Compositional Analysis of Melon Seeds: Insights into the Development of Sustainable Value-Added Products

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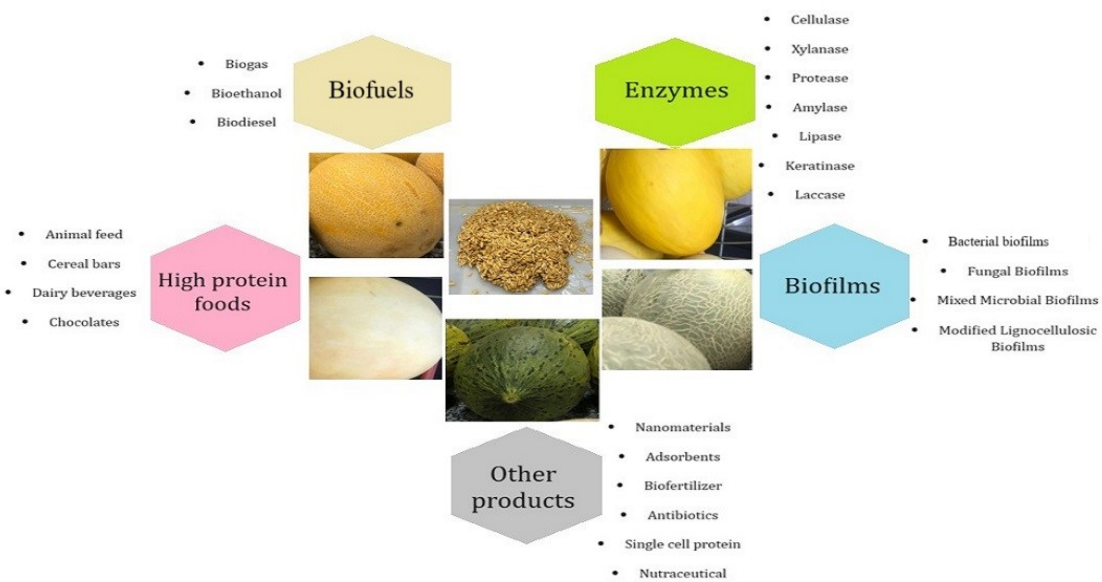
GRAPHICAL ABSTRACT



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Agricultural waste is a growing global concern, with about 30% of food that is currently wasted in Brazil. Melon (*Cucumis melo*), which is widely cultivated in semi-arid regions, generates significant residues, including seeds, peels, and pulp, that are often discarded improperly, causing environmental impacts. These by-products have a rich lignocellulosic composition, making them promising raw materials for biofuels, bioplastics, and other valuable renewable compounds. Importantly, their use does not compete with the food supply, aligning with circular economic principles. This study evaluated the potential of seeds from five melon varieties as lignocellulosic biomass. The seeds underwent pretreatment by drying under controlled conditions and grinding to produce a homogeneous powder for analysis. Moisture, ash, and lignocellulosic components (cellulose, hemicellulose, and lignin) were assessed. Data were analyzed using ANOVA and Tukey's test to identify significant differences among varieties. The caipira and cantaloupe varieties exhibited notably high holocellulose and lignin contents. Elevated holocellulose levels enhance the structural integrity of sustainable materials, while lignin contributes antimicrobial properties and serves as a precursor for high-value compounds such as resins, antioxidants, and bio-based polymers.

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Keywords: Environmental sustainability; Lignocellulosic biomass; Energy transition; Fruit waste; Agricultural production

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INTRODUCTION

The current scenario of growing food demand raises the importance of sustainable practices in agricultural production. Food waste, both in production and consumption, is a crucial challenge to achieving Sustainable Development Goals (SDGs), particularly SDG 2, whose goal is to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture, and SDG 12, whose goal is to ensure sustainable consumption and production patterns (United Nations 2023). These goals aim not only to reduce losses in the food chain but also to promote more efficient and sustainable agriculture that considers both the environment and the health of populations. Additionally, agricultural and industrial activities generate large amounts of waste, such as peels and seeds. Studies indicate that the global production of lignocellulosic biomass reaches 181.5 billion tons annually.

According to WWF and Tesco (2021), approximately 2.5 billion tons of food are lost or wasted annually worldwide. The Food and Agriculture Organization of the United Nations (FAO 2024), however, provides a more recent estimate: about 13.2% of global food production is lost from harvest to retail stages, while 19% is wasted at the consumer level, such as in households, restaurants, and supermarkets. Altogether, this means that roughly 32% of all food produced globally is either lost or wasted. The peels of these fruits account for 15% to 60% of the total fruit waste produced and are usually discarded (Rifna *et al.* 2023). These updated figures show that the problem of food waste remains severe, representing a substantial loss of resources. Moreover, food loss and waste contribute to 8 to 10% of global annual greenhouse gas emissions, further exacerbating environmental degradation and climate change. However, most of these residues, especially those rich in lignocellulose, are not properly valorized and often end up being inadequately discarded in the environment, thereby posing a risk to the ecosystem.

Global efforts have focused on transitioning from the linear model to one based on more sustainable principles, such as the circular bioeconomy (CBE). This approach combines the concepts of the circular economy, which aims to redesign traditional resource use into a more cyclical and efficient system, with the bioeconomy, which relies on renewable biological resources to generate sustainable products and services. By incorporating food and organic waste, such as agricultural residues, human excreta, and wastewater, the CBE promotes nutrient recycling and waste reduction across supply chains. In addition to minimizing pollution risks and reducing environmental impact, this strategy also encourages the production of sustainable goods, aligning with the principles of sustainable development and circular bioeconomy practices (Sekabira *et al.* 2022).

Brazil, a global agricultural powerhouse, is not immune to the issue of food waste and loss, which directly impacts the sector. According to the Food and Agriculture Organization of the United Nations, approximately 30% of global food production is lost or wasted annually (FAO, 2019). In the Brazilian context, losses and waste during the retail process are relatively lower. Globally, the generation of agro-industrial waste is estimated at around 140 Gt annually, according to data from Tripathi *et al.* (2019), who warn about the negative environmental impacts of the improper disposal of such waste. Food loss and waste have significant economic and environmental consequences, as highlighted by Osei-Owusu *et al.* (2023), including the emission of greenhouse gases (GHGs), depletion of natural resources, and challenges in waste management.

The organic waste from domestic, industrial, and agricultural activities can be utilized to generate energy and materials, thereby replacing their fossil-based counterparts (Fonoll *et al.* 2024). These residues, composed of a lignocellulosic structure, represent renewable and biodegradable natural resources, offering environmentally sustainable alternatives. In addition to being widely available and low-cost, they possess satisfactory characteristics and potential for a variety of industrial applications. Compared to synthetic inputs, they present several advantages, such as a wide diversity of extractives from forest sources and agro-industrial residues; low density and reduced energy consumption; high specific resistance and modulus; reactive surfaces that can be easily modified and functionalized by different chemical groups; broad applicability in nanoparticle systems; and recyclability.

Based on Figueirêdo *et al.* (2017), the Brazilian semi-arid region encompasses a vast area that spans parts of the Northeastern states, with unique characteristics that both challenge and drive agricultural production. With adverse climatic conditions such as high temperatures, low humidity, and scarcity of rainfall for much of the year, the region stands out as one of the main hubs in melon production, highlighting the resilience and adaptability of local farmers. The Ministry of Agriculture, Livestock and Supply (MAPA, 2022) states that fruits have been gaining increasing importance in the country, both in the domestic and international markets. In 2023, from January to May, fruits from Brazil were exported to 129 countries. Melon (*Cucumis melo* L.) and Mango (*Mangifera indica* L.) were the fruits that showed the best export performance in 2023, with melons reaching USD 68.1 million and mangoes USD 51.3 million. Additionally, production projections for 2032/2033 highlight melon as one of the fruits with the highest growth, with an increase of 28.7%. In 2022, Brazil produced 699,281 tons of melon, grown in an area of 27,457 hectares. Rio Grande do Norte stands out as the largest producer, responsible for about 63% of the national production. Within the state, the city of Mossoró is the main producer Brazilian Institute of Geography and Statistics (IBGE, 2022).

A significant issue in melon production is the large amount of waste generated and discarded annually. Melon seeds, which make up 10% of the melon's weight, are considered a low-value by-product in the melon supply chain and are often discarded as waste. These seeds are typically produced from household consumption and food processing industries (Gomez-García *et al.* 2020). However, melon seeds are rarely utilized, primarily due to a lack of understanding of their nutritional value and the absence of appropriate processing technologies.

At this moment, there is a growing focus on strategies to add value to melon seeds, driven by circular economy principles and the United Nations Sustainable Development Goals agenda. This by-product has high potential value and can be reused and reintroduced into the supply chain as a promising ingredient in food development. Recent studies have shown that melon seeds are highly nutritious, with high levels of proteins (15 to 45%), lipids (25 to 45%), dietary fiber (19 to 25%), and minerals, particularly potassium (Zhang *et al.* (2024).

Based on da Cunha *et al.* (2020), melon seeds exhibit antiproliferative activity, antioxidant properties, and prebiotic potential. The presence of flavonoids and phenolic compounds highlights the high antioxidant properties of melon seed flour (*Cucumis melo* L.). Furthermore, these seeds contain significant minerals such as magnesium, phosphorus, sodium, and potassium. Regarding lipids, the seeds are particularly rich in polyunsaturated fatty acids, such as linoleic and linolenic acids. They also contain relevant amounts of essential amino acids, such as isoleucine, methionine, tyrosine, phenylalanine, and valine. For the most part, these wastes are directed towards the production of fertilizers and animal-feed, but they have a high potential to produce higher value-added products. To address this challenge, it is essential to implement comprehensive strategies aimed at maximizing the use of these resources. Such measures will not only benefit melon producers but also contribute to the environmental and economic sustainability of the agricultural sector, promoting the full utilization of by-products in the production chain.

This study aimed to add value to the seeds of five melon varieties (yellow, cantaloupe, caipira, calia, and Santa Claus), cultivated at the Federal Rural University of the Semi-Arid in Mossoró (RN), Brazil. Through the characterization of these seeds, the goal was to identify their properties and explore potential industrial uses, such as the production of biofuels, enzymes, biofilms, and other derivatives. The choice of seeds is justified by their status as abundant, low-cost agro-industrial waste with nutritional and bioactive properties, enabling the creation of innovative and environmentally responsible products. Although there already have been studies on melon seeds, few have compared different varieties from a sustainability perspective; this research fills that gap by comparatively evaluating five verities and their potential for sustainable application.

EXPERIMENTAL

This applied research adopted a quantitative approach through experimental procedures focused on characterizing seeds from five types of melons produced on the farm of the Federal University of Semi-Arid (UFERSA), located in the municipality of Mossoró, Rio Grande do Norte, Brazil, and acquired through donation. Its goal was to evaluate the potential of these residues for product development, thereby adding value to the production chain. The experiments were conducted at the Chemistry and Applied General Laboratories of the Federal Rural University of the Semi-Arid, Pau dos Ferros Campus, in Rio Grande do Norte, Brazil. Data analysis was supported by statistical tools, ensuring objective interpretation.

Extraction, Drying, and Grinding of Seeds

The seeds were sanitized by washing in a 0.1% sodium hypochlorite solution for disinfection, then rinsed with running water. They were spread in aluminum trays and dried in a circulating-air (model SL-102, SOLAB Científica) oven at 105 °C to remove moisture without damaging seed compounds. After drying, the seeds were ground into flour using a knife mill (model SL-31, 20 mesh / 0.85 mm, SOLAB Científica), thereby achieving the desired particle size. The flour was then stored in sealed plastic bags to prevent moisture and contamination, preserving its properties for further analysis.

Physicochemical Characterization of Seeds

Characterization is of great relevance to understanding the properties that different types of melon seeds possess and identifying their technological potential for application in the production of chemical inputs. The methodology used for lignocellulosic analyses was based on the Technical Association of the Pulp and Paper Industry (TAPPI) standards cited by Morais *et al.* (2010). The material was characterized in terms of moisture, ash, extractives, lignin, holocellulose, α-cellulose, and hemicellulose contents. The analyses were conducted in triplicate, following the guidelines of the Association of Official Analytical Chemists (AOAC).

Statistical Analysis

For the statistical analysis, Tukey's HSD post hoc test was conducted following one-way ANOVA to compare all pairs of group means. The calculations incorporated the studentized range distribution, sample size, and the mean square of the residuals.

RESULTS AND DISCUSSION

Obtaining Flour from Melon Seeds

The melon seed flour (Fig. 1) exhibited yellowish-brown tones with a finer and more homogeneous appearance, while the flour from the yellow type of melon showed a distinctive visual appearance characterized by a granular, moist texture and a darker hue. This coloration can be attributed to the fixed oil content present inside the seeds, providing suitable energy resources for their germination process. According to Becker and Kruger (2012), the unsaturated fatty acids oleic and linoleic predominate in melon seeds. The drying and grinding stages of melon seeds are crucial to ensuring the quality of the raw material and directly influence the final yield of biofuels and bioactive compounds.

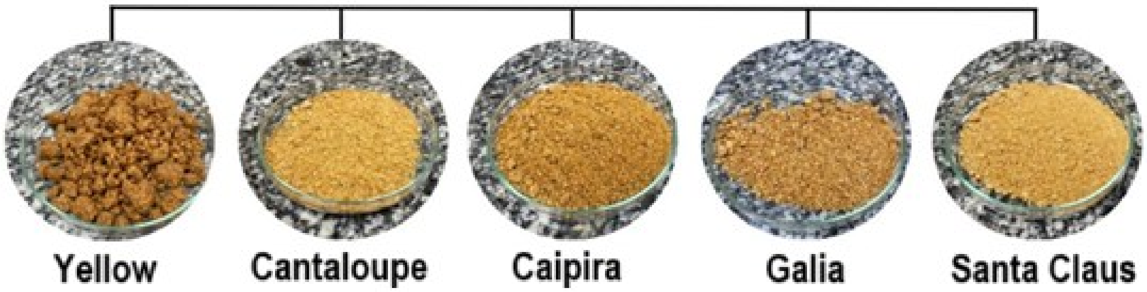

Fig. 1. Melon seed flours

Physicochemical Characterization of the Flours

The data regarding the physicochemical characterization of the lignocellulosic material from the seeds of the melon varieties are presented in Table 1.

Table 1. Lignocellulosic Characterization of Melon Seeds

Type	(TU%)	(TC%)	(TE%)	(TL%)	(THO%)	(TA%)	(THE%)
Yellow	1.89 [a] ± 0.13	3.88 [a] ± 0.04	32.12 [a] ± 0.46	10.50 [a] ± 1.26	47.42 [a] ± 1.55	14.16 [a] ± 1.80	17.13 [a] ± 0.91
Cantaloupe	1.96 [a] ± 0.06	3.37 [b] ± 0.06	33.51 [a] ± 0.31	20.43 [b] ± 1.32	55.64 [b] ± 1.86	24.55 [b] ± 2.87	15.58 [a] ± 1.09
Caipira	1.66 [a] ± 0.08	3.82 [a] ± 0.06	16.51 [b] ± 1.42	20.42 [b] ± 3.81	50.62 [c] ± 1.42	21.69 [b] ± 4.15	19.73 [a] ± 2.99
Galia	1.31 [b] ± 0.22	5.31 [c] ± 0.86	29.15 [c] ± 0.38	8.03 [a] ± 1.13	43.15 [a] ± 2.44	20.32 [b] ± 4.05	15.58 [a] ± 2.67
Santa Claus	0.67 [c] ± 0.04	3.42 [d] ± 0.04	27.62 [d] ± 0.16	17.79 [b] ± 1.75	20.81 [d] ± 2.07	7.34 [c] ± 0.92	6.99 [b] ± 0.50

* **TU%:** moisture content; **TC%:** ash content; **TE%:** extractive content; **TL%:** lignin content; **THO%:** holocellulose content; **TA%:** α-cellulose content; **THE%:** hemicellulose content. Statistical differences by Tukey's test (p≤0.05) are indicated by different letter (a,b,c,d).

Different letters in the same column indicate statistical differences according to the Tukey test ($p \leq 0.05$). The melon seed varieties showed moisture levels between 0.67% and 1.96%. Some types of processes, such as those involving fungi, require low moisture levels in the medium to promote the selective growth of microorganisms. This is essential for fermentation, where extracellular enzymes secreted by fermenting microorganisms play a crucial role (Sadh *et al.* 2018). According to Azhari *et al.* (2024), Mallek-Ayadi *et al.* (2019), Mehra *et al.* (2015), Morais *et al.* (2017), Petkova and Antova (2015), Yanty *et al.* (2008), de Mello *et al.* (2001), and de Melo *et al.* (2000), the nutritional composition of *C. melo* L. seeds is rich in total fat (13 to 37%), crude fiber (7 to 44%), and protein (15 to 36%). Some studies report variable amounts of carbohydrates, ranging from 6 to 28%.

Low moisture levels, as observed in this study, are favorable for preserving organoleptic properties and microbiological quality, meeting specific requirements established for food production. In Brazil, for example, standards dictate a maximum limit of 15.0% moisture content in flour (de Mello *et al.* 2000). In the study by da Cunha *et al.*

(2020), they obtained a moisture content of 5.8% for cantaloupe melon seeds. In Morais *et al.* (2010), a moisture content of 5.04% was identified in the physicochemical characterization of pumpkin seed flour.

Regarding ash content, four of the five analyzed materials showed average values of 3.5 ± 0.5%. This is close to the 3.8% reported by da Cunha *et al.* (2020) for cantaloupe melon seeds, indicating a similar mineral composition. In contrast, Milovanović and Picurić-Jovanović (2005) found 2.9% in bitter melon seeds, highlighting variations among species. Ash content, which reflects the presence of minerals, is an important parameter for assessing product quality and the sustainable use of lignocellulosic residues. The moderate values observed in this study suggest the potential for applications in bioproducts such as fertilizers and bio composites, contributing to the valorization of these residues. Moreover, low ash content is desirable in processes such as biofuel production, as it helps prevent issues such as corrosion and deposit formation during combustion, thereby increasing efficiency and reducing the environmental impact (Frandsen 1998).

The extractive content obtained in this study ranged from 16.5% to 33.5%, while in the study conducted by Monteiro *et al.* (2019) in relation to acai seed biomass, values between 15.45% and 9.89% were identified in two different fruit batches. Extractives can affect the processability of lignocellulosic biomass during conversion processes. A high extractive content can hinder certain types of processing by decomposing into undesirable by-products, thereby increasing the cost and energy required to produce the final products. The work developed by Smit *et al.* (2022) presents a biomass pre-extraction approach using aqueous acetone to remove harmful extractives before fractionation. The pre-extraction reduces the need for acid, minimizes sugar losses, and improves lignin purity, making the biorefinery process more efficient and sustainable and with less variation in product quality.

Upon examining the data presented in Table 1, it is evident that the levels of lignin varied from 8.0% to 20.4%. This range includes the value of 15.9% reported by Spiekermann (2021) for avocado seeds, as well as the content of 13.5% identified in guarana seeds in the study conducted by Pereira (2017). On the other hand, Rolim *et al.* (2018) and Madeira (2017) obtained a content of 2.4% in cantaloupe melon seeds, and Barros *et al.* (2021) observed a content of 24.4% for acai seed in their research. Lignin is a cross-linked, amorphous resin without an exact structure. It is composed of an irregular array of various phenolic groups linked together in a branched manner, thus presenting a complex three-dimensional structure (2017). A high lignin content can negatively or positively affect processes in obtaining new products. Lignin extracted from lignocellulosic biomass has a high calorific value, which commonly leads to lignin being used for energy generation (Galvani *et al.* 2021). Conversely, a lower lignin content is more efficient in the production of biofuels.

The holocellulose contents found in these materials ranged from 20.8% to 55.6%. Spiekermann (2021) reported a holocellulose content of 64.5% in avocado seeds, which is higher compared to the values obtained in this study, showing similarity to those found by Barros *et al.* (2021), who identified a content of 66% in acai seed. The higher value observed for avocado seeds compared to the results of this study is clearly related to the fact that it is a more fibrous material, with a high proportion of raw material corresponding to the fruit. A knowledge of holocellulose contents is crucial for optimizing conversion processes and increasing efficiency in the production of products from lignocellulosic materials. This involves selecting appropriate pre-treatment methods and conversion technologies for different types of biomasses.

Further analysis of the data in Table 1 reveals that the seeds of different types of melons showed an alpha-cellulose content ranging from 7.3% to 24.6%. These values were higher than those found by Kale *et al.* (2020), who, in their study, obtained a content of 2.5% for cantaloupe melon seeds. Rolim *et al.* (2018) and Madeira (2017) obtained a content of 35.0% in cantaloupe seeds, a value higher than the 24.6% found in the cantaloupe type studied in this work. Due to its properties and versatility, α-cellulose presents itself as a linear macromolecule formed by glucose units linked together by glycosidic bonds, offering it a highly regular crystalline structure and providing rigidity to the molecular chain (Granström 2009). This organization gives alpha-cellulose distinct physical properties, such as high mechanical strength and low solubility in water and organic solvents. Alpha-cellulose provides crucial information that paves the way for various applications.

The examined melon varieties revealed a hemicellulose content ranging from 7.0% to 19.7%. This range is like the content of 7.9% found in cantaloupe melon seeds, as evidenced by Rolim *et al.* (2018) and Madeira (2017). Hemicellulose, one of the fundamental components of lignocellulosic materials, differs from alpha-cellulose due to its more complex structure. While alpha-cellulose consists of long chains of glucose forming a crystalline structure, hemicellulose is a more diversified matrix composed of different sugars such as xylose, arabinose, mannose, and galactose. Its amorphous structure and lower degree of polymerization make it more prone to disintegration into monomeric units, thereby facilitating its hydrolysis and conversion into useful products such as biofuels (Debnath *et al.* (2021). However, it is important to consider that the composition of lignocellulosic materials is intrinsically linked to the type of material studied, as well as the cultivation area and climatic conditions to which they are exposed. These factors interact in a complex manner to determine the final properties of the materials, influencing their potential applications in various areas such as biofuels, construction materials, and renewable chemicals.

Industrial Perspectives for the Use of Melon Seeds

Several studies have identified lignocellulosic biomass as a highly promising source to produce valuable compounds. It is important to note that lignocellulosic residues constitute an abundant renewable source on our planet (Velvizhi *et al.* 2023), with significant potential to be transformed into a variety of high-value-added products. This includes, for example, biofertilizers, biofuels, biofilms, and enzymatic complexes, as well as serving as a substrate for a wide range of other important products. This utilization of lignocellulosic biomass can play a significant role in reducing CO_2 emissions and mitigating environmental pollution.

Biofuels

The search for solutions to meet future energy demands is driving the development of sustainable technologies, which are increasingly being recognized as a critical response. These technologies are fundamentally changing the manner of use of lignocellulosic biomass waste, transforming it into a diverse range of valuable products (Sharmili *et al.* 2021). Lignocellulosic biomass represents a key source to produce second-generation biofuels, such as bioethanol and biogas. Unlike first-generation biofuels, which rely on food-based raw materials like corn and sugarcane, second-generation biofuels are produced from organic waste, thus avoiding competition with food production and enhancing environmental sustainability. Furthermore, the valorization of agricultural and forestry residues contributes to the reduction of greenhouse gas emissions and promotes a circular economy through the efficient reuse of discarded materials (Wozniak *et al.* 2025).

The review by Zayed *et al.* (2021) highlights citrus seeds, especially tangerine seeds, as abundant juice industry by-products rich in lignocellulosic fibers (cellulose, hemicellulose, lignin) and bioactive compounds (fatty acids, phytosterols, tocopherols). Their composition enhances functional value and supports applications beyond nutrition, notably in biodiesel production. This combination of high availability, structural richness, and lipid content underscores their strategic potential for sustainable energy development.

Lignocellulosic waste, which includes materials such as straw, bagasse, seeds, and other plant by-products, has emerged as one of the main raw materials for biofuel production (Fig. 2) due to its high abundance, renewability, and low cost. Composed primarily of cellulose, hemicellulose, and lignin, these wastes represent a promising and environmentally low-impact energy source. However, the conversion of these compounds into fermentable sugars can lead to the formation of components such as furfural and HMF (5-hydroxymethylfurfural), which are generated during hydrolysis. These compounds are highly inhibitory to fermentation and can significantly reduce the efficiency of ethanol production.

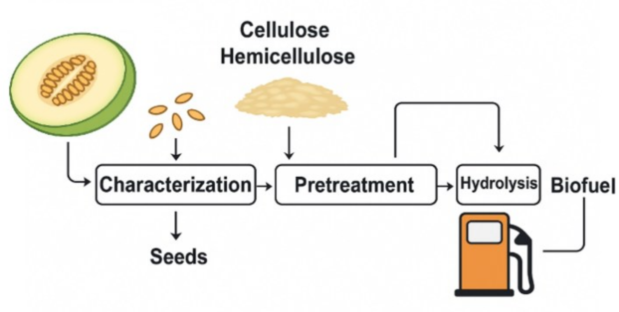

Fig. 2. Process flowchart for biofuel production

The presence of lignin in biofuel production processes poses significant challenges, mainly due to its complex and recalcitrant structure. It hinders the hydrolysis of cellulose and hemicellulose, which are the most valuable fractions for biofuel production, thereby reducing conversion yields and increasing the need for complex pretreatments, such as alkaline catalysis or solvent-based methods. Additionally, lignin is strongly bound to these biomolecules, requiring more energy or reagents to break these bonds. These factors make the process more expensive and less efficient (Vieira *et al.* 2024).

As reported by Vieira *et al*. (2024), the organosolv process showed superior performance in terms of total lignin removal and high cellulose recovery, attributed to its selective ability to interact with lignocellulosic bonds. This mechanism promotes a more intense fragmentation of the biomass, enhanced by alkaline catalysis and by the dissolution of coconut fiber lignin in the solvent, using an ethanol/water (1:1) solution with a solid-to-liquid ratio of 1:25, in the presence of an alkaline catalyst corresponding to 10% by weight of NaOH based on the dry weight. The study by Zhang *et al.* (2011) used commercial activated charcoal and polyderivatives to selectively remove furfural from sugar solutions. The presence of oxygen functional groups in charcoals influenced the selectivity between furfural and sugar. Reducing the furfural concentration from 4 g/L to 0.1 g/L improved the fermentation efficiency, including cell growth, sugar consumption, and ethanol production.

Prasad *et al.* (2018) examined bioethanol production from wheat straw by addressing inhibitors such as furfural and HMF. An optimized pretreatment at 180 °C with

2% H_2SO_4 greatly increased soluble sugar content but also elevated inhibitor levels, which were reduced using activated charcoal. Beyond furans, extractives such as oils, resins, and phenolic compounds can hinder fermentation by inhibiting microorganisms. To improve efficiency, preprocessing strategies, such as removing extractives or applying advanced physicochemical and biological methods, are essential to break down biomass and minimize its inhibitory effects. According to Smit *et al.* (2022), the pre-extraction stage of lignocellulosic biomass before fractionation improves biorefining by reducing the lignin content, increasing hemicellulose sugar production, and promoting higher lignin purity. In addition, it decreases the formation of degradation products such as furfural, thereby benefiting fermentation.

After investigating the seed residues of five melon varieties, with the goal of identifying favorable and unfavorable characteristics for their potential use as sustainable alternatives to fossil sources, it was observed through this study that the cantaloupe and caipira melons exhibited the highest holocellulose content, with 55.6% and 50.6%, respectively. Holocellulose, composed of cellulose and hemicellulose, is essential for generating fermentable sugars, which are crucial in bioethanol production. Although the caipira melon had a slightly lower composition compared to the cantaloupe, it stood out for having a lower percentage of extractives. These substances can interfere with the biomass conversion process into ethanol. This factor makes the caipira melon an attractive option, as the lower presence of extractives facilitates the enzymatic hydrolysis process, resulting in a more efficient conversion for biofuel production.

Therefore, the cantaloupe and caipira varieties appear promising as alternative sources for biofuel production, offering a sustainable and economically viable option to reduce dependence on fossil sources. The use of lignocellulosic biomass is not only critical for the economic viability of biofuel production but also represents an important strategy for addressing climate change by reducing dependence on fossil fuels and decreasing greenhouse gas emissions. This path is crucial for building a more sustainable energy future, promoting a transition to renewable energy sources that minimize environmental impacts and contribute to the mitigation of global warming.

One of the major challenges in producing biofuels from lignocellulosic biomass is the need for effective pretreatment due to the material's natural resistance to degradation. This is attributed to its complex composition, where cellulose, hemicellulose, and lignin are tightly interwoven. To break these bonds and enable the conversion of polysaccharides into fermentable sugars, it is essential to employ advanced technologies such as high-pressure processes or enzymatic treatments. Once released, these sugars can be converted into bioethanol or methane through fermentation (Santos *et al.* 2022).

Enzymes

Recently, there has been a significant increase in interest in the adoption of sustainable and efficient processes. In this evolution, chemical catalysts have been replaced by biochemical catalysts, and several enzymes have been identified and applied in industrial and biotechnological processes. The development of enzymes for biotechnological processes is essential to drive sustainability, particularly in the biofuel, food, pharmaceutical, and biotechnology industries in general. These enzymes not only enable the creation of more sustainable products, but they also facilitate waste valorization and reduce environmental impacts. By fostering innovative solutions, enzymes bridge scientific advancements with the demands of a green economy, playing a key role in shaping a more sustainable and efficient future (Santos *et al.* 2022).

Enzymes are known as biological catalysts or biocatalysts that are responsible for accelerating biochemical reactions in living organisms. They can be extracted from cells and employed to catalyze a wide variety of commercially relevant processes (Robinson 2015). Agro-industrial residues, composed of a variety of organic materials, provide a conducive environment for the growth of microorganisms such as fungi and bacteria, which, during the fermentation process, can synthesize a diversity of valuable enzymes (Sadh *et al.* 2018), as shown in Fig. 3.

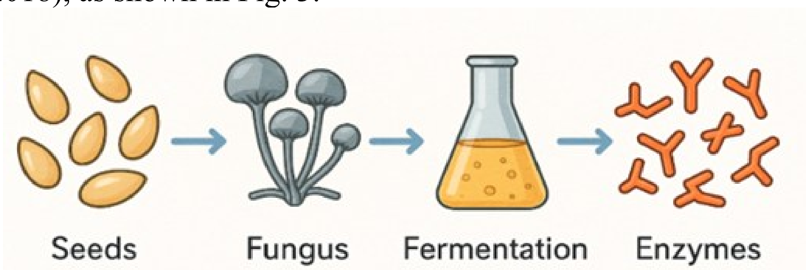

Fig. 3. Enzyme production flowchart

Among the enzymes produced from the utilization of agro-industrial residues, notable ones include amylase, cellulase, pectinase, xylanase, and protease, among others. For instance, amylases are used in the food industry to produce glucose syrups and maltodextrins from grain residues such as corn and wheat. Cellulase is employed in the hydrolysis of cellulose present in plant materials, being essential in the production of biofuels from lignocellulosic biomass. Pectinase is used in the juice and wine industry for the clarification and extraction of fruit juices. Xylanase acts in the hydrolysis of xylan, present in lignocellulosic biomass residues, facilitating the production of ethanol and other products. This promising approach demonstrates the potential of agro-industrial residues as raw materials for the synthesis of high-value-added enzymes. As pointed out by Singh *et al.* (2021), successful applications have been made to obtain products such as enzymes from lignocellulosic materials for industrial use, as they act as biocatalysts. Buenrostro-Figueroa *et al.* (2014) produced Elagitannase, an enzyme composed of different agro-industrial residues such as sugarcane bagasse, corn cob, and coconut husk.

The analysis of the characterization performed on the melon seed varieties showed that the seeds of the yellow varieties have considerable potential for enzyme production due to their high levels of (α-cellulose + hemicellulose), which exceed 45%. Although they contain lower holocellulose levels compared to caipira and cantaloupe melons, they are advantageous due to their lower lignin content. This is beneficial for enzyme production, as reduced lignin levels facilitate enzymatic access to polysaccharides, enhancing efficiency and reducing the need for extensive pretreatment. These components are essential for the generation of cellulolytic enzymes, which are crucial in biotechnological processes. This finding reflects the results obtained by Corrêa (2023), who, when characterizing grape pomace, identified an approximate content of 50% holocellulose, which enabled the production of lignocellulolytic enzymes. Such evidence reinforces the potential of these biomasses as promising sources for producing enzymes with industrial relevance.

According to Rolim *et al.* (2018), and Madeira (2017), melon waste, such as peels and seeds, has great potential as prebiotic ingredients and sources of cellulolytic enzymes due to their significant fiber content, including cellulose and hemicellulose. These fibers can serve as prebiotics, promoting gut health, while cellulolytic enzymes, namely cellulases and hemicellulases, help break down biomass into fermentable sugars. By utilizing these waste materials, such sub-processes support sustainability and the circular economy, offering efficient and environmentally friendly solutions for biotechnological processes. The production of enzymes from fermented residues has been adopted in various industries in recent decades due to their specific characteristics, non-toxicity, cost-effectiveness, and ability to save raw materials, energy, chemicals, and/or water compared to conventional processes.

Biofilms

Lignocellulosic materials are rich in biopolymers such as polysaccharides and proteins. These biopolymers, derived from agricultural by-products, have gained attention for producing biodegradable materials due to their renewable, non-toxic, and biodegradable properties. In addition to serving as a barrier between food and the external environment, depending on the raw material, they can even be consumed alongside the product. The development of edible and biodegradable films (Fig. 4) has attracted significant attention, as they offer sustainable solutions, add nutritional value, and enhance the sensory characteristics of food (de Andrade 2014). The production of biodegradable films for food from fruit and vegetable residues has been studied in recent years, aiming to add value to natural sources rich in bioactive compounds discarded on a large scale during industrial processing. Biodegradable plastics can be produced from various types of agro-industrial residues, such as banana/fruit peels, cassava starch, cellulose, corn, wheat straw, and rice straw (Buenrostro-Figueroa *et al.* 2014; Mustafa *et al.* 2018).

The production of biodegradable films involves the use of at least one component capable of forming a matrix with adequate cohesion and continuity. According to the literature, these films are often made from polysaccharides, proteins, and lipids. The choice of the most suitable components may vary depending on the specific properties desired for the biofilm (such as flexibility, strength, solubility, water resistance, and gas barrier properties). Cellulose is one of the most widely used polysaccharides for producing biofilms due to its abundance, biodegradability, and gas barrier properties. Cellulose can be modified to improve water solubility and the formation of more flexible films (de Andrade 2014). Based on the results of this study, of the five seed varieties analyzed, only the Santa Claus variety has a low cellulose content, making it less ideal as a raw material for producing this sustainable product.

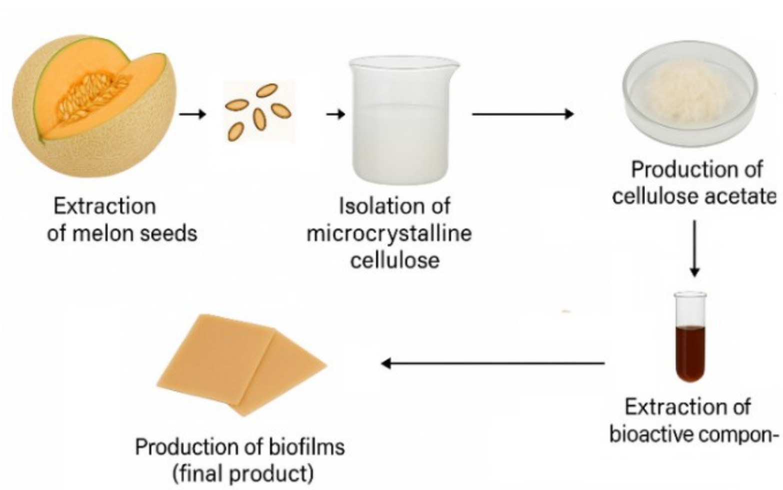

Fig. 4. Biofilm production

High protein foods

The utilization of agro-industrial residues to produce protein-rich foods represents a promising and sustainable strategy to meet the growing demand for high-quality protein sources. This approach involves the utilization of by-products and waste generated during food processing. These byproducts are rich in proteins, fibers, and other nutrients. Through biotechnology and food processing techniques, these residues can be transformed into high-nutritional-value protein ingredients. For instance, protein can be extracted from these residues, purified, and formulated into food products, as shown in Fig. 5.

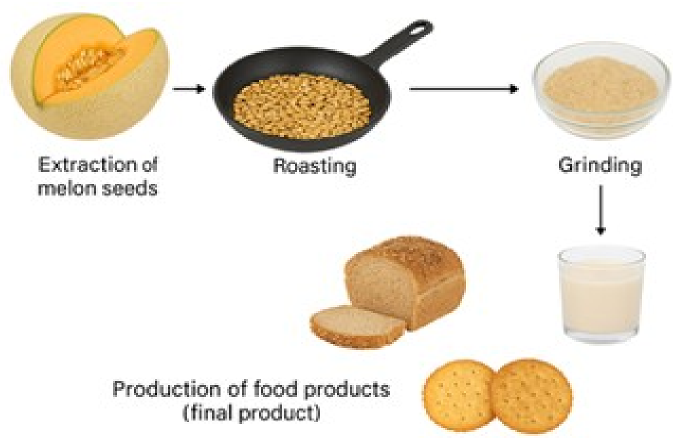

Fig. 5. Process flowchart for high-protein food production

The review by Allaqaband *et al.* (2022) highlights that traditionally underutilized fruit seeds, such as those from tomato, apple, date, and guava, are rich sources of bioactive compounds, including proteins, peptides, carotenoids, polysaccharides, flavonoids, and vitamins, with antioxidant, antimicrobial, and therapeutic potential. Moreover, using these by-products helps reduce agro-industrial waste and adds economic value. In this context, melon seeds, although more exploited, also present relevant phytochemical profiles, including phenolics, flavonoids, and fermentable sugars, demonstrating potential for applications in functional foods, nutraceuticals, and value-added products.

High-protein foods derived from agro-industrial residues can be an economical and accessible option for health and environmentally conscious consumers. Among several studies addressing the use of lignocellulosic residues in the development of protein-rich food products, the study conducted by Rosendo *et al.* (2021) stands out. They used barley malt residue, generated during the brewing process, as the main ingredient in the formulation of cereal bars. This residue is rich in fibers such as cellulose, hemicellulose, and lignin, in addition to containing proteins and B-complex vitamins. The final product showed a protein content of 7.32%, qualifying it as a protein-rich food source with innovative market potential by combining health benefits and functionality. Similarly, pumpkin seeds are highlighted by Fatima *et al.* (2025) as a sustainable source rich in bioactive compounds, including lignocellulosic constituents such as cellulose and hemicellulose, which contribute to digestive health and have great potential for industrial applications. These lignocellulosic components can be used in the development of functional foods, improving the nutritional profile of bakery products, dairy, and snacks, as well as serving as raw material to produce biodegradable packaging with good mechanical and barrier properties.

Data from the study by Madeira (2017) indicates that the flour obtained from melon peel and seeds presents relevant nutritional characteristics for human consumption, with a significant dietary fiber content: 51.8% for seeds and 40.6% for peel. These results are consistent with those obtained in this study, which showed that the fiber composition (cellulose + hemicellulose) in melons from the cantaloupe and caipira varieties exceeds 50%. This finding reinforces the great potential of these materials to be valued and incorporated into the food industry, expanding their applications and contributing to the sustainability of the sector. Additionally, the study by Mallek-Ayadi *et al.* (2019) on the chemical composition of melon seeds from the Maazoun variety showed that they contain a rich variety of nutrients, such as proteins, fibers, and minerals, indicating their potential as a dietary supplement in various relevant applications.

The conversion of melon seeds into food ingredients is an effective strategy for reducing waste and adding value. Recent studies have explored their use in various products. For example, Karakaya *et al.* (1995) developed a mineral- and protein-rich beverage, which was well-received in sensory tests; Zungur Bastıoglu (2016) *et al.* created a plant-based milk suitable for vegans and those who are lactose intolerant; Da Cunha *et al.* (2020) used melon-seed flour in baking, which was well-accepted; Tarjuelo *et al.* (2022) reformulated sausages by replacing pork fat with melon seed oil, improving the nutritional profile; and Zhang *et al.* (2023) replaced wheat flour with defatted seeds in bread, increasing the fiber content but affecting physical characteristics.

Given the information provided earlier, melon seeds exhibit significant promise across various applications, notably in phytotherapeutic oil production (Mallek-Ayadi *et al.* 2023), a diverse range of beverages (Akubor and Obasi (2019), and flours catering to different needs (Akusu and Kim-Kabari 2015). The observations and results presented validate the efficacy of the examined residues as a biomass source for generating secondary products, thereby fostering sustainable innovation.

Antibiotics

Antibiotics, which are essential for combating infections, are produced by microorganisms in fermentation tanks, where they utilize a medium composed of carbon sources, nitrogen, trace elements, and anti-foaming agents. Sources such as glucose and lactose are ideal for this production. Using lignocellulosic waste as a source of glucose can make the process more economical and sustainable (Aradhana and Preetha 2021). These residues, derived from plant material, can be converted into cellulose and, subsequently, into glucose through physical, chemical, or biological methods. With the increasing demand for antibiotics, lignocellulose emerges as a promising and accessible raw material for their production, as shown in Fig. 6.

Lignocellulosic materials are among the most abundant natural materials from renewable sources and possess attractive characteristics such as low density, biodegradability, low cost, high availability, and ecological friendliness. Lignocellulosic biomass can be converted into glucose by fungi such as *Aspergillus niger* and *Trichoderma reesei* during solid-state fermentation, where it is then used by antibiotic-producing microbes (Lobo *et al.* 2021). Among the three main components of lignocellulosic biomass, lignin currently has the least utilization for producing new products. At present, about 98% of the industrially produced lignin is burned as a source of energy, while only the remaining 2% is isolated and commercially applied in products such as resins, additives, and bioactive compounds. However, the growing demand for sustainable solutions has encouraged research to expand the applications of lignin, transforming it into a valuable resource in various industrial sectors (Luo and Abu-Omar 2017).

The use of lignin in medical applications is a growing field. Several reviews have explored its therapeutic potential. The main driving factor behind this interest is the fact that lignin is a non-toxic, biocompatible, and bioactive material. As a polymer with antimicrobial properties, lignin can be applied in antimicrobial therapies, wound treatment and healing, drug delivery, and tissue engineering (Chen *et al.* 2022). Lignin has been widely used in drug delivery due to its amphiphilic structure and its ability to form stable nanoparticles in water. Various drugs have been encapsulated in lignin nanocarriers, enabling controlled and effective release (Alqahtani *et al.* 2019). Lignin emerges as a promising alternative to the antimicrobial agents currently used to combat pathogenic microorganisms (Richter *et al.* 2015).

According to Brebu and Vasile (2010), Menon and Rao (2012), and Yang *et al.* (2018), lignin has shown thermal stability and biological activity, characteristics that make it a promising plant polymer for a wide range of future market applications. Rocca *et al.* (2018) investigated the antibacterial activity of different lignins and lignin-containing nanocomposites with high sugar content against *Staphylococcus aureus* (Gram-positive bacteria) and *Escherichia coli* (Gram-negative bacteria). They concluded that the interaction of nanocomposites with the bacterial cell wall is influenced by the structure of the lignin, which helps not only with the stability of the particles but also with the selectivity of different types of bacteria.

In this context, melon seeds from the caipira and cantaloupe varieties, which have high percentages of holocellulose and lignin, hold promising potential for producing bioactive compounds, including antibiotics. Holocellulose, due to its ability to be converted into glucose, offers the possibility of a more economical process, while lignin, with its antimicrobial properties, contributes to the effectiveness of potential substances. In the specific case of melon seeds, the high concentration of lignin can add additional value to these seeds, as the lignin extracted from them can be explored in the development of new antimicrobial agents, aiding in the fight against bacterial infections, particularly considering the growing issue of resistance to conventional antibiotics.

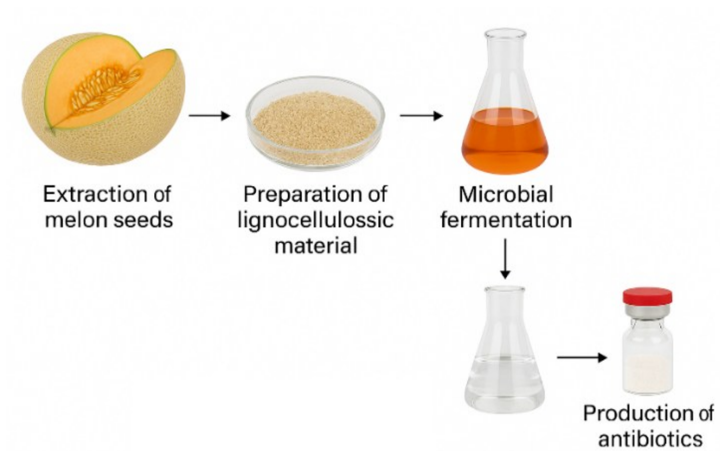

Fig. 6. Antibiotics production flowchart

Based on the results obtained and the identified potential, melon seeds are shown to be a promising raw material to produce a wide range of bioproducts. This utilization contributes not only to the economic viability of the processes but also to the efficient and sustainable management of agro-industrial waste, which is in line with the principles of the circular economy. The high holocellulose content of this material provides structural characteristics favorable to producing sustainable products, while the lignin, in addition to exhibiting antimicrobial properties, can be converted into high-value compounds such as resins and antioxidants. The potential applications of melon seeds in biofuels and biodegradable plastics further reinforce their relevance in the development of environmentally sustainable solutions.

Melon seeds are also recognized as rich sources of bioactive compounds, demonstrating significant potential for applications in the cosmetic, food, pharmaceutical, and nutraceutical industries. These compounds can be extracted using conventional methods with organic solvents or through advanced techniques such as ultrasound-assisted extraction and supercritical fluid extraction, which offer higher yields and reduced environmental impact. The purification process typically involves methods such as chromatography and ultrafiltration to obtain high-purity extracts. Emerging technologies, including continuous extraction systems, integration into biorefineries, and the application of nanotechnology, have further enhanced the scalability, stability, and sustainability of the commercial exploitation of melon seeds.

However, the transition of these processes to an industrial scale still poses significant technological challenges, mainly due to the chemical variability of the material, which directly impacts the standardization and quality of the products. Optimizing extraction and conversion processes is essential to ensure energy efficiency and economic viability, requiring investments in appropriate equipment. The integration of these processes into existing production chains also presents difficulties, especially in the logistics and storage of raw materials. Furthermore, the derived bioplastics must meet mechanical and environmental requirements to compete with conventional materials. Despite these barriers, technological advances and investments can enable large-scale production. The results obtained reinforce the viability of melon seeds as raw material for bioproducts, but additional studies are needed to evaluate the effects of extracts and lignin and to optimize their applications.

The valorization of these residues contributes to cost reduction and strengthens sustainability in the agricultural sector. Currently, there are no industrial pilot projects or large-scale commercial applications, but there are promising academic initiatives, such as the production of biodiesel using catalysts derived from seeds, the development of sustainable paper that can be planted, and the use of seed flour in culinary preparations such as cakes and pies. These examples are still in the early stages and require support in research, investment, and public policies to advance towards industrial production.

CONCLUSIONS

1. Melon seeds have high potential as a lignocellulosic raw material for high value-added products.
2. The caipira and cantaloupe varieties stand out among the types studied due to their lignocellulosic composition.
3. Potential applications include biofuels, biofilms, enzymes, food products, and bioactive compounds.

4. The use of seeds contributes to circular bioeconomy and sustainable production.
5. Research should focus on optimizing pretreatments to increase the efficiency of biofuel production.
6. Efficient resource use and value generation across different sectors reinforce the strategic potential of the seeds.

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Conflict of Interest

The authors declare that there are no competing financial interests.

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