Sustainability and Performance of Starch-based Bioplastics: A Critical Review on Toxicity, Stability, and Environmental Impact

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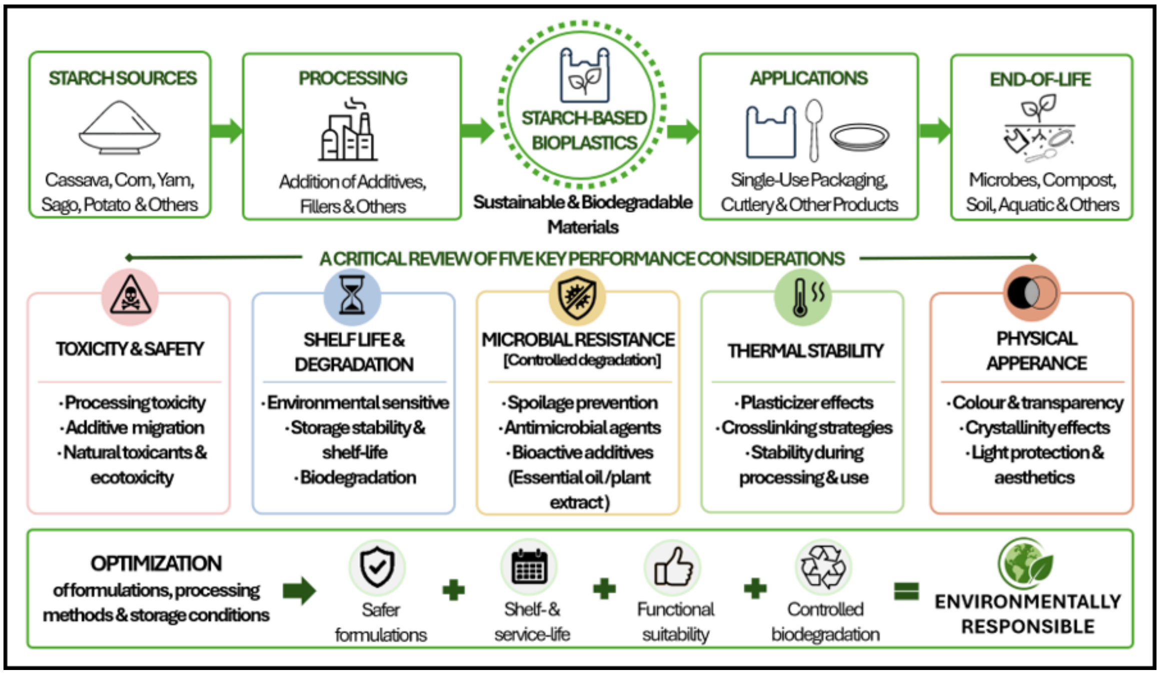
DOI: 10.15376/biores.21.3.Phuah

GRAPHICAL ABSTRACT



Sustainability and Performance of Starch-based Bioplastics: A Critical Review on Toxicity, Stability, and Environmental Impact

Rou Jie Phuah,[a] Amalina Muhammad Afifi,[a,*] Norazilawati Muhamad Sarih,[b,*] and Nor Ishida Zainal Abidin [a]

The utilization of starch-based bioplastics as renewable and environmentally friendly alternatives to replace traditional petroleum plastics has gained significant traction in recent years due to their biodegradability, renewability, and cost-effectiveness. However, their widespread industrial applications are hindered by shelf-life constraints, high moisture sensitivity, and poor performance when subjected to variations in microbial and temperature changes. In addition, starch-based bioplastics are formulated in complex mixtures, which may result in process-related toxicity. This review critically investigates these performance issues in depth, including toxicity potential, shelf-life, microbial resistance development, thermal stability, and physical appearance. Particular emphasis is placed on the safety of natural starch sources, the influences of environmental conditions on degradation behavior, and the incorporation of natural additives to enhance material properties. By considering these factors, this review aims to facilitate the development and selection of sustainable, safer, and environmentally friendly starch-based bioplastics for diverse future applications.

DOI: 10.15376/biores.21.3.Phuah

Keywords: Bioplastics; Starch; Sustainability; Biodegradability; Toxicity

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INTRODUCTION

Plastics, which are known for their lightweight properties, versatile shapes, waterproof nature, and affordability, have become indispensable materials in our daily lives (Iheukwumere *et al.* 2020; Manali Shah *et al.* 2021). For example, polyethylene-based plastics shopping bags, which were first introduced in 1965, rapidly replaced traditional carriage bags made of paper and cloth due to their convenience and durability (UNEP 2021). However, the long-term environmental persistence induced by synthetic polymers has become an increasingly severe ecological issue. Plastic bags, particularly single-use bags, are frequently mismanaged after disposal, leading to the accumulation of substantial amounts of waste in landfills and aquatic environments. Consequently, this accumulation has threatened the living organisms in both terrestrial and marine ecosystems (Jayarathna *et al.* 2022). Recognizing the severity of these issues, Bangladesh implemented a nationwide ban on thin plastic bags in 2002 after they were identified as a major contributor to the blockage of drainage systems during disastrous flooding events. Since then, many other countries have followed suit with similar restrictions or bans on single-use plastic bags (UNEP 2021). In response, alternatives including reusable tote bags and bioplastics have become increasingly prominent. However, the transformation of tote bags into fashion accessories has ironically undermined the environmental rational behind their use. Purchasing new tote bags solely to follow fashion trends, while using them only sparingly rather than maximizing their potential lifespan, consequently reduces their sustainability benefits (Lee and Lee 2024). Ahamed *et al.* (2021) explore the potential environmental burdens, including ecotoxicity potential (in freshwater aquatic, marine aquatic, and terrestrial environments) and global warming potential (GWP) contributed by cotton woven-based tote bags. Their exploratory life cycle analysis found that tote bags may contribute up to 22.91 million kg of carbon dioxide (CO_2) emissions or more if they are used less than 50 times (Ahamed *et al.* 2021).

Therefore, bioplastics from renewable resources, such as starch, can be considered as a promising alternative. Starch-based bioplastics account for approximately 50% of the global bioplastics market, reflecting their prominence as one of the most widely utilized types of bioplastics (Sobeih *et al.* 2025). They are widely used in applications, such as shopping bags, agricultural films, food packaging, and disposable cutlery (Faris *et al.* 2014; Yacob *et al.* 2019). Prior studies have suggested that the biodegradability of starch-based bioplastics promotes environmental sustainability. However, drawbacks such as water sensitivity, brittleness, and the need for plasticizers or additives to enhance the properties of the derived bioplastics require further exploration and improvement.

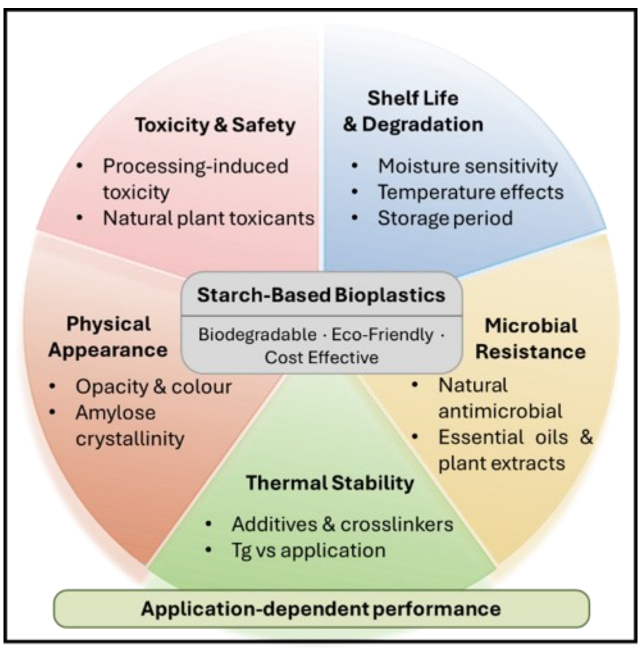


Fig. 1. Summary of this review

In this context, this review considers various factors such as toxicity and safety for food contact, shelf life and degradation behavior, microbial resistance, thermal stability, and physical appearance to provide a holistic perspective on the potential use of starch-based bioplastics as a substitute for traditional petroleum-based plastics, as depicted in Fig. 1. This can be useful for the formulation and processing of sustainable bioplastics in the future.

TOXICITY AND SAFETY FOR FOOD CONTACT

In recent decades, bioplastics have captured market interest as an alternative due to their eco-friendly nature. Starch-based bioplastics have been popular in the market because of their excellent biodegradability potential, availability, eco-friendliness, and cost-effectiveness (Coppola *et al.* 2021; Yu *et al.* 2021; Anitha *et al.* 2024). However, the assumption that bioplastics are inherently less toxic than conventional plastics remains a subject of ongoing debate.

Processing-Induced Toxicity and Chemical Migration

Zimmermann *et al*. (2020) reported that, despite the non-toxic nature of the raw materials commonly used for bioplastic production, such as starch and cellulose, specific changes occurring during processing may induce toxicological responses. The study found that the occurrence of measurable toxicity increased from 40% in the raw materials to 78% in the final bioplastic products. However, these values represent the frequency of tested samples exhibiting measurable toxicological responses rather than the magnitude of toxicity or direct regulatory risk. The higher occurrence of toxicity in the final products suggests that processing steps may introduce or activate compounds of toxicological concern. Nevertheless, the practical implications for human health or the environment cannot be determined from occurrence data alone, as such an interpretation requires dose–response assessments and comparison with established safety benchmarks. Furthermore, developmental toxicity was detected in 30% of the finished products and was attributed to antiandrogenic activity, whereas no such activity was observed in the raw materials. The authors also identified a bioplastic sample containing antiandrogenic compounds that were not found in conventional petroleum-based plastic samples (Zimmermann *et al.* 2020). One possible explanation is that natural occurrences of antiandrogen components present in certain plant-derived raw materials become activated or released during processing. This hypothesis is supported by Grant and Ramasamy (2012), who reported that some plant-based raw materials inherently contain antiandrogen compounds. Interestingly, Zimmermann *et al.* (2020) also observed that several bioplastic samples established slightly higher baseline toxicity than petroleum-based plastics. These findings reflect toxicity responses under *in vitro* test conditions and do not necessarily indicate actual human and environmental exposure risks or the exceedance of established safety thresholds.

Antiandrogens are substances that inhibit the biological effects of androgens such as testosterone and dihydrotestosterone by blocking androgen receptors or interfering with androgen synthesis. These substances are known to occur naturally in some plants which are commonly used in bioplastic fabrication (Grant and Ramasamy 2012). During processing stages involving thermal treatment, enzymatic hydrolysis, or chemical modification, the structural integrity of these natural compounds may be altered, forming more active derivatives that exhibit stronger biological activity, potentially triggering antiandrogenic or endocrine-disrupting effects. Although the actual impact depends on the concentration and exposure level, studies have demonstrated that excessive antiandrogenic activity can disrupt hormonal balance, reduce sperm quality, and impair reproductive development (Kelce and Wilson 1997).

Beyond processing-induced effects, the incorporation of additives and plasticizers has been found to be another important toxicity pathway in fabricating food contact packaging materials. Phthalate compounds are commonly used as plasticizers and added to polymer matrices for flexibility and processability improvements. However, these substances are not chemically bound to the polymer chains and may therefore present health risks due to their known endocrine-disrupting properties (Wang and Qian 2021). In this case, additives represent a vital toxicological concern, as their diffusion into food products has raised concerns regarding the safety of food contact materials.

A recent notable example of additive-related food contamination is the reported migration of phthalates, including di-2-ethylhexyl phthalate (DEHP) and dibutyl phthalate (DBP), from plastic packaging into dairy products during manufacturing, storage, or transportation. Such migration may directly or indirectly pose potential health risks to the consumers and compromise the principle of using exclusively natural ingredients (Fisher *et al.* 2025). Similarly, controversies surrounding food coloring have underscored that colorants and other additives, although used to enhance product appearance, may present toxicological and regulatory challenges when consumer exposure occurs (Bickerton 2025). Therefore, these cases reveal that the development of biodegradable packaging materials, particularly for food applications, must carefully consider both material safety and potential external risks arising from processing conditions and additive incorporation. Consequently, toxicological testing is essential for advancing bioplastics to ensure that the final products are truly sustainable and safe for both society and the environment.

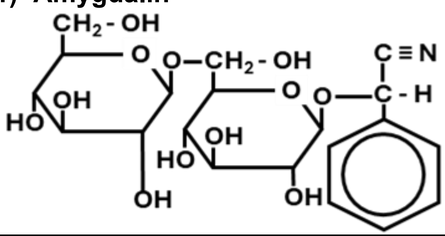
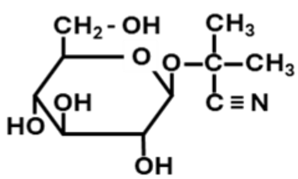
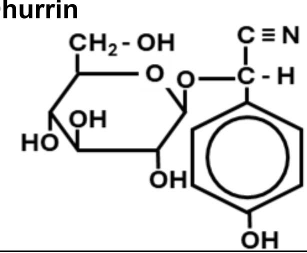
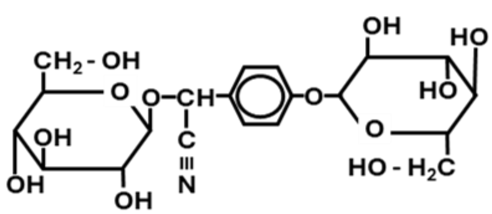
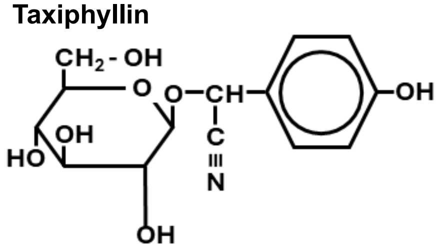
Naturally Occurring Toxicants in Starch Sources

Numerous studies have investigated starch-based bioplastics derived from various tropical food crops, including cassava, sorghum, and bamboo. Rather than focusing solely on cassava tuber, recent research has explored cassava peel as a promising alternative feedstock because of its value-added potential, particularly its starch content (Syuhada *et al*, 2020). Although these natural materials are abundant and readily available, they may also contain naturally occurring toxic compounds that could pose safety risks if not properly treated prior to use. Many plant species, such as apple seeds (Ballhorn 2011; Schrenk *et al.* 2019), almonds (Ballhorn 2011; Schrenk *et al.* 2019), bamboo shoots (Ballhorn 2011; Schrenk *et al.* 2019), lima beans (Ballhorn 2011; Schrenk *et al.* 2019), and cassava peels (Padmaja and Steinkraus, 1995; Schrenk *et al.* 2019), contain toxic cyanogenic compounds, including cyanogenic glycosides. In addition, potatoes and cucumbers species contain naturally occurring toxic compounds – solanine and cucurbitacin, respectively (Beversdorf, 1993; FDA 2024). The major toxicants found in plant-based starch sources are summarized in
Table **1**.

Cyanogenic glycosides (
Table **1**) are nitrile-containing plant metabolites which can bind to glucoses and release hydrogen cyanide (HCN) under specific conditions, such as acidic environments or in the presence of enzyme activity (Bolarinwa *et al.* 2016; Crews and Clarke 2014). According to NIOSH (2011), inhalation of 2.5 ppm HCN for only 10 minutes can produce mild symptoms such as headaches or dizziness, and it can be fatal if the concentration is increased to 27 ppm. The cyanogenic content in several natural sources, specifically those employed for starch-based bioplastics, is illustrated in Table 2.

Cyanogenic glycosides are present in food plants of most countries (Aranguri-Llerena and Siche 2020; Crews and Clarke 2014). For example, in cassava, the cyanogen content is commonly concentrated in its peel. Olutosin and Kayode (2021) also reported a high cyanide content of 119 ppm (mg/kg) in unfermented cassava peel. It is important to consider the toxicity of cyanogen, and it is recommended for future work that these high capacities of cyanogenic compounds could be safely recovered, reduced, collected, or converted into some medical or pharmaceutical by-products. As reported by the John Hopkins Center for Health Security (2022), cyanide is an active ingredient in sodium nitroprusside, a well-known medication for controlling high blood pressure and heart disease (D'Elia *et al.* 2024).

Table 1. Types of Potential Toxicants in Plant Starch

Potential Toxin	Source	References
Cyanogenic glycosides		
(1) Amygdalin 	Apple seed Almond	(Aranguri-Llerena and Siche 2020; Ballhorn 2011; Simeonova and Fishbein 2004)
(2) Linamarin 	Cassava Lima bean	(Aranguri-Llerena and Siche 2020; Ballhorn 2011; Vetter 2000)
(3) Dhurrin 	Sorghum sp. Cocoyam	(Aranguri-Llerena and Siche 2020; Ballhorn 2011; Nyirenda 2020)
(4) Proteacin 	Macadamia nut	(Ballhorn 2011; Dahler *et al.* 1995)
(5) Taxiphyllin 	Bamboo	(Nyirenda 2020; Sang-A-Gad *et al.* 2011)

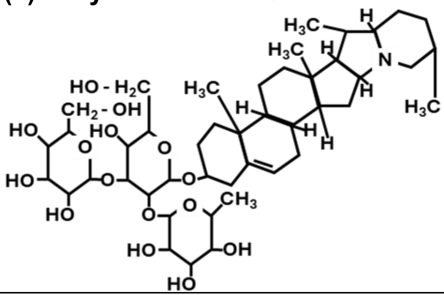
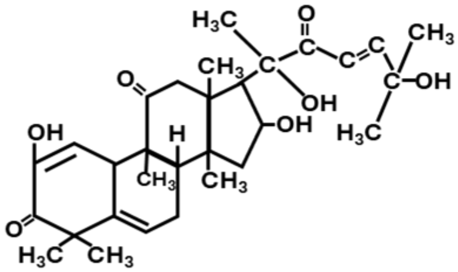
(6) Glycoalkaloid – Solanine 	Potato	(Hameed *et al.* 2017; Karaca and Erbaş 2024)
(7) Cucurbitacin 	Squash	(Chen *et al.* 2005; Varela *et al.* 2022)

Table 2. Cyanogenic Content in Various Sources Used for Starch-Based Bioplastics (Simeonova and Fishbein 2004)

Natural Source	Cyanogen Content (mg/kg)
Bitter Cassava	380
Sweet Cassava	445
Sorghum	2400
Bamboo	7700
Lima Beans	2000 to 3000

Nevertheless, solanine in potatoes and cucurbitacin in squash species are also of concern because they are considered undesirable and potentially harmful to living organisms. According to Karaca and Erbaş (2024), solanine, a poisonous chemical in the glycoalkaloid class, is a toxic alkaloid fabricated by plants as a defense mechanism against insects and other predators. Symptoms of solanine poisoning are visible at a dose of 2.5 mg/kg body weight, including headache, fever, cramps, nausea, diarrhea, and vomiting (Hopkins 1995). In severe cases, fatal outcomes may occur when doses reach 6 mg/kg body weight or more (Karaca and Erbaş 2024). On the other hand, cucurbitacin is also insecticidal and can be poisonous when overconsumed. This was also reported by Stoewsand *et al.* (1985), where the laboratory mice experienced diarrhea, anemia, or death after ingesting 1% cucurbita fruit taken from the cucurbitacin-rich cultivars. These findings indicated that the potential of toxic effects would be at least similar in humans.

However, the occurrence of these toxicants in these plant-based starches does not necessarily indicate the existence of a toxicity risk in purified starch or final bioplastic products. For example, a range from 40 to 70% of total cyanide was reported to transfer into the wash water, while only 5 to 10% remained in the fibrous residues during the cassava starch extraction. Nevertheless, the starch consists of less than 4% of cyanide after sedimentation, and less than 1% of it was observed in the dried starch product, which corresponds to a residual concentration of 1 to 5 ppm (Arguedas and Cooke 1982). Similarly, Driedger and Sporns (1999) also described that during potato starch extraction, the glycoalkaloid solanine toxicants may partition into processing by-products instead of the purified starch fraction. Therefore, the toxicological relevance of the compounds depends on the extent to which they remain after starch isolation, purification, and final material processing.

Ecotoxicological and Biological Safety Assessment

Although starch-based bioplastics are prepared to be environmentally friendly products that can naturally decompose in a natural environment, toxicological assessments are required for safe use in society. They are primarily discarded into two major environments: soil and water. Therefore, short-term laboratory toxicity assays such as microalgae toxicity and nematode toxicity assays are recommended to assess the possible ecological risks of starch-based bioplastics before extensive application.

Microalgae are important bioindicators for environmental because they inhabit both freshwater and marine ecosystems. For example, Mroczkowska *et al.* (2021) evaluated the ecotoxicity of gelatin-potato starch bioplastics using a microalgae toxicity assay. The results were encouraging, demonstrating that the bioplastic samples supported microalgae growth and revealed no adverse effects on the organisms, thereby providing strong evidence that the bioplastics exert minimal impact on the natural aquatic environment. Mroczkowska *et al* (2021) also investigated the ecotoxicity of gelatin-potato starch-based bioplastics using the nematode toxicity assay (Mroczkowska *et al.* 2021). Nematodes are roundworms that are widely used bioindicators of soil health due to their sensitivity to environmental changes. In this study, the nematode reproduction rate served as an indicator of soil condition following the burial of bioplastics. The results confirmed that the bioplastics did not adversely affect the nematode survival or reproduction, which is consistent with the evidence obtained from the microalgae toxicity assay. Collectively, these observations suggest that gelatin-potato starch-based bioplastics are environmentally compatible and pose minimal ecological risks.

Therefore, it is hypothesized that the toxicological safety of starch-based bioplastics is governed more strongly by processing pathways and formulation strategies than by the intrinsic toxicity of the raw starch source alone. During processing, cyanide may be released through enzymatic hydrolysis and acid treatment exposure. Controlled pre-treatment, detoxification, and processing conditions, such as repeated rinsing, heating, and controlled microbial fermentation, can enable the safe utilization of starch derived from cyanogenic biomass without inducing adverse biological effects in the final material (Unigwe *et al.* 2023). These processing methods facilitate the leaching of cyanogenic compounds, the volatilization of free HCN, and the hydrolytic cleavage of glycosidic bonds, thereby minimizing cyanogenic potential and environmental risks while enhancing the suitability of the starch for downstream bioplastic production. This perspective suggests that future research should prioritize the establishment of standardized toxicological assessment protocols specifically tailored for starch-based bioplastics, alongside the optimization of processing parameters to minimize residual toxicants while preserving material performance. Such approaches would support the development of starch-based bioplastics that are not only biodegradable but also demonstrably safe for human and environmental exposure.

Nevertheless, current toxicological evaluations are predominantly adapted from food safety bases, with limited consideration given to alternative exposure pathways relevant to bioplastics, such as direct skin contact during handling. According to Lachowicz *et al.* (2024), exposure to cyanide and its derivatives may occur through inhalation and dermal contact with combustion smoke generated from nitrogen- and carbon-containing materials, such as certain textiles and biological substances, as well as through the consumption of contaminated water and cyanogenic foods. Therefore, the potential risks associated with cyanide exposure should be carefully considered as part of the overall toxicity assessment.

SHELF-LIFE AND DEGRADATION

The shelf life of starch-derived bioplastics refers to the period during which they remain stable with minimal or no degradation under storage conditions. It is closely associated with their degradation behavior, as these materials are designed to remain functional during storage while undergoing biodegradation only after disposal under appropriate environmental conditions. Therefore, maintaining the balance between storage, stability, and environmental degradability is a key consideration in the development of starch-based bioplastics.

Starch-based bioplastics are generally considered short shelf-life materials, making them more suitable for food packaging applications with a storage period of less than six months (Ibrahim *et al.* 2021). This is supported by the findings of Wahyuningtyas and Suryanto (2017), who evaluated the shelf-life of cassava starch-based bioplastics under controlled relative humidity (RH) conditions. The bioplastics samples were stored in a plastic box at limited oxygen or humidity of 45 to 60% RH for 90 days. The results confirmed that this material processes a relatively short shelf-life. However, the shelf-life can be extended through the incorporation of glycerol, which has been reported to inhibit fungal growth under certain conditions, thereby improving the storage stability of the bioplastics (Wahyuningtyas and Suryanto 2017; Winarti *et al.* 2012). Fig. **2** summarizes the key factors influencing the shelf-life of starch-based bioplastics, including moisture, temperature, and microorganism contents.

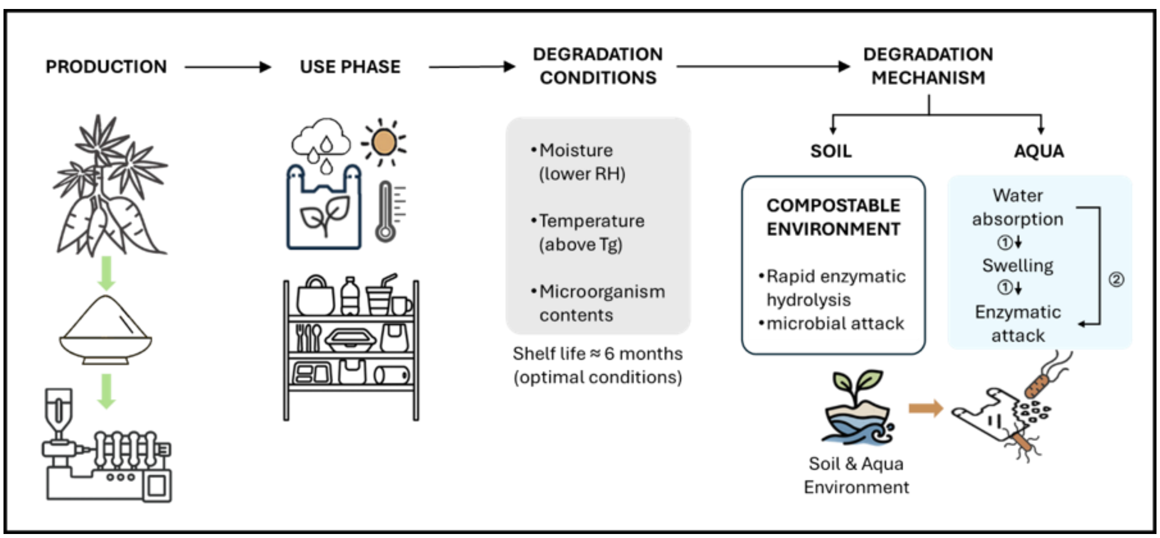


Fig. 2. Factors affecting the shelf-life of starch-based bioplastics

Environmental Factors that Influence Shelf Life

Environmental factors, particularly RH and temperature, strongly influence the degradation and shelf life of starch-based bioplastics. Thakur *et al.* (2019) noted that a relatively low RH (40 to 44%) combined with a high glass transition temperature (T_g) could induce starch retrogradation – a process where the realignment of starch molecules results in a more rigid structure upon cooling after gelatinization (Vroman and Tighzert 2009; Bangar *et al.* 2023). Gelatinization occurs when starch interacts with water around 130 ºC, forming a viscous state. Therefore, relatively high RH conditions (above 44%) can contribute to higher flexibility of starch-based bioplastics when stored at lower temperatures, particularly below their T_g, and potentially can prolong their shelf life. Table 3 depicts the T_g of common starch sources.

Table 3. Glass Transition Temperature (T_g) of Several Starch Sources

Starch Source	Glass Transition Temperature (T_g / ºC)	Reference
Wheat	~ 143	(de Graaf *et al.* 2003)
Potato	~ 152	(de Graaf *et al.* 2003)
Waxy Maize	~ 158	(de Graaf *et al.* 2003)
Pea	~ 75	(de Graaf *et al.* 2003)
Cassava	~ 117	(Arias *et al.* 2024)

Starch-based bioplastics have also been explored in applications beyond food packaging. Ibrahim *et al.* (2021) reported that their relevance in the active antibacterial cosmetic packaging was reinforced with chitosan and chitin for the effectiveness in skin regeneration and antimicrobial activity. These bioplastics exhibited an extended shelf life with a slower rate of biodegradation. However, starch-based bioplastics are generally intended for short-term use and are designed to degrade rapidly compared to petroleum-based plastics, as they are often used for single-use applications. Therefore, a more targeted research area is to focus on shelf-life optimization in relation to the specific end-use requirements.

In most cases, the process of degradation in starch-based bioplastics refers to biodegradation, where organic matter is converted into simpler mineralized compounds by the enzymatic action of microorganisms, mainly bacteria, fungi, and algae (Ahsan *et al.* 2023; Vroman and Tighzert 2009). As natural polymers, bioplastics made of starch easily degrade compared to petroleum-based plastics. According to Ahsan *et al.* (2023), the degradation of bioplastics under major environmental conditions is assessing their breakdown behavior when exposed to natural environments, including compost, soil, and aquatic systems (freshwater or seawater). Due to the highly hydrophilic character of starch, biodegradation methods such as soil burial and hydrolysis tests are ideal to establish the biodegradability of starch-based bioplastics under laboratory conditions. The limited shelf-life of these bioplastics can accelerate their degradation process and promote the microbial growth under moist conditions.

The biodegradation profile of starch-based bioplastics is highly dependent on soil conditions, especially the moisture levels and microbial populations. However, the strength of these factors is limited by the findings of Zoungranan *et al.* (2020). They pointed out that there are several factors that could promote degradation, such as humidity, temperature, and microbial content. The biodegradability of cassava-based bioplastics, for example, demonstrated an increasing trend with increasing soil moisture content. However, a significant decline was observed when the soil moisture exceeded 15% (Zoungranan *et al.* 2020). The authors attributed this unexpected decline to the reduced survival and the activity of the microbial population under excessively moist conditions, which indirectly lowered the biodegradation rate of the bioplastics.

As reported by Pooja *et al.* (2023), biodegradation of the starch-based bioplastics typically occurs through three main processes: photooxidation, hydrolysis, and microbial attack. For instance, Syuhada *et al.* (2020) studied the biodegradability of chitosan-cassava peel starch bioplastics in both soil and river media. They found that the biodegradation was more pronounced in soil, with a more rapid decrease in mass compared to the river environment. This may be attributed to the soil environment, which is more favorable for microbial growth. However, it remains uncertain whether the rapid growth of microorganisms in soil is exclusively due to the soil conditions themselves or is influenced by external factors, such as uncontrolled daily temperature fluctuations.

Biodegradation Conditions and Environmental Media

Remarkably, contrasting trends have been reported regarding the influence of temperature on biodegradability of bioplastics. As discussed, increasing the temperature above 30 ºC may adversely affect soil microorganisms, thereby prolonging the biodegradation process and reducing the biodegradability of cassava starch-based bioplastics (Zoungranan *et al.* 2020). In contrast, Karamanlioglu and Robson (2013) reported higher biodegradation rates for polylactic acid (PLA)-based bioplastics at elevated temperatures, particularly at 37 ºC or above. These conflicting findings indicate the need for further investigation into the effects of temperature across different environmental media, as well as the influence of other factors that may regulate microbial activity and, subsequently, biodegradation performances. Kliem *et al.* (2020) provided benchmark temperature conditions for laboratory degradation studies. In their study, seawater and freshwater systems (either under stagnant or dynamic conditions) were generally maintained below 30 and 25 ºC, respectively, while the laboratory soil environments were kept at 20 ± 2 ºC. These standardized environmental conditions are important for improving comparability among biodegradation studies and for understanding how microorganism activity influences degradation rates. Building on this need for standardized environmental conditions, existing biodegradation standards are generally designed as performance-based assessments rather than microorganism-specific tests. For example, ISO14855 assesses the ultimate aerobic biodegradability of plastic materials under controlled composting conditions by using compost inoculum with biodegradation quantified through CO_2 evolution and the degrees of disintegration after exposure (ISO, 2012). Similarly, EN13432 requires compostable plastics to disintegrate after 12 weeks and achieve complete biodegradation within 6 months under industrial composting conditions, with at least 90% of the organic carbon converted to CO_2 (Bazart *et al*. 2026; European standards 2000). Therefore, it can be concluded that these existing standards prioritize reproducible test conditions, mixed microbial inocula, and measurable biodegradation instead of depending solely on individual microbial indicators.

It is important to distinguish general degradation from biodegradation. According to Balangao (2023), general degradation is a broader process that can involve abiotic factors, including ultraviolet radiation, temperature, oxidation, and mechanical fragmentation. However, biodegradation specifically involves biological activity, particularly by microorganisms and their enzymes, which transform polymeric materials into lower molecular weight compounds and eventually into products such as CO_2, water, methane, biomass, and mineral salts under suitable environmental conditions (Balangao 2023; Ishigaki *et al*. 2004). This distinction reflects the fact that biodegradation is typically driven by complex microbial communities whose composition and activity vary with inoculum source, environmental medium, temperature, pH, oxygen availability, and nutrient status (Bher *et al*. 2022; Kliem *et al*. 2020; Payanthoth *et al*. 2024), while the rate and extent of biodegradation are also affected by polymer characteristics (Abe *et al*. 2021; Bher *et al*. 2022; Tokiwa *et al*. 2009).

Table 4. Microorganisms from Soil and Aquatic Environments

Microorganism	Soil	Water	Reference
Acinetobacter baumanni	**+**	N/A	(Demisie *et al.* 2024)
Aspergillus niger	**+**	N/A	(Kiprotich *et al.* 2025; Rafiq *et al.* 2018)
Bacillus anthracis	**+**	N/A	(Rafiq *et al.* 2018)
Bacillus cerus	**+**	N/A	(Rafiq *et al.* 2018)
Bacillus subtilis	**+**	N/A	(Kiprotich *et al.* 2025; Rafiq *et al.* 2018)
Brevibacterium sp.	**+**	N/A	(Rafiq *et al.* 2018)
Candida albicans	**+**	N/A	(Demisie *et al.* 2024)
Cladosporium cladosporides	**+**	N/A	(Rafiq *et al.* 2018)
Epicoccum nipponicum	**+**	N/A	(Rafiq *et al.* 2018)
Escherichia coli	**+**	**+**	(Assembly of Life Sciences (US), 1977; Cabral 2010; Demisie *et al.* 2024)
Francisella tularensis	N/A	**+**	(Assembly of Life Sciences (US), 1977)
Micrococcus roseus	N/A		(Rafiq *et al.* 2018)
Leptospira sp.	N/A	**+**	(Assembly of Life Sciences (US), 1977)
Rhizocotania sp.	**+**	N/A	(Kiprotich *et al.* 2025; Rafiq *et al.* 2018)
Salmonella typhi	+	+	(Assembly of Life Sciences (US), 1977; Cabral 2010; Demisie *et al.* 2024)
Salmonella paratyphi	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010)
Salmonella	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010; Demisie *et al.* 2024)
Shigella dysenterias	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010)
Shigella fiexneri	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010; Demisie *et al.* 2024)
Shigella sonnei	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010)
Staphylococcus aureus	+	N/A	(Demisie *et al.* 2024)
Streptococcus bovis	N/A	+	(Assembly of Life Sciences (US, 1977)
Streptococcus equinus	N/A	+	(Assembly of Life Sciences (US), 1977)
Streptococcus pyogens	+	N/A	(Demisie *et al.* 2024)
Trichocladium opacum	+	N/A	(Rafiq *et al.* 2018)
Vibrio cholerae	N/A	+	(Assembly of Life Sciences (US), 1977; Cabral 2010; Gregory *et al.* 2000)
Yersinia enterocolitica	N/A	+	(Assembly of Life Sciences (US), 1977)

* The sign ‘**+**’ stands for **existence**.

Although standardized tests are valuable for determining whether a material satisfies biodegradation or compostability criteria, they provide limited information on the specific microorganisms, functional groups, or enzymes responsible for the degradation process. Therefore, microbial profiling can be integrated with standardized biodegradation tests to provide additional mechanistic insight into the microbial taxa and metabolic functions associated with polymer degradation. Recent advances in plastic-microbial community analysis further support this approach by enabling the characterization of interactions between plastics and microbial communities, as well as the identification of microorganisms and enzymes potentially involved in polymer degradation across different environments (Viljakainen and Hug 2021).

Table 4 presents microbial taxa reported in soil and aquatic environments. Their occurrence across different environmental matrices may indicate broad environmental distribution and potential involvement in polymer transformation. However, the environmental occurrence alone does not confirm biodegradation capability. Therefore, these microorganisms should be interpreted as reported microbial taxa along with biodegradation-related environmental conditions instead of universal indicator strains for laboratory testing. Their functional relevance can be further evaluated by combining controlled biodegradation assays (Pires *et al*. 2022; Sander *et al*. 2023) with microbial community analysis, enrichment, isolation, and enzymatic or molecular approaches (Abe *et al*. 2021; Tokiwa *et al*. 2009; Viljakainen and Hug 2021).

It is also important to note that rapid biodegradation does not inherently reflect high performance in bioplastics. Ghasemlou *et al.* (2024) reported that thermoplastic starch food waste bags biodegraded in soil within 14 to 100 days, providing baseline values for further studies. Another study by Wicaksono *et al.* (2022) found that cassava bioplastics degraded in one month, losing over half of their weight (56%) and retaining only 26% of their original mass at 120 days. This degradation is primarily due to enzymatic action, where starch glycoside linkages are disrupted by amylases, facilitating microorganism growth (Maran *et al.* 2014; Wicaksono *et al.* 2022). However, degradation rates of starch-based bioplastics tend to decrease with time, most likely due to the depletion of starch content, which is more readily biodegradable in the early stages. This claim is evident in Polman *et al.* (2021), who observed that with decreasing starch content, the hydrophilic component is also depleted; hence the remaining bioplastic matrix becomes more resistant to microbial attack.

In addition to starch-based bioplastics, oxo-biodegradable plastics have also attracted attention as an environmentally friendly alternative. However, their degradation mechanisms differ markedly from those of starch-based bioplastics (da Luz *et al.* 2013). Among biodegradable alternatives, cassava starch-based bioplastics have shown significantly faster degradation than oxo-low-density polyethylene (oxo-LDPE). Although oxo-materials containing pro-oxidants primarily undergo oxidative degradation, microbial and activities also contribute to the subsequent biodegradation of the oxidized products, thereby completing the overall degradation (Abdelmoez *et al.* 2021). Notably, Jakubowicz *et al.* (2011) demonstrated that oxo-LDPE can be completely degraded in soil within two years.

Although starch-based bioplastics are biodegradable, they may temporally generate microplastic-sized fragments (microbioplastics) during degradation processes. These bio-derived residual particles may still pose ecological risks before undergoing further degradation. Kaur and Chauhan (2024) reported that the degradation of bioplastics in soil can alter soil pH and adversely affect soil quality. In addition, these microbioplastics may increase phytotoxicity in plants by acting as carriers for residual additives, such as plasticizers that are-present in the original bioplastic matrix, hence raising concerns about their potential long-term environmental impacts (Abdelmoez *et al.* 2021). These findings emphasize that despite their bio-based origin and biodegradability, starch-based bioplastics may still result in unintended environmental consequences during the degradation process.

It is hypothesized that the shelf-life and biodegradability in starch-based bioplastics are governed by fundamental matrix properties, including moisture content, plasticizer mobility, and microbial accessibility. Increased moisture sensitivity and plasticizer mobility can accelerate biodegradation but may also promote degradation and fungal growth during storage (Wypych 2004; Brebu 2020; Huntrakul and Harnkarnsujarit 2020). Conversely, strategies to extend shelf life, such as crosslinking, the addition of antimicrobial additives, or reduced hydrophilicity, may slow down environmental degradation. Therefore, future research should focus on application of specific design strategies that balance storage stability with controlled end-of-life degradation, supported by standardized testing protocols that integrate storage performance, environmental conditions, and biodegradation potential. Such an approach would facilitate the rational design of starch-based bioplastics with predictable functional lifespans tailored to their intended uses rather than simply maximizing biodegradability. These proposed relationships are schematically illustrated in Fig. 3.

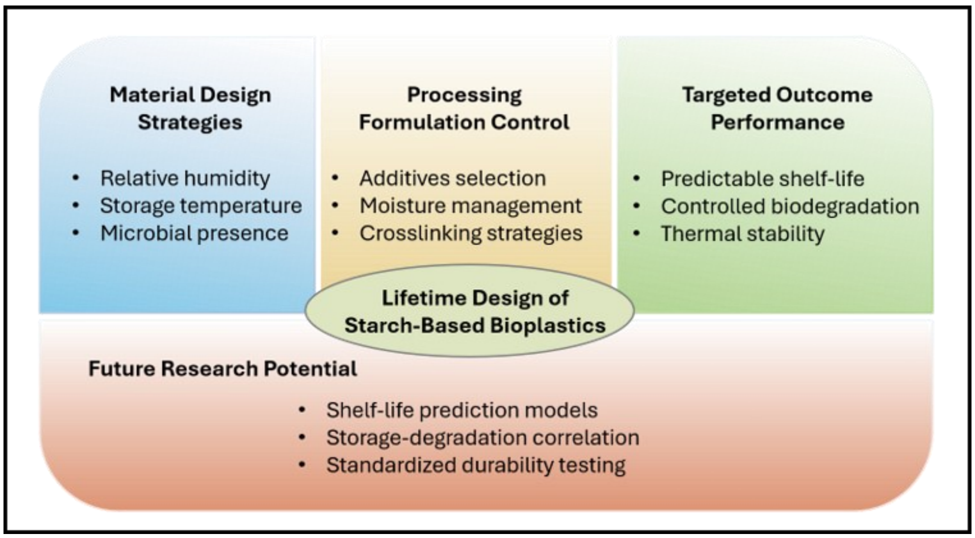


Fig. 3. Future design strategies for shelf-life and degradation balance

MICROBIAL RESISTANCE

Microbial resistance is a critical parameter for starch-based bioplastics, as it plays a dual role in maintaining material performance during use and ensuring biodegradability upon disposal. In fact, bioplastics with antimicrobial properties offer notable advantages, particularly in food packaging applications, by preserving products freshness and reducing the need for chemical preservatives. However, unanticipated microbial attack can compromise the structural integrity and shelf life of bioplastics. Therefore, the incorporation of antimicrobial agents has become a common strategy.

For example, Jha (2020) demonstrated that a chitosan-corn starch-based film plasticized with sorbitol, when combined with potassium sorbate and grapefruit seed extract as antimicrobial agents, prevented fungal growth on bread for up to 20 days at room temperature. This finding emphasizes the capacity of natural antimicrobial agents to increase the lifespan of bioplastics. Several sources that enhance microbial resistance in starch-based bioplastics are given in Table 5.

Table 5 lists the effectiveness of antimicrobial agents obtained from natural resources used in starch-based bioplastics. For instance, Hernández *et al.* (2023) reported that the incorporation of oregano essential oil into the cassava starch-based films (containing glycerol, chitosan, and citric acid) resulted in excellent antimicrobial activity. These films effectively inhibited the growth of external yeast such as *Z. bailii*, indicating that they can be considered as good candidates for packaging acidic food products such as sausages and cheese. Nonetheless, among several essential oils tested, lemongrass oil exhibited outstanding antimicrobial performance compared to other essential oils such as fingerroot, guava, and kaffir lime oil. Perdana *et al.* (2021) found that the use of chitosan-cassava starch films with lemongrass essential oil showed good performance as an antifungal, antiradical, and antibacterial agent, which effectively inhibited the growth of mold, yeast, and both Gram-positive and Gram-negative bacteria. The shelf-life of ripe chilies was about 16 days longer when they were covered with the starch film, as evidenced by both lower weight loss and microbial spoilage during the storage period than the uncoated chilies.

Table 5. Several Sources that Consist of Antimicrobial Functions

Bioplastic	Antimicrobial Agent	Reference
Corn starch with sorbitol and chitosan	Potassium sorbate Grapefruit seed extract	(Jha 2020)
Cassava starch with glycerol, chitosan, and citric acid	Oregano essential oil	(Hernández *et al.* 2023)
Cassava starch with chitosan	Lemongrass essential oil	(Perdana *et al.* 2021)
Corn starch	Roselle extract	(Gómez-Aldapa *et al.* 2021)
Sago starch	Black cumin seeds methanol extract	(Ekramian *et al.* 2021)
Sago starch	Betel leaf extract	(Nasution and Wulandari 2021)

In another study, Gómez-Aldapa *et al.* (2021) explored the use of roselle extract as a substitute for distilled water in the fabrication of corn starch-based bioplastics. Antimicrobial activity increased linearly with increasing roselle extract concentration, with films containing 100% roselle extract exhibiting the strongest inhibitory effects against the tested foodborne pathogens, including *L. monocytogenes*, *S. aureus*, *E. coli*, and *Salmonella* spp. These findings affirm the potential of roselle-incorporated starch-based bioplastics for antimicrobial food packaging applications. Similarly, sago starch-based films formulated with methanolic extracts of black cumin seeds have also exhibited noticeable inhibitory activities against both *S. aureus* (Gram-positive) and *E. coli* (Gram-negative) bacteria. The antibacterial potential was attributed to the presence of hydroxyl groups in the phenolic compounds of the methanolic extract of black cumin seeds (Ekramian *et al.* 2021). Furthermore, antimicrobial function is also known to exist in betel leaf extract. Betel leaf extract has indicated promising antimicrobial activity when incorporated into sago starch-based bioplastics. Nasution and Wulandari (2021) reported that the presence of flavonoids and tannins in betel leaf effectively suppressed the growth of *B. cereus*. These natural bioactive compounds can restrict bacterial proliferation directly and indirectly.

In short, the incorporation of natural antimicrobial agents, for example, essential oils, plant extracts, and phenolic compounds, has been the focus of many studies. They offer a natural, environmentally friendly, and sustainable alternative to synthetic or artificial preservatives. These bioactive materials are not only helpful in enhancing microbial resistance but also contribute towards global efforts to develop eco-friendly and sustainable packaging materials.

THERMAL STABILITY

Thermal stability refers to the ability of a material to maintain its structural and functional properties when exposed to elevated temperatures. While often confused with thermal degradation, the two terms are related but distinct. Thermal degradation describes the breakdown of the chemical structure of materials upon heating (Badia *et al.* 2017; Bhuvaneswari 2018; Anju *et al.* 2020), whereas thermal stability represents the resistance of materials to such breakdown when exposed to specified temperatures (Saleh 2022). For starch-based bioplastics, thermal stability is essential to ensure their strength, flexibility, and durability during applications.

Jha (2020) reported enhanced thermal stability of chitosan-grapefruit seed extract-corn starch films plasticized with sorbitol and glycerol. At the final stage of thermal degradation between 350 and 400 °C, the film containing sorbitol exhibited a higher residual mass (33%) than the film containing glycerol (29%). This difference indicates that sorbitol imparts higher thermal resistance to the film. The improved thermal stability can be attributed to the stronger intermolecular hydrogen bonding between sorbitol and the polymer matrix, which enhances its stability at elevated temperatures. Moreover, Hernández *et al.* (2023) observed that the incorporation of citric acid into oregano oil-chitosan-cassava starch-based bioplastics improved their thermal stability. This enhancement was attributed to the crosslinking effect of citric acid, which increased the thermal resistance of the bioplastic matrix.

Conversely, Abdullah *et al.* (2020) reported instability in melting temperature when chitin was incorporated into glycerol-cassava starch-based bioplastics, as analyzed by differential scanning calorimetry (DSC). A declining trend in the enthalpy change of the bioplastics was observed with increasing chitin content. This means that chitin may initiate the amylose chain mobility and inhibit retrogradation by lowering the heat flow (Rosa and Andrade 2004; Abdullah *et al.* 2020). The additional of chitin also influenced the thermal transitions of the starch-based bioplastics. Although an increase in the melting temperature (T_m) indicated that a higher temperature was required to initiate melting, the concurrent decrease in enthalpy (ΔH) suggests that less energy was needed to melt the remaining crystalline regions. These findings indicate that chitin modified the crystalline structure and thermal behavior of the starch-based bioplastics rather than directly improving their thermal stability.

However, the opposite finding was observed with increased glycerol content. In cassava starch-based bioplastics, a higher glycerol concentration reduced the stability of the crystalline structure and lowered thermal resistance. Hanif *et al.* (2019) explained that glycerol increases the free volume within the bioplastic matrix, resulting in a less dense structure that decomposes more rapidly under heat due to energy requirements. In addition, Gómez-Aldapa *et al.* (2021) found that replacing distilled water with roselle extract in the fabrication of corn starch-based bioplastics yielded positive results. The T_g of bioplastics made with roselle extract increased significantly, nearly doubling that of the control sample, indicating a great improvement in their thermal properties. It is hypothesized that this enhancement may be explained by the complex molecular structure of roselle extract, which contains a variety of polyphenolic compounds, organic acids, and polysaccharides with relatively higher molecular weights (Amaya-Cruz *et al.* 2018; Ahmed and Khalid 2025). These compounds possess multiple hydroxyl and aromatic functional groups capable of forming extensive hydrogen bonds and secondary interactions with the starch chains (Boukerche *et al.* 2024). These interactions restrict the molecular mobility of the polymer matrix, reduce the evaporation of volatile components, and act as natural crosslinkers that stabilize the bioplastic structure. Consequently, the formation of these molecular complexes, which are less volatile and more rigid, leads to a significant increase in the T_g and improves the thermal stability of the bioplastics.

For single-use disposable packaging and short-term consumer products, materials are typically required to maintain adequate performance at ambient or appliance operating temperatures while retaining sufficient flexibility and structural integrity. Table 6 presents various everyday scenarios involving the use of plastic packaging in Malaysia.

Table 6. Typical Household Conditions for Plastic Packaging in Malaysia

Condition	Appliance	Temperature Range (ºC)	Reference
Normal Ambient Use	-	20 to 32	(Weather Atlas 2024)
Heating	Microwave Oven	Room Temperature – 260	(Beko 2023; LG 2025; Panasonic 2011; Toshiba 2024)
Cooling	Fridge	1.1 to 7.7	(Electrolux 2025; Maytag 2026; Samsung 2012)
	Freezer	-25.5 to -13.3	

Compared to conventional plastics such as polyethylene, polypropylene, and polyethylene terephthalate, starch-based bioplastics generally exhibit lower thermal degradation onset temperatures, reflecting their limited tolerance to high-temperature processing environments. Table 7 summarizes the degradation temperatures for various types of plastics.

Table 7. Degradation Temperatures for Various Types of Plastics

Plastic Type	Degradation Onset Temperature (ºC)	Reference
Polyethylene	400 to 525	(Natesakhawat *et al.* 2024; Verho and Vaari 2022)
Polypropylene	~ 300	(Altepeter *et al.* 2023; Paik and Kar 2008)
Polyethylene terephthalate	~ 400	(Rosdi and Alias 2019)
Starch-based	~ 160 to 280	(Oliver *et al.* 2024; Zhu *et al.* 2018)

The difference in degradation temperatures should not be interpreted solely as poor performance, as it reflects the distinct degradation mechanisms of the materials. Starch-based bioplastics are designed to undergo hydrolytic and microbial degradation under natural conditions, enabling faster environmental breakdown and reducing long-term persistence (hundreds of years), whereas conventional plastics primarily fragment into microplastics before eventual degradation (Hussain *et al.* 2024; Mishra *et al.* 2024; Subramani *et al.* 2024). Consequently, starch-derived bioplastics offer advantages in terms of environmental degradability and energy-efficient decomposition, while conventional plastics remain superior for end-users requiring prolonged thermal and mechanical stability at elevated temperatures. Therefore, if the starch-based bioplastics satisfy the thermal and mechanical performance requirements of the intended single-use purpose, it can be considered as suitable for practical use. Future improvements in thermal stability are primarily necessary for utilizations involving prolonged service life or exposure to elevated temperatures.

In summary, formulation components such as plasticizers, crosslinkers, and bioactive additives can significantly influence the thermal stability of starch-based bioplastics. Further research is encouraged to deepen the understanding of these relationships, particularly in optimizing formulations for applications that demand higher thermal tolerance.

PHYSICAL APPEARANCE

The physical appearance of starch-based bioplastics plays a crucial role in attracting end-user attention and should be considered during product development. Among the various physical characteristics, colour and opacity contribute not only to aesthetic appeal but also to functional performance. For instance, bioplastics with high-opacity provide effective protection against light and ultraviolet (UV) radiation, making them particularly suitable for packaging of light-sensitive products such as milk and vitamin-enriched foods. By limited light transmission, the packaging helps preserve product freshness and quality while minimizing the photodegradation of light-sensitive components.

Oluwasina and Awonyemi (2021) demonstrated that cassava starch bioplastics incorporated with citrus lemon peel extract have considerable potential for fish packaging. The addition of the extract increased the opacity of the bioplastics, reducing lipid oxidation in the packaged fish. This improvement was attributed to the oily compounds present in the lemon peel extract, which reduced light transmission through enhanced light scattering within the bioplastics matrix. Similar findings were reported in their previous study by Oluwasina *et al.* (2019), in which the incorporation of oxidized cassava starch also increased the opacity of starch-based bioplastics. The enhanced opacity was attributed to the presence of dispersed oxidized starch domains, which acted as barriers within the starch matrix, reducing light transmission and limiting light penetration.

Several studies have also associated changes in the opacity of starch-based bioplastics with moisture-related factors. For example, Ulyarti *et al.* (2021) found that chitosan-yam starch-based bioplastics exhibited lower opacity than clove oil-yam starch-based bioplastics. This difference was due to the lipid components in clove oil, which caused moisture accumulation on the surface of bioplastics, increasing light scattering and reducing light transmission. Likewise, increasing the chitosan content in cassava starch-based bioplastics resulted in higher opacity and a darker appearance. In addition to influencing opacity, Hernández *et al.* (2023) observed that increasing the chitosan content shifted and increased the red-green axis (a^*) value, indicating a reduction in the greenness of the bioplastics. These findings suggest that the opacity of starch-based bioplastics can be modified through the addition of natural additives to meet consumer and market demands. Fig. 4 illustrates the relationship between additive types, the structural mechanisms, and the resulting opacity levels in starch-based bioplastics, along with their associated applications. Overall, low-opacity bioplastics are more suitable for packaging in which products visibility is desirable, such as bread and other bakery products, whereas high-opacity bioplastics are better suited for protecting light-sensitive products from light-induced deterioration or for uses where an opaque appearance is preferred.

Conventional fillers can also influence the physical appearance of bioplastics, including their opacity, whiteness, and light scattering behavior. Unlike those natural functional additives such as plant extracts, essential oils, and chitosan, fillers are often relatively inert material additives in commercial bioplastic formulations. For example, fillers such as calcium carbonate, talc, and clay (Fig. 4) can modify the visual appearance of materials by increasing light scattering and altering the optical properties, with extended effects depending on the filler characteristics and their dispersion within the matrix (Gaskin *et al*. 2024; Hubbe and Gill 2016). Biopolymer composites with fillers, for instance, may also affect the resulting stiffness and surface characteristics (Helanto *et al*. 2021). Therefore, these conventional fillers should be distinguished from the natural functional additives, as fillers may contribute to both visual and structural effects, such as opacity and brightness in terms of physical appearance, while functional additives may simultaneously influence appearance and active packaging performance.

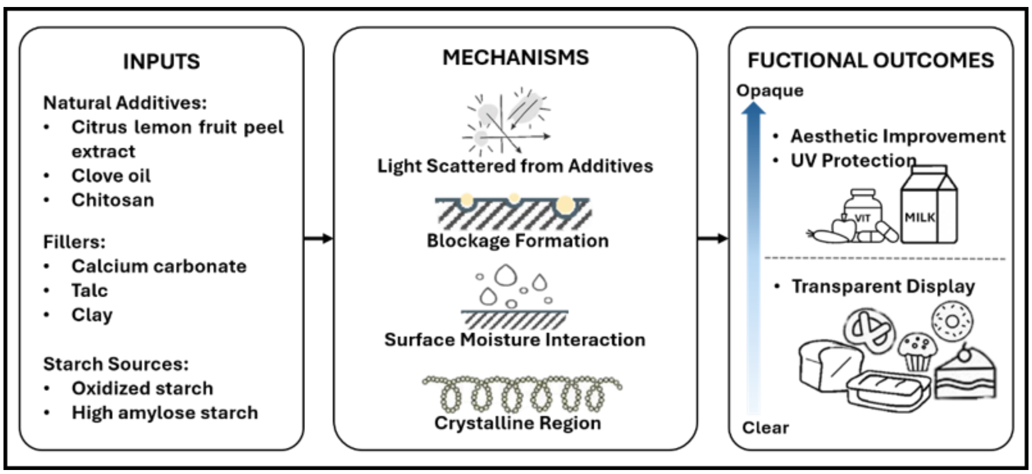


Fig. 4. Factors affecting the opacity of starch-based bioplastic

Beyond aesthetics, Fig. 4 shows that opacity also serves important functional roles by providing light protection and product concealment. One of the key factors influencing the opacity of starch-based bioplastics is the amylose content in the starch. Starch comprises two major polysaccharides, namely amylose and amylopectin, with the linear amylose molecules playing a dominant role in determining opacity. Higher amylose content promotes the formation of more crystalline regions within the bioplastic matrix, which enhances light scattering and consequently increases opacity (Pooja *et al.* 2024). Consistent with this mechanism, Pooja *et al.* (2024) showed that rice starch-based bioplastics, which contain a higher amylose content, exhibited greater opacity than potato starch-based bioplastics. These findings underscore the close relationship between amylose content, crystallinity, and opacity properties, suggesting that controlling the amylose content of starch is an effective strategy for tailoring the light-scattering ability, opacity, and barrier performance of starch-based bioplastics for specific packaging applications.

Nevertheless, from a practical and industrial perspective, starch-based bioplastics offer considerable flexibility in modifying their physical appearance, including colour and transparency, comparable to that of conventional petroleum-based plastics. Native starch-based films typically exhibit inherent colour and transparency that depend on their botanical origin and processing conditions. These optical properties can be readily modified through the incorporation of food-grade dyes, natural pigments, or bio-derived colorants during formulation as sustainable alternatives to the synthetic dyes commonly used in conventional plastics. Examples of natural dyes have been tabulated in Table 8. Furthermore, the ability to control colour and transparency is closely related to the molecular structure of starch. Higher amylose content promotes greater crystallinity and light scattering, resulting in increased opacity, whereas amylopectin-rich starches generally produce more transparent materials (Varghese *et al.* 2022). Therefore, manipulating the amylose-to-amylopectin ratio provides a practical strategy for optimizing the optical properties of starch-based bioplastics to suit their intended applications.

Table 8. Various Natural Dyes

Natural Dye Source	Colour	Reference
Butterfly pea	Blue	(Baskaran *et al.* 2019; Fuzetti *et al.* 2022)
Rubia root	Red	(Derksen *et al.* 2021; Yusuf *et al.* 2013)
Brazil wood/ Sappan wood	Red	(Dapson and Bain, 2015; Nasilowska *et al.* 2025; Sharma *et al.* 2023)
Morinda root/ bark	Red	(Arya *et al.* 2014; Rahman *et al.* 2018)
Turmeric	Yellow	(Popescu *et al.* 2025; Sadaf *et al.* 2024)
Pandan leaf	Green	(Berghuis *et al.* 2024; Kamal *et al.* 2024; Nor Diyana Md Sin *et al.* 2024)
Oak gall	Brown	(Eslammanesh *et al.* 2025; Sutlović *et al.* 2024)

Although petroleum-based plastics are synthesized from chemically uniform monomers derived from crude oil, starch-based bioplastics originate from renewable biological resources, leading to greater compositional variability that must be carefully managed through formulation and processing control.

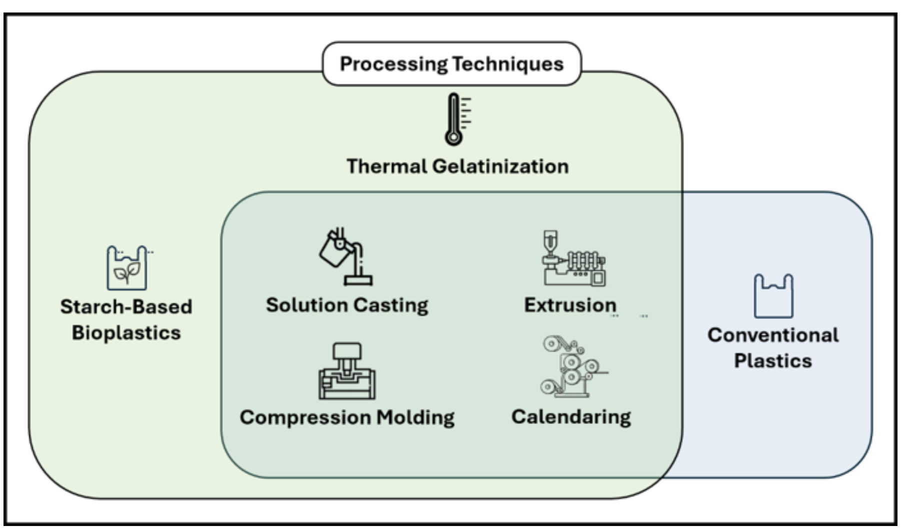


Fig. 5. Processing techniques for conventional plastics and starch-based bioplastics

Nevertheless, many processing techniques such as thermal gelatinization, solution casting, compression molding, extrusion, and calendaring, are conceptually similar to conventional plastic processing methods. This compatibility enables the partial adaptation of existing manufacturing infrastructure for starch-based bioplastic production, as illustrated in

Fig. **5**. Consequently, starch-based bioplastics offer substantial flexibility in tuning their aesthetic and functional properties while maintaining the advantages of renewability, biodegradability, and compatibility with established polymer processing technologies.

CONCLUSIONS

Starch-based bioplastics currently represent one of the largest segments of the global bioplastics market owing to their excellent biodegradability, cost-effectiveness, and the availability of renewable feedstocks. Thus, this review has emphasized that their wider industrial adoption depends on continued research to optimize critical performance parameters, including toxicity, shelf-life, microbial resistance, thermal stability, and physical appearance. As global demand for sustainable materials continues to increase, starch-based bioplastics offer a promising strategy for reducing society's reliance on plastics. This means that starch-based microplastics can help to mitigate pollution and environmental degradation.

The findings presented in this review also support environmental initiatives, including Malaysia's Roadmap Towards Zero Single-Use Plastics 2018-2030, by providing a scientific basic for the development of starch-based bioplastic that can facilitate the transition toward a circular and sustainable economy. In addition, advances in starch-based bioplastics technologies contribute directly to several of the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

Consequently, the ecological risks posed by these biopolymers to terrestrial and aquatic ecosystems are considerably lower than those associated with persistent petroleum-based plastics. They are derived from renewable resources and are designed to undergo biodegradation under appropriate environmental conditions. These characteristics enhance their potential for eco-friendly packaging and reinforce their role in promoting sustainable production and long-term environmental conservation. Finally, this comprehensive review serves a practical framework for the development and selection of safer, more durable, and environmentally compatible materials, exhibiting their strong potential as sustainable alternatives to conventional petroleum-based plastics across a broad range of applications.

ACKNOWLEDGEMENTS

This research was financially supported by the Universiti Malaya Grant under Bantuan Khas Penyelidikan, Fakulti Kejuruteraan 2024 [UMG001A-2024], the Department of Mechanical Engineering, Faculty of Engineering, and the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme (FRGS), [FRGS/1/2024/STG05/UM/02/4; Project Number: FP048-2024].

REFERENCES CITED

Abdelmoez, W., Dahab, I., Ragab, E. M., Abdelsalam, O. A., and Mustafa, A. (2021). "Bio- and oxo-degradable plastics: Insights on facts and challenges," *Polymers for Advanced Technologies* 32(5), 1981-1996. https://doi.org/10.1002/pat.5253

Abdullah, A. H. D., Fikriyyah, A. K., and Furghoniyyah, U. (2020). "Effect of chitin addition on water resistance properties of starch-based bioplastic properties," *IOP Conference Series: Earth and Environmental Science* 483(1), article 012002. https://doi.org/10.1088/1755-1315/483/1/012002

Abe, M. M., Branciforti, M. C., and Brienzo, M. (2021). "Biodegradation of hemicellulose-cellulose-starch-based bioplastics and microbial polyesters," *Recycling* 6(1), article 22. https://doi.org/10.3390/recycling6010022

Ahamed, A., Vallam, P., Iyer, N. S., Veksha, A., Bobacka, J., and Lisak, G. (2021). "Life cycle assessment of plastic grocery bags and their alternatives in cities with confined waste management structure: A Singapore case study," *Journal of Cleaner Production* 278, article 123956. https://doi.org/10.1016/j.jclepro.2020.123956

Ahmed, A. M. A., and Khalid, K. A. (2025). "Anticancer properties of roselle (*Hibiscus sabdariffa* L.): A review," *Vegetos* 38(4), 1297-1308. https://doi.org/10.1007/s42535-024-01043-7

Ahsan, W. A., Hussain, A., Lin, C., and Nguyen, M. K. (2023). "Biodegradation of different types of bioplastics through composting—A recent trend in green recycling," *Catalysts* 13(2), article 294. https://doi.org/10.3390/catal13020294

Altepeter, M., Schöppner, V., Wanke, S., Austermeier, L., Meinheit, P., and Schmidt, L. (2023). "Polypropylene degradation on co-rotating twin-screw extruders," *Polymers* 15(9), article 2181. https://doi.org/10.3390/polym15092181

Amaya-Cruz, D. M., Perez-Ramirez, I. F., Ortega-Diaz, D., Rodriguez-Garcia, M. E., and Reynoso-Camacho, R. (2018). "Roselle (*Hibiscus sabdariffa*) by-product as functional ingredient: Effect of thermal processing and particle size reduction on bioactive constituents and functional, morphological, and structural properties," *Journal of Food Measurement and Characterization* 12(1), 135-144. https://doi.org/10.1007/s11694-017-9624-0

Anitha, R., Jayakumar, K., Samuel, G. V., Joice, M. E., Sneha, M., and Seeli, D. S. (2024). "Synthesis and characterization of starch-based bioplastics: A promising alternative for a sustainable future," *Engineering Proceedings* 61, article 30. https://doi.org/10.3390/engproc2024061030

Anju, S., Prajitha, N., Sukanya, V. S., and Mohanan, P. V. (2020). "Complicity of degradable polymers in health-care applications," *Materials Today Chemistry* 16, article 100236. https://doi.org/10.1016/j.mtchem.2019.100236

Aranguri-Llerena, G., and Siche, R. (2020). "Superior plants with significant amounts of cyanide and their toxicological implications," *Reviews in Agricultural Science* 8, 354-366. https://doi.org/10.7831/ras.8.0_354

Arguedas, P., and Cooke, R. D. (1982). "Residual cyanide concentrations during the extraction of cassava starch," *International Journal of Food Science and Technology* 17(2), 251-262. https://doi.org/10.1111/j.1365-2621.1982.tb00180.x

Arias, L. V. A., Silva, V. de S., Vieira, J. M. M., Fakhouri, F. M., and de Oliveira, R. A. (2024). "Plant-based films for food packaging as a plastic waste management alternative: Potato and cassava starch case," *Polymers* 16(17), article 2390. https://doi.org/10.3390/polym16172390

Arya, L., Verma, M., and Gupta, V. (2014). “Conservation and molecular characterization of *Morinda* sp.: An emerging economical bio-sorbent,” in *Global Sustainability Transitions: Impacts and Innovations*, pp. 285-290.
Assembly of Life Sciences (US), Safe Drinking Water Committee, and National Research Council (US), Commission on Life Sciences (1977). *Drinking Water and Health*, Vol. 1, National Academy of Sciences, Washington, DC, USA.
Badia, J. D., Gil-Castell, O., and Ribes-Greus, A. (2017). “Long-term properties and end-of-life of polymers from renewable resources,” *Polymer Degradation and Stability* 137, 35-57. https://doi.org/10.1016/j.polymdegradstab.2017.01.002
Balangao, J. K. (2023). “Degradation of plastics-a brief review,” *Journal of Chemical Health Risks* 13(6), 1413-1420.
Ballhorn, D. J. (2011). “Cyanogenic glycosides in nuts and seeds,” in *Nuts and Seeds in Health and Disease Prevention*, Elsevier, pp. 129-136. https://doi.org/10.1016/B978-0-12-375688-6.10014-3
Bangar, S. P., Singh, A., Ashogbon, A. O., and Bobade, H. (2023). “Ball-milling: A sustainable and green approach for starch modification,” *International Journal of Biological Macromolecules* 237, article 124069. https://doi.org/10.1016/j.ijbiomac.2023.124069
Baskaran, A., Mudalib, S. K. A., and Izirwan, I. (2019). “Optimization of aqueous extraction of blue dye from butterfly pea flower,” *Journal of Physics: Conference Series* 1358(1), 012001. https://doi.org/10.1088/1742-6596/1358/1/012001
Bazart, H., Guillard, V., Gontard, N., and Chatellard, L. (2026). “Material-to-compost ratio is key for biodegradation of microbial polyester-based composite in home-composting conditions,” *Results in Materials* 2026, article 100908.
Beko (2023). *Over the Range Convection Microwave Oven: User Manual (MWOTR 30200 CSS)*, Beko.
Berghuis, N. T., Isnaeni, L. A., Shaleha, K. N., Kusumaningrum, A. T., Maryana, E., and Kurniawati, F. (2024). “Extraction of chlorophyll from pandan wangi leaves (*Pandanus amaryllifolius* Roxb.) as natural textile dyes,” *EduChemia: Jurnal Kimia dan Pendidikan* 9(2), 162-169. https://doi.org/10.30870/educhemia.v9i2.24963
Beversdorf, W. D. (1993). *Traditional Crop Breeding Practice: An Historical Review to Serve as a Baseline for Assessing the Role of Modern Biotechnology*, Organisation for Economic Co-operation and Development (OECD), Paris, France.
Bher, A. Mayekar, P. C., Auras, R. A., and Schvezov, C. E. (2022). “Biodegradation of biodegradable polymers in mesophilic aerobic environments,” *International Journal of Molecular Sciences* 23(20), article 12165. https://doi.org/10.3390/ijms232012165
Bhuvaneswari, G. H. (2018). “Degradability of polymers,” in *Recycling of Polyurethane Foams*, Elsevier, pp. 29-44. https://doi.org/10.1016/B978-0-323-51133-9.00003-6
Bickerton, J. (2025). “Mars ‘toxic’ food dyes in M&M’s, Skittles under scrutiny—Texas AG,” *Newsweek*. https://www.newsweek.com/mars-toxic-food-dyes-mms-skittles-under-scrutiny-2100143
Bolarinwa, I. F., Oke, M. O., Olaniyan, S. A., and Ajala, A. S. (2016). “A review of cyanogenic glycosides in edible plants,” in: *Toxicology – New Aspects to This Scientific Conundrum*, InTech. https://doi.org/10.5772/64886
Boukerche, H., Malki, F., Saidji, N., Ghaliaoui, N., Bensalem, A., and Mokrane, H. (2024). “Combination of ultrasound, microwave and conventional extraction techniques for roselle (*Hibiscus sabdariffa* L.) total anthocyanins and phenolics recovery: Effect on antioxidant and structural properties,” *Biomass Conversion and*

Biorefinery 14(15), 18051-18063. https://doi.org/10.1007/s13399-023-04029-8
Brebu, M. (2020). "Environmental degradation of plastic composites with natural fillers—A review," *Polymers* 12(1), article 166. https://doi.org/10.3390/polym12010166
Cabral, J. P. S. (2010). "Water microbiology: Bacterial pathogens and water," *International Journal of Environmental Research and Public Health* 7(10), 3657-3703. https://doi.org/10.3390/ijerph7103657
Chen, J. C., Chiu, M. H., Nie, R. L., Cordell, G. A., and Qiu, S. X. (2005). "Cucurbitacins and cucurbitane glycosides: Structures and biological activities," *Natural Product Reports* 22(3), 386-399. https://doi.org/10.1039/b418841c
Coppola, G., Gaudio, M. T., Lopresto, C. G., Calabrò, V., Curcio, S., and Chakraborty, S. (2021). "Bioplastic from renewable biomass: A facile solution for a greener environment," *Earth Systems and Environment* 5(2), 231-251. https://doi.org/10.1007/s41748-021-00208-7
Crews, C., and Clarke, D. (2014). "Natural toxicants: Naturally occurring toxins of plant origin," in: *Encyclopedia of Food Safety*, Elsevier, pp. 261-268. https://doi.org/10.1016/B978-0-12-378612-8.00173-6
da Luz, J. M. R., Paes, S. A., Nunes, M. D., da Silva, M. de C. S., and Kasuya, M. C. M. (2013). "Degradation of oxo-biodegradable plastic by *Pleurotus ostreatus*," *PLoS ONE* 8(8), article e69386. https://doi.org/10.1371/journal.pone.0069386
Dahler, J., McConchie, C., and Turnbull, C. (1995). "Quantification of cyanogenic glycosides in seedlings of three *Macadamia* (Proteaceae) species," *Australian Journal of Botany* 43(6), 619-628. https://doi.org/10.1071/BT9950619
Dapson, R., and Bain, C. (2015). "Brazilwood, sappanwood, brazilin and the red dye brazilein: From textile dyeing and folk medicine to biological staining and musical instruments," *Biotechnic and Histochemistry* 90(6), 401-423. https://doi.org/10.3109/10520295.2015.1021381
de Graaf, R. A., Karman, A. P., and Janssen, L. P. B. M. (2003). "Material properties and glass transition temperatures of different thermoplastic starches after extrusion processing," *Starch/Stärke* 55(2), 80-86. https://doi.org/10.1002/star.200390020
D'Elia, S., Franzese, R., Gentile, C., Solimene, A., Luisi, E., Caiazzo, A., Natale, F., Loffredo, F. S., Golino, P., and Cimmino, G. (2024). "Sodium nitroprusside: The forgotten vasodilator? A brief guide for informed and safe use from heart failure to hypertensive crisis and aortic dissection," *Future Pharmacology* 5(1), 1-12. https://doi.org/10.3390/futurepharmacol5010001
Demisie, S., Oh, D. C., Abera, A., Tasew, G., Satessa, G. D., Fufa, F., Shenkutie, A. M., Wolday, D., and Tafess, K. (2024). "Bioprospecting secondary metabolites with antimicrobial properties from soil bacteria in high-temperature ecosystems," *Microbial Cell Factories* 23, article 332. https://doi.org/10.1186/s12934-024-02589-6
Derksen, G. C. H., van Holthoon, F. L., Willemen, H. M., Krul, C. A. M., Franssen, M. C. R., and van Beek, T. A. (2021). "Development of a process for obtaining non-mutagenic madder root (*Rubia tinctorum*) extract for textile dyeing," *Industrial Crops and Products* 164, article 113344. https://doi.org/10.1016/j.indcrop.2021.113344
Driedger, D. R., and Sporns, P. (1999). "Glycoalkaloid concentration in by-products of potato starch extraction as measured by matrix-assisted laser desorption ionization mass spectrometry," *Journal of Food Processing and Preservation* 23(5), 377-390.
Ekramian, S., Abbaspour, H., Roudi, B., Amjad, L., and Nafchi, A. M. (2021). "Influence of *Nigella sativa* L. extract on physico-mechanical and antimicrobial properties of

sago starch film," *Journal of Polymers and the Environment* 29(1), 201-208. https://doi.org/10.1007/s10924-020-01864-y

Electrolux (2025). "What is the right temperature for your refrigerator?" *Product Support: Refrigerators*. https://www.electrolux.in/support/refrigerators/

Eslammanesh, T., Pour Masoomi, H., Molashahi, N., Mohammadkhani, S., Rezaei, M., and Rezaei, M. (2025). "A systematic review of the antimicrobial properties of dye-producing plants," *Gene, Cell and Tissue* 12(2), article e155656. https://doi.org/10.5812/gct-155656

European standards. (2000). "Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging" (BS EN 13432:2000).

Faris, N. A., Noriman, N. Z., Sam, S. T., Ruzaidi, C. M., Omar, M. F., and Kahar, A. (2014). "Current research in biodegradable plastics," *Applied Mechanics and Materials* 679, 273-280. https://doi.org/10.4028/www.scientific.net/AMM.679.273

FDA (2024). *Foods Derived from Plants Produced Using Genome Editing: Guidance for Industry (Contains Nonbinding Recommendations)*, U.S. Food and Drug Administration, Silver Spring, MD, USA.

Fisher, L. T., Venditti, J. K., and Glatt, J. B. (2025). *Class Action Complaint – Jury Trial Demanded*, Case No. 3:25-cv-00907-JES-VET, United States District Court, Southern District of California, USA.

Fuzetti, C. G., Castilhos, M. B. M., and Nicoletti, V. R. (2022). "Microencapsulation of natural blue dye from butterfly pea (*Clitoria ternatea* L.) flowers: The application of different carriers," *Journal of Food Processing and Preservation* 46(4), article e16420. https://doi.org/10.1111/jfpp.16420

Gaskin, E., Reed, G., Preston, J., and Biza, P. (2024). "The use of minerals in fiber-based packaging and pulp molding," *TAPPI J.* 23(1), 25-32.

Ghasemlou, M., Barrow, C. J., and Adhikari, B. (2024). "The future of bioplastics in food packaging: An industrial perspective," *Food Packaging and Shelf Life* 43, article 101279. https://doi.org/10.1016/j.fpsl.2024.101279

Gómez-Aldapa, C. A., Díaz-Cruz, C. A., Castro-Rosas, J., Jiménez-Regalado, E. J., Velázquez, G., Gutiérrez, M. C., and Aguirre-Loredo, R. Y. (2021). "Development of antimicrobial biodegradable films based on corn starch with aqueous extract of *Hibiscus sabdariffa* L.," *Starch/Stärke* 73(1-2), article 2000096. https://doi.org/10.1002/star.202000096

Grant, P., and Ramasamy, S. (2012). "An update on plant derived anti-androgens," *International Journal of Endocrinology and Metabolism* 10(2), 497-502. https://doi.org/10.5812/ijem.3644

Gregory, M. R., Tonya, K. R., Fred, C. D., Lisa, A. D., Timothy, M., Anwarul, H., and Rita, R. C. (2000). "Global spread of microorganisms by ships," *Nature* 408, 49-50. https://doi.org/10.1038/35040629

Hameed, A., Ijaz, S., Mohammad, I. S., Muhammad, K. S., Akhtar, N., and Khan, H. M. S. (2017). "Aglycone solanidine and solasodine derivatives: A natural approach towards cancer," *Biomedicine and Pharmacotherapy* 94, 446-457. https://doi.org/10.1016/j.biopha.2017.07.147

Hanif, A., Abdullah, D., Putri, O. D., and Sugandi, W. W. (2019). "Effects of starch-glycerol concentration ratio on mechanical and thermal properties of cassava starch-based bioplastics," *Jurnal Sains Materi Indonesia* 20(4), 95-102.

Helanto, K., Talja, R., and Rojas, O. J. (2021). "Effects of talc, kaolin and calcium carbonate as fillers in biopolymer packaging materials," *Journal of Polymer Engineering* 41(9), 746-758. https://doi.org/10.1515/polyeng-2021-0076

Hernández, M. S., Ludueña, L. N., and Flores, S. K. (2023). "Citric acid, chitosan and oregano essential oil impact on physical and antimicrobial properties of cassava starch films," *Carbohydrate Polymer Technologies and Applications* 5, article 100307. https://doi.org/10.1016/j.carpta.2023.100307

Hopkins, J. (1995). "The glycoalkaloids: Naturally of interest (but a hot potato?)," *Food and Chemical Toxicology* 33(4), 323-328. https://doi.org/10.1016/0278-6915(94)00148-H

Hubbe, M. A., and Gill, R. A. (2016). "Fillers for papermaking: A review of their properties, usage practices, and their mechanistic role," *BioResources* 11(1), 2886-2963.

Huntrakul, K., and Harnkarnsujarit, N. (2020). "Effects of plasticizers on water sorption and aging stability of whey protein/carboxymethyl cellulose films," *Journal of Food Engineering* 272, article 109809. https://doi.org/10.1016/j.jfoodeng.2019.109809

Hussain, M. A., Mishra, S., Agrawal, Y., Rathore, D., and Chokshi, N. P. (2024). "A comparative review of biodegradable and conventional plastic packaging," *Iran Journal of Science and Technology, Transactions A: Science* 48(1), 126-140. https://doi.org/10.1007/s10751-024-01968-0

Ibrahim, N. I., Shahar, F. S., Hameed Sultan, M. T., Md Shah, A. U., Azrie Safri, S. N., and Mat Yazik, M. H. (2021). "Overview of bioplastic introduction and its applications in product packaging," *Coatings* 11(11), article 1423. https://doi.org/10.3390/coatings11111423

Iheukwumere, S. O., Nkwocha, K. F., Tonnie-Okoye, N., and Umeh, P. P. (2020). "A look at plastic bags and alternatives," *Journal of Geography, Meteorology and Environment* 3(1), 121-134.

Ishigaki, T., Sugano, W., Nakanishi, A., Tateda, M., Ike, M., and Fujita, M. (2004). "The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors," *Chemosphere* 54(3), 225-233. https://doi.org/10.1016/S0045-6535(03)00750-1

ISO. (2012). "Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions – Method by analysis of evolved carbon dioxide – Part 1: General method" (ISO 14855-1:2012). https://www.iso.org/obp/ui/en/#iso:std:57902:en

Jakubowicz, I., Yarahmadi, N., and Arthurson, V. (2011). "Kinetics of abiotic and biotic degradability of low-density polyethylene containing prodegradant additives and its effect on the growth of microbial communities," *Polymer Degradation and Stability* 96(5), 919-928. https://doi.org/10.1016/j.polymdegradstab.2011.01.031

Jayarathna, S., Andersson, M., and Andersson, R. (2022). "Recent advances in starch-based blends and composites for bioplastics applications," *Polymers* 14(21), article 4557. https://doi.org/10.3390/polym14214557

Jha, P. (2020). "Effect of plasticizer and antimicrobial agents on functional properties of bionanocomposite films based on corn starch-chitosan for food packaging applications," *International Journal of Biological Macromolecules* 160, 571-582. https://doi.org/10.1016/j.ijbiomac.2020.05.242

Johns Hopkins Center for Health Security (2022). "Cyanide factsheet," *Daily Med*. https://dailymed.nlm.nih.gov/dailymed/drugInfo.cfm?setid=ff4941b3-9901-4aab-adcf-c5327bede34e

Kamal, F. P., Murwanti, A., and Hazmi, F. Al (2024). "Application of natural dyes in the woven pandan leaf: Experimental study on craft products in Tipang village," *Dewa Ruci: Jurnal Pengkajian dan Penciptaan Seni* 19(2), 194-202. https://doi.org/10.33153/dewaruci.v19i2.6258

Karaca, M., and Erbaş, O. (2024). "Solanine poisoning: Effects, risks, and management strategies," *Journal of Experimental and Basic Medical Sciences* 5(2), 189-193. https://doi.org/10.5606/jebms.2024.1090

Karamanlioglu, M., and Robson, G. D. (2013). "The influence of biotic and abiotic factors on the rate of degradation of poly(lactic) acid (PLA) coupons buried in compost and soil," *Polymer Degradation and Stability* 98(10), 2063-2071. https://doi.org/10.1016/j.polymdegradstab.2013.07.004

Kaur, R., and Chauhan, I. (2024). "Biodegradable plastics: Mechanisms of degradation and generated bio-microplastic impact on soil health," *Biodegradation* 35(6), 863-892. https://doi.org/10.1007/s10532-024-10092-3

Kelce, W. R., and Wilson, E. M. (1997). "Environmental antiandrogens: Developmental effects, molecular mechanisms, and clinical implications," *Journal of Molecular Medicine* 75, 198-207.

Kiprotich, K., Muema, E., Wekesa, C., Tavasi, N., Muoma, J., Omayio, D., Ochieno, D., Motsi, H., Mncedi, S., and Tarus, J. (2025). "Unveiling the roles, mechanisms and prospects of soil microbial communities in sustainable agriculture," *Discover Soil* 2, 10. https://doi.org/10.1007/s44378-025-00037-4

Kliem, S., Kreutzbruck, M., and Bonten, C. (2020). "Review on the biological degradation of polymers in various environments," *Materials* 13(20), article 4586. https://doi.org/10.3390/ma13204586

Lachowicz, J. I., Alexander, J., and Aaseth, J. O. (2024). "Cyanide and cyanogenic compounds—Toxicity, molecular targets, and therapeutic agents," *Biomolecules* 14(11), article 1420. https://doi.org/10.3390/biom14111420

Lee, S. E., and Lee, K.-H. (2024). "Environmentally sustainable fashion and conspicuous behavior," *Humanities and Social Sciences Communications* 11(1), article 498. https://doi.org/10.1057/s41599-024-02955-0

LG (2025). "The ultimate oven temperature guide," *LG Story: Helpful Guide (Cooking Appliances)*. https://www.lg.com/ae/lg-story/helpful-guide/oven-temperature-guide

Maran, J. P., Sivakumar, V., Thirugnanasambandham, K., and Sridhar, R. (2014). "Degradation behavior of biocomposites based on cassava starch buried under indoor soil conditions," *Carbohydrate Polymers* 101, 20-28. https://doi.org/10.1016/j.carbpol.2013.08.080

Maytag (2026). "Recommended refrigerator and freezer temperature settings," *The Info Hub: Kitchen*, Maytag. https://www.maytag.com/blog/kitchen/best-refrigerator-freezer-temperatures.html

Mishra, S., Bauri, K. P., and Panigrahi, S. (2024). "Addressing plastic pollution: Sustainable alternatives and advanced waste management," *World Journal of Advanced Research and Reviews* 23(2), 1948-1957. https://doi.org/10.30574/wjarr.2024.23.2.2527

Mroczkowska, M., Germaine, K., Culliton, D., Duarte, T. K., and Neves, A. C. (2021). "Assessment of biodegradation and eco-toxic properties of novel starch and gelatine blend bioplastics," *Recycling* 6(4), article 81. https://doi.org/10.3390/recycling6040081

Nasiłowska, I. A., Pawlak, K., and Lech, K. (2025). "From logwood to brazilwood: A

chemometric approach to classifying wood-derived dyes in artworks," *Journal of Cultural Heritage* 73, 325-335. https://doi.org/10.1016/j.culher.2025.04.012
Nasution, H., and Wulandari, G. (2021). "The effect of betel (*Piper betle*) leaf extract as antimicrobial agent on characteristics of bioplastic based on sago starch," *IOP Conference Series: Materials Science and Engineering* 1122(1), article 012098. https://doi.org/10.1088/1757-899X/1122/1/012098
Natesakhawat, S., Weidman, J., Garcia, S., Means, N. C., and Wang, P. (2024). "Pyrolysis of high-density polyethylene: Degradation behaviors, kinetics, and product characteristics," *Journal of the Energy Institute* 116, article 101738. https://doi.org/10.1016/j.joei.2024.101738
NIOSH (2011). *Hydrogen Cyanide (AC): Systemic Agent*, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.
Md Sin, N. D., Mamat, M. H., Hussin, M. Z., Md Zain, N., Suhaidah, F., Muhamad, N. A., Asli, N. A., Zulkefle, H., Abdullah, M. H., and Setiawan, E. A. (2024). "A systematic review of synthesis and application base nanomaterial using *Pandanus* extract plant," *Journal of Advanced Research in Micro and Nano Engineering* 23(1), 61-76. https://doi.org/10.37934/armne.23.1.6176
Nyirenda, K. K. (2020). *Toxicity Potential of Cyanogenic Glycosides in Edible Plants*, Medical Toxicology.
Oliver, I., Conesa, J. A., and Fullana, A. (2024). "Thermal decomposition of bio-based plastic materials," *Molecules* 29(13), article 3195. https://doi.org/10.3390/molecules29133195
Olutosin, D. A., and Kayode, J. F. (2021). "Use of agrowaste (cassava peels) to cultivate *Aspergillus niger* for biomass production," *International Journal of Biochemistry, Biophysics and Molecular Biology* 6(1), 11-18. https://doi.org/10.11648/j.ijbbmb.20210601.14
Oluwasina, O. O., and Awonyemi, I. O. (2021). "Citrus peel extract starch-based bioplastic: Effect of extract concentration on packed fish and bioplastic properties," *Journal of Polymers and the Environment* 29(6), 1706-1716. https://doi.org/10.1007/s10924-020-01990-7
Oluwasina, O. O., Olaleye, F. K., Olusegun, S. J., and Mohallem, N. D. S. (2019). "Influence of oxidized starch on physicomechanical and thermal properties of cassava starch bioplastic film," *International Journal of Biological Macromolecules* 135, 282-293. https://doi.org/10.1016/j.ijbiomac.2019.05.150
Padmaja, G., and Steinkraus, K. H. (1995). "Cyanide detoxification in cassava for food and feed uses," *Critical Reviews in Food Science and Nutrition* 35(4), 299-339. https://doi.org/10.1080/10408399509527703
Paik, P., and Kar, K. K. (2008). "Kinetics of thermal degradation and estimation of lifetime for polypropylene particles: Effects of particle size," *Polymer Degradation and Stability* 93(1), 24-35. https://doi.org/10.1016/j.polymdegradstab.2007.11.001
Panasonic (2011). *Operating Instructions and Cookbook: Microwave Oven (Model NN-ST641W)*, Panasonic Corporation.
Payanthoth, N. S., Mut, N. N. N., Samanta, P., Li, G., and Jung, J. (2024). "A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments," *Applied Biological Chemistry* 67(1), article 110. https://doi.org/10.1186/s13765-024-00959-7
Perdana, M. I., Ruamcharoen, J., Panphon, S., and Leelakriangsak, M. (2021). "Antimicrobial activity and physical properties of starch/chitosan film incorporated

with lemongrass essential oil and its application," *LWT - Food Science and Technology* 141, article 110934. https://doi.org/10.1016/j.lwt.2021.110934
Pires, J. R. A., Souza, V. G. L., Fuciños, P., Pastrana, L., and Fernando, A. L. (2022). "Methodologies to assess the biodegradability of bio-based polymers—Current knowledge and existing gaps," *Polymers* 14(7), article 1359. https://doi.org/10.3390/polym14071359
Polman, E. M. N., Gruter, G. J. M., Parsons, J. R., and Tietema, A. (2021). "Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: A review," *Science of the Total Environment* 753, article 141953. https://doi.org/10.1016/j.scitotenv.2020.141953
Pooja, N., Chakraborty, I., Rahman, M. H., and Mazumder, N. (2023). "An insight on sources and biodegradation of bioplastics: A review," *3 Biotech* 13(7), article 220. https://doi.org/10.1007/s13205-023-03638-4
Pooja, N., Shashank, S., Singh, B. N., and Mazumder, N. (2024). "Advancing sustainable bioplastics: Chemical and physical modification of starch films for enhanced thermal and barrier properties," *RSC Advances* 14(33), 23943-23951. https://doi.org/10.1039/D4RA04263H
Popescu, V., Alexandrescu, A.-D., Popescu, G., and Vasilache, V. (2025). "Eco-friendly extraction of curcumin from turmeric and dyeability of textile fibers," *Fibers* 13(6), article 73. https://doi.org/10.3390/fib13060073
Rafiq, A., Khan, S. A., Akbar, A., Shafi, M., Ali, I., Rehman, F. U., Rashid, R., Shakoor, G., and Anwar, M. (2018). "Isolation and identification of antibiotic producing microorganisms from soil," *International Journal of Pharmaceutical Sciences and Research* 9(3), 1002-1011. https://doi.org/10.13040/IJPSR.0975-8232.9(3).1002-11
Rahman, A., Muktiningsih, M., Andika, F. L., Kartini, I., and Slamet, R. (2018). "Extraction of natural dye powder from *Morinda citrifolia* and its application as antibacterial dyes for cotton fabrics," *IOP Conference Series: Materials Science and Engineering* 434, article 012096. https://doi.org/10.1088/1757-899X/434/1/012096
Rosa, R. C. R. S., and Andrade, C. T. (2004). "Effect of chitin addition on injection-molded thermoplastic corn starch," *Journal of Applied Polymer Science* 92(4), 2706-2713. https://doi.org/10.1002/app.20292
Rosdi, M. R., and Alias, R. (2019). "Kinetic analysis of polyethylene terephthalate (PET) by using TGA," (publication details incomplete).
Sadaf, S., Saeed, A., Hassan, K., Ahmad, Z., and Butt, M. N. (2024). "Extraction and application of turmeric dye on silk fabric," *Journal of Innovative Sciences* 10(1), 1-6. https://doi.org/10.17582/journal.jis/2024/10.1.1.6
Saleh, T. A. (2022). "Properties of nanoadsorbents and adsorption mechanisms," in: *Nanoadsorbents for Water Treatment*, Elsevier, pp. 233-263. https://doi.org/10.1016/B978-0-12-849876-7.00010-5
Samsung (2012). *Refrigerator User Manual (Model RSG257AARS/XAA)*, Samsung Electronics Co., Ltd.
Sander, M., Weber, M., Lott, C., Zumstein, M., Künkel, A., and Battagliarin, G. (2023). "Polymer biodegradability 2.0: A holistic view on polymer biodegradation in natural and engineered environments," in: *Synthetic Biodegradable and Biobased Polymers: Industrial Aspects and Technical Products 293*, 65-110. Cham: Springer International Publishing. https://doi.org/10.1007/12_2023_163
Sang-A-Gad, P., Guharat, S., and Wananukul, W. (2011). "A mass cyanide poisoning from pickling bamboo shoots," *Clinical Toxicology* 49(9), 834-839.

https://doi.org/10.3109/15563650.2011.618456

Schrenk, D., Bignami, M., Bodin, L., Chipman, J. K., del Mazo, J., Grasl-Kraupp, B., Hogstrand, C., Hoogenboom, L., Leblanc, J., Nebbia, C. S., Nielsen, E., Ntzani, E., Petersen, A., Sand, S., Vleminckx, C., Wallace, H., Benford, D., Brimer, L., Mancini, F. R., and Schwerdtle, T. (2019). "Evaluation of the health risks related to the presence of cyanogenic glycosides in foods other than raw apricot kernels," *EFSA Journal* 17(4), article e05662. https://doi.org/10.2903/j.efsa.2019.5662

Shah, M., Rajhans, S., Pandya, H. A., and Mankad, A. U. (2021). "Bioplastic for future: A review then and now," *World Journal of Advanced Research and Reviews* 9(2), 56-67. https://doi.org/10.30574/wjarr.2021.9.2.0054

Sharma, B., Sharma, S., and Harchand, A. (2023). "Bioactive compounds, pharmacological activity and food application of *Biancaea sappan* (Indian red wood): A critical review," *Journal of Wood Chemistry and Technology* 43(5), 253-270. https://doi.org/10.1080/02773813.2023.2237488

Simeonova, F. P., and Fishbein, L. (2004). *Hydrogen Cyanide and Cyanides: Human Health Aspects*, Concise International Chemical Assessment Document 61, World Health Organization, Geneva, Switzerland.

Sobeih, M. O., Sawalha, S., Hamed, R., Ali, F., and Kim, M. P. (2025). "Starch-derived bioplastics: Pioneering sustainable solutions for industrial use," *Materials* 18(8), article 1762. https://doi.org/10.3390/ma18081762

Stoewsand, G. S., Jaworski, A., Shannon, S., and Robinson, R. W. (1985). "Toxicologic response in mice fed *Cucurbita* fruit," *Journal of Food Protection* 48(1), 38-41.

Subramani, R., Mustafa, M. A., Ghadir, G. K., Al-Tmimi, H. M., Alani, Z. K., Rusho, M. A., Rajeswari, N., Haridas, D., Rajan, A. J., and Kumar, A. P. (2024). "Exploring the use of biodegradable polymer materials in sustainable 3D printing," *Applied Chemical Engineering* 7(2), article 3870. https://doi.org/10.59429/ace.v7i2.3870

Sutlović, A., Pečeк, V., and Brlek, I. (2024). "Dyeing cotton fabrics with natural mordant dyes of plant origin," *Tekstilna Industrija* 72(4), 4-13. https://doi.org/10.5937/tekstind2404004S

Syuhada, M., Sofa, S. A., and Sedyadi, E. (2020). "The effect of cassava peel starch addition on bioplastic biodegradation based on chitosan in soil and river water media," *Biology, Medicine, and Natural Product Chemistry* 9(1), 7-13. https://doi.org/10.14421/biomedich.2020.91.7-13

Thakur, R., Pristijono, P., Scarlett, C. J., Bowyer, M., Singh, S. P., and Vuong, Q. V. (2019). "Starch-based films: Major factors affecting their properties," *International Journal of Biological Macromolecules* 132, 1079-1089. https://doi.org/10.1016/j.ijbiomac.2019.03.190

Tokiwa, Y., Calabia, B. P., Ugwu, C. U., and Aiba, S. (2009). "Biodegradability of plastics," *International Journal of Molecular Sciences* 10(9), 3722-3742. https://doi.org/10.3390/ijms10093722

Toshiba (2024). *Instruction Manual: Steam Oven (Model MS5-STR30SFZBK)*, Toshiba Corporation. https://www.manua.ls/toshiba/ms5-str30sfzbk/manual?p=37

Ulyarti, U., Lavlinesia, L., Surhaini, S., Siregar, N., Tomara, A., Lisani, L., and Nazarudin, N. (2021). "Development of yam-starch-based bioplastics with the addition of chitosan and clove oil," *Makara Journal of Science* 25(2), 85-92. https://doi.org/10.7454/mss.v25i2.1155

UNEP (2021). "From birth to ban: A history of the plastic shopping bag," United Nations Environment Programme. https://www.unep.org/news-and-stories/story/birth-ban-

history-plastic-shopping-bag
Unigwe, C. R., Mhomga, L. I., Igwe, I. R., and Egwu, L. U. (2023). "Cassava peels as feed resource for animal production—A review," *World Scientific News* (pagination not available).
Varela, C., Melim, C., Neves, B. G., Sharifi-Rad, J., Calina, D., Mamurova, A., and Cabral, C. (2022). "Cucurbitacins as potential anticancer agents: New insights on molecular mechanisms," *Journal of Translational Medicine* 20(1), article 630. https://doi.org/10.1186/s12967-022-03828-3
Varghese, S., Awana, M., Mondal, D., Rubiya, M. H., Melethil, K., Singh, A., Krishnan, V., and Thomas, B. (2022). "Amylose–amylopectin ratio," in: *Handbook of Biopolymers*, Springer Nature, Singapore, pp. 1-30. https://doi.org/10.1007/978-981-16-6603-2_48-1
Verho, T., and Vaari, J. (2022). "Analytical and numerical modeling of degradation and pyrolysis of polyethylene: Measuring aging with thermogravimetry," *Polymers* 14(13), article 2709. https://doi.org/10.3390/polym14132709
Vetter, J. (2000). "Plant cyanogenic glycosides," *Toxicon* 38(1), 11-36. https://doi.org/10.1016/S0041-0101(99)00128-2
Viljakainen, V. R., and Hug, L. A. (2021). "New approaches for the characterization of plastic-associated microbial communities and the discovery of plastic-degrading microorganisms and enzymes," *Computational and Structural Biotechnology Journal* 19, 6191-6200. https://doi.org/10.1016/j.csbj.2021.11.023
Vroman, I., and Tighzert, L. (2009). "Biodegradable polymers," *Materials* 2(2), 307-344. https://doi.org/10.3390/ma2020307
Wahyuningtyas, N., and Suryanto, H. (2017). "Analysis of biodegradation of bioplastics made of cassava starch," *Journal of Mechanical Engineering Science and Technology* 1(1), 24-31. https://doi.org/10.17977/um016v1i12017p024
Wang, Y., and Qian, H. (2021). "Phthalates and their impacts on human health," *Healthcare* 9(5), article 603. https://doi.org/10.3390/healthcare9050603
Weather Atlas (2024). "Climate and monthly weather forecast: Malaysia," Weather Atlas. https://www.weather-atlas.com/en/malaysia-climate
Wicaksono, J. A., Purwadaria, T., Yulandi, A., and Tan, W. A. (2022). "Bacterial dynamics during the burial of starch-based bioplastic and oxo-low-density polyethylene in compost soil," *BMC Microbiology* 22(1), article 291. https://doi.org/10.1186/s12866-022-02729-1
Winarti, C., Miskiyah, and Widaningrum (2012). "Teknologi produksi dan aplikasi pengemas edible antimikroba berbasis pati," *Jurnal Penelitian dan Pengembangan Pertanian* 31(3), 85-93.
Wypych, G. (2004). "Effect of plasticizers on properties of plasticized materials," in *Handbook of Plasticizers*, ChemTec Publishing, Toronto, Canada, pp. 209-332.
Yacob, N., Yusof, M. R., Mohamed, A. Z., and Badri, K. H. (2019). "Effect of cellulose fiber loading on the properties of starch-based films," *AIP Conference Proceedings* 2111, article 020019. https://doi.org/10.1063/1.5111257
Yu, X., Chen, L., Jin, Z., and Jiao, A. (2021). "Research progress of starch-based biodegradable materials: A review," *Journal of Materials Science* 56(19), 11187-11208. https://doi.org/10.1007/s10853-021-06063-1
Yusuf, M., Shahid, M., Khan, S. A., Khan, M. I., Islam, S.-U., Mohammad, F., and Khan, M. A. (2013). "Eco-dyeing of wool using aqueous extract of the roots of Indian madder (*Rubia cordifolia*) as natural dye," *Journal of Natural Fibers* 10(1), 14-28.

https://doi.org/10.1080/15440478.2012.738026
Zhu, X., He, Q., Hu, Y., Huang, R., Shao, N., and Gao, Y. (2018). "A comparative study of structure, thermal degradation, and combustion behavior of starch from different plant sources," *Journal of Thermal Analysis and Calorimetry* 132(2), 927-935. https://doi.org/10.1007/s10973-018-7030-4
Zimmermann, L., Dombrowski, A., Völker, C., and Wagner, M. (2020). "Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition," *Environment International* 145, article 106066. https://doi.org/10.1016/j.envint.2020.106066
Zoungranan, Y., Lynda, E., Dobi-Brice, K. K., Tchirioua, E., Bakary, C., and Yannick, D. D. (2020). "Influence of natural factors on the biodegradation of simple and composite bioplastics based on cassava starch and corn starch," *Journal of Environmental Chemical Engineering* 8(5), article 104396. https://doi.org/10.1016/j.jece.2020.104396

Article submitted: 21 April 2026; Peer review completed: May 25, 2026; Revised version received: July 15, 2026; Accepted: July 16, 2026; Published: July 31, 2026.
DOI: 10.15376/biores.21.3.Phuah