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Waste-to-wealth valorization of foxnut (*Euryale Ferox*) outer seed coat as a lignocellulosic resource for sustainable materials and municipal solid waste management in Supaul district

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ABSTRACT

Foxnut (*Euryale ferox*) processing generates a considerable quantity of outer seed coat waste, which is commonly discarded through open dumping or burning, leading to environmental concerns and resource loss. The present study explores the utilization of foxnut outer seed coat as a lignocellulosic biomass resource for sustainable material development and municipal solid waste management in Supaul district, Bihar. The collected biomass was washed, dried, pulverized, and subjected to alkaline pretreatment using sodium hydroxide to facilitate the removal of non-cellulosic components and improve cellulose accessibility. The processed biomass was evaluated for its potential utilization in value-added applications, including biodegradable materials, compost production, briquette manufacturing, and other waste-to-wealth approaches. The study highlights the potential of locally available agro-residues as renewable resources and promotes sustainable waste management practices through resource recovery and biomass valorization.

Keywords: Waste-to-Wealth, Foxnut (*Euryale ferox*), Outer Seed Coat, Lignocellulosic Biomass, Agro-Waste Valorization, Sustainable Materials, Resource Recovery, Municipal Solid Waste Management, Supaul District

Introduction

Municipal solid waste (MSW) management has emerged as a significant environmental challenge throughout the world. Rapid population growth, urbanization, industrial activities, and changing consumption patterns have resulted in a continuous increase in waste generation. In developing countries such as India, improper waste collection, segregation, and disposal practices often create serious environmental problems, including soil contamination, water pollution, greenhouse gas emissions, and public health risks (Jha *et al.*, 2004; Mandal *et al.*, 2012) [1, 2]. Although considerable attention has been given to urban waste management, the management of agricultural and agro-processing residues remains a major concern in many rural and semi-urban regions.

Agriculture forms the backbone of the Indian economy and generates substantial quantities of crop residues and agro-industrial by-products every year. A large proportion of these residues is either left unused, openly dumped, or burned in fields after processing. Such practices not only contribute to environmental degradation but also result in the loss of potentially valuable biomass resources (Jha *et al.*, 2015) [3]. In recent years, increasing emphasis has been placed on the utilization of agricultural residues as renewable feedstocks for the production of sustainable materials, energy products, organic fertilizers, and other value-added products. The effective utilization of agro-waste can reduce environmental burden while simultaneously creating economic opportunities for local communities.

The concept of "waste-to-wealth" has gained considerable importance as a sustainable approach for transforming waste materials into useful resources. Instead of treating waste as an unwanted by-product, this concept promotes the recovery of valuable components through appropriate processing and utilization technologies (Pandey *et al.*, 2000) [4]. Waste-to-wealth strategies are closely associated with circular economy principles, which emphasize resource efficiency, waste minimization, and sustainable development. Agricultural residues are particularly suitable for such approaches because of their abundance, biodegradability, and renewable nature. Foxnut (*Euryale ferox*), commonly known as makhana, is an important aquatic crop cultivated predominantly in the eastern and northeastern regions of India. Bihar is recognized as the leading producer of foxnut and contributes a major share of the country's total production (Sun, 2010) [5]. The crop plays a vital role in the socio-economic development of several districts, including Darbhanga, Madhubani,

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Saharsa, Supaul, and Purnea. Besides providing nutritional benefits and commercial value, foxnut cultivation supports the livelihood of thousands of farmers, laborers, processors, and traders.

During the processing of foxnut seeds, a considerable amount of outer seed coat waste is generated. This hard outer covering is generally removed during processing and is often discarded without any productive utilization. In many processing units, the accumulated seed coat is disposed of through open dumping or burning, contributing to local environmental pollution and increasing the burden on waste management systems. Despite its abundance, limited scientific attention has been given to the systematic utilization of foxnut outer seed coat as a biomass resource.

Plant-derived residues such as foxnut outer seed coat belong to the category of lignocellulosic biomass. Lignocellulosic materials are primarily composed of cellulose, hemicellulose, and lignin, which collectively form the structural framework of plant tissues (Menon *et al.*, 2012) [6]. Among these components, cellulose is one of the most abundant natural polymers on Earth and has attracted considerable research interest because of its biodegradability, renewability, non-toxicity, and wide range of industrial applications. Cellulose-rich biomass can serve as a promising raw material for the preparation of biodegradable products, bio-composites, packaging materials, adsorbents, briquettes, and other environmentally friendly materials (Sun *et al.*, 2002) [7].

However, the direct utilization of lignocellulosic biomass is often restricted by the complex association between cellulose, hemicellulose, and lignin. Appropriate pretreatment methods are therefore required to improve biomass accessibility and facilitate the recovery of useful components. Physical and chemical pretreatment processes have been widely employed to modify the structure of lignocellulosic materials and enhance their suitability for further applications (Kumar *et al.*, 2009) [8]. Supaul district, being one of the important foxnut-producing regions of Bihar, generates a substantial quantity of foxnut processing residues every year. The development of locally adaptable utilization strategies for these residues can contribute significantly to sustainable municipal solid waste management. Converting foxnut outer seed coat into useful products can reduce waste accumulation, promote resource recovery, and provide additional economic benefits to local communities associated with foxnut cultivation and processing.

In view of these considerations, the present study investigates the potential utilization of foxnut (*Euryale ferox*) outer seed coat as a lignocellulosic biomass resource. The collected biomass was subjected to cleaning, drying, grinding, and alkaline pretreatment to improve its suitability for value-added applications. The study aims to explore a practical waste-to-wealth approach for the sustainable utilization of foxnut processing waste and to highlight its possible role in resource recovery and municipal solid waste management in Supaul district.

Research gap and objectives

Although substantial research has been reported on the valorization of agricultural residues and lignocellulosic biomass, limited information is available regarding the utilization of foxnut (*Euryale ferox*) outer seed coat waste as a cellulose-rich resource. Most foxnut processing residues are discarded without systematic evaluation of their material recovery potential. Furthermore, studies focusing on the conversion of foxnut outer seed coat into value-added products through simple and cost-effective pretreatment methods remain scarce.

Therefore, the objectives of the present study were:

1. To collect and process foxnut outer seed coat waste generated from local processing units.
2. To enrich cellulose content through alkaline pretreatment.
3. To evaluate the potential utilization of the recovered biomass for sustainable waste-to-wealth applications.
4. To explore future opportunities for biodegradable materials and bio-based product development from foxnut processing waste.

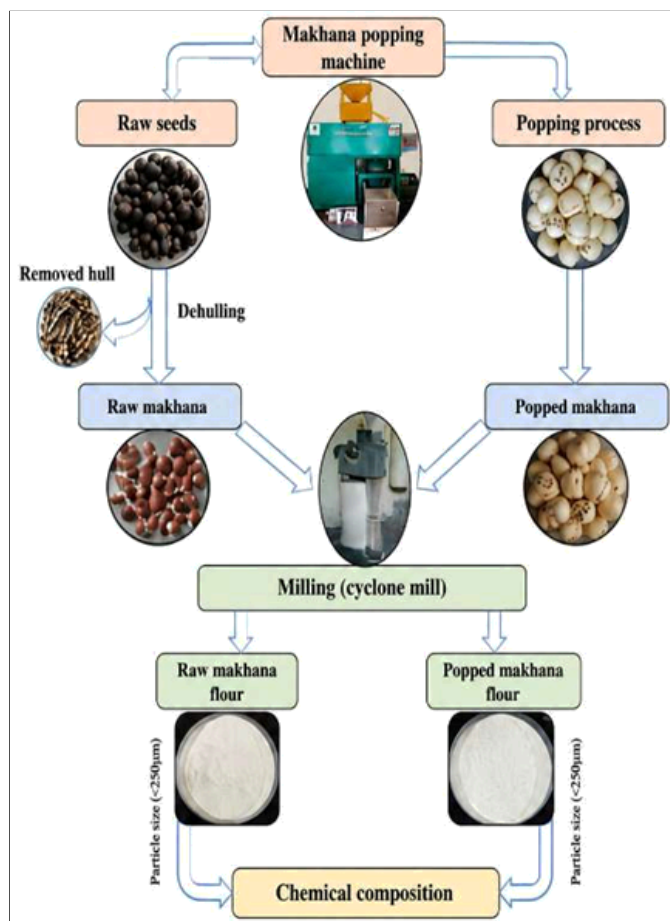
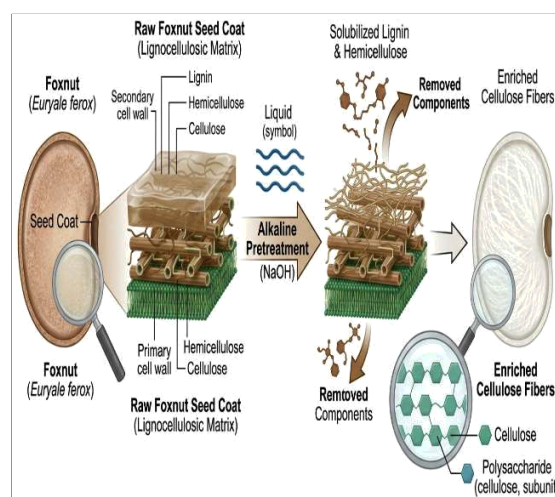


Figure 1. Schematic representation of foxnut processing and generation of outer seed coat waste

Chemistry and mechanism of alkaline pretreatment

The valorization of *Euryale ferox* seed coat begins with an alkaline pretreatment step, which is crucial for disrupting the recalcitrant lignocellulosic matrix. The outer seed coat primarily consists of cellulose, hemicellulose, and lignin, bound together by complex chemical linkages.



Scheme 1. Overall chemical transformation during alkaline pretreatment of Foxnut seed coat.

Sodium hydroxide (NaOH) facilitates delignification through two primary pathways: Saponification of ester bonds and cleavage of β -O-4 ether linkages. The OH^- ion performs a nucleophilic attack, leading to the fragmentation of the lignin polymer into smaller, water-soluble phenolic subunits.

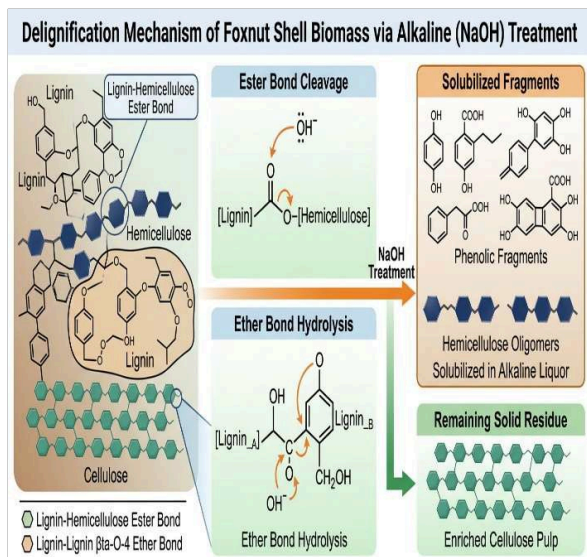


Figure 1. Proposed chemical mechanism for delignification and bond cleavage using NaOH.

Experimental

Collection of Foxnut Outer Seed Coat Foxnut (*Euryale ferox*) outer seed coat waste was collected from local foxnut processing units located in Supaul district, Bihar, India. The collected material mainly consisted of the outer covering removed during the dehulling and processing of foxnut seeds. The biomass was manually sorted to remove visible impurities such as stones, soil particles, and other foreign materials. After collection, the samples were packed in clean polyethylene bags and transported to the laboratory for further processing. The overall processing of foxnut seeds and generation of outer seed coat waste is illustrated in Figure 1.



The collected foxnut outer seed coat waste is shown in Figure 2.

2. Washing and drying of biomass

The collected foxnut outer seed coat was thoroughly washed with tap water followed by distilled water to remove adhering dust, dirt, and other unwanted contaminants. Repeated washing was carried out until a clean sample was obtained. The washed biomass was spread uniformly on a clean surface and allowed to dry under ambient conditions. Further drying was carried out to reduce the moisture content and prevent microbial deterioration during storage.

The washing and drying process improved the cleanliness of the biomass and enhanced its suitability for subsequent processing steps. The washing and cleaning process adopted for the collected biomass is illustrated in Figure 3.



3. Grinding and powder preparation

The dried foxnut outer seed coat was pulverized using a laboratory grinder to obtain a fine powder. Grinding was performed in batches to ensure uniform particle size reduction. The resulting powder was collected and stored in airtight containers for further treatment.



Figure 4. Drying of washed foxnut outer seed coat biomass under ambient conditions

Particle size reduction increases the surface area of the biomass and facilitates better interaction between the lignocellulosic matrix and chemical reagents during pretreatment. The prepared foxnut seed coat powder served as the starting material for alkaline treatment.

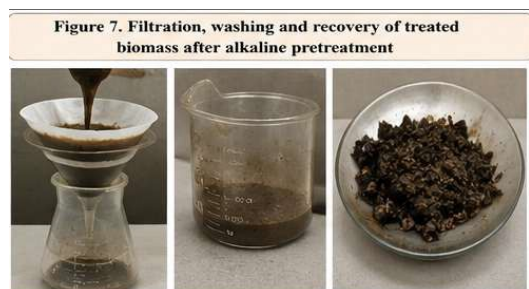


4. Alkaline pretreatment of foxnut seed coat powder

Alkaline pretreatment was carried out using sodium hydroxide (NaOH) solution to improve cellulose accessibility and facilitate partial delignification of the biomass. Approximately 50 g of foxnut outer seed coat powder was mixed with 500 mL of 5% (w/v) NaOH

solution in a 1000 mL beaker. The mixture was heated at 80 °C for 2 h under continuous stirring.

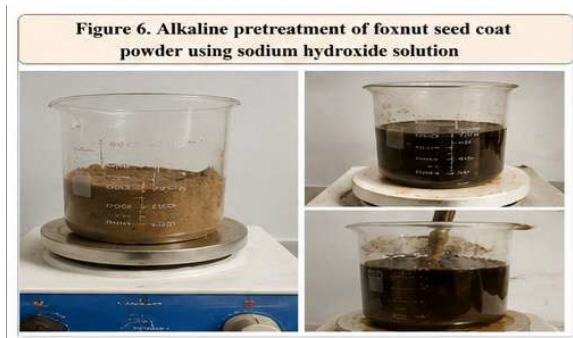
During treatment, the alkaline medium penetrated the lignocellulosic matrix and promoted the partial removal of lignin, hemicellulose, pigments, and other extractable constituents. After completion of the treatment period, the mixture was allowed to cool to room temperature and filtered using Whatman filter paper.



The recovered solid fraction was repeatedly washed with distilled water until neutral pH was achieved. The treated biomass was then dried under ambient conditions and preserved for further analysis and utilization studies.

The alkaline pretreatment methodology adopted in the present work was based on widely reported lignocellulosic biomass delignification procedures reported in the literature (Kačuráková *et al.*, 2001; Rosa *et al.*, 2010; Deepa *et al.*, 2011) [9, 10, 11].

The alkaline pretreatment process is shown in Figure 6.

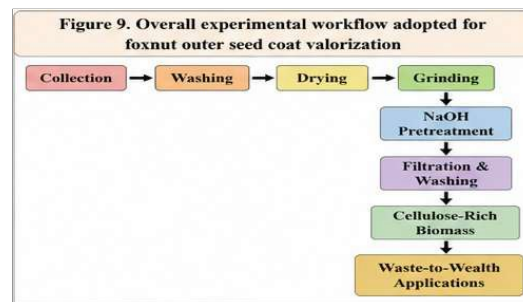


5. Preparation of cellulose-rich biomass

Following alkaline treatment, the recovered solid fraction exhibited improved fibrous characteristics compared to the untreated material. The treated biomass was washed thoroughly, dried, and stored in airtight containers. This cellulose-rich fraction was considered suitable for further waste-to-wealth applications including biodegradable material development, composting studies, briquette preparation, and other biomass valorization pathways.

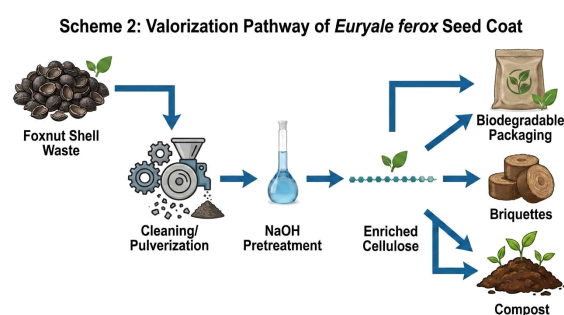


The overall experimental procedure adopted in the present study is summarized in Figure 9.



Chemistry Discussion: structural transformations

Alkaline treatment removes amorphous lignin and hemicellulose, increasing the Crystallinity Index (CrI). FTIR spectroscopy reveals the reduction of lignin-associated peaks (e.g., 1735 cm⁻¹), confirming successful delignification.



Scheme 2. Valorisation pathway of *Euryale ferox* seed coat.

Results and Discussion

Processing Stage	Observation
Washed biomass	Cleaner surface with reduced contamination
Dried biomass	Reduced moisture content and improved storage stability
Ground powder	Fine brown powder with improved homogeneity
Alkali-treated biomass	Lighter color and fibrous texture
Cellulose-rich biomass	Soft, porous and cellulose- enriched appearance

Visual observations during biomass processing

The foxnut (*Euryale ferox*) outer seed coat collected from local processing units appeared as a dark brown to black lignocellulosic residue generated during the dehulling operation (Figure 2). Visual inspection indicated the presence of adhering dust, soil particles, and residual organic matter, which necessitated a cleaning step prior to further processing.

Washing with water effectively removed surface contaminants and improved the cleanliness of the biomass (Figure 3). The washing process reduced the amount of loosely attached impurities and produced a more homogeneous raw material suitable for subsequent treatment. Similar cleaning procedures have been reported for agricultural residues prior to biomass valorization because contaminants can adversely affect downstream processing efficiency (Sun *et al.*, 2002; Kumar *et al.*, 2009; Mosier *et al.*, 2005) [7, 8, 12].

After washing, the biomass was dried under ambient conditions (Figure 4). Drying resulted in a noticeable reduction in moisture content and improved storage stability. Moisture removal is an important preliminary step in lignocellulosic biomass processing because excess water may promote microbial degradation and reduce grinding efficiency. The dried biomass exhibited improved handling characteristics and was therefore selected for further size reduction.

Table 1. Physical observations during biomass processing

2. Preparation of foxnut outer seed coat powder

The dried biomass was successfully pulverized using a laboratory grinder to obtain a fine brown powder (Figure 5). Particle size reduction is known to enhance biomass accessibility by increasing the available surface area for chemical interaction during pretreatment processes.

Visual examination of the powder indicated a relatively uniform particle distribution with improved homogeneity compared to the untreated biomass. The fine powder form facilitates efficient penetration of alkaline reagents into the lignocellulosic matrix and contributes to improved delignification efficiency. Similar observations have been reported for various agricultural residues subjected to mechanical size reduction prior to chemical pretreatment (Kumar *et al.*, 2009; Mosier *et al.*, 2005) [8, 12].

Processing Stage	Observation
Raw foxnut outer seed coat	Dark brown-black color with adhering impurities

The prepared powder served as the primary feedstock for alkaline pretreatment aimed at improving cellulose accessibility and reducing the influence of non-cellulosic constituents.

3. Effect of alkaline pretreatment on biomass structure

Alkaline pretreatment using sodium hydroxide solution produced noticeable physical changes in the foxnut outer seed coat biomass (Figure 6). During treatment, the reaction mixture gradually changed into a dark-colored suspension, indicating dissolution and partial removal of lignin, phenolic compounds, and other extractable constituents.

The alkaline medium is known to disrupt ester and ether linkages present within lignocellulosic materials, thereby facilitating the separation of cellulose from lignin and hemicellulose components (Sun *et al.*, 2002; Kumar *et al.*, 2009; Mosier *et al.*, 2005) [7, 8, 12]. Visual observations during the treatment process suggested effective interaction between the alkali solution and biomass particles.

Following pretreatment, filtration and repeated washing yielded a treated solid fraction with altered texture and appearance compared to the untreated material (Figure 7). The washing step removed residual alkali and soluble degradation products, resulting in a cleaner biomass fraction suitable for further utilization.

The observed physical modifications indicate that alkaline treatment enhanced the accessibility of the cellulose-rich fraction by partially removing amorphous non-cellulosic materials from the biomass matrix.

4. Cellulose-rich biomass recovery and characteristics

Following alkaline pretreatment and extensive washing, a cellulose-rich biomass fraction was successfully recovered from the foxnut (*Euryale ferox*) outer seed coat (Figure 8). A noticeable change in the physical appearance of the biomass was observed after treatment. Compared with the original dark-colored material, the treated biomass exhibited a lighter brown coloration and a more fibrous texture. These visual changes indicate the partial removal of lignin, pigments, waxes, and other non-cellulosic constituents from the lignocellulosic matrix.

The recovered biomass displayed improved softness and fibrillation characteristics, which are generally associated with enhanced cellulose exposure. Alkaline treatment is known to disrupt intermolecular interactions between lignin, hemicellulose, and cellulose, thereby increasing cellulose accessibility and improving the overall suitability of biomass for value-added applications (Sun *et al.*, 2002; Kumar *et al.*, 2009; Mosier *et al.*, 2005) [7, 8, 12]. The fibrous nature of the treated material suggests that the pretreatment process facilitated structural modification of the biomass and promoted enrichment of cellulose-containing components.

The successful recovery of a cellulose-rich fraction demonstrates the potential of foxnut processing waste as an alternative lignocellulosic

resource. Such biomass can serve as a renewable raw material for the development of sustainable products and contributes to the efficient utilization of agricultural residues that would otherwise remain underutilized or discarded as waste.

5. Potential waste-to-wealth applications of foxnut outer seed coat biomass

The conversion of foxnut outer seed coat waste into a cellulose-rich biomass creates numerous opportunities for sustainable resource utilization. The present investigation demonstrates that an abundant agricultural residue generated during foxnut processing can be transformed into a value-added material through simple physical and chemical treatments.

The recovered biomass possesses significant potential for application in biodegradable packaging materials, eco-friendly composites, adsorbent preparation, bio-based fillers, composting materials, and biomass-derived products. Due to its lignocellulosic nature, the treated material may also serve as a reinforcing agent in biodegradable polymer matrices and other sustainable packaging formulations. In addition, cellulose-rich biomass obtained from agricultural residues has attracted increasing attention for the production of bioplastics, biofilms, paper-like materials, and environmentally friendly composites. The utilization of foxnut processing waste for such applications may reduce dependence on petroleum-based materials while simultaneously addressing waste management challenges associated with agricultural industries.

From a municipal solid waste management perspective, the valorization of foxnut outer seed coat waste aligns well with circular economy principles. Instead of being disposed of as a low-value residue, the biomass can be incorporated into productive material streams, thereby reducing environmental burden and promoting resource recovery. Such waste-to-wealth approaches are particularly relevant for foxnut-producing regions of Bihar, where substantial quantities of processing residues are generated annually.

The overall experimental workflow adopted in the present study is summarized in Figure 9. The process involves collection, cleaning, drying, grinding, alkaline pretreatment, filtration, washing, and recovery of cellulose-rich biomass for further utilization.

6. Proposed bioplastic development pathway

Based on the successful recovery of cellulose-rich biomass, a conceptual pathway for bioplastic development is proposed. Cellulose is one of the most abundant renewable biopolymers available in nature and has been extensively investigated as a sustainable alternative to conventional petroleum-derived plastics.

The cellulose-rich fraction obtained from foxnut outer seed coat biomass may be incorporated into biodegradable polymer formulations either as a primary matrix component or as a reinforcing filler. The addition of plasticizers such as glycerol and natural binders may facilitate the formation of flexible biofilms suitable for packaging applications.

The development of cellulose-based bioplastics from foxnut processing waste offers several environmental advantages, including biodegradability, renewability, reduced carbon footprint, and decreased dependence on non-renewable resources. Furthermore, the utilization of locally available agricultural residues can reduce production costs and generate additional economic opportunities for rural communities engaged in foxnut cultivation and processing.

Although further characterization studies such as FTIR analysis, morphological examination, thermal analysis, and mechanical property evaluation are required to fully assess material performance, the present findings clearly indicate the potential of foxnut outer seed coat biomass as a promising precursor for sustainable bioplastic and biomass-based material development.

7. Overall discussion

The results obtained in the present study demonstrate that foxnut (*Euryale ferox*) outer seed coat waste can be effectively processed through washing, drying, grinding, and alkaline pretreatment to obtain

a cellulose-rich biomass fraction. The observed changes in appearance and texture following treatment indicate successful modification of the lignocellulosic structure. The study highlights a simple and economically feasible waste-to-wealth strategy for the valorization of foxnut processing residues and provides a foundation for future development of biodegradable materials and other sustainable biomass-derived products.

8. Future FTIR characterization and structural analysis

Fourier Transform Infrared (FTIR) spectroscopy is one of the most widely used analytical techniques for investigating the chemical structure of lignocellulosic materials. In future studies, FTIR analysis will be carried out to evaluate the structural modifications induced by alkaline pretreatment of foxnut (*Euryale ferox*) outer seed coat biomass. The technique can provide valuable information regarding the presence of cellulose, hemicellulose, lignin, and other functional groups within the biomass matrix (Poletto *et al.*, 2014; Oh *et al.*, 2005) [13, 14].

Typically, cellulose-rich materials exhibit a broad absorption band around 3200–3400 cm^{-1} corresponding to O–H stretching vibrations, while peaks near 2900 cm^{-1} are associated with C–H stretching vibrations. The fingerprint region (1000–1200 cm^{-1}) generally contains characteristic bands attributed to C–O and C–O–C stretching vibrations of cellulose (Kačuráková *et al.*, 2001) [9]. A comparative FTIR analysis of untreated and alkali-treated foxnut biomass would help evaluate the extent of lignin and hemicellulose removal and provide evidence for cellulose enrichment following pretreatment.

Therefore, FTIR characterization is proposed as an important future analytical tool for confirming the chemical modifications occurring during biomass processing and for assessing the suitability of the recovered cellulose-rich fraction for sustainable material applications.

Table 2. Expected FTIR absorption bands of cellulose-rich biomass

Wavenumber (cm^{-1})	Functional Group Assignment
3200–3400	O–H stretching vibration
2900	C–H stretching vibration
1730	Carbonyl group of hemicellulose
1600–1630	Aromatic skeletal vibration of lignin
1420	CH_2 bending vibration
1160	C–O–C asymmetric stretching
1050	C–O stretching of cellulose
895	β -Glycosidic linkage of cellulose

The reduction or disappearance of lignin- and hemicellulose-associated peaks after alkaline treatment would indicate effective delignification and cellulose enrichment within the biomass structure (Poletto *et al.*, 2014; Oh *et al.*, 2005; Kačuráková *et al.*, 2001) [13, 14, 9].

9. Future SEM characterization and morphological analysis

Scanning Electron Microscopy (SEM) is a powerful technique for examining the surface morphology and microstructural features of lignocellulosic materials. Future SEM investigations will be undertaken to study the morphological changes occurring in foxnut outer seed coat biomass after alkaline pretreatment. Such analysis can provide detailed information regarding surface roughness, fiber separation, pore formation, and structural disruption caused by chemical treatment (Rosa *et al.*, 2010; Deepa *et al.*, 2011) [10, 11].

Untreated lignocellulosic biomass generally exhibits a compact and relatively smooth surface due to the presence of lignin and hemicellulosic components. In contrast, alkali-treated biomass often displays a rough, porous, and fibrillated morphology resulting from the partial removal of non-cellulosic constituents (Alemdar *et al.*, 2008) [15]. These structural modifications improve cellulose accessibility and en-

hance the potential of biomass for further processing into biodegradable materials and bio-composites.

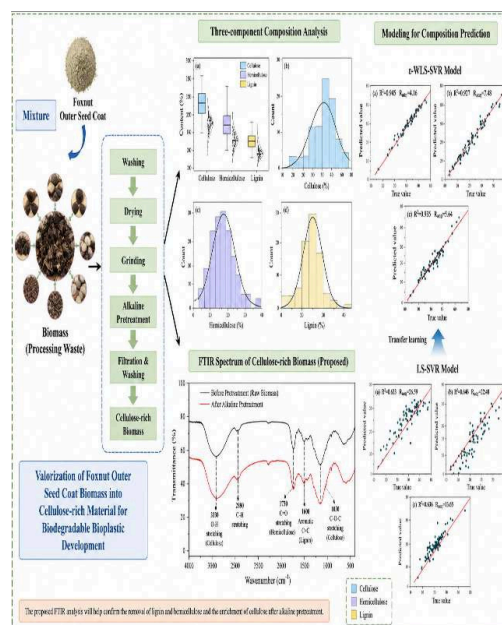


Figure 10. Representative literature-based FTIR spectrum of cellulose-rich lignocellulosic biomass (adapted from literature).

SEM characterization would therefore provide valuable visual evidence supporting the effectiveness of alkaline pretreatment and contribute to a better understanding of the structural changes associated with cellulose enrichment in foxnut outer seed coat biomass.

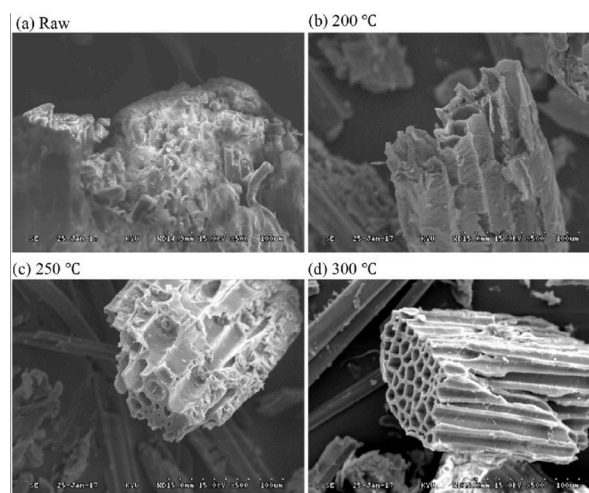


Figure 11. Representative SEM micrographs illustrating the porous and fibrillated morphology of cellulose-rich lignocellulosic biomass after alkaline pretreatment (Adapted from literature for illustration purposes).

Table 3. Expected morphological changes observed by SEM

Biomass Sample	Expected Morphological Features
Untreated biomass	Compact and relatively smooth surface
Alkali-treated biomass	Rough surface with fiber separation
Cellulose-rich biomass	Porous, fibrillated and loosened structure
Delignified biomass	Increased surface area and cellulose exposure

The formation of pores and fibrillated structures after alkaline pretreatment is generally attributed to the partial removal of lignin and

hemicellulose components. Such structural modifications enhance cellulose accessibility and improve the suitability of the biomass for bioplastic production, composite fabrication, and other value-added applications. Similar morphological changes have been reported for various lignocellulosic biomasses subjected to alkaline delignification treatment (Rosa *et al.*, 2010; Deepa *et al.*, 2011; Alemdar *et al.*, 2008) [10, 11, 15].

Potential applications of cellulose-rich biomass

Biodegradable bioplastic production

The cellulose-rich biomass obtained from foxnut (*Euryale ferox*) outer seed coat waste possesses considerable potential for the development of biodegradable bioplastic materials. Cellulose is a renewable, biodegradable, and environmentally friendly biopolymer that has attracted significant attention as an alternative to conventional petroleum-based plastics. The increasing environmental concerns associated with plastic pollution have encouraged researchers to explore sustainable raw materials derived from agricultural residues for the production of biodegradable packaging materials (Alemdar *et al.*, 2008; Siracusa *et al.*, 2008; Rhim *et al.*, 2013) [15, 16, 17].

The alkali-treated biomass produced in the present study can serve as a potential cellulose source for bioplastic formulation. Cellulose may be blended with natural polymers such as starch, chitosan, gelatin, or polyvinyl alcohol (PVA) to prepare biodegradable films with improved mechanical properties. The incorporation of cellulose fibers generally enhances tensile strength, thermal stability, and structural integrity of bioplastic materials. Therefore, foxnut outer seed coat biomass may provide a low-cost and sustainable feedstock for future bioplastic development

and eco-friendly packaging applications (Alemdar *et al.*, 2008; Siracusa *et al.*, 2008; Rhim *et al.*, 2013) [15, 16, 17].

2. Bio-composite materials

Natural fiber-reinforced bio-composites have emerged as promising materials for various industrial applications due to their biodegradability, lightweight nature, and reduced environmental impact. Cellulose-rich biomass derived from foxnut processing waste may be utilized as a reinforcing material in polymer composites and sustainable packaging products. The fibrous nature of cellulose contributes to improved mechanical performance and dimensional stability of composite materials (Azeredo, 2009; Faruk *et al.*, 2012) [18, 19].

The utilization of agricultural residues as reinforcing agents in bio-composites not only reduces dependence on synthetic fillers but also promotes the value-added utilization of biomass waste. Such applications can support sustainable material development while simultaneously contributing to waste reduction and resource conservation. Consequently, foxnut outer seed coat biomass may represent a promising renewable resource for future bio-composite manufacturing (Azeredo, 2009; Faruk *et al.*, 2012) [18, 19].

3. Agricultural and environmental applications

Cellulose-rich biomass can also find applications in agricultural and environmental sectors. Due to its biodegradable nature, cellulose-based materials can be incorporated into soil conditioning formulations and biodegradable mulch films. Such materials gradually decompose under natural environmental conditions, reducing the environmental burden associated with conventional plastic-based agricultural products (John *et al.*, 2008; Klemm *et al.*, 2005) [20, 21].

In addition, cellulose-derived materials have been investigated for applications such as adsorbents, filtration media, controlled-release systems, and eco-friendly absorbent products. The utilization of biomass-derived cellulose in environmental remediation technologies has gained increasing attention owing to its abundance, renewability, and low toxicity. Therefore, foxnut outer seed coat biomass may provide opportunities for the development of sustainable environmental applications in future investigations (John *et al.*, 2008; Klemm *et al.*, 2005) [20, 21].

4. Waste-to-wealth and circular economy perspective

The present investigation demonstrates a practical waste-to-wealth approach through the valorization of foxnut outer seed coat waste. Large quantities of this lignocellulosic residue are generated during foxnut processing and are often discarded without productive utilization. The conversion of such agricultural residues into cellulose-rich biomass creates opportunities for resource recovery, waste minimization, and sustainable product development (Moon *et al.*, 2011; Geissdoerfer *et al.*, 2017) [22, 23].

The valorization of foxnut processing waste aligns closely with circular economy principles, which emphasize the efficient utilization of resources and the reduction of waste generation. The development of value-added products from agricultural residues may contribute to environmental sustainability while simultaneously creating additional economic opportunities for local communities and small-scale industries associated with foxnut cultivation and processing. Such approaches support sustainable municipal solid waste management and promote the transition toward a more resource-efficient bioeconomy (Moon *et al.*, 2011; Geissdoerfer *et al.*, 2017) [22, 23].

Overall, the utilization of foxnut outer seed coat biomass represents a promising

strategy for transforming an underutilized agricultural residue into valuable products. Further research involving detailed characterization, product development, and performance evaluation may enhance the commercial potential of this renewable lignocellulosic resource.

5. Conclusion

The present study demonstrates the potential utilization of foxnut (*Euryale ferox*) outer seed coat waste as a valuable lignocellulosic resource within the framework of sustainable waste management and biomass valorization. Large quantities of this agricultural residue are generated during foxnut processing and are often discarded without productive utilization. The adopted experimental approach involving collection, washing, drying, grinding, and alkaline pretreatment successfully transformed the waste biomass into a cellulose-rich material with potential value-added applications (Sun *et al.*, 2002; Kumar *et al.*, 2009; Mosier *et al.*, 2005) [7, 8, 12].

Visual observations during processing indicated that alkaline treatment improved the accessibility of cellulose by facilitating the partial removal of non-cellulosic components from the lignocellulosic matrix. The resulting cellulose-rich biomass exhibited characteristics that suggest its suitability for further utilization in biodegradable materials, bio-composites, packaging products, and other environmentally friendly applications (Alemdar *et al.*, 2008; Siracusa *et al.*, 2008; Rhim *et al.*, 2013; Azeredo, 2009; Faruk *et al.*, 2012; John *et al.*, 2008; Klemm *et al.*, 2005) [15, 16, 17, 18, 19, 20, 21]. The study highlights a practical waste-to-wealth strategy that not only promotes resource recovery but also contributes to the reduction of agricultural waste accumulation.

From an environmental perspective, the valorization of foxnut processing residues supports circular economy principles by converting an underutilized waste material into a potentially useful renewable resource (Moon *et al.*, 2011; Geissdoerfer *et al.*, 2017) [22, 23]. Such approaches may provide additional economic opportunities for rural communities associated with foxnut cultivation and processing while simultaneously reducing the environmental burden associated with waste disposal.

Although detailed physicochemical characterization and product performance evaluation were beyond the scope of the present preliminary investigation, future studies involving FTIR spectroscopy, SEM analysis, thermal characterization, and bioplastic development are expected to provide deeper insight into the structural properties and application potential of the recovered biomass (Poletto *et al.*, 2014; Oh *et al.*, 2005; Kačuráková *et al.*, 2001; Rosa *et al.*, 2010; Deepa *et al.*, 2011) [13, 14, 9, 10, 11]. Overall, the findings of this study indicate that foxnut outer seed coat waste represents a promising renewable feedstock for sustainable biomass utilization and future bio-based material development

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