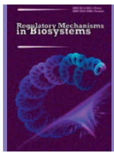

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Waste-free processing of cassava in the food industry and bioenergy

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The development and implementation of waste-free resource- and energy-saving technologies is the basis for increasing production efficiency, which will help produce a comprehensive solution to the problem of resource supply of the economy and environmental protection. The production of food products, in particular starch, from non-traditional raw materials is increasingly attracting the attention of both researchers and manufacturers, as the population becomes more aware of the impact of healthy nutrition. This article provides a detailed review of current research on the use of cassava (*Manihot esculenta)* in the food and processing industries. During the literature review, the ability to use waste-free technology for cassava processing was considered, namely, obtaining food starch and flour from this type of raw material. Cassava flour, and accordingly, products from it, are suitable for consumption by people suffering from gluten intolerance, as well as people who seek to eat healthy food. This raw material is also promising for obtaining food starch. Wastes generated in the agro-industrial complex make up a significant share in the field of bioenergy production, including their consumption in the production of ethanol and biofuels, which has been the focus of attention of many researchers over the past decade due to the depletion of fossil oil reserves. Biofuel production from cassava starch began at the end of the last century, and the use of cassava residues, such as peel, bagasse, stem, root and leaves, is currently being intensively studied by researchers to identify their potential in biofuel production. Analysis of the scientists' research showed that it is worth highlighting several main areas of work on the use of cassava for partial or complete replacement of wheat flour with cassava flour in the production of bakery products, the production of starch for the food industry, biodegradable material for food packaging and the production of bioethanol. The data obtained contain practical value regarding the possibility of using cassava and its waste-free processing, which is a relevant issue today.

Keywords: food starch; biodegradable material; biofuel; extraction; edible coating.

Introduction

The use of starch, as a major component of the human diet, is widespread not only in the food industry, but also in non-food industries such as paper, clothing and construction. Starch is known to be an ideal material for the development of biodegradable food packaging. The use of edible starch sources (for example corn, sweet potato, cassava, potato and wheat) is a common approach to the development of biodegradable food packaging based on starch.

Potatoes and edible tubers, such as sweet potatoes, cassava, Jerusalem artichoke, etc., have a high content of starch and inulin. They are grown for human consumption, as a food product; used in the processing industry, for plant reproduction or for feeding farm animals (Xu et al., 2021).

Among them, we can single out cassava (*Manihot esculenta*), which is also called manioc or yuca. This vegetable is common in Africa and South America as a food product, it is used in food fresh or in the form of flour for making bread. Research by Jensen (2015) has shown that wheat flour can be replaced by 30% with cassava flour, which is gluten-free. Therefore, this flour, and accordingly, products made from it, are suitable for consumption by people suffering from gluten intolerance, as well as people who strive to eat healthy food.

Cassava contains a large amount of starch. According to the results of Olekwu & Aliyu (2014), up to 25% starch can be obtained from 100 kg of cassava roots, of which about 60% can be obtained from dry cassava chips and 10% from dry pulp. The above-mentioned authors in their work investigated the possibility of using cassava starch as an additive at an optimal amount of 6% for obtaining fired bricks. Starches from rhizomes differ from cereal starches in that they contain more amylopectin, which results in a softer gel that does not have a "grainy taste." These starches include potato and tapioca. The latter is nothing more than starch obtained from cassava rhizomes (Saranraj et al., 2019).

Obtaining starch from the rhizomes of *Anemarrhena asphodeloides* was studied by the authors Zhu et al. (2022), who used in their work extraction of polysaccharides with water under pressure with optimization by the response surface method. Cavenaghi-Altemio & Graciano (2024) investigated the partial replacement of wheat flour with corn and cassava flour in the production of fish fingers as an alternative to gluten-containing food products.

Eduardo et al. (2014) investigated the effect of adding water and xylanase and laccase enzymes on the quality of wheat and cassava composite bread. They found that adding 70% water and enzyme preparations Panzea® BG (Panzea) containing xylanase and laccase Novozym® 51003 resulted in a more structured and softer bread.

The purpose of the study was to analyze scientific research on the use of cassava in the food and processing industry in the production of starch and flour for the food industry, obtaining food film, and producing fuel for the agro-industrial complex.

Composition of cassava

Cassava is a perennial evergreen bushy plant that has 3–5 m height. The stem is cylindrical with a thickness of 2–7 cm, branched, well leafy and fragile. Cassava has a gray-green, silver or crimson color. Depending on the color, its surface can be either smooth or rough. Cassava fruit is presented in the form of a three-leafed box, which has the ability to crack when ripe. The seeds are small, elliptical in shape, and gray or brown in color.

The countries with the largest share of cassava in agriculture are Zaire, Tanzania, Uganda and Nigeria in Africa, Thailand, Indonesia and Vietnam in Southeast Asia, Brazil, Venezuela and Colombia in South America. The yield of this crop depends on many factors, including rainfall (Nykytiuk & Kravchenko, 2024), soil cultivation (Lykhovyd et al., 2024), growth stimulants (Rohach et al., 2024) etc.

Table 1 presents the physicochemical composition of cassava tubers, from which it can be seen that among carbohydrates, starch prevails in the amount of 32.4 g/100 g of raw material, macronutrients – potassium, calcium and phosphorus in the amounts of 394.0, 26.0 and 32.0 mg/100 g, respectively, and ascorbic acid (34 mg/100 g of raw material). Proteins and dietary fiber, iron, sodium and ash were found in small quantities. The moisture content in raw cassava reaches 65.5%, and in terms of caloric content, this raw material corresponds to 135 kcal.

Table 1
Physicochemical composition of cassava tubers according to research data by Pandey (2000)

Substance	Content, per 100 g of raw material	
	total weight	dry matter
Proteins, g	1.0	1.4
Fats, g	0.2	0.5
Carbohydrates (starch), g	32.4	80.6
Dietary fiber, g	1.1	1.2
Ash, g	0.9	1.8
Calcium, mg	26.0	96.0
Phosphorus, mg	32.0	81.0
Iron, mg	0.9	7.9
Sodium, mg	2.0	–
Potassium, mg	394.0	–
Vitamin B_2, mg	0.04	0.06
Ascorbic acid, mg	34.0	0.0
Niacin, mg	0.6	0.8
Cyanide, %	–	1.6
Calories, kcal	135.0	335.0
Humidity, %	65.5	15.7

Therefore, the large amount of starch in cassava allows us to use and process this raw material to obtain starch itself. Therefore, further research was conducted to study those scientific works that highlight the processing of cassava to produce starch, which can be used both in the food industry and as a renewable energy source.

Cassava as a source of starch

Starch is the most accessible and cheapest product that is completely biodegradable in many environments (Abotbina, 2022). Starch is one of the most common substances in nature and refers to a renewable and almost unlimited resource. It is mainly used as food, but is also easily converted through chemical, physical and biological processes into many useful products. Starch is used to produce products as diverse as food, paper, textiles, adhesives, beverages, confectionery, pharmaceuticals and building materials. Starch has high viscosity, transparency indicators and stability during freezing and thawing, which are advantages for many industries.

Cassava starch is produced by wet grinding fresh cassava roots. In some countries, fresh tubers are processed during the season, and dried chips are processed during the off-season. The extraction of starch from fresh cassava roots involves five main stages: preparation, which includes such technological operations as cleaning and washing, grinding, refining (starch washing), drying, and final mechanical processing – crushing and packaging.

For cassava, the starch extraction process is relatively simple because the roots contain only a small amount of secondary substances, such as protein. When cassava roots are harvested or selected for starch extraction, the age and quality of the root are critical factors. Cassava roots must be processed almost immediately after harvest because they are highly perishable and enzymatic processes can accelerate spoilage within a few days. High-quality starch can be obtained from cassava using only water, making the processing of cassava starch and flour particularly suitable for developing countries and for agricultural industries.

Weligama Thuppahige et al. (2023) proved the potential of starch extraction from cassava waste-peel and bagasse and developed a method for extracting starch from these wastes. The results of the experiments showed that the yield of starch from cassava peel was 30 ± 2%, and from bagasse – 8 ± 1%. Scanning electron microscopy analyses showed that starches extracted from cassava peel and bagasse and directly from cassava have similar morphological and functional groups. It was experimentally proven that cassava peel and bagasse are potential alternative sources of starch for its use as a biodegradable material for food packaging.

Table 2 presents the chemical composition of cassava residues according to research data from various scientists. In cassava pulp, the starch content varies from 32.6% to 79.5%, the hemicellulose content from 2.8% to 13.0%. Such a large difference between the values is possible when using cassava from different regions, where growth and yield and quantitative chemical composition are affected by various factors, including the amount of precipitation and solar radiation. The method of obtaining starch in the technological process of processing raw materials also has an important impact on the content of components in the raw materials (Zheplinska et al., 2022a). It is also possible that there may be a discrepancy in the amounts of the main components due to the methods used by the authors to determine certain indicators (Burova et al., 2021).

Table 2
Biochemical composition of cassava residues

Raw	Content, %				Reference to a literary source
	starch	sugar	cellulose	hemicelluloses	
Pulp	65.6	–*	8.1	2.8	Wongskeo (2012)
	60.1	–	15.6	4.6	Aregheore & Toxicology (1991)
	79.5	–	–	–	Pattiya (2012)
	48.0	–	23.0	9.0	Adetunji (2015)
	32.6	18.0	–	–	Dahniya (1994)
	49.7		21.5	13.0	Jaramillo (2015)
	57.8	88.4	–	–	Padi & Chimphango (2019)
Stem	8.4	–	21.4	11.6	McKendry (2002)
	–	–	56.4	20.2	Marx & Nquma (2013)
Peel	15.8	–	35.9	9.3	Edhirej et al. (2017)
	67.0	–	–	–	Chotiprayon et al. (2020)
Leaf	28.7	29.0	–	–	Demirbas (2005)
Rhizome	–	–	27.8	39.7	Banerjee et al. (2010)

Note: * data missing.

From Table 2 it can be seen that in the peel, along with the pulp, there is also a large amount of starch (from 15.8% to 67.0%), which once again confirms the fact that there is an excellent opportunity to use cassava waste for processing and thus make a completely waste-free technology for its processing. In the stems, peel and rhizomes there is a significant amount of cellulose, which can be used in the paper industry as packaging for food products. In the rhizomes, a large amount of hemicellulose has been studied, as well as in sugar pulp (88.4%). Therefore, the prospects for waste-free technology for cassava processing are quite large for the processing industry. And one of these prospects is the use of cassava starch to obtain a food (edible) coating for food products.

Buksa (2018) extracted starch from different parts of rye grain by traditional and developed enzymatic methods and compared the physical, chemical and molecular properties of the isolated starches, with a particular focus on the susceptibility to the formation of resistant starch.

Food coating

A food coating is a thin film of an edible substance that can be consumed as part of a food product. Such coatings are good at protecting the product from harmful biological, physical, and chemical modifications. They help prevent desiccation of products and selectively allow respiratory gases such as carbon dioxide and oxygen to pass through. Due to its strong mechanical properties, starch is one of the food materials used as a film coating. Beeswax was the first edible coating in the 12th century for oranges and lemons. The English used fats to extend the shelf life of meat products, known as lard. These coatings were already used in the 20th century to prevent water loss and add a glossy layer to fruits and vegetables. As noted by Weligama, Thuppahige & Karim (2022); Stadnyk et al. (2021), the development of biodegradable packaging for ready-to-eat foods is complicated by its poor mechanical properties, hydrophilicity and excessive sensitivity to humidity. Numerous research attempts by various authors on the extraction of starch and the characterization of the obtained starch from rhizomes (Algar et al., 2019), grains (De Schepper et al., 2021), tuberous roots (Ascheri et al., 2014; Babu & Parimalavalli, 2014; Andrade et al., 2017) and stems (Aziz & Sobri, 2015) have already investigated its application as food ingredients, functional biomaterials, and coagulants for wastewater treatment. Although research on alternative starch sources for biodegradable food packaging has recently become a research interest, these potential implications have received little attention. Experimental studies on replacing conventional food starch sources with alternative, non-traditional starch sources as biodegradable units for food packaging have been conducted. Therefore, agro-industrial wastes generated from cassava deserve to be studied as alternative sources of starch. The continuous growth of cassava starch production has led to incredibly large volumes of cassava peel and bagasse (Anyanwu et al., 2015). However, such waste is discarded, which poses a serious threat and environmental pollution, as directly indicated by scientists (Adeboye et al., 2021). Cassava peel, according to Anyanwu et al. (2015), and bagasse, as a result of research by da Silva et al. (2022) have been found to contain a large amount of starch. Scientists Maulida et al. (2016), Silviana et al. (2018) and Silviana & Dzulkarom (2019) have paid attention to the high starch content in cassava peel and bagasse, evaluating its potential as a biodegradable raw material for food packaging.

Starch extraction methods used by scientists in their experiments Silviana et al. (2018), Silviana & Dzulkarom (2019) were limited to dissolving bagasse in water with filtration. However, starch extraction from cassava bagasse is a complex process that requires more complex procedures due to the fibrous components, as reported in the scientific paper by Srirotha et al. (2000). These authors claim that enzymatic processing of raw materials contributes to the effective extraction of starch from bagasse. In this regard, recommendations were made for further research to effectively extract starch from cassava bagasse, but no one has taken advantage of it.

Méndez et al. (2022) investigated cassava and banana starch modified with maleic anhydride-polyethylene glycol methyl ether for use as a coating for strawberries. The authors of the study proposed a simple route to obtain grafted starch copolymers from cassava and banana starches. The starches were extracted from cassava pulp and banana and were characterized using atomic spectroscopy, amylose content, scanning electron microscopy, thermogravimetric analysis, differential scanning calorimetry and average molecular weight. It was found that the weight loss of strawberries during coating ($15.5 \pm 5.7\%$) was lower than that of the control sample ($18.6 \pm 3.3\%$).

Important properties of edible coatings include those voiced by the following authors (Nor & Ding, 2020; Maringgal et al., 2020; Palamarchuk et al., 2024a): they should not ferment, should not curdle, should not have an off-flavor and should not deteriorate during storage; they should be evenly distributed, dry quickly and be easy to remove from the machine; should not crack, corrode or peel during storage and handling; should not be stored in a package and react with food; they should provide adequate gas exchange to avoid any off-flavors or deterioration during storage; the coating should be a moisture barrier to avoid wetting.

The benefits of using edible coatings are known to include improved appearance and structural properties, as well as reduced water loss, gas diffusion, and mold growth, as noted by Suhag et al. (2020). The authors prepared a suspension of cassava starch under constant stirring at 60 °C. The food to be coated was then immersed in the solution and allowed to dry at room temperature. The concept of this technology is to create a modified atmosphere around the fruit surface that could preserve the quality characteristics of the fruit. Water-soluble polysaccharides in coated fruits and vegetables have the ability to reduce oxygen content and increase carbon dioxide content in a modified environment. This allows the reduction of the normal respiration process. Similarly, the shelf life of fresh produce can be extended using controlled atmosphere storage. There are several methods for coating edible material, such as dipping, drip coating, fluidized bed coating, panning, and spraying. Sondari et al. (2018) conducted a study on the effect of cassava starch coatings with or without potassium sorbate on the quality of processed strawberries. The results of the study showed that the water vapor resistance test of edible cassava starch coatings did not affect the surface color of the strawberries and demonstrated high acceptability. The coatings also contributed to a decrease in respiration rate and improved the susceptibility of the samples to water vapor. Garcia et al. (2010) conducted a study on the effect of cassava starch and carboxymethyl starch coating on the organoleptic properties of papaya during processing. The result of their scientific work shows that edible cassava coating increases shelf life by reducing respiration rate. Lago-Vanzela et al. (2013), Utami et al. (2014) and Silva et al. (2019) found that a modified gas environment reduces food weight loss and improves its quality indicators by applying gloss to it.

Bioethanol production

Increasing energy consumption and climate change have led to huge advances in the global search for renewable energy sources. In addition, bioethanol is a promising renewable fuel and is already being blended with gasoline in many countries. In 2017, global bioethanol production was estimated to be 27.05 billion gallons, with the United States contributing about 58%, or 15.8 billion gallons (Pradyawong et al., 2018). The global economy is heavily dependent on fossil energy resources, with combustion contributing approximately 98% of carbon emissions (Hajar et al., 2017; Efeovbokhan et al., 2019). Bioethanol fuel is produced mainly by fermenting the sugar components of biomass, including cassava starch, sugarcane juice and other carbon sources, as pointed out by Andrić et al. (2017).

The advantage of cassava is its ability to be converted into components such as methane and ethanol, which in most countries will be more than enough for human needs, as directly indicated by the authors Gupta & Prakash (2015). In addition, cassava has the ability to grow on degraded lands and marginal soils and has high drought tolerance and is second only to sugar beet and sugarcane in yield (Popp et al., 2014; Zheplinska et al., 2022b).

Cassava is widely used for bioethanol production using waste peel as feedstock for microbiological and enzymatic hydrolysis. Studies by Wangpor et al. (2017) found that cassava peel waste has a high cellulose content of about 43.63%. Bioethanol produced from cassava starch by fermentation, enzymatic hydrolysis and ex situ nanofiltration was investigated. Cassava starch was liquified and converted into sugar by gluco-amylase and alpha-amylase respectively before fermentation to produce bioethanol. Bioethanol is also produced from hybrid cassava peel and pulp by acid and microbial hydrolysis. The results were obtained by converting cassava peel to easily identify a beneficial way to manage cassava waste for the environment. The results were investigated by Emeka, Oseghale & Okoye (2015) and showed that cassava peel starch is easily biodegradable and *Aspergillus niger* can produce bioethanol. Xiang et al. (2022), Mushtruk et al. (2024) and Palamarchuk et al. (2024b) have shown that the resulting bioethanol was similar to regular ethanol.

In addition, bioethanol production was carried out from liquid waste of cassava dough as an enzyme stimulator in the processing of fine powder gari, which in West Africa is made from the root of the cassava tuber. The latter is converted into edible dry granules during the production process, which was studied by Adinsi et al. (2019).

Thanks to research by Egloso (2014), an integrated continuous bioethanol production system resulted in the production of fuel bioethanol with a purity of up to 99.8%, which is a technically and economically feasible investment for the enterprise.

Oyeleke et al. (2011) showed that cassava and sweet potato peels were used as raw materials for bioethanol production with maximum yield of finished products by hydrolysis of *Pleurotus ostreatus* and *Gloeophyllum sepiarium* and fermentation of yeasts *Saccharomyces cerevisiae* and *Zymomonas mobilis*. Highly concentrated bioethanol was obtained by repeated hydrolysis and periodic application of yeast to cassava stems.

Kazumasa et al. (2018) carried out research on the production of high content bioethanol (about 40 g/L) by studying the effect of yeast with intermittent feeding on ethanol fermentation, hydrolysate concentration and acid hydrolysis conditions. They showed that bioethanol can be obtained from cassava starch, its roots, peel, pulp and stem. The ease of access to these sources is explained by the fact that cassava can be grown on depleted fields. In addition, the low cost of cassava and its high suitability as one of the best sources for obtaining bioethanol make it a promising raw material for obtaining waste-free technologies (Emeka et al., 2015).

Thus, the findings of foreign scientists suggest conducting research and using cassava for various products in the food and processing industries not only abroad, but also in Ukraine. Therefore, our further recommendations will concern farmers, who should think about using fields for planting this valuable crop and the huge opportunities to use raw materials for waste-free production in the food and processing industries of Ukraine.

Conclusion

The paper presents an overview of cassava, which has many advantages for starch production, manifested in a high level of purification, excellent thickening characteristics, mild taste and appropriate textural characteristics. The analyzed literature sources allowed us to establish that a relatively cheap source of raw materials – cassava contains a high starch content, which can be the same as or exceed the properties of corn, wheat starches and starch obtained from potatoes and rice. According to experiments conducted by foreign authors, it has been proven that cassava starch can be easily obtained through a simple process (compared to other starches) and can be produced on a small scale and with limited capital. The development of both food and non-food uses of cassava starch has made significant progress and has a place in the future. Having analyzed the research of scientists, it is worth highlighting several main areas of research ; the use of cassava for partial or complete replacement of wheat flour with cassava flour in the production of bakery products, the production of starch for the food industry, biodegradable material for food packaging and the production of bioethanol. Based on the research results of various authors, we conclude that it is possible to replace commercial cassava starch with starch extracted from cassava waste to obtain biodegradable food packaging, as well as to produce cheap bioethanol from cassava starch, its roots, peel, pulp and stems.

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