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Physicochemical and Lignocellulosic Characterization of Jackfruit (*Artocarpus heterophyllus*) Processing Waste as a Potential Biomass Resource

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Abstract

A Considerable amount of peel, rind, core, and fibrous residues are produced from the processing of Jackfruit (*Artocarpus heterophyllus* Lam.), which are generally discarded, though they contain valuable lignocellulosic components. Limited information is available on the composition of the combined jackfruit processing waste stream. Thus, the present study evaluates the physicochemical and lignocellulosic properties of jackfruit processing waste obtained from local markets and prepared with equal proportions of peel, rind, fibrous rags, and core. Proximate analysis revealed moisture, ash, crude protein, crude fat, crude fibre, and available carbohydrate contents of 8.18 ± 0.28, 4.18 ± 0.24, 8.50 ± 0.08, 3.10 ± 0.18, 13.50 ± 0.18, and 62.54 g/100 g, respectively. The lignocellulosic material was characterized by the cellulose, hemicellulose, and lignin contents of 23.35 ± 0.68, 25.50 ± 0.72, and 18.32 ± 0.62

g/100 g, respectively. The measured values of neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) were 67.17 ± 1.17, 41.67 ± 0.92, and 18.32 ± 0.62 g/100 g, respectively. The maximum theoretical ethanol yield was calculated at 28.06 g per 100 g dry biomass or approximately 35.56 mL ethanol per 100 g biomass based on the structural carbohydrate composition. The results indicate that jackfruit processing waste contains large amounts of carbohydrate-rich biomass fractions and provide baseline compositional data for future studies on biomass conversion and resource recovery. The performance of this feedstock in bioconversion processes requires further experimental investigation.

Keywords

Jackfruit waste; lignocellulosic biomass; physicochemical characterization; cellulose; hemicellulose; theoretical ethanol yield

1. Introduction

Large quantities of organic residues are produced by the agricultural and food processing industries in the world. These by-products are often disposed of without any valorization, resulting in environmental burdens such as greenhouse gas emissions, leachate contamination, and increasing waste management costs [1, 2]. Such residues also represent an underutilized pool of lignocellulosic biomass that could be diverted to bioenergy, biochemicals, biomaterials, and other value-added products. Increased awareness of these opportunities has positioned agricultural waste valorization as an important building block of circular bioeconomy frameworks that seek to enhance resource efficiency and reduce environmental impact [1-4].

Jackfruit (*Artocarpus heterophyllus Lam*.) belongs to the family Moraceae and is one of the largest edible fruits in the world. It is widely cultivated in the tropical and subtropical regions, with the major production concentrated in India, Bangladesh, Sri Lanka, Thailand, and Indonesia [1, 5]. The fruit is valued for its nutritional value and culinary versatility. Nevertheless, the commercial processing and household consumption of jackfruit produce large quantities of residual biomass. Depending on fruit size and maturity as well as processing practices, 40-50% of the total fruit mass is discarded as waste in the form of peel, rind, fibrous rags (perianth), and core [1, 2]. The expansion of jackfruit cultivation and its commercial processing in the producing regions is proportionally increasing the volume of the processing waste. Therefore, effective scientifically informed strategies for the management and utilization of the processing waste are urgently required [2, 5].

The physicochemical and structural composition is the basic determinant of the suitability of any lignocellulosic biomass for downstream conversion. The three major structural components of plant cell walls, cellulose, hemicellulose and lignin, collectively determine the behavior of biomass during biological, chemical and thermochemical processing [6-9]. Polysaccharide fractions, cellulose and hemicellulose, can be hydrolyzed to fermentable hexose and pentose sugars that serve as substrates for bioethanol fermentation and other biochemical transformation pathways [8, 10, 11]. In contrast, lignin provides structural rigidity to the cell wall. It is the main barrier to enzymatic saccharification, thus influencing the pretreatment requirements and overall process economics of lignocellulosic biorefinery operations [9, 11, 12]. Reliable baseline compositional data are therefore an essential prerequisite for selecting suitable conversion strategies and evaluating the economic and technical feasibility of biomass utilization [7, 13].

Due to their wide availability, renewable nature and relatively good carbohydrate to lignin ratios, fruit-processing residues have received considerable scientific attention as lignocellulosic substrates [14, 15]. Various fruit waste streams such as banana peels, mango peels, citrus peels and other tropical fruit residues have been investigated as potential feedstocks for bioethanol production, composting, anaerobic digestion and the production of biodegradable materials [3, 14-16]. Widely recognized as the critical first step in evaluating their bioconversion potential and identifying the most suitable valorization pathways, the characterization of such residues for cellulose, hemicellulose and lignin contents, as well as conventional proximate parameters, has been widely reported [17-19].

Most published studies on jackfruit waste have focused on individual fractions, particularly the peel, rather than the complete processing waste stream. Previous investigations have demonstrated the successful extraction of cellulose and cellulose nanocrystals from jackfruit peel, highlighting its potential as a renewable source of high-value materials for biodegradable packaging and composite applications [12, 13, 20]. In addition, the feasibility of converting jackfruit waste into biobutanol via enzymatic saccharification and fermentation has been demonstrated, while recent reviews have emphasized the broader potential of jackfruit waste for sustainable bioenergy production and other value-added applications [1, 2, 21]. However, these studies have largely concentrated on individual waste fractions and do not adequately represent the mixed processing waste generated during commercial fruit handling. Consequently, comprehensive physicochemical and lignocellulosic characterization of the composite processing waste stream remains limited, highlighting the need for reliable baseline compositional data to support future biomass valorization and biorefinery applications [3, 4, 20].

However, there is a critical gap in the characterization of jackfruit processing waste as a composite stream in the ever-increasing body of literature. The waste generated in the practical operations of processing is not a single homogeneous fraction, but a mixture of peel, rind, fibrous rags, and core, all of which may vary in their chemical composition and structural properties. This composite waste stream has been studied to a relatively limited extent with respect to its physicochemical and lignocellulosic properties [13, 20, 22]. The properties of the combined waste, which would be realistically available for bulk collection and valorisation, cannot be inferred from studies of individual fractions. This distinction is important because compositional differences between fractions influence the choice of pretreatment, conversion technology and product target. Additionally, the growing relevance of using agricultural waste for bioenergy, biochemical production and biodegradable nanocomposite materials highlights the need for complete baseline datasets that include realistic, mixed waste streams rather than individual components [3, 4]. The present study therefore directly addresses this gap by characterizing the composite jackfruit processing waste stream consisting of peel, rind, fibrous rags and core in equal proportions. This representation more accurately reflects the waste generated during commercial fruit handling than studies limited to individual fractions.

The present study was carried out to determine the physicochemical & lignocellulosic composition of jackfruit. Processing waste was analysed using standard proximate and detergent fibre analysis. Moisture, ash, crude protein, crude fat, crude fibre and available carbohydrate contents were determined by proximate analysis, and cellulose, hemicellulose, lignin, neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) by lignocellulosic analysis. Theoretical bioethanol yield was also estimated from the structural carbohydrate composition using stoichiometric conversion factors. The results are expected to provide reliable baseline compositional data for the composite jackfruit processing waste stream and serve as a basis for future studies on pretreatment, hydrolysis, fermentation, and other biomass valorization pathways [23-25].

2. Materials and Methods

2.1 Collection and Preparation of Jackfruit Waste

The processing waste of Jackfruit comprising of peel, rind, fibrous rags (perianth) and core was collected from local fruit markets of Greater Noida, Uttar Pradesh, India during harvesting season. Waste materials were collected from at least five local vendors and pooled together to obtain a representative composite sample. Equal quantities of peel, rind, fibrous rags, and core in a 1:1:1:1 (w/w) ratio were mixed and homogenized thoroughly before analysis. Equal proportions were used for the major fractions of jackfruit processing waste and to facilitate evaluation of the overall waste stream.

The collected biomass was thoroughly washed with tap water, then with distilled water to remove adhering dirt and extraneous matter. The cleaned material was air-dried at room temperature for 24 h and then oven-dried at 60°C for 48 h to reduce moisture content and facilitate grinding. The dried material was ground in a laboratory grinder and screened to a uniform particle size. The powdered samples were kept in sealed polyethylene containers at room temperature until further analysis.

It should be noted that the drying step at 60°C was performed for sample preparation and storage purposes. Moisture content was measured separately by standard AOAC methods by drying representative samples at 105°C to constant weight [22].

2.2 Analysis of Proximate Composition

The proximate composition of jackfruit waste was determined as per standard AOAC methods [22]. All analyses were carried out in triplicate, and results are expressed as mean ± standard deviation.

2.2.1 Moisture Content

Moisture content was determined according to the standard AOAC methods [22]. About 2 g of the sample was dried in a hot-air oven at 105°C to constant weight.

$$Moisture\ (\%) = [(W_2 - W_1)/W_2] \times 100$$

Where: W_1 = weight of oven-dry sample, W_2 = weight of sample prior to oven drying.

The moisture values reported in this study correspond to the AOAC moisture determination and not to the residual moisture content after the pre-drying step at 60°C. Though the use of 105°C for drying might cause some loss of volatile compounds along with water, oven-drying is a widely accepted standard procedure and permits comparison with previous biomass characterization studies.

2.2.2 ASH Content

Ash content was determined by standard AOAC methods [22]. Approximately 2 g of dried sample was burned in a muffle furnace at 550°C until a constant weight was achieved.

$$Ash\ (\%) = Weight\ of\ ash \times 100\ Weight\ of\ sample$$

2.2.3 Crude Protein

Crude protein content was analyzed by the Kjeldahl method [22] based on standard AOAC methods. Protein content was calculated from the nitrogen content determined by Kjeldahl analysis using a nitrogen-to-protein conversion factor of 6.25 [26].

$$Crude\ Protein\ (\%) = Total\ Nitrogen\ (\%) \times 6.25$$

2.2.4 Crude Fat

Crude fat content was determined by Soxhlet extraction with petroleum ether as the solvent, according to the standard AOAC method [22, 27]. The fat content was determined gravimetrically and expressed as g/100 g dry weight.

$$Crude\ Fat\ (\%) = (Weight\ of\ extractable\ fat/Weight\ of\ sample) \times 100$$

2.2.5 Crude Fibre

Crude fibre was determined by standard AOAC methods [22] using sequential digestion in acid and alkali and gravimetric determination of the insoluble residue.

$$Crude\ Fibre\ (\%) = [(W_1 - W_2)/W] \times 100$$

Where: W is the weight of the original sample, W_1 is the weight of the residue before ashing, and W_2 is the weight of the residue after ashing.

The crude fibre method is a traditional method used in proximate analysis. However, it does not represent the total structural carbohydrate fraction of lignocellulosic biomass, as parts of hemicellulose and cellulose may be extracted during the acid-alkali digestion. Therefore, crude fibre values should not be directly compared with cellulose and hemicellulose values obtained through detergent fibre analysis.

2.2.6 Available Carbohydrates (Extracts, Nitrogen-Free)

The amount of available carbohydrate (also called nitrogen-free extract (NFE)) was determined by difference [22]:

$$Available\ Carbohydrate\ (\%) = 100 - [Moisture\ (\%) + Ash\ (\%) \\ + Crude\ Protein\ (\%) + Crude\ Fat\ (\%) + Crude\ Fibre\ (\%)]$$

The calculated value is carbohydrate available and should not be regarded as soluble carbohydrate. This study did not involve the direct determination of soluble sugars.

2.3 Lignocellulosic Content Analysis

The lignocellulosic composition of jackfruit waste was determined using the conventional detergent fibre system as described by Van Soest et al. [9]. Main fibre fractions were determined as neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL). Samples were defatted during the crude fat extraction step prior to analysis to minimize interference from lipids and other extractives during fibre determination.

NDF determination was carried out under reflux in a neutral detergent solution at about 100°C for 60 min. The residue was filtered, washed with hot distilled water and then with acetone, dried to constant weight and weighed. ADF was subsequently determined from the NDF residue by acid detergent solution under reflux at approximately 100°C for 60 min. The product was filtered, washed, dried, and weighed. Heat-stable amylase was not used in NDF determination as jackfruit processing waste is not expected to contain sufficient starch to interfere with cell wall fibre estimation.

Determination of ADL: The ADF residue was treated with 72% sulphuric acid at room temperature for 3 h with occasional stirring. Then the residue was filtered, washed till acid-free, oven-dried, weighed, and finally ignited in a muffle furnace at 550°C. The acid detergent lignin content was determined by weight loss after ignition [9, 10].

All fibre fractions were measured in triplicate and expressed on a dry weight basis.

NDF is the total cell wall fraction containing cellulose, hemicellulose and lignin, while ADF is composed mainly of cellulose and lignin. ADL is the fraction of acid-insoluble lignin [9, 10].

The following equations calculate the structural carbohydrate fractions:

$$Hemicellulose\ (\%) = NDF - ADF$$

$$Cellulose\ (\%) = ADF - ADL$$

$$Lignin\ (\%) = ADL$$

The primary NDF, ADF, and ADL values are reported alongside the derived cellulose, hemicellulose, and lignin contents to facilitate verification of the calculations and comparison with other lignocellulosic biomass studies [10, 17].

It should be noted that the ADL method measures mainly acid-insoluble lignin and may underestimate the total lignin content because the acid-soluble lignin was not included in the determination [10].

2.4 Estimation of Theoretical Bioethanol Yield

Theoretical ethanol production potential of jackfruit waste from its cellulose and hemicellulose contents was estimated by using stoichiometric conversion factors commonly used for lignocellulosic biomass [23-25].

$$Theoretical\ Ethanol\ Yield\ (g/100\ biomass) = (Cellulose \times 1.111 \times 0.511 + Hemicellulose \times 1.136 \times 0.511)$$

where 1.111 is the hydrolysis factor for conversion of cellulose to glucose, 1.136 is the hydrolysis factor for conversion of hemicellulose to fermentable pentose sugars, and 0.511 is the theoretical conversion factor of fermentable sugars to ethanol.

The corresponding ethanol volume was estimated using the density of ethanol (0.789 g mL^{-1}):

$$Ethanol\ Volume\ (mL/100\ g\ biomass) = Theoretical\ Ethanol\ Yield\ (g)/0.789$$

The calculated values represent the maximum theoretical yields under ideal hydrolysis and fermentation conditions and do not consider process losses. The theoretical yield was predicted only to indicate the potential of jackfruit waste as a lignocellulosic feedstock and does not imply experimentally validated ethanol production.

2.5 Statistical Analyses

All analyses were done in triplicate (n = 3), and results are presented as mean ± standard deviation (SD). The reported standard deviations are for analytical replicates, not for biological variation between independent collection events.

2.6 Ethics Statement

This study did not involve human participants, animals, or clinical samples. Therefore, ethical approval was not required for this research.

3. Results

3.1 Proximate Composition of Jackfruit Processing Waste

Table 1 shows the proximate composition of jackfruit processing waste. Moisture content was 8.18 ± 0.28 g/100 g and ash content was 4.18 ± 0.24 g/100 g. The crude protein and crude fat contents were 8.50 ± 0.08 g/100 g and 3.10 ± 0.18 g/100 g, respectively. Crude fibre content was 13.50 ± 0.18 g/100 g. The available carbohydrate by difference was 62.54 g/100 g dry weight.

Table 1 Proximate composition of jackfruit processing waste.

Parameter	Value (g/100 g)
Moisture	8.18 ± 0.28
Ash	4.18 ± 0.24
Crude protein	8.50 ± 0.08
Crude fat	3.10 ± 0.18
Crude fibre	13.50 ± 0.18
Available carbohydrate	62.54

Values are expressed as mean ± standard deviation (n = 3).

The measured components showed that the largest proportion of the biomass consisted of available carbohydrate. Table 1 summarizes the values obtained for moisture, ash, protein, fat and fibre.

3.2 Composition of Lignocellulosic Jackfruit Processing Waste

The lignocellulosic composition of jackfruit processing waste is shown in Table 2. The cellulose content was 23.35 ± 0.68 g/100 g and the hemicellulose content was 25.50 ± 0.72 g/100 g. Lignin content was 18.32 ± 0.62 g/100 g.

Table 2 Lignocellulosic and Derived Fibre Composition of Jackfruit Processing Waste.

Parameter	**Value (g/100 g dry weight)**
Cellulose	23.35 ± 0.68
Hemicellulose	25.50 ± 0.72
Lignin	18.32 ± 0.62
Neutral Detergent Fibre (NDF)	67.17 ± 1.17
Acid Detergent Fibre (ADF)	41.67 ± 0.92
Acid Detergent Lignin (ADL)	18.32 ± 0.62

NDF = Neutral Detergent Fibre; ADF = Acid Detergent Fibre; ADL = Acid Detergent Lignin.
Values are expressed as mean ± standard deviation (n = 3).

The NDF, ADF and ADL obtained were 67.17 ± 1.17, 41.67 ± 0.92 and 18.32 ± 0.62 g/100 g, respectively. The calculated cellulose and hemicellulose values were in agreement with the measured detergent fibre fractions.

3.3 Theoretical Prediction of Bioethanol Production

Based on the cellulose and hemicellulose contents determined in the present study, the theoretical ethanol production potential of jackfruit processing waste was estimated. The theoretical ethanol yield calculated was 28.06 g/100 g of dry biomass.

This yield, using the density of ethanol (0.789 g mL^{-1}), corresponds to approximately 35.56 mL of ethanol per 100 g dry biomass. The potential for ethanol production was estimated at about 356 L per ton of jackfruit processing waste on a dry biomass basis.

The estimated potential for ethanol production was ~356 L/tonne of jackfruit processing waste on dry biomass basis.

4. Discussion

4.1 Comparison with Selected Lignocellulosic Biomass

The lignocellulosic composition of jackfruit processing waste was compared with the selected agricultural and fruit biomasses reported in the literature (Table 3). The cellulose content of jackfruit processing waste (23.35%) was lower than the normal values reported for rice straw (32-47%), wheat straw (28-40%) and sugarcane bagasse (32-45%) which are the most studied feedstocks for lignocellulosic bioconversion [6, 28]. However, the cellulose content was much higher than that reported for banana peel biomass (7.6-9.6%) [29]. The hemicellulose content (25.50%) was within the range reported for wheat straw and sugarcane bagasse, suggesting a significant fraction of potentially fermentable structural carbohydrates.

Table 3 Comparison of lignocellulosic composition of jackfruit processing waste with selected lignocellulosic biomass reported in the literature.

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)	C + H Total (%)	Analytical Method	Basis	Reference
Jackfruit processing waste	23.35 ± 0.68	25.50 ± 0.72	18.32 ± 0.62	48.85	Van Soest	db	Present study
Rice straw	32-47	19-32	5-24	~60	Van Soest	db	[6]
Wheat straw	28-40	18-28	15-22	~58	Van Soest	db	[6]
Sugarcane bagasse	32-45	20-32	17-32	~65	Van Soest/NREL	db	[28]
Banana peel	7.6-9.6	6.4-9.4	6-12	~17	Van Soest	db	[29]

Note: C + H = Cellulose + Hemicellulose; db = dry basis. Literature values are reported as ranges from published studies. Variations among studies may arise due to differences in biomass source, analytical methodology, and sample preparation procedures.

The lignin content of jackfruit processing waste (18.32%) was in the same range as the reported lignin content of wheat straw (15-22%) and within the reported range of lignin content of sugarcane bagasse (17-32%). The detected lignin content shows that pretreatment is required for efficient biochemical conversion. Lignin acts as a physical barrier to enzymatic access to cellulose and hemicellulose. However, the biomass is less recalcitrant than several conventional lignocellulosic feedstocks [30, 31].

The major structural carbohydrate pool that can be potentially converted into biofuels, biochemicals, and other value-added products is the combined cellulose and hemicellulose fraction (48.85%). This value is lower than those reported for cereal straws and sugarcane bagasse, but is much higher than that reported for banana peel biomass. The findings indicate that jackfruit processing waste could be a moderate-quality lignocellulosic carbohydrate feedstock for bioconversion applications in the future.

Direct comparisons between studies should be made with caution as the composition of biomass can be influenced by cultivar, stage of maturity, geographical origin, seasonal variation, sample preparation procedures, analytical methodology and basis of reporting. Table 3 data are thus intended to provide a rough compositional context, not a strict statistical comparison of different biomass resources [18].

Since the comparative values presented in Table 3 were obtained from independent literature sources with different biomass origins, cultivars, geographical locations, sample preparation procedures, and analytical methodologies, direct statistical comparisons were not performed. Therefore, the literature values are provided only to establish compositional context and facilitate qualitative comparison with commonly studied lignocellulosic feedstocks.

4.2 Proximate Composition of Jackfruit Processing Waste

The physicochemical properties of biomass are important for determining its suitability for storage, handling, and subsequent processing. The moisture content of jackfruit processing waste (8.18 g/100 g) was considerably lower than the 15-20% moisture level generally associated with increased microbial spoilage and deterioration during biomass storage [14, 24]. Such low moisture content may improve storage stability and reduce the energy required for additional drying prior to thermochemical or biochemical conversion processes. Moisture content is considered an important parameter in biomass utilization because excessive moisture increases transportation costs, reduces thermal efficiency, and adversely affects storage stability [14, 24].

The inorganic mineral content of biomass, ash, can impact processing performance in biochemical and thermochemical conversion. The ash content (4.18 g/100 g) was within the range generally reported for fruit-processing residues and remained below the approximately 10% level often associated with operational challenges such as slagging, fouling, and ash accumulation during thermal conversion processes [24, 25]. Therefore, the ash content observed in the present study is unlikely to impose major limitations on biomass utilization, while still contributing mineral nutrients that may support biological conversion processes such as composting and anaerobic digestion [15, 32]. The crude protein and crude fat contents indicate the presence of organic constituents with nutritional value in jack fruit processing waste. Although these components are not targeted for lignocellulosic bioconversion, they may contribute positively to microbial growth in biological treatment processes such as composting and anaerobic digestion [15, 32]. The available carbohydrate fraction was the highest fraction of the biomass, indicating the abundance of carbohydrate-based materials in jackfruit residues. This agrees with the high carbohydrate content in many fruit processing by-products reported in the literature [2, 33].

The crude fibre value determined in the present investigation was lower than the sum of structural carbohydrate fractions determined by detergent fibre analysis. This difference is expected because the traditional method for crude fibre removes fractions of hemicellulose and cellulose during acid and alkali digestion, thus underestimating the real structural carbohydrate content of lignocellulosic biomass [9, 18]. The detergent fiber analysis thus gives a more realistic picture of the biomass composition for bioresource application.

4.3 Lignocellulosic Content and Biomass Utilization Potential

The cellulose, hemicellulose, and lignin contents obtained in this study indicate that jackfruit processing waste is rich in structural carbohydrates. Cellulose and hemicellulose, which can make up to nearly half of the dry biomass, indicate a rich reserve of fermentable carbohydrates that could be potentially converted into biofuels and biochemicals through suitable pretreatment and hydrolysis processes [8, 13, 23].

Cellulose is mostly known as the primary polysaccharide from which fermentable sugars are obtained, while hemicellulose provides additional carbohydrate fractions that can improve the overall efficiency of biomass conversion [11, 30]. Thus, the cellulose and hemicellulose contents reported in the present study indicate that jackfruit processing waste could be a potential feedstock for application in lignocellulosic biorefineries. Similar observations have been reported for several fruit processing residues and agricultural by-products studied for bioethanol production and other value-added applications [15, 16, 32]. It should be noted that the lignin content reported in the present study was determined using the acid detergent lignin (ADL) method, which primarily measures acid-insoluble lignin. Therefore, the total lignin content of jackfruit processing waste may be slightly higher than the reported value due to the presence of acid-soluble lignin fractions that were not quantified in the present investigation [9].

Lignin content is an important parameter affecting biomass recalcitrance as it forms a protective matrix around the structural carbohydrates and limits enzyme accessibility during hydrolysis [30, 34]. The lignin content of this study suggests the need for pretreatment for effective biochemical conversion. Published studies have shown that increasing lignin content generally reduces enzymatic saccharification efficiency because lignin restricts enzyme accessibility to structural carbohydrates and promotes non-productive enzyme adsorption [30, 32]. Various pretreatment methods such as dilute acid, alkaline, steam explosion, and biological treatments have been reported to enhance the accessibility of cellulose and hemicellulose in lignocellulosic feedstocks with comparable lignin contents [7, 12, 34, 35].

Apart from the production of biofuel, the composition of jackfruit processing waste also indicates the possibility of recovery of cellulose-rich materials. Several studies have demonstrated the extraction of cellulose and nanocellulose from jackfruit peel and other waste products from fruit processing for biodegradable materials and sustainable packaging systems [4, 13, 17, 20]. The present work further proposes to investigate such value-added applications with high cellulose content.

4.4 Theoretical Yield of Bioethanol Production

The theoretical ethanol yield based on the measured contents of cellulose and hemicellulose provides an initial indication of the bioconversion potential of the waste from jackfruit processing. The calculated yield represents the maximum quantity of ethanol obtainable from a specific feedstock under ideal hydrolysis and fermentation conditions and thus serves as a useful benchmark for evaluating the feedstock's suitability [23, 25, 28].

It should be noted that actual ethanol yields are usually lower than theoretical values due to incomplete hydrolysis, sugar degradation, inefficient microorganisms, and process inefficiencies during fermentation [28, 30, 31]. However, the estimated yield obtained in the present study indicates that the jackfruit processing waste contains sufficient structural carbohydrates to be further explored as a potential lignocellulosic bioethanol feedstock. Similarly, studies on fruit-derived biomass and agricultural residues have shown the potential of carbohydrate-rich feedstocks as a promising substrate for second-generation bioethanol production following appropriate pretreatment strategies [25, 28, 32].

Apart from bioethanol production, the carbohydrate-rich composition of jackfruit waste can also be used in other biological conversion processes such as anaerobic digestion, composting, and the production of platform biochemicals. Thus, the potential utilization of this biomass should not be limited to ethanol production but can be extended to a broader range of biorefinery applications [1, 15, 29].

4.5 Limitations of the Study

The present study was limited to physicochemical and lignocellulosic characterization of jackfruit processing waste from one geographic region. Values are for the composite sample analysed and may vary with cultivar, season, and source of collection. Moreover, the bioethanol production potential in this study was estimated using theoretical calculations from compositional data and was not experimentally validated by hydrolysis or fermentation studies. The next step should be the experimental evaluation of the biomass conversion pathways and the optimization of the processes.

5. Conclusion

The present study presented the physicochemical and lignocellulosic characterization of jackfruit (Artocarpus heterophyllus) processing waste of peel, rind, fibrous rags and core. The results indicate that jackfruit processing waste warrants further experimental investigation as a potential lignocellulosic biomass resource, as it contained considerable amounts of available carbohydrates along with substantial fractions of cellulose and hemicellulose. The lignocellulosic composition revealed that jackfruit processing waste is a carbohydrate-rich biomass resource with properties similar to a number of agricultural residues studied for bioconversion and biomass utilization.

The measurements of NDF, ADF and ADL enabled a more complete evaluation of the structural composition of the biomass and allowed an estimation of the cellulose, hemicellulose and lignin contents. The theoretical ethanol yield from the measured structural carbohydrate fractions suggests that jackfruit processing waste may serve as a feedstock for future experimental studies on bioethanol production. The findings of this work provide baseline compositional data for a composite jackfruit processing waste stream, not for individual fruit fractions. Such data can be useful in the design and evaluation of future biomass conversion, biorefinery and resource recovery studies. However, further studies on pretreatment, hydrolysis, fermentation, and other valorization steps are needed to experimentally verify the feasibility of this biomass utilization. These findings provide a scientific basis for future pretreatment, hydrolysis, fermentation and biorefinery studies utilizing composite jackfruit processing waste.

Author Contributions

Shivani Kohli: Investigation, data curation, formal analysis, writing—original draft preparation. Sujata Pandit Sharma: Conceptualization, methodology, supervision, review and editing. Dolli Chauhan: Validation, data interpretation, visualization. Nikita Singh: Formal analysis, literature review, manuscript editing. All authors have read and approved the final version of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AI-Assisted Technologies Statement

Artificial intelligence (AI)-assisted tools were used only for basic language refinement and grammatical improvement during manuscript preparation. These tools were utilized solely to improve readability and clarity of the English language. All scientific content, experimental work, data interpretation, and conclusions were independently developed and verified by the authors. The authors carefully reviewed and edited the manuscript and take full responsibility for the accuracy and integrity of the content.

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