10]. These inherent weaknesses restrict the widespread application of starch bioplastics in various fields.

To overcome these limitations, several modification strategies have been developed, including the addition of fillers, plasticizers, natural fibers, and nanoparticles, as well as improved processing techniques. For instance, Minakawa et al., developed a simple ultrasonication method to produce starch micro- and nanoparticles (SNPs and SMPs) from cassava, corn, and yam, reporting improved particle characteristics [11]. Building on this, Tan et al. optimized ultrasound-assisted extraction from sago pith waste, achieving 71.4% yield in 5 minutes and producing starch with higher purity and enhanced film-forming properties [12]. Rezghi Rami et al. reviewed advances in fungal-synthesized nanoparticles for biopolymer-based smart food packaging, highlighting their role in enhancing mechanical, barrier, and antimicrobial properties while offering sustainable and eco-friendly alternatives to petroleum-based plastics [13]. Fatima et al. emphasized the role of resistant starch (RS) as a preferred polymer for biodegradable food packaging due to its superior film-forming ability, mechanical strength, water resistance, and thermal stability [6]. Similarly, da Silva et al. compared TiO_2 nanoparticles and TiO_2/OMMT clay blends in PBAT matrices, highlighting their effects on stiffness, hydrophilicity, and biosafety [14].

Other studies demonstrated the benefits of combining starch with biopolymers and additives to enhance performance. Maryam et al. applied a combined hydrolysis-precipitation process on sago starch to strengthen bioplastics [15], while Rahadi et al. showed that chitosan-glycerol incorporation in nata de soya-based bioplastics improved tensile strength and reduced water absorption [16]. Similarly, Muñoz-Gimena et al. highlighted that metal nanoparticles (ZnO, Ag, TiO_2), nanoclay, and active compounds such as essential oils can enhance thermal resistance, water vapor barrier properties, and morphological stability of bioplastics under environmental stress [17].

Environmental factors, particularly UV radiation, significantly affect the structural integrity of bioplastics. Quispe et al. reported that UV-A exposure induces oxidative degradation in TPS, leading to reduced molecular weight, carbonyl formation, surface cracks, and decreased elongation at break [18]. Sulaeman et al. investigated the Tawaro sago variety from South Sulawesi, revealing that UV exposure increased the elastic modulus due to structural modifications in the polymer matrix [19]. Photodegradation not only affects the morphology of bioplastics but also results in reduced mechanical performance, surface discoloration, and functional deterioration [20,21]. These challenges highlight the need for the materials industry to adopt more effective and cost-efficient UV stabilizer systems, particularly in applications involving wood and bioplastic composites, to extend their durability and functionality [22].

While there has been substantial research on the enhancement of starch-based bioplastics through various modification methods, a critical knowledge gap remains regarding the specific impact of UV radiation on the morphological degradation of Palopo sago starch bioplastics. Previous studies have primarily focused on the general effects of UV radiation on thermoplastic starch (TPS), without investigating its influence on the unique properties of sago starch bioplastics from South Sulawesi. This study specifically addresses this gap by exploring how UV exposure influences internal structural changes and mechanical performance in Palopo sago starch bioplastics, a material that has not been previously studied in the context of UV degradation. By focusing on this specific material, our research makes a unique contribution to the field, as it provides insights into how UV radiation affects a locally sourced bioplastic that could have broader applications in sustainable packaging solutions. Through this exploration, the results contribute to the development of more environmentally resistant sago bioplastics, thus supporting the transition to biodegradable alternatives and promoting the circular economy by reducing reliance on synthetic plastics.

2. Materials and Methods

2.1. Materials

The sago starch used in this study was sourced from the Tawaro Sago tree in Palopo, South Sulawesi, an area known for its substantial sago production. The region's sago palms are abundant and cultivated in large quantities, ensuring a sustainable and reliable supply of raw material for bioplastic manufacturing. This makes the adoption of sago starch for industrial bioplastic production highly feasible, meeting the growing demand for biodegradable alternatives to synthetic plastics. The composition ratio, resulting from the milling of sago trunks into sago starch, was 22.542% processed sago starch; 71.125% distilled water; 4.742% glycerol; and 1.00% acetic acid solution.

2.2. Sago Bioplastic Manufacturing Process

The fabrication of sago bioplastics involves several key stages, as shown in Fig. 1. Initially, sago starch is extracted from the sago trunk through a series of steps: cutting, skin separation, pith collection, grinding, filtration (using 100 and 200 mesh), and subsequent starch separation and drying. This extracted sago starch is then used as the raw material for bioplastic production, which involves mixing the starch and plasticizer, heating to form a paste, moulding, and specimen drying. Subsequently, the prepared specimens are exposed to UV radiation under controlled variations and durations. Finally, changes in the morphological structure of the bioplastic's fracture surface are analyzed using Scanning Electron Microscopy (SEM).

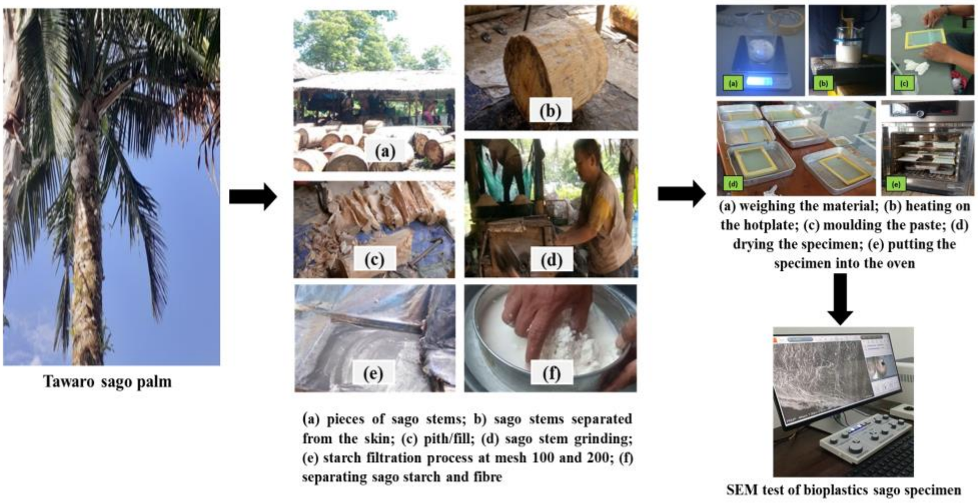


Fig. 1. A scheme of sago starch extraction was used to obtain the samples (*Metroxylon* sp.)

2.3. Desain Experimental

This study employed an experimental design utilizing variations in UV radiation exposure time as the primary treatment. The bioplastic specimens were subjected to the treatment variations, as shown in Table 1.

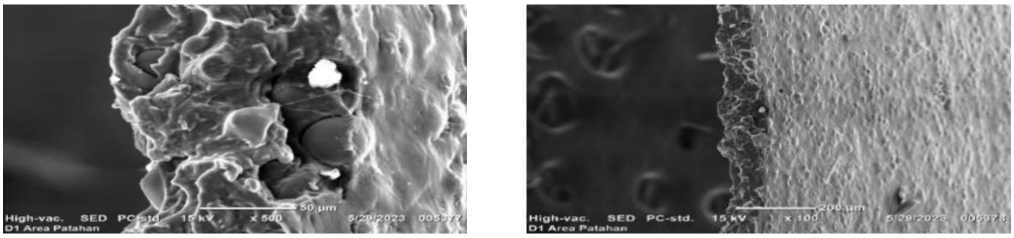
Morphological data acquired from SEM testing were analyzed to evaluate the effect of UV radiation exposure duration on the morphological structure of the sago starch bioplastic.

Table 1. Variation of UV Radiation Exposure Time

Parameters	Exposure Time UV Radiation	Units
Bioplastic (control)	Pure	-
Bioplastic UV	24	Hours
	48	Hours
	72	Hours

3. Results and Discussion

SEM characterization of sago starch bioplastic sheets revealed significant morphological changes induced by exposure to UV radiation. These alterations were distinctly visible on both the surface cross-section of the specimens.



(a) (b)

Fig. 2. Morphology of sago bioplastic specimen without UV radiation

Based on Fig. 2, the analysis results of the fracture morphology of bioplastic samples without UV radiation treatment clearly show the characteristics of brittle fractures with heterogeneous internal structures. In Fig. 2(a), the fracture surface appears significantly rough and uneven, characterized by protrusions, depressions, and dispersed particles that are not perfectly integrated within the matrix. These particles are most likely undissolved sago starch, and the presence of small voids indicates poor dispersion of the bioplastic components. Such voids facilitate crack propagation and reduce the material's overall ability [23]. Furthermore, Fig. 2(b) reveals a fracture pattern that tends to be straight with minimal signs of plastic deformation, further reinforcing the brittle fracture characteristics. The absence of significant plastic deformation on the fracture surface suggests that the material possesses a limited capacity to absorb energy before fracture [24]. An inhomogeneous surface, with distinct boundaries between areas of varying density, implies that the bioplastic matrix has not fully formed a uniform structure. This condition directly impacts the structural integrity and mechanical properties of the bioplastics.

Fig. 3 presents the morphological interpretation of bioplastic specimens subjected to 24 hours of UV exposure. Noticeable changes are observed in the fracture surface structure. Specifically, the formation of small cracks and micro-cavities has commenced, indicating early signs of the photodegradation process induced by UV radiation exposure. This photodegradation process triggers polymer bond breaking (chain scission) within the structure, though significant structural damage may not yet be evident. The onset of photodegradation is attributed to the absorption of UV energy by the polymer molecular bonds [25].

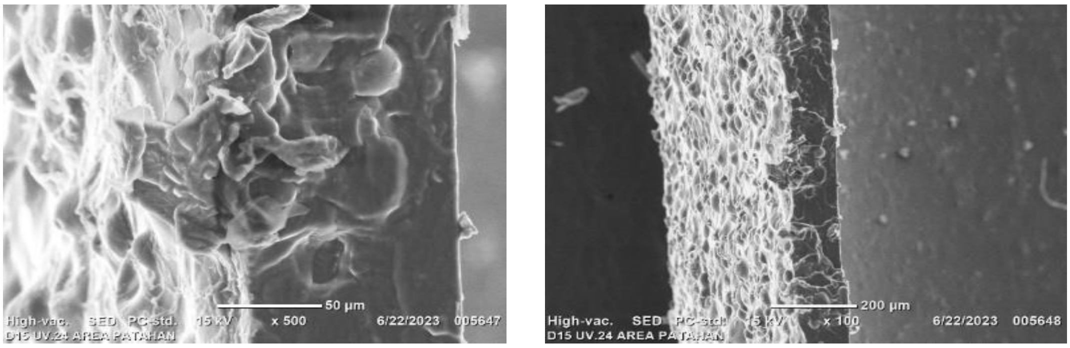


Fig. 3. Morphology of sago bioplastic specimen with 24-hour UV radiation

This phenomenon aligns with the findings of Syarifa et al. [26], who reported that short-term exposure to UV light leads to a decrease in tensile strength due to surface degradation but does not yet cause massive microstructural damage. This resilience is likely due to the ability of the main biopolymer molecular chains to reduce the degradation rate, thereby maintaining adequate structural resistance of the material layer [26].

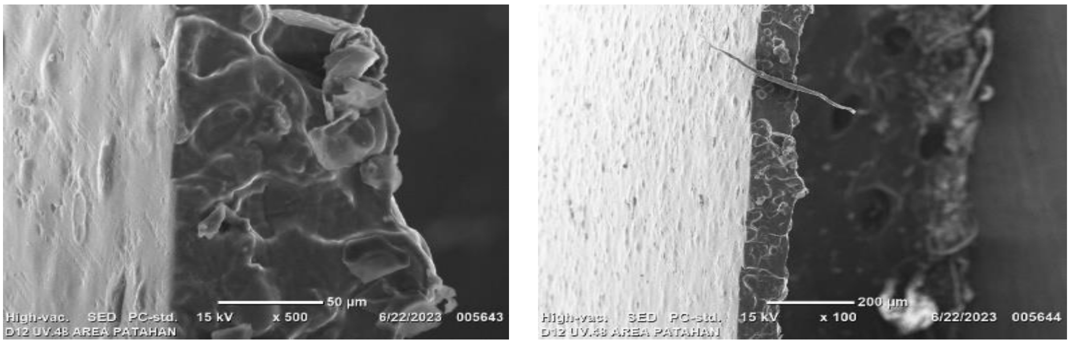


Fig. 4. Morphology of sago bioplastic specimen with 48-hour UV radiation

Fig. 4 presents the fracture morphology of bioplastic samples after 48 hours of UV exposure. The surface appears smoother yet still exhibits indications of uneven tensile deformation. The fracture surface reveals a transition from brittle fracture to partial ductile fracture, which is hypothesized to be due to the local plasticizing effect of residual plasticisers, such as glycerol. Prolonged UV exposure leads to some structural regions undergoing amorphous and crystalline phase changes, thereby influencing the deformation pattern during fracture. This observation is corroborated by the study of Gamage et al., who reported that increasing UV exposure duration can result in a bioplastic surface that appears flatter but is internally brittle, a consequence of plasticizer migration and microvoid formation [27]. Starch-based bioplastics generally exhibit low resistance to UV exposure, which significantly accelerates their degradation rate through photooxidation mechanisms.

Conversely, specimens subjected to 72 hours of UV irradiation exhibited severe morphological deterioration, as evidenced by layered, rough, and porous fracture surfaces (Fig. 5). The appearance of micronodular textures and extensive crack propagation indicated continuous depolymerization through intensive polymer chain scission. This prolonged degradation is most likely induced by sustained photo-oxidation, which accelerates the migration of plasticizers from the polymer matrix and repeatedly disrupts intermolecular bonds. Moreover, UV radiation is known to be influenced by environmental factors such as humidity, elevated temperature, and air pollutants, which further intensify the degradation process [28,29].

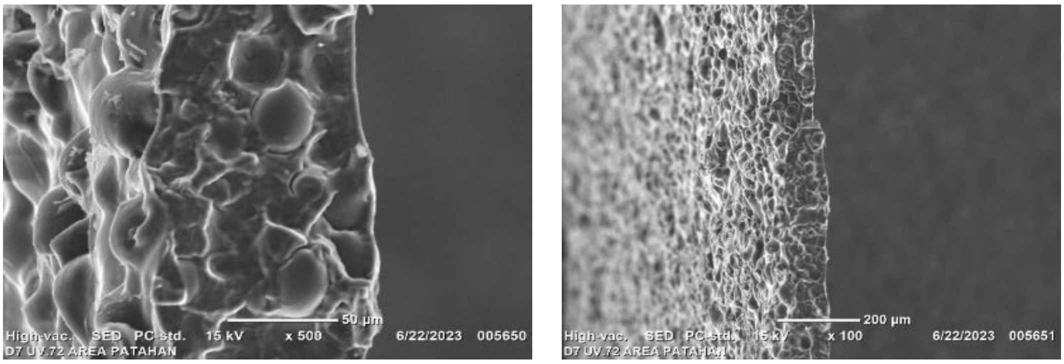


Fig. 5. Morphology of sago bioplastic specimen with 72-hour UV radiation

These findings are consistent with those of Quispe et al., who reported that thermoplastic starch (TPS) exposed to UV-A exhibited a drastic reduction in molecular weight, along with pore and crack formation as observed through SEM analysis. Their study also revealed the generation of new carbonyl groups, confirming oxidative degradation, while mechanical performance was severely compromised, highlighted by a reduction of elongation at break by up to 95% after only 24 hours of UV exposure [18]. This strong correlation reinforces the notion that photodegradation accelerates structural embrittlement in starch-based bioplastics.

The present study provides similar evidence, wherein prolonged UV irradiation of sago starch-based bioplastics resulted in severe morphological disruption and mechanical failure [30]. This behavior is characteristic of semi-crystalline polymers, where UV-induced chain scission leads to increased brittleness. SEM micrographs corroborated this observation, displaying crack formation, surface irregularities, and heterogeneity that intensified with longer irradiation.

Despite these challenges, mechanical performance can still be enhanced through post-treatment strategies such as Heat Moisture Treatment (HMT). A more homogeneous distribution of sago starch granules achieved through HMT was shown to improve tensile strength, even under UV-induced degradation conditions [2,31]. These insights underscore the potential of combining formulation adjustments with stabilizing agents to enhance UV resistance and extend the functional lifetime of bioplastics.

Overall, the development of sago starch-based bioplastics and semi-synthetic starch composites presents a promising pathway for sustainable material innovation. Their inherent advantages, including biodegradability, renewability, low production cost, lightweight properties, and adaptability to processing techniques, position them as viable candidates for diverse industrial applications. These range from food packaging and agricultural films to biomedical materials and automotive components. However, the optimization of their performance is determined not only by the material composition but also by strategies to enhance stability against environmental stressors, particularly excessive UV irradiation.

4. Conclusions

This study demonstrates that exposure to ultraviolet (UV) radiation significantly influences the morphological structure of sago starch-based bioplastics. A longer exposure duration leads to a greater extent of structural damage, characterized by the formation of cavities, micro-cracks, and ultimately, total depolymerization. These morphological changes directly impact the mechanical properties of the bioplastic, making more brittle and structurally unstable. Therefore, the strategy of incorporating UV stabilizer additives is highly recommended to enhance the bioplastic's resistance to environmental exposure. The findings of this study contribute to the development of more robust, environmentally friendly local bioplastics suitable for long-term applications, particularly in the packaging and renewable material-based industries.

Abbreviations

UV	ultraviolet
TPS	Thermoplastic Starch
HTM	Heat Moisture Treatment
SEM	Scanning Electron Microscopy

Data availability statement

Data supporting this study will be made available will be shared upon reader request and relevant.

Credit authorship contribution statement

Pria Gautama: Conceptualization, Methodology, Conceptual, Validation, Data curation, Writing. **Budiawan Sulaeman:** Conceptualization, Supervision, Validation, Data Curation, Software, Writing-Reviewing. **Nurhidayanti:** Data curation, Methodology flow, Validation, Writing-Original Draft, Formal analysis, Reference source, Writing-Reviewing, Editing, and Administration.

Declaration of Competing Interest

The authors declare that they have no known financial or personal relationships that could have appeared to influence the work reported in this paper.

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