Exploring the Potential of Sago Residue for Eco-Friendly Construction Materials

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Sago residue is being explored as an alternative material in construction materials because of its natural source, good performance, eco-friendly nature, and biodegradable properties. Sago residue is categorized into particles and fiber, so it has various fabrication methods and applications. This study examines various sago residue extraction methods, including traditional manual techniques, mechanical processes, and chemical or enzymatic methods, highlighting their impact on the properties of construction materials. Furthermore, factors such as constituent materials, processing methods, composition, fiber and particle size, environmental conditions, and manufacturing processes can all influence the physical and mechanical properties of sago residue-based construction materials. This review emphasizes the importance of material characterization in understanding their suitability for specific construction applications, ensuring product quality and safety, and identifying opportunities for sustainable development in the construction industry. It was also shown that this study provides important insights and explores the potential of sago waste as a construction material that can be degraded in the environment. Future research may explore the impact of fiber and fiber orientation treatments on the heat resistance, sound absorption ability, and tribology properties of construction materials made from sago waste.

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INTRODUCTION

Sago, which is derived from the inner part of several tropical palm stems, particularly the metroxylon sago species, plays a vital role as a primary food source for communities in New Guinea, the Maluku Islands, and Southeast Asia, namely Indonesia and Malaysia. The substance is transformed into pearls or a viscous paste and ingested in many preparations, including spherical shapes, adhesive-like consistency, or flat cakes. In order to get sago, palm trees are felled before reaching full maturity in order to avoid the exhaustion of starch reserves, usually at approximately 15 years old. The stems are split, and the starchy pith is extracted, ground, and washed to collect the starch. Approximately 360 kg of dry starch can be obtained from a single palm (Binoj *et al*. 2016; Tengsuthiwat *et al*. 2021).

Sago plants typically produce residue that is easily transformed into other products (as shown in Fig. 1). However, appropriate methods must be employed to prevent environmental damage. Drying and storage techniques play a crucial role in maintaining the quality of the waste before it is processed for optimal use in various applications. This underscores the importance of ongoing research into the potential utilization of sago waste within the community (Rasyid *et al*. 2020). Starch and fiber are parts of the plant and waste products from sago that offer various advantages to be chosen as alternative materials in industry (Tabari 2017) and converted into a number of products, including food fiber concentrates (Pramana *et al*. 2023), food and fuel alternative (Bujang 2014), fish meal (Wuniarto *et al*. 2014), automotive component (Abral *et al*. 2019b), super absorbent (Yacob *et al*. 2014), composting (Ch'ng *et al*. 2014), bio-film (Arafat *et al*. 2014), bio ethanol (Thangavelu *et al*. 2014; Vincent *et al*. 2015), optical sensing receptor (Tan *et al*. 2014), adsorber (Droepenu *et al*. 2020), bio-hydrogen (Jenol *et al*. 2014), electrochemical devices (Jinitha *et al*. 2018a), bioelectricity (Jenol *et al*. 2019), block compost (Yasin *et al*. 2020), composite film (Zhu 2019), dan biomedical application (Mandal *et al*. 2014). Apart from that, in the fabrication process, sago shows the lowest CO_2 emission type by-products compared to processing palm and paddy oil, which is evaluated according to life cycle assessment (LCA) for consideration of environmental aspects (Wulan *et al*. 2015). This can also be seen from the significant differences between sago, maize, and potato starch during the harvesting process and transportation from the plantation to the factory (Yusuf *et al*. 2018). This is mainly because the production process of potato starch, corn starch, and cassava flour requires electricity and natural gas-based energy (Yusuf *et al*. 2019a). In addition, sago palm is an ecologically sustainable plant. The fibrous roots of the sago tree are able to remove heavy metals, pollutants, and fecal contaminants while capturing the load of sludge. Sago forests also act as a good carbon sink for carbon sequestration, thereby helping to reduce the greenhouse effect and global warming problems (Zhu 2019).

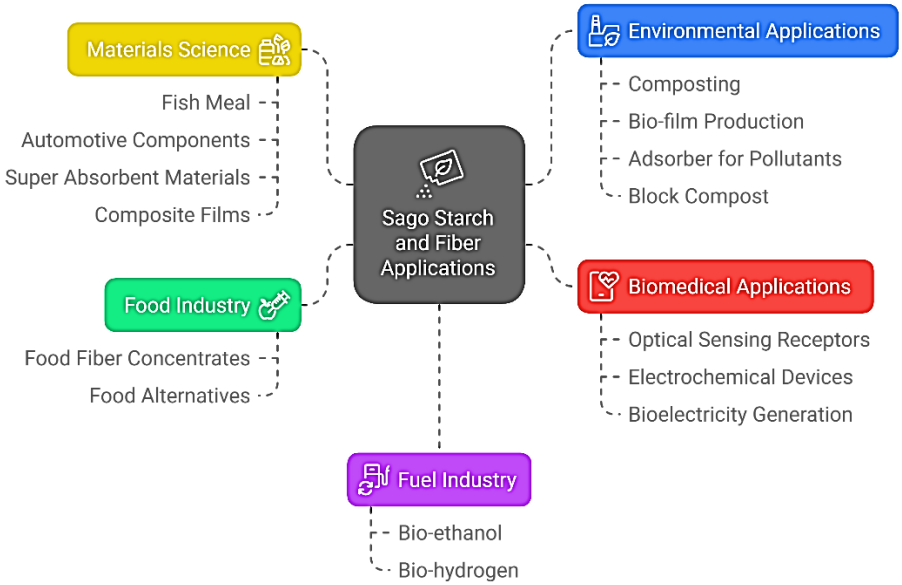

Fig. 1. Sago starch and fiber in several industries field

The incorporation of silica into starch/polyvinyl alcohol (PVOH) to create films composite that can enhance their tensile strength, but it decreases their elongation at break, when compared to films without silica. The addition of silica leads to decreased water absorption and water vapor transmission. Nevertheless, it has been discovered that an increased silica content hinders the degradation process of the sago/PVOH film when examining its biodegradability (Ismail and Zaaba 2014). The addition of nanocrystalline cellulose (NCC) derived from rattan biomass, along with acetic acid as a co-plasticizer, generally enhances the tensile strength of biocomposite of starch sago. The optimal tensile strength is achieved when the NCC content is 3% by weight and the acetic acid content is 30% by weight (Brinchi *et al*. 2013). The observed increase can be attributed to the robust interfacial interaction between starch and cellulose, wherein NCC is incorporated into the matrix, enabling effective transfer of stress. Nevertheless, when the NCC composition contains 4% of heavy particles, the pulling force either decreases or stabilizes. There was a significant positive correlation between the accumulation of filler material within the matrix and the less uniform distribution of stress (Bensely *et al*. 2008). The tensile strength of the biocomposite is also affected by the concentration of acetic acid, which reaches its maximum point at a weight percentage of 30%. Acetic acid function as cross-linking agents and co-plasticizers, disrupting the structure of starch particles and enabling the creation of additional hydroxyl chains, thus enhancing tensile strength. Furthermore, the hydrogen bonds created in the cellulose filler due to the presence of acetic acid greatly influence the biocomposite's tensile strength (Nasution *et al*. 2019).

Sago waste has light and eco-friendly properties, so it has been widely used to make urea formaldehyde particle board. The sago particles were mixed and sprayed with urea-formaldehyde and ammonium chloride (NH_4Cl) hardener for 5 min until they reached homogeneity. Then it was poured into the mold to go through hot pressing at 40 bars for 2.0 min at a temperature of 1600 °C. Factors that influence thickness swelling are particle size, particle geometry, duration of soaking time, and density, while water absorption is influenced by the weight fraction of the resin and sago particles. Sago particles have played an important role in making particle boards as an alternative material to replace the use of

wood from forests, thereby supporting nature conservation and preventing climate change (Chiang *et al*. 2014).

Various benefits from sago waste have been reported by previous researchers as a valuable natural material that has the potential to contribute to sustainable development in many industries. In the past few decades, research on the use of sago waste as a construction material has been reported. However, only a limited number of previous studies to explore the application of sago waste in the construction industry. Therefore, the aim of this study is to comprehensive review and explain the development of sago as a construction material, including its extraction, treatment, characteristics, fabrication, performance, and ability to degrade in the environment.

Natural Plant in Construction Material

Material selection in the construction industry is one of the primary aspects of creating environmentally friendly construction materials while maintaining key qualifications. Eco-friendly materials can be obtained from plants that are abundant in nature and can reproduce, thus supporting a sustainable construction industry. Natural materials can be combined with other construction materials to improve their properties, which can be applied to products such as concrete, composites, insulation, and gypsum (Aramwit *et al.* 2023; Dong *et al*. 2023). This is in line with building construction and the use of construction materials, which must consider environmental aspects. The use of natural plants as construction materials can be seen in Table 1.

Table 1. Utilization of Natural Plant as Building Materials

Material	Fabrication Method	Application	Authors
Kenaf fiber	NaCl treatment, hot pressing	Composite board	(Setyayunita *et al*. 2022)
Sago starch	Filler ratio, mixing	Bio-composite	(Ruamcharoen *et al*. 2023)
Water hyacinth fiber	Length of fiber, mixing	Fiber concrete	(Verdian and Muin 2023)
Palm kernel shell	Extraction condition, pressing	Particle board	(Boonsombuti *et* al. 2023)
Jute	Sandwich, compression molding	Composite panel	(Aly *et al*. 2021)
Corn straw fiber	Fiber content, mixing	Cement-stabilized	(Wang *et al*. 2022b)
Banana fiber	Chemical treatment, mixing	Concrete	(Saad *et al*. 2022a)
Sugarcane bagasse ash	Time treatment, mixing	Pastes and mortars	(Siqueira and Cordeiro 2022)
Bamboo sawdust	Particle size, mixing	Cementitious materials	(Tong *et al*. 2021)
Cotton stalk and palm leaf	Mass ratio, mixing	Concrete aggregates	(Amin *et al*. 2021)
Coir fiber	Weight percent, compression molding	Gypsum, wall panel, and sound suppression board	(Imran *et al*. 2024a)

Overall, there seems to be some evidence to indicate that the performance of natural plants in the construction material industry can be affected by various fundamental factors, including the fabrication process of thermal and sound insulation materials (Bumanis *et al*.

2023), the methods used for fiber synthesis and characterization in phosphogypsum-based composites (Zhang *et al*. 2023), the technique employed for modifying the cement matrix and fiber surface in cement-based compounds (Wang *et al*. 2022a), the types of reinforcement used in building insulation (Kadhom *et al*. 2022), as well as the types of binder and coupling agents, material composition, temperature, and melting time of materials in composite boards (Pu *et al*. 2022). Building materials derived from soil and biomass have considerable potential to mitigate the environmental consequences of construction methods. Constructing structures using materials such as bars, lightweight clay, and compressed dirt not only creates a pleasant indoor environment for the residents but also results in significant energy conservation when compared to traditional materials across different climates. One of the most noticeable environmental aspects of construction material is the life cycle assessment (LCA). In 2021, Ben-Alon *et al*. (2021) demonstrated that this natural material has the potential to significantly decrease energy consumption in different climate zones. Although there are difficulties related to its execution, the results emphasize the significance of considering natural materials as a feasible and environmentally friendly option for global ecological construction.

Extraction, Treatment, and Characterization of Sago

This part of the method provides a brief overview of the extraction, variety of treatments, and characterization of sago. The sago extraction method has become essential for obtaining starch, fiber, and other components that have significant importance in many industrial applications. To enhance production efficiency and product quality, as well as gain insight into the pertinent chemical and physical features (Noora *et al*. 2019), it is imperative to have a comprehensive understanding of the sago extraction process. Hence, the exploration and advancement of sago extraction techniques have significant promise for bolstering several sectors that depend on sago as a primary resource. Various techniques are employed for sago extraction, encompassing traditional manual dissolution, mechanical extraction employing machines, and chemical as well as enzymatic approaches (Kasim 2019; Yusuf *et al*. 2019b; Arham *et al*. 2021). In another major study by Darma (2018), mechanical techniques were employed to handle sago. A variety of methods are used to process the sago, including initial preparation of sago palm logs, removal of bark, dry rasping of the pith, wet maceration of the rasped pith, screening to separate the fiber, settling and washing of the starch, additional purification, drying, and ultimately obtaining sago starch as the final product (Darma 2018). An illustration of the processing of sago from sago palm into sago fiber and sago starch can be seen in Fig. 2.

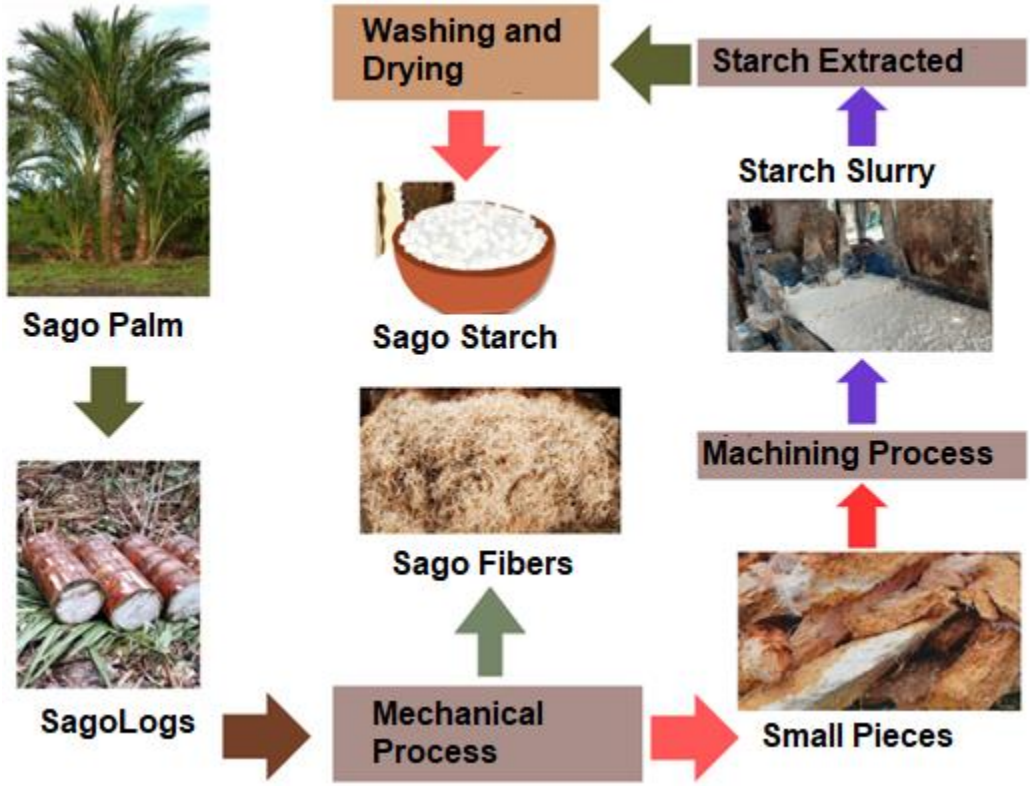

Fig. 2. Sago plant processing for fiber and starch production

Previous studies have been developed to treat sago. Each has its own positive impact. The production of aerogels from aerosol wastes of sago involves a three-stage procedure, resulting in the creation of sago cellulose nanofibrils. The process involves dewaxing and delignification, followed by homogenization, and finally aerogel production through freeze-drying (Beh *et al*. 2020). In their study, Pinyo *et al*. (2017) explored various pretreatment methods, including ultrasonic, microwave, enzymatic, and combination techniques, to improve the extraction yield and quality of sago starch from sago tree pith. The application of various methods is greatly influenced by several important parameters, such as intensity and frequency, microwave power and time, type and concentration of enzymes, as well as temperature and treatment time. (Pinyo *et al*. 2017). Sago plants can be classified into different products such as sago pith flour, sago starch, and sago hempas (Sunarti *et al*. 2018). It was clear that there are a number of important parts of sago that can be utilized, and each method affects the characteristics of the product. The combination of acid methanol and heat moisture-content treatment (HMT) of sago was proven to be more effective in reducing starch digestibility compared to HMT alone. Methanolic acid treatment produces short linear chains that facilitate the rearrangement of starch molecules during HMT, resulting in a higher proportion of resistant starch (RS) in both raw and gelatinized starch. This doubly modified starch also retained a higher proportion of RS after gelatinization. In its raw state, doubly modified starch exhibits a lower glycemic index, consistent with a higher RS content. The relationship between RS content and glycemic index is very strong, especially in raw starch. However, this correlation was not observed in gelatinized starch. Compared to HMT alone, the combination of acid methanol and HMT treatment resulted in relatively higher gelatinization temperatures and crystallinity, but lower degrees of retrogradation

and viscosity. Furthermore, after HMT and double modification, the granular surface is eroded, and the crystal pattern shifts from type C to type A. Surprisingly, changes in RS content did not appear to be related to the relative crystallinity or crystal pattern of starch. Type A starch has a regular crystal pattern and is usually more easily decomposed, while type C starch has a more complex crystal structure and is more difficult to decompose. This method is very important for obtaining materials that have a faster biodegradable rate (Ng *et al*. 2018).

Liestianty *et al*. (2016) highlights the need to characterize sago starch based on different categories: Sago pati without modification and fortification, sago sodi with heat moisture content (HMT), sago mori fortified with 7% phytoplankton extract 1, and sago sali fortified with 7% phytoplankton extract 2. This research identifies the impact of HMT treatment on changes in the crystalline and amorphous structure of sago starch, where this treatment causes manipulation to the granular shape of sago, resulting in a hollow surface. This clearly shows that changes in sago structure contribute to increasing thermal stability (Liestianty *et al*. 2016). In a large longitudinal study, Sumardiono *et al*. (2018) found that the quantity of unprocessed fiber is affected by both the type and duration of pretreatment. The immersion of a NaOH solution, followed by the addition of *Trichoderma* sp. and a fermentation period of 14 days, led to a reduction in the raw fiber content from 33.37% to 17.36% (Sumardiono *et al*. 2018). Introducing the local microorganism (MOL) "ginta" to sago leads to a reduction in crude fibers when compared to sago without the introduction of MOL. The incubation duration was extended from 0 to 144 h for crude oil. The fiber content exhibited a linear relationship, with the lowest raw fiber content observed after 144 hours of incubation (Ginting and Pase 2018).

The amorphous regions of hampas, sago fiber and starch were eliminated by acid modification in methanol. Immersing hampas sago in this solution results in a deep-colored filtrate, which is generated by the oxidation of phenolic chemicals. Under acidic circumstances, phenolic compounds and certain reducing sugars dissolve, leading to the formation of acid-modified void sago, which accounts for 91% to 94% of the final product. This treatment enhances the color and performance of hampas sago in comparison to its initial condition. Lignin, an amorphous and non-carbohydrate chemical composed of phenolic components, is also dispersed in an acidic solution. This technique has a minimal impact on the fiber composition, specifically lignin, hemicellulose, and cellulose. However, it significantly alters the molecular weight and content of starch (Sunarti *et al*. 2018). Dewi *et al*. (2019) produced cellulose acetate from pure sago through the stages of activation, acetylation, hydrolysis, sedimentation, and drying. As more acetic anhydride is added, the greater is the yield strength (Dewi *et al*. 2019).

X-ray diffraction (XRD) was applied to identify the formation of crystalline regions in sago seed shell powder (SSP) for both pre-treatment and post-treatment conditions with alkali and peroxide. The untreated sample's XRD results showed a typical semi-crystalline pattern with a large amorphous region. This showed that there were crystalline cellulose components within the amorphous matrix of lignin, hemicellulose, and wax. After being treated with alkali, the XRD analysis showed two clear peaks at $2\theta = 16°$ and 22°. These peaks corresponded to the (110) and (002) crystallographic planes of cellulose type I. This indicates a significant increase in the crystalline fraction due to amorphous material removal. Crystallinity index (CI) values calculated using the Segal empirical method showed an increase in CI from 15% in untreated SSP to 50% after alkali treatment, indicating a dramatic increase in crystallinity. In contrast, peroxide treatment resulted in

lower CI values of 40% for BSSP and 38% for DSSP compared to alkali treatment, with alkali-treated SSP showing maximum crystallinity index values (Jinitha *et al*. 2018b).

Jinitha *et al*. (2016) subjected SSP to chemical treatment using different types of alkali: Sodium hydroxide (NaOH) at a concentration of 5% (SSP), benzoyl peroxide at a concentration of 5% (BSSP), and dicumyl peroxide at a concentration of 6% (DSSP). The chemical structure of sago seed shell samples was analyzed using Fourier transform infrared (FTIR) spectroscopy, both before and after undergoing various treatments. The spectrum shows that the untreated sago seed shells have hydroxyl, carbonyl, and ether functional groups. The broad peak observed in the 3600 to 3200 cm^{-1} range in the spectra of unaltered sago seed shells corresponds to the distinctive O-H stretching vibrations and hydrogen bonding of hydroxyl groups. The frequencies of 2921 and 2854 cm^{-1} correspond to the CH stretching vibrations of C-H and CH_2 in cellulose and hemicellulose components, respectively. The frequency of approximately 1734 cm^{-1} corresponds to the carbonyl stretching (C=O) of the acetyl groups present in hemicellulose. Nevertheless, this frequency was absent in samples treated with alkali and peroxide, suggesting that hemicellulose was eliminated through chemical treatment. The presence of extra water absorption on the sample surface is indicated by a frequency of 1638 cm^{-1}. Also, between 1250 and 1056 cm^{-1} there are frequencies that are made up of C-O stretching vibrations of aliphatic primary and secondary alcohols found in lignin, cellulose, hemicellulose, and extractives. The peak at 897 cm^{-1} on the other hand, which is caused by β-glucosidic bonds, shows that O-C-O is stretching during C-H deformation of cellulose, and this is most noticeable in samples that were treated with alkali or peroxide (Jinitha *et al*. 2018b). Another study compared the functional and chemical properties of commercial sago starch and modified sago starch. To change sago starch samples, different amounts of sodium trimetaphosphate (0.5, 1.0, and 2.0 g) and sodium chloride catalyst (2.0 g and 4.0 g) were added to the reactor in a water bath hotplate that was set to 70 °C and 300 rpm for 1.0 h. Based on the results of the FTIR spectra, this clearly shows a new band related to phosphorylation, with increased intensity at the bending-P=O vibration peaks at 1150–1414 cm^{-1} and stretched P–O–C at 995–1050 cm^{-1} in the sample spectrum. The results of the analysis carried out by the FTIR spectrum showed the success of commercial sago starch modification (Sondari *et al*. 2022).

In other work, Arnata *et al*. (2019) tested the presence of bleach agents and processing times on the characterization of cellulose sago fronds powder. Hydrogen peroxide (HP) at 30% (v/v), peraceticacid (PA), and alkaline hydrogen peroxide (AHP) at pH 10.0 were used as bleaching agents. They divide the processing time into 1.0 h (T1) and 2 h (T2). The research results showed that the type of bleaching agent and its duration during the bleaching process made a significant contribution to the degree of cellulose crystallinity (P-value <0.05). In addition, the use of PA and AHP agents for 2 h presented the highest degree of crystallinity, and no significant differences were seen in both of them. In contrast, the bleaching procedure involving HP resulted in a decrease in crystallinity levels due to the detrimental impact of HP on the cellulose structure. The XRD examination indicated that the initial cellulose II-delineated sago frond fiber (DSF) reverted to type I following the bleaching procedure, resulting in an augmented level of crystallinity. Nevertheless, the bleaching procedure does not induce alterations in the cellulose composition, as indicated by the persistent presence of field peaks 110, 110, and 200 on 2 thetas, each maintaining a value of approximately 14.5°, 16.5°, and 22.5°. This is corroborated by the mean value of the distance (d) that remains constant across the treatment combinations. Furthermore, the bleaching procedure decreases the d-distance

measurement from an initial value of 0.53 nm to 0.51 nm, indicating a denser fiber structure. Typically, as chemical reactivity and water absorption decrease, there is a corresponding rise in physical and mechanical qualities, such as stiffness and tensile strength. This is because of the increase in crystalline size and degree of crystallinity. In this comprehensive study of the sago treatment, they concluded that the bleaching procedure significantly influences the characteristics of cellulose, hence affecting its appropriateness for multiple applications (Arnata *et al*. 2019).

The thermal characteristics of untreated and previously treated sago bark (SB) are examined using thermogravimetric analysis (TGA), as depicted in the TGA and DTG curves (Derivative Thermogravimetry). Pyrolysis involves the thermal decomposition of biomass, where each constituent of a biomass sample might experience alterations in its composition within a specific temperature range. The weight loss behavior of individuals with previously untreated and treated SB can be categorized into three distinct periods. The initial stage takes place within the temperature range of 25 to 125 °C because of the vaporization of both bound and unbound water. The second stage, occurring at temperatures ranging from 150 to 400 °C, entails the initial thermal breakdown of cellulose and hemicellulose, leading to the most substantial reduction in weight. The initial treatment resulted in significant weight loss, mostly attributed to the partial breakdown of hemicellulose and amorphous cellulose, as well as the partial removal of lignin. Prior to the treatment. The use of a 0.01 N (0.08% w/v) sodium bicarbonate ($NaHCO_3$) solution led to a higher amount of weight loss compared to a 0.1 N (0.8% w/v) NaOH solution. During phase three, untreated SB exhibited a higher degree of mass loss compared to the samples that were first treated, most likely due to variations in lignin composition. The presence of temperature peaks at 260 and 350 °C suggests the occurrence of hemicellulose and cellulose breakdown. While there is no distinct peak identified for lignin, it is possible that its peak coincides with the peak of cellulose. Jin and his colleagues observed a minor lignin peak occurring at a temperature of 340 °C. After the removal of lignin, there was a distinct change in the cellulose peak observed in the treated SB samples compared to the untreated SB (Ethaib *et al*. 2020).

Through an acid hydrolysis process and a centrifugation process, Naduparambath *et al*. (2018) turned sago seed shells into a 53-µm powder that was then turned into cellulose nanocrystals (CNC). Cellulose nanocrystals were characterized using scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM), including particle size distribution and zeta potential measurements. The morphology of sago seed shells, α-cellulose, and CNC were observed. The study found that the surface of sago seed shells was very rough and clumped together, while α-cellulose had a structure that formed itself with piles of flakes because of strong hydrogen bonds. As a result of the acid hydrolysis process, the size of the CNCs is reduced significantly, resulting in the removal of the amorphous phase. Drying CNCs is critical for their storage and transportation, as they tend to aggregate around ice crystals during freezing (Naduparambath *et al*. 2018b).

The isolated CNCs presented network-shaped and spherical structures with a size of 10 to 15 nm that could be observed *via* TEM. The processing method, hydrolysis conditions, and ultrasonic treatment all influence their size and contribute to the production of spherical CNCs. The spherical CNCs are formed through the self-assembly of short cellulose rods, facilitated by interfacial hydrogen bonding. The robust hydrogen bonding among CNCs surpasses surface repulsion, leading to the formation of a self-assembled porous network. The drying procedure reveals an abundance of spherical CNCs, which are

believed to be embedded in a network-like structure. Another potential explanation is that the excessive electron beam irradiation during TEM investigations leads to the formation of network-structured cellulose (Naduparambath *et al*. 2018b).

An AFM analysis was conducted to examine the surface morphology of individual CNCs. This analysis revealed distinct topographic features, highlighting the presence of both soft and hard polymer segments. The size of α-cellulose was found to exceed 100 nm, exhibiting distinct regions of light and dark that indicate crystalline and amorphous characteristics. On the other hand, looking at CNCs shows a bright picture that indicates their whole crystalline structure, which includes both spherical shapes and ones that are less than 50 nm in size. The dimensions of the fiber are influenced by the processing method, and sulfuric acid hydrolysis is commonly used to decrease the fiber diameter from microns to nanometers. Nevertheless, AFM measurements can potentially exaggerate the dimensions as a result of tip broadening, particularly in the case of spherical nanoparticles. The result of AFM analysis has shown that nanocellulose has a large surface area, which promotes better interactions between nanocellulose and polymers during the creation of composites (Naduparambath *et al*. 2018b).

A variety of methods are used to examine the surface morphology. A well-known particle size analyzer (PSA) has been utilized for the characterization of sago starch grains, exhibiting an average size of 57.6 μm. The PSA test revealed a reduction in particle size during the hydrolysis and precipitation phases, leading to the production of starch nanoparticles. This method shows the potential to efficiently reduce the size of sago starch granules into nanoparticles. Ethanol and butanol were identified as effective precipitates, and these parameters indicate ethanol to be a more economical choice for large-scale production. The resulting particle size was smaller than that achieved in other studies, where a complex precipitation method was used based on the properties of amylose, forming complex inclusions with hydrophobic components such as ethanol and n-butanol. The left helix structure is formed in this stage, where retrogradation or rearrangement of the starch structure after gelatinization creates a crystal structure (Kasim 2020).

Muslimin *et al*. (2019) analyzed the surface structure of sago fiber (SF) after obtaining liquid smoke from coconut shells with variations in un-treatment and treatment time, including 1, 2, 3, 4, and 5 h of soaking. The SEM test results depict a relatively smooth SF surface under un-treatment conditions, indicating the presence of a lot of lignin on the fiber surface. This surface structure shows a regular rectangular pattern. However, the treatment results show gradual surface hardening after treatment with liquid smoke for 1 to 5 h each. The roughness increases with the 1.0 h length of treatment of soaking displays the beginnings of a groove pattern, which becomes clearer and more regular after 2 h of treatment. With 3 h of treatment, the groove pattern becomes more prominent, and 4 h of soaking shows a rougher pattern with clearer pores. This modification is anticipated to enhance the interaction between the fiber and the matrix chemical, potentially resulting in a stronger link between the two. Immersing the fiber in liquid smoke for a duration of 5 h leads to a reduction in the OH group concentration, resulting in a surface that is rougher, grooved, and porous in comparison to untreated fiber. The roughness is heightened due to the buildup of lignin, which has a higher concentration of hydrogen and oxygen components, on the surface of the fiber. Additionally, the number of carbon bonds also contributes to this rise (Muslimin *et al*. 2019).

Identification of the composition and characterization of natural materials such as cellulose, hemicellulose, and lignin (Imran *et al*. 2024b), plays a crucial role in the performance of a product because it can influence mechanical properties, moisture

absorption, thermal degradation, and biological degradation, as shown in Fig. 3 (Balla *et al*. 2019). Lignocellulosic fibers containing cellulose, hemicellulose, and lignin have great market potential for lightweight and environmentally friendly applications (Darie-Nita *et al*. 2022). However, water absorption, dimensional and thermal stability, and poor compatibility with the fiber matrix require special treatment to improve its performance (Ornaghi *et al*. 2023). The thermal degradation behavior of plant fibers containing cellulose, hemicellulose, and lignin can be predicted based on their chemical composition (Apaydın Varol and Mutlu 2023). The reactivity of cellulose and hemicellulose degradation in wood cell walls is influenced by the presence of lignin and uronic acid, which can be modified through ball milling (Wang *et al*. 2021).

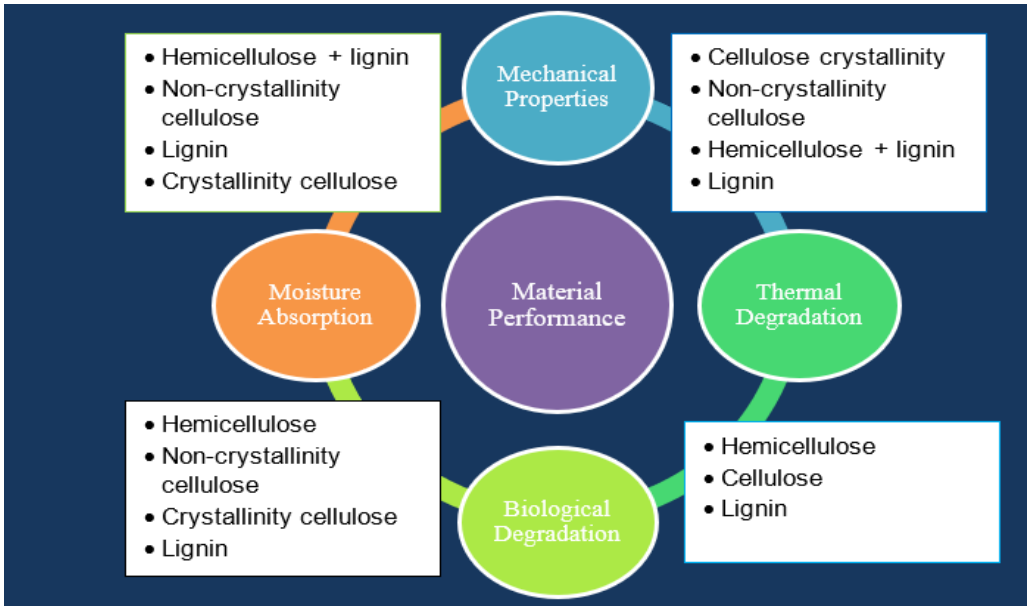

Fig. 3. Impact of natural fiber components on material performance (Balla *et al*. 2019).

Fabrication and Material Testing

Fabrication is an important stage to produce products of superior quality. This section aims to describe the parameters and stages used in processing sago waste into construction materials, as well as several references to material testing standards. Understanding fabrication parameters plays an important role because failed procedures can create poor material strength because they result in an uneven distribution of raw material, thus triggering the formation of agglomeration, porosity, and poor interfacial bonding (Syafri *et al*. 2019). One of the fabrication methods applied is the selection of drying methods applied in the research of Rosli *et al*. (2018), which used a fluidized bed dryer (FBD). They modeled the sago into a two-dimensional (2D) FBD and simulated it using ANSYS Fluent 17.1, where the Euler-Eulerian multiphase model and turbulence model were applied to evaluate the turbulent flow in the dryer. Parameters such as speed and temperature are 1.30 m/s and 50 °C, based on previous experimental data. Additionally, the water content is 10%, or a humidity ratio of 0.25. Then the drying rate and fluidization profile were analyzed at air velocities ranging from 0.6 to 2.2 m/s. The results showed that a speed between 1.0 and 2.2 m/s was the optimal speed for fluidization and drying of sago dregs with a particle size of 2000 µm in a 1-h drying simulation. On the other hand, they also tested the drying rate at air temperatures of 50 °C, 60 °C, 70 °C, and 80 °C, as well as

the fluidization profile at particle sizes of 200, 500, 1000, and 2000 μm. It was finally found that excellent fluidization occurred in the particle size range of 500 μm to 2000 μm at a speed of 1.3 m/s (Rosli *et al*. 2018).

Aside from that, the process of separating sago waste into cellulose fiber also needs to pay attention to several aspects. This stage was carried out by Yacob *et al*. (2018) by soaking sago waste in hot water at 40 °C for 2 h, followed by drying in an oven at 40 °C for 48 h to remove starch and impurities. After that, it goes through chemical treatment using 2% NaOH at a temperature of 60 °C for one hour. The next stage was repeated filtration and washing with distilled water until it reached neutral pH, and the sample was dried at 40 °C for 48 h to determine the cellulose yield and sample composition. Alkaline-treated sago underwent subsequent bleaching treatment involving exposure to a mixture of sodium chlorite and glacial acetic acid ($NaClO_2$/glacial CH_3COOH) at 80 °C for 4 h with mechanical stirring. After that, the samples were washed thoroughly with distilled water and dried at 60 °C. Each treatment was repeated three times to ensure the removal of other constituents present in the waste (Yacob *et al*. 2018). Extraction and treatment methods play a crucial aspect in modifying fiber properties, such as fineness, breaking strength, thermal stability, and chemical composition. On the other hand, the use of glycerol as a solvent and microwave-assisted heating can limit alkali penetration and accelerate the temperature rise, resulting in fibers with appropriate fineness and high fracture strength (Sarath and Tamiloli 2022). In addition, alkali treatment can also affect the physical properties, chemical composition, morphology, and tensile strength of the extracted fibers (Dong *et al*. 2022). Moreover, the duration of alkali treatment can affect the chemical structure and morphology of the fiber, thereby significantly contributing to changes in its tensile properties (García-Méndez *et al*. 2023).

The use of sago in the construction industry needs to be evaluated to meet construction material standards. This aims to ensure that sago is a raw material that shows superior quality and is sustainable. This also facilitates the comparison of quality across various goods and ensures the safety and intended performance of construction materials that use natural plants, such as sago, as their primary raw material. Ali *et al*. (2021) utilized the EN ISO 140-8 standard to measure the decrease in transmission noise caused by floor coverings. On the other hand, EN ISO 717-2 provides a method for calculating a single value of transmission noise for floors (Aly *et al*. 2021). The term EN ISO is generally understood to mean an acronym for "European Standard-International Organization for Standardization," which refers to a global organization that creates standards for different sectors. Several studies have assessed the performance of construction materials according to the American Society for Testing and Materials, as indicated in Table 2. This testing standard is widely available and has been used in many investigational studies.

Table 2. Displays the Standard for Material Testing

Types of Testing	Standards	Authors
Particle size distribution	ASTM D-422	(Mohammad *et al*. 2021)
Moisture content	ASTM D-2974	(Mohammad *et al*. 2021)
Organic content	ASTM D-2974	(Mohammad *et al*. 2021)
Fiber content	ASTM 1997	(Mohammad *et al*. 2021)
Specific gravity	ASTM D-854	(Mohammad *et al*. 2021)
Liquid limit	ASTM D-4318	(Mohammad *et al*. 2021)
Unconfined compression strength	ASTM D-2166	(Mohammad *et al*. 2021)
Light transmission	ASTM D-1003	(Yacob *et al*. 2018)
Tensile strength	ASTM D-882-97	(Yacob *et al*. 2018)

Tensile strength, young's modulus, elongation at break	ASTM D-882-02	(Tan *et al*. 2021)
Melt flow index	ASTM D-1238-01	(Zaman and Beg 2021a)
Izod impact strength	ASTM D-256	(Zaman and Beg 2021a)
Tensile strength	ASTM D-638-03	(Zaman and Beg 2021a)
Flexural strength	ASTM D-790	(Zaman and Beg 2021a)
Impact test	ASTM D-6110	(Maryanto *et al*. 2022)

Properties of Sago Composites

Generally, physical and mechanical capabilities and the degradation ability of construction materials that use sago, are influenced by various aspects, including the composition of the raw materials, which encompasses the type and percentage of materials utilized. Treatment, processing, and drying techniques used during manufacturing all can have an impact on the microstructure and physico-mechanical properties of materials (Rahim *et al*. 2022). Materials qualities are influenced by environmental variables, including air humidity, creatures, and temperature (Ahmad *et a*l. 2022). The physical and mechanical qualities of construction materials can be altered by using supplementary elements such as reinforcement or filler, along with implementing specific structural designs (Dewi *et al*. 2022; Silviana *et al*. 2022). Composite boards fabricated from sago/thatch leaf stalks utilizing epoxy and fiberglass fillers not only fulfil but also surpass the established criteria for physical properties. Furthermore, boards filled with fiberglass exhibit reduced levels of water absorption in comparison to boards filled with epoxy. From an economic standpoint, including fiberglass catalysts in the production process proves to be highly cost-efficient, rendering it a feasible substitute for achieving the water absorption criteria in composite board manufacturing (Samad *et al*. 2022).

Mechanical Performance and Material Durability

Ma *et al*. (2020) conducted a study to examine the influence of incorporating sago fibers into concrete on its mechanical properties, with a specific focus on its implementation at the Nazixia Hydroelectric Power Plant. The study evaluated four distinct fiber densities (0.6, 0.9, 1.2, and 1.5 kg/cm^3). The concrete mix design ratio was established at 1:0.47:2.74:5.09 (cement: water: sand: aggregate), with a water-cement ratio of 0.47. They performed mechanical tests such as strength, energy absorption capacity, and toughness. Cellulose fiber-reinforced concrete (CFRC) with a fiber content of 0.9 kg/m^3 was found to produce better compressive, split tensile, and flexural strength than plain concrete (PC). Furthermore, an evaluation of CFRC faceplates for a 5-year performance duration based on changes in temperature, stress, and strain revealed that the addition of cellulose fibers improved the quality and performance of the faceplate concrete, allowing it to maintain stability in cold climates and during seismic events. This clearly outlines that CFRC is considered a suitable material for concrete slabs in extreme environmental conditions (Ma *et al*. 2020).

When sago fiber is used in building materials, it goes through a surface treatment step that changes the structure of the fiber by getting rid of lignin, cellulose, hemicellulose, and other impurities and making the structure porous to help the fiber stick to other materials better. Strong bonds can improve the physical and mechanical properties of materials. Sago pith and nano-silica from rice husk ash, when combined with PLA (polylactic acid) as a matrix, improve mechanical bonds, making the material more rigid and sturdy and contributing to increased hardness properties. On the other hand, when construction materials are used in high-temperature environments, the presence of

nanosilica becomes a critical aspect of creating excellent thermal insulation and a slow thermal desorption mechanism during the thermal exposure process (Masnar and Coorey 2017). This can be seen when sago starch biocomposite is combined with 3% CNC from rattan biomass and 30% citric acid, which contributes to increased tensile strength because this composition is relatively sufficient for citric acid to play a role in creating strong cross-links between the matrix and CNC, where it interacts with the hydroxyl groups of starch and cellulose molecules through the formation of ester groups (Nasution *et al*. 2017).

Halimatul *et al*. (2019) looked at how sago starch biopolymer composite films mixed with natural particles form sugar palm and mixed with water after being soaked for 2, 4, 6, 8, 10, and 24 h. Also, they looked at what happened when they added small particles with a concentration of 10, 20, 30, 40, and 50 wt.% to sago starch thermoplastic biopolymer composite films. The presence of sugar palm particle in the sago starch film causes a decrease in the film's percentage of water absorption and solubility. This is most likely caused by the formation of a hydrophobic structure and the presence of lignin in the composite, along with an increase in sugar palm particle content. Moreover, the decrease in water absorption and solubility resulting from the increase in crystallinity and good compatibility between matrix and reinforcement contribute to. After soaking for 10 h, the second stage of the water absorption phenomenon also occurred because it was likely caused by water penetration into the sugar palm particles, which was characterized by an increase in water absorption after soaking for 10 h. The results suggest that by adding palm sugar particles, it is possible to produce stronger sago starch films. This is significant for the advancement of biopolymer composite films used in packaging (Halimatul *et al*. 2019). Previous study has reported that the purpose of water vapor barrier qualities is to prevent or minimize the transfer of moisture between the plastic film and the surrounding atmosphere. Chitosan enhances the water vapor barrier characteristics of the film, which is a crucial attribute in the context of construction material applications (Azadi *et al*. 2020).

The weight fraction is a versatile parameter commonly used to assess the efficacy of items, including construction materials made from composite materials. Sago composites possess the benefit of being biodegradable and readily combinable with diverse binders and additional reinforcements. Sarifuddin *et al*. (2014) conducted an analysis on the performance of incorporating sago starch into kenaf core fiber-reinforced polyethylene, specifically examining its resistance to un-weathering and weathering over a duration of 3 and 6 months. The material composition is constructed using different weight fractions. An inverse relationship was established between the rise in kenaf core fiber loading and the decrease in tensile strength, Young's modulus, and elongation at break. This correlation was attributed to exposure to natural weather conditions lasting between 3- and 6-months. Examination using a SEM micrograph reveals that at lower loadings of kenaf core fiber, the morphology exhibits an uneven surface with specific pores occupied by fungi. Nevertheless, composites with a greater proportion of kenaf core fibers exhibited noticeable fungal colonization and the development of substantial fissures. The existence of carbonyl and hydroxyl groups suggests the deterioration of the components during the course of weathering. As the kenaf core fiber content and weathering period rose, the weight loss of the composite also increased. This suggests that there is a possibility of microbial attack on the starch or fiber and hydrolysis of the matrix components (Sarifuddin *et al*. 2014). In a separate study, Sarifuddin *et al*. (2014) found that incorporating sago starch into low-density polyethylene (LDPE) reinforced with kenaf core fiber resulted in elevated thermal stability, water absorption, and hydrophilic behavior. Sago hempas exhibits a high affinity for water molecules, facilitating easy bonding. The addition of

glycidyl methacrylate to free sago results in a reduction in the initial rate of water absorption, which is attributed to the formation of a strong link between the empty sago and the resin (Jamaludin *et al*. 2015).

Sago particleboard serves as a substitute for wood particleboard, aiding in the preservation of forest functions. The physical and mechanical qualities of particleboard made from sago starch can be influenced by numerous key parameters, including material composition, binder type, treatment, manufacturing process, and porosity and void volume (Yani *et al*. 2020). Chiang *et al*. (2015) combined sago particles of different diameters (0.6, 1.18, and 2 mm) with a mixture of sago particles and urea formaldehyde. They used different percentages of 90%, 85%, 80%, 75%, and 70%. The assessment of sago particleboard was conducted according to the Japanese Industrial Standard (JIS) criteria for moisture content, bending strength, internal bonding, and screw test. The composite, consisting of particles with a diameter of 1.18 mm and a weight percentage of 80 wt%, exhibited the maximum internal bond strength. Raising the amount of resin in a material enhances the bonding strength; however, excessively high proportions can diminish strength as a result of resin evaporation during the heating procedure. Moreover, a weight fraction of 80 wt% yielded the highest tensile strength across a broad spectrum of particle sizes. Furthermore, a weight fraction of 80 wt% produced the most optimal tensile strength over a wide range of particle sizes, while increasing resin content and denser packing increased the composite's tensile and screw draw strength (Chiang *et al*. 2015). Another study added fiberglass fillers to particle board composites to improve their physical properties, especially in reducing water absorption. The higher the percentage of fiberglass filler in the composite material, the better it fills the voids in the material, thereby causing a decrease in water absorption (Rahayu *et al*. 2018).

In making concrete bricks, important parameters such as compressive strength and water absorption have a crucial role in determining the quality and usefulness of the final product. High compressive strength can guarantee excellent structural strength, while low water absorption can increase resistance to weather and humidity (Umar *et al*. 2020). Sago's structure is hydrophilic, which means that it easily binds to water molecules. This means that concrete bricks with the right amount of sago and low porosity can keep working well (Norhayati *et al*. 2023; Wahab *et al*. 2023). Sago bricks have a very ductile failure pattern compared to cement bricks because they are influenced by fibers (Nanlohy *et al*. 2023). Sago fiber has good compressive strength and does not crumble easily when subjected to loads because of the contribution of sago fiber in supporting its strength. These fibers also help maintain the bonds within the paste, which consists of sand and cement, under pressure, ensuring the paste remains intact and tough. As a result, sago fiber concrete bricks have strong compressive strength (Umar and Mustafa 2023).

Concrete bricks made from a combination of sago husk, fly ash, and clay were also evaluated by Ornam *et al*. (2017). They studied bulk density, initial rate of absorption (IRA) and salt content, and compressive strength. The sago skin began drying in direct sunlight and was then cut into small pieces approximately 1.2 cm long using a cutting tool. The composition of clay and sago bark was between 1.3% and 3.3%. The clay was mixed with 7% fly ash, fine sago bark, and water it until it can be shaped and was no longer sticky. Each composition was used to print 24 bricks in a rectangular mold ($20 \times 11 \times 4$ cm^3). The bricks were then dried naturally under direct sunlight. The burning process was carried out by maintaining the temperature of the bricks at approximately 550 °C with a fire temperature of around 600 °C. The results show that the composition of the amount of fly ash contributed significantly to bulk density, initial rate of absorption, and compressive

strength, whereas the addition of 3.3% sago husk filler in brick making had the effect of reducing the compressive strength of fly ash bricks from 24 to 16 MPa (Ornam *et al*. 2017). The decrease in compressive strength with an increase in the percentage of sago waste can be caused by differences in particle size and shape, which affect the adhesion and bonding in the brick matrix. Additionally, the presence of sago waste can introduce pores or weak spots in the brick structure, which further reduces the load capacity and allows water to seep into the brick more easily, which in turn increases the overall water absorption capacity (Norhayati *et al*. 2023).

The compressive strength test is carried out to evaluate the composite's ability to withstand compressive forces until it reaches the point of becoming brittle or fracturing. The load is applied gradually to the specimen from above, causing brittleness and breakage due to its limited compression-bearing capacity. Supu and Jaya (2018) studied the compression strength of a sago pulp fiber-reinforced composite by dividing three sample categories based on geometry, drying time, and drying condition. Evaluation results showed that compressive strength varies based on diameter size. Sample-1 showed the highest compressive strength of 0.1221 MPa, while Sample-2 showed a decrease to 0.0671 MPa. Sample-3 had a compressive strength of 0.1067 MPa, and Sample-4 had a compressive strength of 0.1091 MPa. The decrease in compressive strength in Sample-2 was caused by the presence of air voids, as shown in previous research. The correlation between load and loading was directly proportional to the size of the sample, meaning that larger diameter samples will undergo higher levels of stress. Fiber, when combined with water and gypsum in a 1:2:1 ratio, acts as a reinforcing agent that enhances the mechanical characteristics of the composite and decreases the requirement for resin. The ability of a material to withstand force-induced deformation is known as stiffness, whereas its capacity to withstand stress until it fractures is known as toughness. The attainment of stiffness is accomplished by implementing structural modifications that enhance the rigidity of the composite material when subjected to flexibility testing. Sample-1 exhibits the greatest compressive strength in comparison to Samples-2, -3, and -4, which is attributed to its high density and careful selection of fibers. The disparities in outcomes among gypsum fiber samples underscore the diverse attributes of reinforcement materials and their influence on strength. To optimize outcomes, it is crucial to carefully assess the percentage of fiber addition, despite the fact that it normally enhances strength qualities (Supu and Jaya 2018). The dimensions of the test sample and the separation between supports have an impact on the maximum load. Smaller dimensions and shorter support distances lead to higher loads. The strength of sago dreg composite board is contingent upon variables such as the amount of crude fiber present, the type of glue used, and the specific manufacturing procedure employed. External influences, like humidity, density, and temperature, also have an impact on the mechanical properties (Parrangan and Rahayu 2019).

The indigenous knowledge of a region is a valuable resource that enhances the distinctiveness and identity of that region. Sago tree fronds are frequently utilized as a substitute material for fabricating roof tiles for roofing and other components of structures, particularly in indigenous dwellings. While prior research has not investigated the usage of sago leaves in buildings, empirical evidence indicates that sago leaves are still used in traditional dwellings, potentially as a means to mitigate the urban heat island (UHI) phenomenon. Utilizing sago frond fiber, recognized for its thermal and mechanical characteristics in composite materials, can effectively counteract the consequences of rising urban air temperatures in relation to the surrounding regions. Maryanto *et al*. (2021) used the hand lay-up method to fabricate composite materials while manipulating the

NaOH concentration at levels of 4%, 4.5%, 5%, 5.5%, and 6%, along with the epoxy resin-catalyst matrix. The NaOH concentration of 6% and the resin catalyst matrix of 97.5% and 2.5% were tested using impact and differential scanning calorimetry (DSC) tests. The alkaline treatment effectively removed lignin, hemicellulose, and impurities from the fibers, thereby increasing the mechanical capabilities of the material. Furthermore, the results from DSC test indicated that the material's transition temperature decreased by 20% with the addition of NaOH. This shows that the higher the percentage of NaOH, the lower the heat resistance value of the natural composite material reinforced with sago frond fiber (Maryanto *et al*. 2022).

The quality of cement board depends on how well cement and lignocellulosic biomass particles are compatible. Hermawan *et al*. (2020) investigated the suitability of cement with particles from four types of tropical wood (mangium, teak, gelam, and dadap) and sago stems, and determined the physical and mechanical properties of mangium cement board produced with the addition of $MgCl_2$ as a raw material for the accelerator. This study was done in two stages. First, the hydration temperature of the cement particle mixture, including sago stems, was measured with varying $MgCl_2$ concentrations (0%, 2.5%, 5%, and 7.5% based on cement weight). Then two types of mixtures from the first stage were used to produce cement board with a target density of 1.2 g/cm^3. Physical and mechanical testing adheres to the ISO 8335-1987 requirements set by the International Organization for Standardization (ISO). The hydration temperature results indicated that all combinations were categorized as "low inhibition," with the exception of the cement-mangium particle combination without a catalyst, which was classified as "medium inhibition." The test results showed that mangium cement boards made with wood particles and 5% $MgCl_2$ as a catalyst were better in quality than mangium cement boards made without a catalyst (Hermawan *et al*. 2020).

The phenomenon of clay swelling has diverse effects on civil engineering construction. The community has experienced substantial damage upon realizing the detrimental effects on various civic structures constructed on clay. Attempts to stabilize clay soil have been undertaken through the use of stabilizing agents and advancements in soil improvement techniques. Mukti *et al*. (2022) introduced a novel soil stabilization material that involves utilizing sago fiber pulp derived from the combustion residue of sago residue. The test was conducted to assess the viscosity threshold of the clay both before and after its combination with burnt sago pulp fiber ash. The initial soil analysis includes testing for soil compaction and stabilization, as well as determining the soil's bearing capability using the California Bearing Ratio Test (CBR). The findings indicated that the inclusion of ash derived from the combustion of sago dregs had a discernible impact on the properties of the clay. By incorporating 6% bagasse ash, the liquid limit of the soil decreased by 31.1% compared to its initial state. Similarly, the plastic limit decreased by 6.39%, resulting in an 87.8% decrease in the plasticity index. Additionally, the specific gravity experienced a decrease of 4.6% from the original soil condition. On the other hand, the optimum water content increased by 48.4% compared to the original soil condition. The incorporation of ash derived from the combustion of sago pulp exerts an impact on the CBR of clayey soil. The highest CBR value was attained by using 6% ash derived from the combustion of sago dregs. The addition of ash from burning sago dregs resulted in a 28.6% rise in CBR penetration for a value of 0.1, whereas for a value of 0.2, the CBR penetration was 23.8%. The chemical makeup of sago dregs, particularly their silica and alumina concentrations, significantly contributes to enhancing soil stability (Ashad 2022a). The aforementioned components have the ability to undergo a chemical reaction with the

calcium hydroxide present in the ash. This reaction results in the formation of cementation, a process that binds soil particles together and fills the empty spaces between aggregates. Consequently, clay that has been treated with sago pulp ash has notable stabilization capabilities (Ashad 2022b).

Composites play an important function in construction, as they can integrate the qualities of multiple materials to manufacture products with exceptional properties. Zaman and Beg (2021) conducted an experiment in which they reinforced LPDE with sago starch. They assessed the flexural and impact strengths of the material. The starch composition had been divided into 5%, 10%, 15%, 20%, 25%, and 30%. Increased flexural strength and flexural modulus were caused by two things: more starch being added and a better connection between the polymer and starch at the interface. Nevertheless, elevating the starch content leads to a reduction in impact strength, suggesting that the interaction between fillers becomes more apparent compared to the interaction between the matrix and fillers. Furthermore, the process of converting starch into a liquid form might result in a decrease in the ability of the material to withstand impact. This is because the impact strength does not adequately reinforce the composite and can cause it to break prematurely (Zaman and Beg 2021a). The use of 40% sago palm fiber in the composition results in superior interlayer bonding and interfacial strength compared to compositions containing 91% and 64% sago palm fiber. Consequently, it exhibits high impact strength (Saad *et al*. 2022b).

Sago starch can be employed for manufacturing biodegradable edible film material. Film material has the potential to be utilized in construction materials such as wallpaper and as a composite film that serves to conceal house property during cleaning and moving due to its lightweight and transparent characteristics. Tabari (2018) developed a biodegradable edible film using sago starch that was enhanced with carboxymethylcellulose nanoparticles. The film's mechanical characteristics, water absorption capacity, density, and heat sealability were assessed. The composite film was produced *via* a casting technique, incorporating nano-carboxymethyl cellulose at varying weight percentages of 0%, 1%, 2%, 3%, 4%, and 5%. The thermal sealing capability of films used in packaging is of utmost significance. The addition of a modest quantity of nano-CMC resulted in an enhancement of the seal strength of the semolina film. The observed increase is attributed to enhanced hydrogen and other intermolecular bonds formed on the surface of the film due to the presence of nano-CMC. Nevertheless, increasing the proportion of kaolin will diminish the film's capacity to seal, maybe as a result of decreased water content and flexibility. The study examined the influence of CMC nanoparticles on the mechanical characteristics of films. The findings indicate that when the concentration of CMC nanoparticles rises from 0 to 5%, the tensile stress of the film experiences a corresponding increase from 20.2 to 27.0 MPa. Nevertheless, the Young's modulus exhibited an early decline when the content of CMC nanoparticles ranged from 1% to 5%, followed by a little increase at 5% and a subsequent drop. The film using CMC nanoparticles exhibited significantly greater tensile strength in comparison to the control film. Nevertheless, the inclusion of CMC nanoparticles did not have a noteworthy impact on reducing the elongation of the film. The elongation fell from 17.7 to 15.4 as the concentration of CMC nanoparticles increased (ranging from 0 to 5%). The increase in tensile strength was due to better surface contacts between the starch matrix and the filler. This is because their polysaccharide structures are chemically similar (Tabari 2018). The enhancement in tensile characteristics may be attributed to the uniform dispersion of cellulose fibers inside the sago starch matrix. Another factor is the occurrence of hydrogen

bonding interactions between the fiber and the matrix, wherein the cellulose hydroxyl groups might engage with the hydroxyl groups of the starch matrix. Both cellulose fibers and the starch matrix exhibit hydrophilic properties and are mutually compatible. Consequently, the fibers exhibit strong adherence to starch, facilitating efficient transfer of stress from the matrix to the fibers (Yacob *et al.* 2019).

Abral *et al*. (2018) applied an ultrasonication treatment to sago starch film. The point of the study was to look into the features of sago starch films made by ultrasonication, focusing on the amylopectin-rich parts that can change the film's properties. Employing an ultrasonication probe for gelatinization, with durations of 2.5, 5, and 10 min led to alterations in the film's structure and characteristics. The process of ultrasonication led to a partial reduction of gelatinized granules, resulting in films that have a denser structure and decreased permeability to water vapor compared to films that have not been treated. A film with the best transparency and thermal resistance was achieved when it was exposed for the longest duration, which was 10 min. When the film was sonicated for 5 min, its tensile strength increased by 227% and its water absorption decreased by 29.8% compared to films that were not sonicated. Furthermore, subjecting the films to 10 min of ultrasonication resulted in a 7% elevation in the melting temperature when compared to films that were not subjected to sonication. This study clearly shows that ultrasonic treatment contributes to improving the tensile and physical properties of starch-based films (Abral *et al*. 2019a).

The material's ability to absorb sound can affect room acoustics, user comfort, and the quality of sound in the room. By testing the sound absorption of various materials, it is possible to determine the most suitable material to meet a room's acoustic needs. Kusno *et al*. (2019) looked at the sound properties of Sago Midrib composite board with specimen thicknesses of 0.02 m (SM20) and 0.03 m (SM30). They also compared it to plywood with thicknesses of 0.013 m (PW13) and 0.016 m (PW16). They discovered that the absorption coefficient (α) of the SM20 sago frond composite fluctuated below 0.4, with a peak of 0.3 at 400 and 1250 Hz and a peak of 0.4 at 1550 Hz. Likewise, the SM30's α showed a fluctuating pattern, generally below 0.4, with peaks of 0.2 at 400, 950, and 1550 Hz. On the other hand, a comparison of the absorption coefficient between sago composites (SM20, SM30) and plywood (PW16) showed that while PW16 remained stable around 0.05 at all frequencies, SM20 and SM30 produced fluctuations with an average of 0.2. By increasing the thickness of the sago composite from 2 cm to 3 cm, its weight will increase by 25% and its density will decrease from 83 to 73 kg/m^3. This will lead to improved absorption in the mid-frequency range (800 to 1100 Hz) while maintaining similar performance in the high-frequency range (1400 to 1600 Hz). Even though the plywood samples (PW13 and PW16) had a lower absorption coefficient, the dense structure and smoother surface of the industrially manufactured plywood samples gave more consistent measurement results compared to the hand-made, porous composite structure of sago fronds (SM20 and SM30). In general, sago frond composites have greater sound absorption capacity in comparison to plywood. However, their absorption capability varies according to structural irregularities and surface porosity (Kusno *et al*. 2019).

Characterization of Sago Composite

Material characterization is an important aspect in the development and understanding of materials for practical applications and research. By using techniques such as FTIR (Fourier Transform Infrared Spectroscopy), TGA (Thermogravimetric Analysis), XRD (X-Ray Diffraction), and DSC (Differential Scanning Calorimetry),

researchers have previously obtained in-depth information about the structure, composition, and properties of waste. The influence of particle size and weight fraction of Urea Formaldehyde (UF) - Sago particleboard on particleboard performance was evaluated based on FTIR, TGA, and DSC analysis. The particle size indicates the type of sample; samples A, B, and C had small, medium, and large particles. The chemical bonds created in the board were analyzed using FTIR to identify characteristic peaks, where the C-H stretching from UF was at 2914 cm^{-1}, the C=O of the primary amino at 1645 cm^{-1}, and the C-N or NCN stretch of the methylene bond at 1028 cm^{-1}, indicating interactions in the composite. In addition, the percentage of weight loss during decomposition due to changes in temperature was obtained from TGA analysis, with samples A, B, and C occurring at temperatures of 75, 82, and 86 °C. On the other hand, the evaluation of water content and volatile components is known based on the DSC test, where endothermic peaks were observed at temperatures such as 88 °C for sample C, 82 °C for sample B, and 76 °C for sample A. It is clear that the particles and heavy fractions contribute significantly to the thermal stability and curing properties of UF/Sago composite materials (Chiang *et al.* 2016). The degradation of sago fiber in construction materials due to increased temperature can occur under a variety of conditions. Fibers experience water loss and degradation of low-molecular-weight components that are not chemically bound into the fiber in the temperature range of 50 to 150 °C. Then, at temperatures of 150 to 240 °C and 200 to 350 °C, the phenomenon of thermal dehydration of water vapor and hemicellulose degradation becomes apparent. When the temperature reaches 320 and 400 °C, cellulose experiences degradation, which is indicated by structural changes and property changes. Meanwhile, at temperatures from 100 to 900 °C, degradation occurs in lignin, where this condition shows a large influence on the overall thermal behavior of the fiber. Degradation phenomena are very important for optimizing the performance and durability of construction materials when exposed to temperature changes (Sutrisno *et al*. 2019). Other studies report that the particle size and distribution in the composite material as well as the specific characteristics of the resin matrix play a major role in the thermal degradation behavior of UF, Phenol Formaldehyde (PF), and sago particle boards. It is historically clear that particle size has an impact on heat distribution and chemical reactions, thereby influencing the thermal stability of particle board (Tay *et al*. 2016).

The rapid growth of the construction sector has led to a shortage of natural building materials, prompting a shift to more environmentally friendly construction practices. With around 40% of CO_2 emissions coming from construction and building use and 15% from material production, adopting an environmentally friendly approach is essential. Excessive use of natural resources such as river sand and the production of agricultural waste increasingly burdens environmental sustainability. However, agricultural residues, which are usually thrown away, offers a solution as a sustainable alternative material for the construction of green buildings. Exploratory studies of agricultural residue in construction, assessing physical, thermo-mechanical, and ecological impacts, demonstrate commercial viability and the potential to reduce pressure on natural resources (Sangmesh *et al*. 2023). Green materials can be made from bio-composites as thermal insulation panels (Benallel *et al*. 2023). Naduparambath *et al*. (2018) made green material from polyvinyl alcohol (PVOH) and microcrystalline cellulose (MMC) measuring 90 µm from sago seed shells. A significant factor in this research is the heavy fraction of MMC, which is added to PVOH to make green material from sago seed shells. The addition of MMC in various weight fractions (1%, 2%, and 3%) affects the optical properties and morphology of the composite film. The UV-Visible analysis results show that adding more MMC makes the composite

films less clear. In the visible range, the 5PVA-1MCC and 5PVA-2MCC films exhibited the same amount of transmittance. It can be seen that no chemical changes occurred in the composite because no red or blue color changes were observed. In addition, the spherical MMC particles were evenly distributed into the PVOH, as seen from atomic force microscopy (AFM) observations. Furthermore, the use of eco-friendly materials, such as sago seed shells, plays a sustainable role in the construction industry (Naduparambath *et al*. 2018a). Other researchers evaluated membrane composites made from PVA-sago, also made and evaluated by Alamaria *et al*. (2019). Samples were categorized into normal pure (N), chemical (CH), thermal treated (TH), and chemical + thermal (CH + TH) conditions. The results of DSC analysis show that changes in melting temperature for chemical treatment and normal treatment occurred at temperatures of 96 and 60 °C. In addition, TH treatment and CH + TH treatment underwent a melting process at temperatures of 208 and 90 °C (Alamaria *et al*. 2019).

The distribution of sago in the matrix can also be observed using SEM. This is also applied in analyzing 3% sago waste cellulose fiber (SFSW) into sago starch (SF). In the cross section, the SFSW shows several holes and cracks, indicating the exit of the fibers from the matrix and the interaction between the fibers and the matrix. However, the presence of holes indicates reduced binding between the fibers and the starch matrix, potentially explaining the slight increase in tensile properties. Methods such as fiber treatment or plasticizer addition can be considered to improve adhesion (Yacob *et al*. 2018). SEM observations provide information on the bond between particles and the matrix, as well as the distribution of particles in the matrix. Surface incompatibility between particles of different sizes causes weak interfacial adhesion. Furthermore, the particles' insolubility in the UF-matrix means that they tend to clump rather than distribute evenly, which can result in an insufficient contact area between the particles and the matrix. As a result, the bond between the particles and the matrix becomes less strong, increasing the risk of particle detachment and the formation of voids in the material structure (Tay *et al*. 2016). Other research utilizes the method of immersion in liquid smoke to change the surface morphology of sago fiber to make it harder, porous, and grooved, effectively improving the compatibility of sago fiber and epoxy matrix (Muslimin 2022).

Biodegradation Properties of Sago Composites

The significance of biodegradability in construction materials lies in its capacity to mitigate environmental effects by fostering sustainability and minimizing waste accumulation. Biodegradable materials are a sustainable option because they organically decompose over time, reducing the environmental impact associated with construction and infrastructure development. The inclusion of sago in construction materials greatly contributes to deterioration processes in the natural environment, primarily through the actions of water, alkali, natural weathering, and microbes (Demmallino 2020; Zaman and Beg 2021b). Oxygen (O_2) and water (H_2O) play a crucial role in increasing the activity of microorganisms in decomposing construction material waste, as shown in the illustration in Fig. 4.

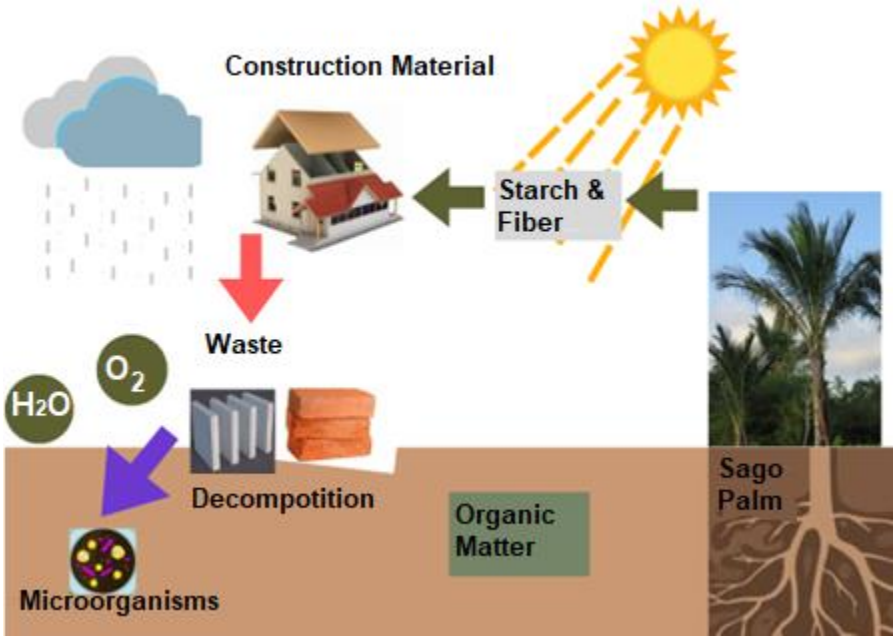

Fig. 4. Schematic illustration of the degradation mechanism of construction materials made from sago-based raw materials.

Future construction materials will need to possess advantageous physical and mechanical features, as well as being environmentally friendly and biodegradable. Beg *et al*. (2021) studied how different conditions can change LDPE that has been mixed with sago starch, urea, manganese stearate, and benzoyl peroxide to start radical reactions. These conditions include hydrolysis, exposure to fungus habitats, natural weathering, and burial in the soil. LDPE and sago starch were dehydrated to a moisture content of less than 1% by subjecting them to a temperature of 80 °C for 24 h. This was done to avoid the creation of a permeable layer. A range of starch concentrations (5% to 30% by weight) consisting of granular sago starch and LDPE with degradant additives (2% urea and 0.1% manganese stearate) were fully combined in a master batch containing 30% starch and subsequently extruded using a Brabender twin screw extruder. The extrusion conditions were configured with temperatures of 150 °C/150 °C/140 °C from the feeder to the die and a screw speed of 80 revolutions per minute. The extruded strands underwent air-cooling, pelleting, and subsequently drying at a temperature of 80 °C for a duration of 24 h in a vacuum oven. Afterward, they were chilled to room temperature in preparation for sample preparation through injection molding. The pellets were utilized to fabricate dumbbell-shaped samples by an injection molding machine with a clamping force of 180 T, operating at a temperature of 160 °C. Distilled water and NaOH were used in the hydrolysis process for 3 to 18 h. NaOH plays a dominant role in accelerating the degradation process by releasing polymer chains due to failures such as cracks, voids, and holes. In addition, samples containing sago starch worked in a moldy environment for 30 days, causing biological mechanisms to emerge from microorganisms, resulting in weight loss. The biodegradation process was observed for 1-, 3-, and 6-months using heat and oxygen as an indication of oxidation and changes in properties due to the formation of free radicals in polyethylene. Moreover, the collapse of the matrix surface was caused by cracks and large holes. The results of this study generally conclude that bleaching, dissolution, or degradation of starch due to microorganism attack causes weight loss (Beg *et al*. 2015).

The biodegradation process can also occur in biopolymers from sago starch, clay, cellulose, zinc oxide, and chitosan, which was reported by Bahruddin *et al*. (2018) and evaluated for biodegradability and water uptake based on ASTM D570 and DIN EN ISO 846. They found that the presence of chitosan contributed to water resistance and made it easy to biodegrade. Biopolymers are relatively easier to decompose in nature due to the presence of OH groups in the bonds between sago, chitosan, and glycerol. On the other hand, the presence of zinc oxide and clay in biopolymers is an inhibitory agent for the biodegradation process because they are hydrophilic (Bahruddin *et al*. 2018). A biocomposite degradation process that also utilized sago starch was reported and analyzed by Syafri *et al*. (2019) through the soil burial test method with a pH of 6.5, a water content of 36.24%, and a relative humidity of 78%. The samples were in the soil for 5 and 15 days, then cleaned with pure water and dried again in an oven at 40 °C for 24 h. After that, it was stored in a desiccator for 24 h to prevent moisture, and then a weight test was carried out. The results of biodegradation testing showed that microorganisms cause the fibers to decompose, and on the other hand, the cellulose content of microfibers contributes as a barrier agent against microorganisms and reduces the rate of biodegradation (Syafri *et al*. 2019). In addition, the study evaluated the biodegradability for 28 days in a landfill of the heavy fraction of sago fiber and its binder with a composition of 1:0, where the decomposition level was the highest compared to other ratios including 1:1, 6:4, 7:3, 8:2, and 9:1 (Konruang *et al*. 2020).

Hendrawati *et al*. (2020) made foam from sago starch and polyvinyl alcohol (PVOH), which was applied to walls, roofs, and floors. They evaluated the contribution of PVOH in foam with different concentrations of 1, 10, 20, 30, 40, and 50 wt%. Biodegradable foam was fabricated for 1.0 h at a temperature of 125 °C using a baking process. The research results show that the higher the concentration of PVOH, the better the water absorption properties and biodegradability. The biodegradable foam samples, when immersed in soil for a duration of 14 days, had a biodegradability of 23.3% in accordance with established criteria. The findings indicate that the biodegradable foam produced from sago starch exhibits a biodegradability range of 4.2% to 47.3%. There was a clear correlation between the rise in PVOH concentration and the increase in biodegradability. Incorporating PVOH to improve the mechanical properties of biodegradable foam does not change how quickly it breaks down; in fact, adding more PVOH makes it easier for the foam to break down. PVOH has a hydroxyl group that makes it easier for bio-foam products to soak up water. Consequently, a higher concentration of PVOH results in a greater degree of water absorption. Water enhances the metabolism of bacteria, leading to an increased capacity for sample degradation (Hendrawati *et al*. 2020). As the duration of the sample's presence in the soil increases, so does the activity of microorganisms that consume starch and create more holes in the polymer, leading to a faster disintegration process (Zaman and Beg 2021a).

CONCLUSION

This review has highlighted sago residue as a promising sustainable alternative for construction materials, valued for its natural abundance, eco-friendly properties, and versatility as both particles and fibers, by examining various extraction methods, from traditional manual techniques to advanced chemical and enzymatic processes. Recently, developments in processing approaches have significantly influenced material

performance. The finding of this review is that key factors, including composition, fiber and particle size, and manufacturing conditions, critically impact the physical and mechanical properties of sago-based materials, underscoring the importance of thorough characterization to ensure safety and suitability for construction applications. In addition, this study contributes valuable insights into sago's potential as a biodegradable construction solution. The limitations in current research are particularly notable in terms of long-term durability and scalability for industrial use. Future work should investigate the effects of fiber treatment on heat resistance, sound absorption, and tribological properties.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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