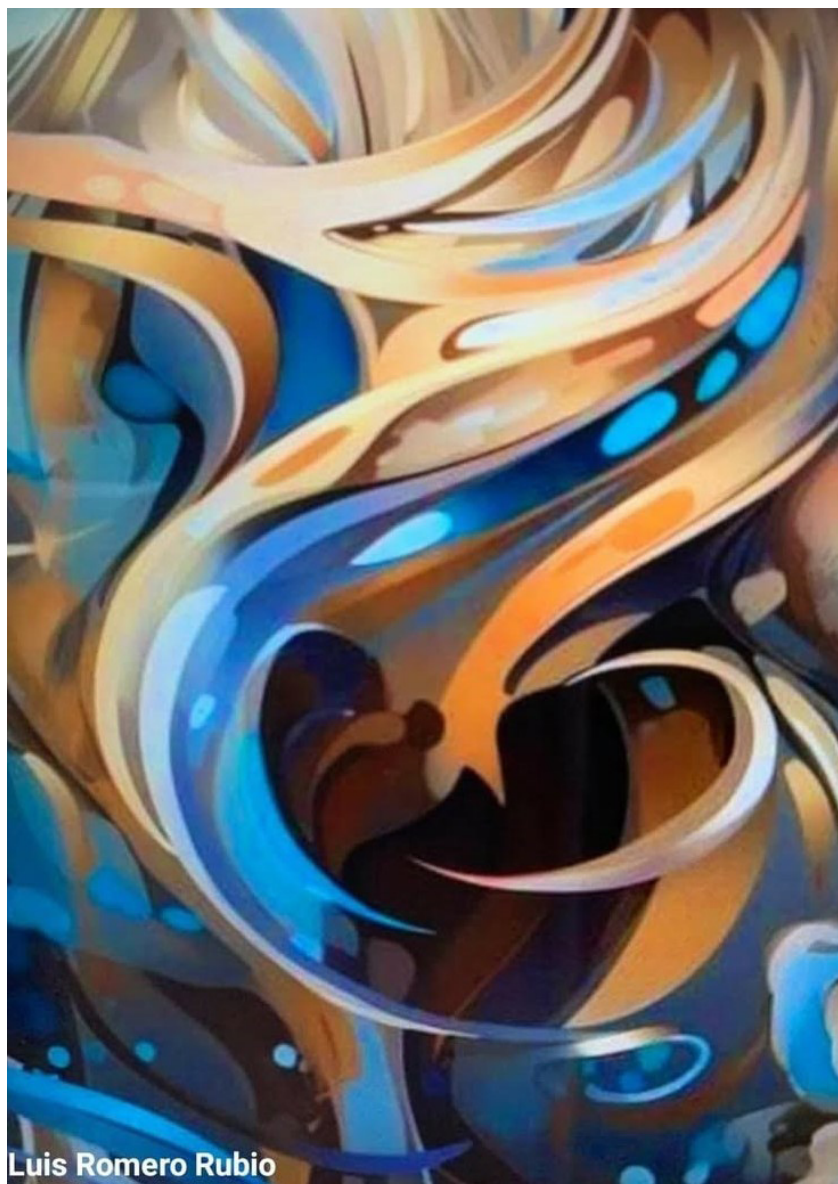




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Cassava cultivation: a review on waste valorization for livestock and agricultural applications

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Abstract

Cassava (*Manihot esculenta* Crantz) is a strategic tropical crop, yet root processing generates large solid and liquid residue streams, approximately 200–300 kg of solids and about 600 L of manioc juice (manipueira) per ton of roots, whose inadequate disposal burdens soils and water bodies. Therefore, this review synthesizes the physicochemical profiles and cyanogenic risk attributes of major residues (peels, bagasse/pulp fiber, aerial biomass, and processing effluents) and critically discusses valorization pathways, with an emphasis on livestock feeding and agricultural applications within a circular bioeconomy perspective. Evidence indicates that solid fractions rich in starch and lignocellulose can be incorporated into ruminant, swine, and poultry diets after detoxification and nutritional balancing, while also serving as substrates for bioenergy routes (e.g., second-generation ethanol and biogas) and biobased materials. The manioc juice, also known as manioc juice or manioc water, is characterized by high organic load and free cyanide, and requires controlled management; anaerobic digestion stands out for coupling methane generation with nutrient recovery and biofertilizer production. Composting/co-processing of solid residues further supports nutrient cycling, whereas emerging options (e.g., biochar-based soil amendments and advanced bioproducts) remain conditioned by process costs, moisture-driven logistics, and the lack of standardized quality and biosafety protocols. Finally, research priorities and policy levers are outlined to accelerate scale-up and regional implementation of integrated, low-cost agro-industrial systems.

Keywords: Cassava waste; waste valorization; sustainable applications; bioeconomy; agro-industrial residues; cyanogenic compounds; animal feed; biofertilizer; anaerobic digestion

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Cultivo de la yuca: una revisión sobre la valorización de los residuos para aplicaciones ganaderas y agrícolas

Resumen

La yuca (*Manihot esculenta* Crantz) es un cultivo tropical estratégico; sin embargo, su procesamiento genera grandes flujos de residuos sólidos y líquidos, aproximadamente entre 200 y 300 kg de sólidos y unos 600 litros de jugo de yuca (manipueira) por tonelada de raíces, cuya eliminación inadecuada supone una carga para los suelos y las masas de agua. Por lo tanto, esta revisión sintetiza los perfiles fisicoquímicos y los atributos de riesgo cianogénico de los principales residuos (cáscaras, bagazo/fibra de pulpa, biomasa aérea y efluentes de procesamiento) y analiza críticamente las vías de valorización, haciendo hincapié en la alimentación del ganado y las aplicaciones agrícolas desde una perspectiva de bioeconomía circular. Las pruebas indican que las fracciones sólidas ricas en almidón y lignocelulosa pueden incorporarse a las dietas de rumiantes, porcinos y aves de corral tras su desintoxicación y equilibrio nutricional, al tiempo que sirven como sustratos para vías bioenergéticas (p. ej., etanol de segunda generación y biogás) y materiales de origen biológico. El jugo de yuca, también conocido como jugo de mandioca o agua de yuca, se caracteriza por una alta carga orgánica y cianuro libre, y requiere una gestión controlada; la digestión anaeróbica destaca por combinar la generación de metano con la recuperación de nutrientes y la producción de biofertilizantes. El compostaje y el coprocesamiento de residuos sólidos contribuyen además al ciclo de los nutrientes, mientras que las opciones emergentes (por ejemplo, los acondicionadores de suelo a base de biocarbón y los bioproductos avanzados) siguen estando condicionadas por los costes de los procesos, la logística relacionada con la humedad y la falta de protocolos normalizados de calidad y bioseguridad. Por último, se esbozan las prioridades de investigación y las medidas políticas necesarias para acelerar la ampliación y la implementación regional de sistemas agroindustriales integrados y de bajo coste.

Palabras clave: Residuos de yuca; valorización de residuos; aplicaciones sostenibles; bioeconomía; residuos agroindustriales; compuestos cianogénicos; piensos para animales; biofertilizantes; digestión anaeró

Introduction

Cassava (*Manihot esculenta* Crantz) is one of the most strategic food crops in the world, grown in more than 100 countries (Matheus *et. al.*, 2023), particularly in tropical regions of Africa, Asia, and South America. World production in 2023 was estimated at 319.5 million tons, with Sub-Saharan Africa accounting for more than half of this total (Cruz *et. al.*, 2021), followed by Asia, where Thailand stands out as the main exporter of cassava products (Aboitbina *et. al.*, 2022).

In Brazil, cassava holds a prominent position in the Latin American context, as the largest producer in the region, with a production of 17.97 million tons in 2023 (IBGE, 2025). The crop is present in all Brazilian states, with greater relevance in the North and Northeast regions, where family farming and traditional cultivation by local communities

predominate (Cruz *et. al.*, 2021). On the other hand, in the states of Paraná, Mato Grosso do Sul, and São Paulo, which account for approximately 98% of national starch production in 2022, production is highly mechanized, with a strong presence of agribusiness and a focus on exports (Methodio Groxko Prognóstico: Mandioca, 2018). This regional distribution highlights the socioeconomic role of the Cassava Production Chain, which contributes to job creation and the revitalization of local economies, especially in rural areas (Andrade Cruz *et. al.*, 2022).

Brazilian starch exports, however, have faced challenges such as low agricultural productivity and high industrial idleness. In 2023, for example, there was a 43% reduction in exports between January and August compared to the same period in the previous year (Roberta Martins, 2026). As for the varieties grown in Brazil, they are mainly classified into two groups: “mansa” (or table) cassava, with low cyanogenic compound content, intended for direct human consumption; and “brava” cassava, with higher hydrocyanic acid content, intended for industrial starch and flour production (Fukuda *et. al.*, 2002). Each cultivar has specific characteristics in terms of production cycle, starch content, climate adaptation, and response to agricultural management. This genetic diversity is strategic for simultaneously meeting food and industrial demands, in addition to allowing the development of new plant materials adapted to different producing regions in the country.

In addition to its importance as a strategic food crop in tropical regions, cassava (*Manihot esculenta* Crantz) plays a central role in global food security and in supplying raw materials to various industrial sectors, such as food, pharmaceuticals, pulp and paper, and bioplastics (Jumaidin *et. al.*, 2023; Sunvittayakul *et. al.*, 2025; De Oliveira Schmidt *et. al.*, 2023). Its resilience to climate change and ability to adapt to poor soils reinforce its value in policies to combat hunger and promote sustainable development (Cruz *et. al.*, 2021; Sunvittayakul *et. al.*, 2025; Veiga *et. al.*, 2016). In addition to being an essential source of carbohydrates (flour, starch, and derivatives), the crop represents a vital economic activity for thousands of families in rural areas (Cruz *et. al.*, 2021; (Andrade Cruz *et. al.*, 2022). Its production chain has great potential for adding value through local processing, agro-industrialization, and product diversification, contributing to the strengthening of regional economies and social inclusion (Abotbina *et. al.*, 2022; Obonukut; Alabi; Jock, 2023).

Cassava is an extremely versatile crop, and its derivatives are widely used in a variety of production chains, both in the food sector and in the chemical and bioproducts industries (Abotbina *et. al.*, 2022). The processing of the root generates products with high added value, among which starch, flour, sweet and sour cassava flour, modified starch, biofuels, adhesives, and even bioplastics stand out (Jumaidin, 2023; Sanchez-Ledesma; Rodríguez-Victoria; Ramírez-Malule, 2024).

In addition to food use, cassava provides strategic raw material for a wide range of industrial sectors. Starch can be transformed into modified starch, with applications in paper and cardboard, textiles, cosmetics, biodegradable packaging, adhesives, and industrial glues (Matheus *et. al.*, 2023; Jumaidin, 2023). Another relevant industrial use is in the production of ethanol and biofuels from starch, reinforcing the role of the crop in the energy transition and bioeconomy (Abotbina *et. al.*, 2022; Oluwagbotemi, 2024). In addition, research has advanced in the development of biopolymers and bioplastics based on cassava starch, offering a sustainable alternative to petroleum-based plastics (Matheus *et. al.*, 2023; Abotbina *et. al.*, 2022).

These multiple applications, both in the food and industrial sectors, highlight

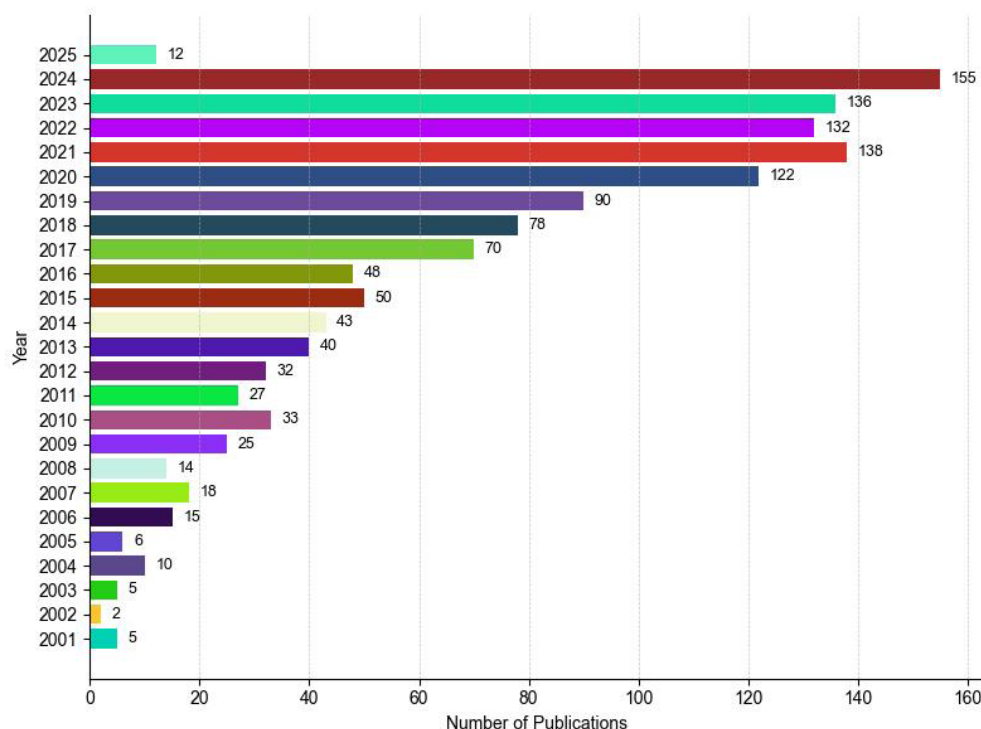
the high potential of cassava to add value, stimulate local production chains, and foster innovation in bioindustries, especially in tropical regions where the crop is predominant.

Despite its economic importance and versatility, cassava (*Manihot esculenta* Crantz) processing generates large volumes of solid and liquid waste, estimated at 200–300 kg and 600 liters, respectively, per ton of processed root (Oghenejoboh *et. al.*, 2021; Olukanni and Olatunji, 2018). Much of this material, consisting of peelings, fibers, pressed cakes, and manioc juice (the liquid extracted during pressing), is often disposed of improperly, polluting soil and water bodies Cruz *et. al.*, 2021; Andrade *et. al.*, 2023). In addition to the environmental impact, this disposal represents a loss of biomass with high potential for reuse in the generation of biogas, bioethanol, biocomposites, and biodegradable packaging (Luchese *et. al.*, Padi and Chimphango, 2021).

Methodology

In this context, waste recovery emerges as a promising strategy to transform environmental liabilities into economic assets, boosting the regional bioeconomy and social inclusion. However, technological and regulatory advances are still needed to enable its large-scale use. Scientific interest in the topic is growing, as demonstrated by the significant increase in publications over the last decade (Figure 1), especially in countries such as Brazil, Thailand, and China, where cassava plays a strategic role in production chains. This research drew on literature from Scopus and Web of Science published over the years within the scientific community.

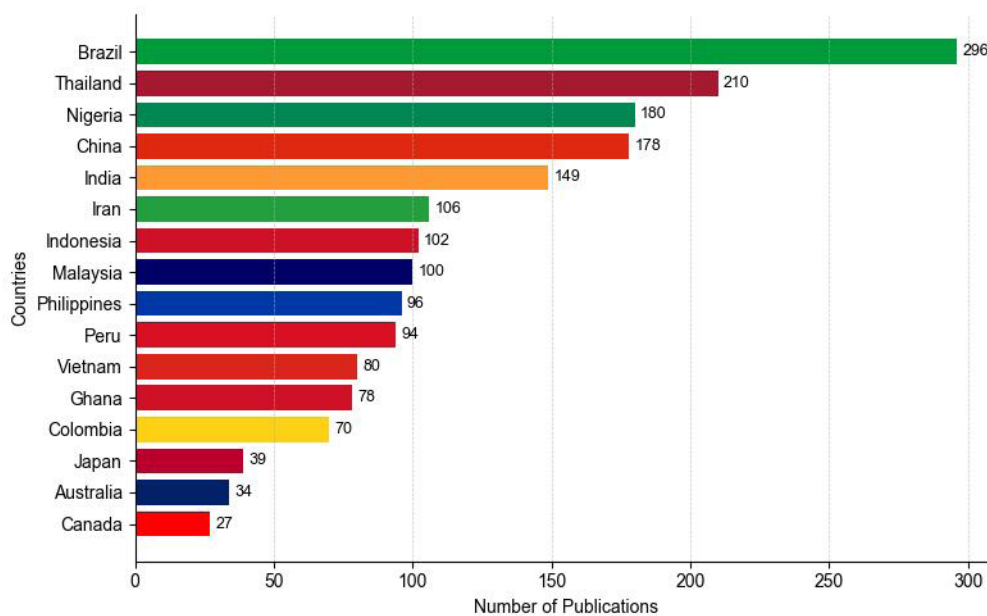
Figure 1. **Number of papers published in the last 25 years on cassava residues.**



Source: Authors, (2026).

Regarding the countries that have been working most on this topic, Brazil leads in the number of publications, followed by Thailand, China, Nigeria, and India (Figure 2), which highlights the relevance of research on this topic in countries where cassava plays a significant agricultural and economic role. Other countries, such as Indonesia, Malaysia, the United States, Colombia, and South Africa, also contribute significantly to the scientific literature on the reuse and recovery of cassava waste.

Figure 2. Countries that have published the most on cassava residues in the last 25 years.



Source: Authors, (2026).

Recent studies highlight the potential for valorizing cassava residues, transforming them into value-added products and mitigating environmental impacts. Among the residues, manioc pulp stands out for its high polluting potential, which requires treatment and controlled use. Given this scenario, this study aims to review the main strategies for reusing cassava waste, highlighting applications in bioenergy, food, the chemical industry, and agriculture, with a focus on sustainability and the principles of the circular economy.

Applications of Cassava residues

1. Residues generated in cassava processing

The industrial processing of cassava to produce flour and starch results in large volumes of solid and liquid residues, the improper disposal of which can cause serious environmental impacts. Solid waste includes peels, husks, fibers, bran, and sweepings, while liquid waste includes manioc juice, a highly polluting by-product due to its hydrocyanic acid content (De Oliveira Schmidt *et. al.*, 2023; Oghenejoboh *et. al.*, 2021). Due to the high organic load and the presence of cyanogenic compounds, this waste is toxic to aerobic

organisms (Andrade *et. al.*, 2023). To mitigate these impacts, several alternatives have been studied, such as its use in animal feed, organic fertilization, and biofertilizer production (Adetunji *et. al.*, 2015; Padi and Chimphango, 2022).

The key wastes and their attributes are summarized in Table 1.

Table 1. Details on waste from cassava flour production.

Waste	Origin in the process	Main characteristics	Associated environmental problems	Potential for reuse/sustainable use
Outer bark and inner bark	Peel the roots before washing and grinding.	10–15% of root weight; rich in lignocellulosic fibers (cellulose 25–35%, hemicellulose 15–25%, lignin 10–20%); contains residual starch (5–15%).	Release of methane and contamination of water bodies when disposed of without treatment.	Production of biogas, 2G bioethanol, composting, nanocellulose, bioplastics, and natural adsorbents.
Bagasse (fiber)	Starch extraction and dough pressing	High moisture (>80%); residual starch (50–80%), fiber (~11%), low protein and lipid content	Rapid microbiological deterioration and odor emission	Production of 2G bioethanol, animal feed, biodegradable composites
Manioc juice (liquid effluent)	Pressing the dough after grating	Milky-looking liquid; high BOD (3,000–6,000 mg/L) and COD (7,000–30,000 mg/L); contains hydrocyanic acid (HCN) and nutrients (K, P, N)	High toxicity; soil and water contamination; CH ₄ emissions	Anaerobic biodegradation for biogas and biofertilizers; controlled agricultural use after treatment
Bran and sweepings	Sifting, grinding, and cleaning the floor of the flour mill	Heterogeneous mixture of fine particles of starch, fibers, and impurities	Local contamination and unpleasant odors	Animal feed supplement; organic composting
Leaves, stems, and shoots	Aerial part discarded after harvest	20–30% of total biomass; high protein content (14–28%) and fibrous	Decomposition releases odors and methane; risk of surface contamination	Production of corn stover hay; animal feed; green manure and composting

Source: Authors, (2026).

Considering its potential, different studies have explored sustainable applications for this waste, both to mitigate environmental impacts and to generate new sources of income for producers. Some of these alternatives will be reviewed below:

a) Peels

In animal feed, this waste is processed by drying, grinding, ensiling, or alkaline hydrolysis, and is an alternative in the formulation of feed for ruminants. Trials with sheep have indicated that the inclusion of this by-product in the diet does not alter zootechnical performance or ruminal morphology, with alkaline hydrolysis showing better economic efficiency (Faria *et. al.*, 2011). Similarly, in dairy cattle, partial replacement of corn with this residue reduced dry matter intake and digestibility, as well as milk production; however, it did not alter milk composition, indicating viability in contexts of greater residue availability (Dos Santos *et. al.*, 2015). In addition to zootechnical applications, the husk is considered a promising substrate for anaerobic fermentation, aiming at the production of biogas and

second-generation ethanol (Aisien and Aisien, 2020; Murata *et. al.*, 2021; Hierro-Iglesias *et. al.*, 2024). This residue also has potential as a raw material for high-value-added compounds, including biofertilizers, nanocellulose, bioplastics, and natural adsorbents, strengthening the bioeconomy and sustainability in local agro-industrial chains (Cruz *et. al.*, 2021; Aisien and Aisien, 2020; Fronza *et. al.*, 2024; Nandiyanto *et. al.*, 2025; Simate; Ndlovu and Seepe, 2015).

b) Bagasse

Bagasse is a solid by-product generated during the extraction of starch from cassava roots and is characterized by high moisture content (over 80%), which makes storage and transportation difficult and promotes rapid microbiological deterioration (Matheus *et. al.*, 2022; Abotbina *et. al.*, 2022; Obonukut; Alabi and Jock, 2023).

Chemically, this by-product has a high carbohydrate content, especially residual starch (50 to 80% on a dry basis), as well as crude fiber (~11% of dry matter) (Obonukut; Alabi and Jock, 2023; Ronko; Travalini and Demiate, 2020) and low levels of protein, lipids, and ash (less than 5% of dry matter) (Abotbina *et. al.*, 2022). However, these levels vary depending on the variety of cassava, growing conditions, and extraction technology. Due to its composition, bagasse has potential for various applications, such as in the production of second-generation bioethanol (Suriyachai *et. al.*, 2024; Seer and Nandong, 2016), animal feed (Abotbina *et. al.*, 2022), and the development of biodegradable composite materials, (Matheus *et. al.*, 2023; Abotbina *et. al.*, 2022).

c) Wastewater from processing

The wastewater generated in cassava processing, known as manipueira, manioc juice, or manioc water, has a composition that can cause severe environmental impacts when not treated properly. This effluent has a high organic load, with BOD (biochemical oxygen demand) values ranging from 3,000–6,000 mg/L and COD (chemical oxygen demand) values ranging from 7,000–30,000 mg/L, in addition to an acidic pH (4.0–7.5), depending on the type of processing and the cultivar used (Cruz *et. al.*, 2021; Andrade Cruz *et. al.*, 2022; Conceição *et. al.*, 2013). The presence of free cyanide significantly increases its toxicity, making it capable of causing eutrophication, reducing dissolved oxygen, and killing aquatic fauna, in addition to contaminating groundwater even at low concentrations (Cruz *et. al.*, 2021; Oghenejoboh, *et. al.*, 2021; Andrade *et. al.*, 2023).

When improperly disposed of in the soil, the manioc juice can alter the chemical balance, increasing salinity and reducing pH, which compromises plant growth. In aquatic environments, it promotes the degradation of water quality and the death of aerobic organisms. In addition, open storage contributes to the emission of methane (CH₄), a potent greenhouse gas that exacerbates climate change (Andrade *et. al.*, 2023; Hansupalak *et. al.*, 2016). To mitigate these risks, different treatment technologies have been investigated, with anaerobic biodigestion standing out as a viable alternative. In (Feiden, 2001), for example, a two-stage biodigester system was developed on a pilot scale, achieving removals of up to 77% of total organic carbon (TOC), COD, and 66% of total solids present in the manioc juice, in addition to enabling biogas production.

In addition to treatment, the manioc juice can also be used as an input in the production of biofertilizers and for energy generation, provided it is treated beforehand. According to (Santos *et. al.*, 2024), cassava starch industries in Paraná have adopted clean technologies, such as biodigesters, with a view to reusing the biogas generated and

minimizing environmental impacts. These practices are part of the concept of cleaner production, combining sustainability and industrial efficiency.

Therefore, although the manioc juice is a waste product with high polluting potential, its proper management allows it to be transformed into an input for bioenergy and biofertilizers, exemplifying how the circular economy can add value to agro-industrial waste and promote more sustainable production chains.

d) Leaves and stems

Cassava leaves and stems, parts that are largely underutilized in the agro-industrial context, are residues with significant nutritional composition and can be used in different applications, including animal and human food (Adetunji *et. al.*, 2015). These structures are notable for their high protein, fiber, and mineral content, justifying their use in sustainable production chains (Adetunji *et. al.*, 2015). According to (Adetunji *et. al.*, 2015), the aerial parts of cassava varieties have considerable protein content, reaching around 20%, in addition to a high fiber concentration. This composition makes the material a relevant alternative source for feeding ruminants, and it can be used in the form of hay, with good forage value (Adetunji *et. al.*, 2015; Souza *et. al.*, 2012).

In addition to their use in ruminants, the components of the aerial part of cassava have also been evaluated for human consumption as a strategy for full utilization. According to (Storck *et. al.*, 2013), leaves, stalks, peels, and seeds of unconventional vegetables have high protein (up to 9.56%) and dietary fiber (up to 16.02%) contents, often higher than those traditionally consumed. In addition, the aerial part of cassava, consisting of stems, branches, and leaves, can be used to produce maniva hay, a forage for animal feed. According to (De Arruda *et. al.*, 2012), cassava maniva hay can be incorporated as a supplement in the diet of free-range poultry, ensuring animal health and contributing to cost reduction in family farming. These uses reinforce the strengthening of local production chains, sustainability, and the efficient use of agricultural waste. These applications demonstrate the potential to transform cassava waste into new products, contributing to the mitigation of environmental impacts. Among these wastes, manioc water, a liquid effluent generated during root processing, stands out as a significant environmental concern, especially in regions with a predominance of small agro-industries and flour mills (Cruz *et. al.*, 2021). Although it has potential for agricultural use as a biofertilizer, manioc juice is characterized by high organic load and high concentrations of toxic substances, such as hydrocyanic acid, in addition to macro and micronutrients such as potassium, nitrogen, phosphorus, calcium, and magnesium (De Oliveira Schmidt *et. al.*, 2023; Filho; Curto and Eustáquio, 2015).

Studies indicate that a considerable portion of the waste generated in these processing units is disposed of improperly: dumped directly into landfills, released into water bodies, or burned in open fires (Cruz *et. al.*, 2021; Oghenejoboh *et. al.*, 2021; Olukanni, and Olatunji, 2018). Such practices not only aggravate environmental pollution but also pose risks to public health, especially in nearby communities (Cruz *et. al.*, 2021). In these locations, there is a high incidence of diseases related to the consumption of contaminated water, the proliferation of vectors, and air pollution resulting from the burning of waste (Cruz *et. al.*, 2021; Oghenejoboh *et. al.*, 2021). This reality highlights the urgent need for management and reuse technologies capable of inserting the manioc juice into more sustainable production chains, reconciling environmental protection with the promotion of public health.

2. Applications for cassava residues

The residues generated in the cassava production chain have potential for recovery in different technological and agro-industrial routes. Their chemical and structural characteristics vary according to the fraction, influencing the most appropriate type of use. The table summarizes these fractions, with information on composition, risks, and possibilities for reuse, serving as a basis for the applications described in the following subsections.

Table 2. Characterization of the main residues from cassava processing and preferred recovery routes.

Residue / Fraction	Share of total mass (% fresh weight)	Approximate composition (dry basis %)	Risk / Cyanogenic compounds (HCN)	Preferential valuation route
Outer bark and inner bark	10–15% of the root	Cellulose (25–35%), hemicellulose (15–25%), lignin (10–20%), residual starch (5–15%)	Low to moderate (residue from “brava cassava” may contain up to 370 mg HCN/kg)	Production of biogas and bioethanol; formulation of feed (pre-treated); composting; obtaining nanocellulose and bioplastics
Bagasse (fiber from starch extraction)	10–20% of the processed root	Residual starch (50–80%), fiber ($\approx$ 11%), protein, lipids, and ash (<5%)	Low	2G bioethanol; animal feed; biocomposites and biodegradable packaging
manioc juice (liquid effluent)	$\sim 600 \text{ L t}^{-1}$ of root	BOD 3.000–6.000 mg/L; COD 7.000–30.000 mg/L; pH 4,0–7,5	High – contains free hydrocyanic acid (cyanogenic glycosides)	Anaerobic biodigestion (biogas and biofertilizers); nutrient recovery; integrated biological treatment
Leaves and stems (aerial part)	20–30% of the plant	Proteins (14–28%), fiber, minerals (Ca, Mg, Fe, P)	Moderate (presence of linamarin and lotaustralin)	Corn stalk hay; animal supplementation; composting; extraction of proteins and natural pigments
Bark and bagasse ash	—	Predominant SiO_2 , K_2O , CaO , P_2O_5	Null	Use as pozzolan in cement matrices and soil stabilization
Bran and sweepings	2–5%	Residual starch, fiber, and protein in low proportions	Low	Animal feed and organic composting

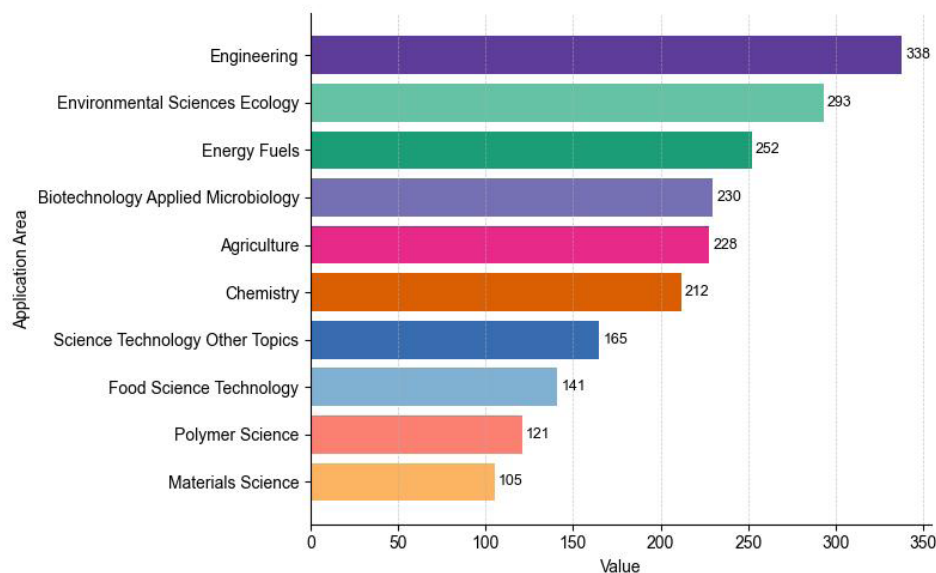
Source: Authors, (2026).

Figure 3 presents a treemap illustrating the main areas of application of cassava waste over the last 25 years, based on a search conducted on Web of Science on February 2, 2025, using the keywords “cassava” + “waste.” The size of the blocks is proportional to the number of scientific publications in each area, highlighting the relevance of studies on the topic in different fields of knowledge. The highest concentration of research is in the engineering area, with 338 publications, reflecting interest in the development of industrial processes for the use of cassava waste. Next, the area of environmental sciences and ecology, with 293 publications, highlights the environmental impact of improper disposal and possible strategies for its mitigation. The area of fuels and energy, with 252 publications, demonstrates the potential of waste in the production of biofuels and bioenergy.

Other fields of research also make significant contributions, such as biotechnology and applied microbiology, with 230 publications, where waste is used in the production of enzymes and other bioproducts. Agriculture, with 228 publications, explores the use

of this waste as fertilizer or animal feed. Chemistry, with 212 publications, investigates the composition and chemical transformation of cassava by-products. Food science and technology, with 141 publications, evaluates applications in the food industry, while polymer science, with 121 publications, studies the development of biodegradable materials from waste. In addition, materials science, with 105 publications, analyzes the production of new sustainable materials, and other topics in science and technology, with 165 publications, cover different approaches to the subject. These data highlight the growing importance of studies on cassava waste and its potential for use in various areas, promoting innovative solutions for sustainability and adding value to these by-products.

Figure 3. Main areas of application of cassava waste in the last 25 years.



Source: Authors (2026).

3. Animal feed

Cassava residues are promising ingredients for animal feed due to their high carbohydrate and fiber content, especially roots, husks, and bagasse, although their low protein and essential amino acid levels may limit direct dietary use (Adetunji et al., 2015). Cassava leaves, however, contain higher crude protein, minerals, and vitamins, but their use requires caution because of cyanogenic glycosides such as linamarin and lotaustralin (Adetunji et al., 2015; Hossain et al., 2025; Soares et al., 2024). Pretreatments such as drying, boiling, fermentation, ammoniation, and combined fermentation can reduce toxicity, improve digestibility and palatability, and support safer inclusion in animal diets (Pujaningsih; Mukodiningsih and Pakpahan, 2017). Thus, cassava residues can contribute to sustainable livestock production by reducing feed costs, minimizing waste, and transforming agro-industrial by-products into valuable nutritional resources.

3.1 Ruminants

Cassava bagasse and peel can partially replace corn, hay, and soybean meal in ruminant diets due to their high fiber and structural carbohydrate content, which supports ruminal fermentation and energy supply (Adetunji et al., 2015; Hossain et al., 2025). However, their low protein content and the presence of cyanogenic glycosides require protein supplementation and pretreatments such as drying, fermentation, alkaline hydrolysis, and ammoniation to improve safety and nutritional value (Adetunji et al., 2015; Hossain et al., 2025). Fermentation with yeast can substantially increase the protein content of cassava bagasse, while hay from cassava stems and leaves may serve as a fibrous supplement for controlled ruminal fermentation (Adetunji et al., 2015; Soares et al., 2024). In goats, combined ammoniation and fermentation has been shown to improve palatability, intake, and nutritional quality, supporting its use in zero-waste feeding systems (Pujaningsih; Mukodiningsih and Pakpahan, 2017).

3.2 Swine

In swine diets, cassava leaf and root flour can serve as alternative energy sources when properly processed to reduce antinutritional factors and cyanide toxicity (Hossain et al., 2025; Soares et al., 2024). Fermented cassava flour may be included at levels of up to 30% without impairing growth, provided that limiting amino acids such as lysine and methionine are adequately balanced (Hossain et al., 2025). Dehydrated cassava leaves can also improve fiber and mineral intake after cyanide reduction treatments (Soares et al., 2024). Recent evidence shows that cassava residue meal and fermented cassava residue meal do not negatively affect piglet performance and may improve pork quality by increasing intramuscular fat, enhancing color attributes, improving lipid profile, and favoring desirable muscle fiber characteristics, with fermentation further reducing antinutritional factors and improving palatability (Jiang et al., 2025).

3.3 Poultry

Cassava by-products, such as root flour, dried leaves, peels, straw, and cassava starch residue, show potential as alternative ingredients in poultry diets by reducing feed costs and supporting more sustainable production systems (Hossain et al., 2025; Pujaningsih; Mukodiningsih and Pakpahan, 2017). However, their use is limited by cyanogenic glycosides, insoluble fiber, low energy density, and nutritional imbalances, requiring processing methods such as sun drying, fermentation, ammoniation, enzymatic supplementation, and amino acid balancing to improve safety, digestibility, and performance (Diarra, 2018; Hossain et al., 2025). Recent evidence indicates that cassava starch residue can replace corn at levels of up to 30% in broiler diets without impairing weight gain or feed conversion, while higher inclusion levels may reduce performance (Osei-Adjei et al., 2025). Future research should focus on microbial fermentation, product quality, life cycle assessment, and low-cost processing technologies to strengthen the role of cassava residues in circular economy and zero-waste animal production systems.

4. Application in agriculture

4.1. Production of biofertilizers and composting

Manioc juice, a liquid effluent from cassava pressing or grinding, contains starch, glucose, hydrocyanic acid derived from cyanogenic glycosides such as linamarin, as well as proteins, lipids, and nutrients such as potassium and phosphorus (De Oliveira Schmidt et al., 2023; Conceição et al., 2013; Fioretto, 2001). Although its composition gives it agronomic potential as a nutrient source, its cyanogenic compounds and high organic load pose toxicological and environmental risks when used or discarded without proper treatment, dilution, or management (De Oliveira Schmidt et al., 2023; Conceição et al., 2013). Therefore, controlled recovery strategies, including treatment, rational fertigation, and anaerobic digestion, are necessary to reduce environmental impacts and enable safer use (Souza et al., 2019).

4.1.1 Liquid biofertilizers (fertigation; treated effluents)

Manioc juice can be used as a biofertilizer in crops when properly treated and applied at suitable doses. In lettuce, doses around 45 m³ ha⁻¹ improved plant height, leaf area, and biomass, while anaerobically treated effluent showed benefits for corn by increasing soil pH, base saturation, and nitrogen absorption efficiency (Duarte et al., 2012; Ribas; Cereda and Villas Bôas, 2010). However, high concentrations of raw manioc juice may cause phytotoxicity, seedling mortality, chlorosis, and soil imbalance, especially during early crop development, reinforcing the need for pretreatment and crop-specific dosing protocols (Costa et al., 2023). Anaerobic digestion and co-digestion with manure, glycerol, biochar, or mineral additives can convert manioc juice into biogas and generate digestate with fertilizer value, provided that residual cyanogens, conductivity, pathogens, and metals are controlled according to regulations (Hansupalak et al., 2016; Watthier et al., 2019; Andrade Cruz et al., 2022; Lin et al., 2021; Cruz et al., 2021; Padi and Chimphango, 2020).

4.1.2 Composting and biological co-processing of solid waste

For solid fractions (peels, bagasse), composting is a simple, low-cost, and technically validated route in family farming contexts. Surveys in northeastern Pará (Brazil) show that farmers already incorporate peels and bagasse as fertilizer in fruit trees and vegetables, albeit with empirical management; the literature recommends standardizing C/N ratios, moisture, and aeration, as well as co-processing with nitrogen sources (manure) to accelerate maturation and increase N, Ca, and Mg levels in the final compost (Souza *et al.*, 2019). In terms of optimization, a recent study identified that a 1:1 ratio (cassava peel:pig manure) achieved a final pH of ~6.6, moisture content of ~30%, C/N ratio of ~11.9, total N ~0.6%, and microbial counts of the order of 10⁶ CFU (bacteria), indicating maturity and stability of the compost at the end of the process, parameters compatible with agronomic use in soil fertility management (Ediene and Iren, 2025).

4.1.3 Best practices and gaps for R&D

In summary, the data indicate that:

- (i) Manioc juice has potential as a biofertilizer when treated, for example, after

anaerobic digestion and/or diluted with an optimal dose specific to each crop (lettuce: 45 m³ ha⁻¹, under the conditions of the study), mitigating phytotoxicity and environmental risks;

(ii) Peels/bagasse have robust application in composting, with superior performance in co-processes (manure), achieving stable/mature compounds; and (iii) integration of biorefinery (biogas + digestate) with solid composting closes C, N, and K cycles, reduces pollutant load, and partially replaces mineral inputs. Nevertheless, significant gaps remain: quality standards (residual cyanogens, BOD/COD, salinity), dose-response curves by crops (especially in seedlings and sowing), biosafety (pathogens, eggs/larvae), and regional protocols for safe use in humid tropical climates.

Results such as those in (Costa *et. al.*, 2023; Souza *et. al.*, 2019) highlights the lack of knowledge about residues and phytotoxicity at high concentrations, reinforcing that process engineering (treatment, neutralization/dilution, application control) is a prerequisite for scaling up cassava biofertilizers safely and effectively.

4.1.4 Use of fermented peel and residues as organic fertilizers

Controlled fermentation of cassava by-products, particularly peel and manioc juice (liquid effluent), has been explored to produce organic inputs with lower toxicological risk and greater agronomic efficiency. The logic is twofold: (i) to reduce the phytotoxicity associated with cyanogenic glycosides/HCN present in the effluent and fresh fractions; and (ii) to stabilize organic matter and nutrients, converting them into forms that are more assimilable and less labile in the field (e.g., digestates and matured composts).

4.1.5 Anaerobic digestion (liquid waste in digestate/biofertilizer)

An experimental milestone is the use of anaerobically treated manioc pulp (in two phases: acidogenic stabilized with NaOH or dolomitic limestone, followed by methanogenesis) as fertilizer in corn. In the classic 30-day pot trial, treatments with stabilized and methanized effluent raised the soil pH to >7.5 and base saturation (V%) to ~90%; N absorption by plants reached 64–80% in effluent treatments, depending on the dose, showing an alkalizing effect and competitive nitrogen supply in relation to mineral NPK (reference treatment) (Ribas; Cereda and Villas Bôas, 2010). These results support the use of liquid digestate (post-methane) as a biofertilizer; however, it is recommended to calibrate doses per crop and check conductivity/residual cyanogenic content, in addition to complying with local health requirements.

Complementing the liquid route, studies fermenting organic mixtures with cassava peel demonstrate the viability of liquid biofertilizers with microbial inoculants (*Bacillus*, *Pseudomonas*, *Lactobacillus*, *Aspergillus*), with growth gains in corn and okra; soil application outperformed foliar application in the first five weeks under greenhouse conditions (indicating greater efficiency via the rhizosphere) (Okolie *et. al.*, 2019). In tropical contexts, arrangements with lactic fermentation/“liquid bokashi” are also described (including fractions of cassava leaves and other plants in mixtures), but the nutritional composition and regulatory compliance vary and require analytical standardization before widespread (Chodijah *et. al.*, 2025).

4.1.6 Composting waste to increase organic matter in the soil

Composting cassava residues, including peel, bagasse, and leaves, is an effective strategy to recycle nutrients, increase soil organic matter, and reduce environmental risks from direct disposal (He et al., 2023). Optimal composting conditions, such as a C/N ratio near 25, moisture around 60%, adequate aeration, and microbial inoculation, can promote organic matter degradation, thermophilic stabilization, and compost maturity (He et al., 2023; Ediene and Iren, 2025). Field studies show that cassava peel and leaf compost can improve soil fertility, crop growth, nutrient availability, and residual effects in cassava, corn, and rice, with recommended application rates generally ranging from 10 to 15 t ha⁻¹ depending on soil and crop conditions (Adeyeye et al., 2017; Adebayo et al., 2025; Hawlader et al., 2020). However, compost maturity and safety must be verified through indicators such as germination index, pH, electrical conductivity, C/N ratio, and the absence of toxic compounds, metals, and pathogens before agricultural application (Andrade Cruz et al., 2022; Andrade et al., 2023; Martins et al., 2022).

4.1.7 Safety and quality of compostable material

Although aerobic composting promotes the oxidation/hydrolysis of cyanogenic precursors, HCN control is essential when the raw material includes fractions rich in linamarin/manioc juice. Evidence from targeted fermentations shows reductions of ~79–80% in HCN within 5–15 days with bacterial inoculants (e.g., *Citrobacter freundii* HT1; *Proteus vulgaris* HT3), reinforcing the viability of biological pretreatments to mitigate risks prior to composting or agricultural application (Triani et al., 2025).

4.1.8 Practical summary for increasing soil organic matter – SOM and soil ecosystem services

- Formulation: prefer co-composting (e.g., bark:manure = 1:1) to achieve a mature carbon/nitrogen (C/N) ratio in the range of 11–15 and pH ~6.5–7.0, with good stability and nutrient content (Ediene and Iren, 2025);
- Process parameters: initial C/N of approximately 25, moisture around 60%, aerobic management to ensure thermophilia and a high germination index (GI ≥ 80%) at the end He et al., 2023).
- Field dose: ranges of 10–15 t ha⁻¹ have shown yield gains and positive residual effects for various crops such as cassava, maize, and rice, especially in soils with low SOM stocks (Adeyeye et al., 2017);
- Monitoring: verify maturity through germination index (GI), electrical conductivity (EC), pH, and C/N ratio tests, health (indicator CFU, absence of pathogens), and, when relevant, residual cyanogenic content before use in nurseries/sensitive stages.

In weathered tropical soils, repeated application (consecutive crops) tends to accumulate particulate SOM associated with minerals, improving structure, water retention, and cation exchange capacity (CEC). Residual effect data, as in the case of corn cultivation, and post-harvest availability data, as in rice production, support this approach, but longer time series and field-scale carbon balance are still desirable to quantify C sequestration and positive environmental externalities (Adebayo et al., 2025).

4.2. Soil conditioners and erosion control

Mulch made from bark, fibrous bagasse/bran, and cassava leaves, applied between rows or in strips on the soil, acts as a physical barrier to the impact of raindrops, reducing splash, surface runoff, and soil loss, as well as mitigating sealing and compaction in the surface layer. In family farming systems in the eastern Amazon, these fractions are already being used empirically as fertilizer and mulch for fruit trees and vegetables, indicating logistical feasibility and local acceptance (Souza *et. al.*, 2019). From an operational standpoint, a thickness of 3–6 cm of fragmented fibrous material, such as 2–5 cm bark to create loose mulch, usually ensures good coverage ($\geq 50\%$ of the surface), a level at which, in tropical soils, there is a substantial reduction in runoff and erosion and an increase in infiltration; values close to 85% coverage tend to eliminate erosion on gentle slopes (Adekalu; Okunade and Osunbitan, 2006). In cassava systems managed over several cycles, the continued use of plant cover increases the organic carbon content, effective porosity, and availability of potassium (K), calcium (Ca), and magnesium (Mg), and may even increase root yield when combined with minimum tillage and maintenance of residues on the soil (Howeler; Oates and Allem, 2000).

When there is a strong odor, high leachability, or risk of phytotoxicity (fractions with cyanogenic glycosides), it is recommended to compost the solid fractions (peels/leaves) beforehand and only then apply them as mulch. On an industrial scale, co-composting organic mixtures for approximately 120 days (with a thermophilic phase $> 60^\circ\text{C}$) promotes sanitization, raises the pH to the stability range, adjusts the C/N ratio to lower values (≤ 20), and reduces phytotoxicity, cytotoxicity, and genotoxicity, producing a material that is safe for agricultural use as mulch/conditioner (Martins *et. al.*, 2022). In humid tropical contexts, cassava peel compounds co-processed with manure (1:1 ratio, m/m) have shown a final pH of around 6.6, a C/N ratio between 11 and 12, total nitrogen (N) of approximately 0.6%, and high microbial activity, compatible with use as mulch and for improving soil structure (Ediene and Iren, 2025). For specific purposes (anti-sealing, improvement of ion exchange capacity – IEC, and water retention), a thin layer of cassava peel biochar can also be intercalated under the organic mulch to obtain better results; recent data suggest physical gains and phytosanitary effects when combined with organic sources (Cookey *et. al.*, 2025).

Thus, the use of cassava fibers and residues as soil cover is a promising technique for erosion control and surface compaction relief, with additional benefits for moisture, soil temperature, and nutrient cycling. To standardize the use of this technique on a large scale, it is recommended to:

- (i) ensure good visual coverage ($\geq 50\%$) immediately after planting and replenishing after heavy rains;
- (ii) prioritize pre-composted material when there is a risk of phytotoxicity;
- (iii) integrating mulch with conservation practices (contour planting, maintenance of post-harvest residues).

The consolidation of these practices in cassava cultivation, with quantitative tests of soil loss, infiltration, and hydraulic conductivity by texture/slope, is an immediate front for applied research.

4.3. Biochar production

4.3.1 Cassava Residue Pyrolysis Process

Pyrolysis is a promising route for converting cassava residues, especially peels and pulp, into biochar, bio-oil, and gas under limited oxygen conditions, with product distribution strongly influenced by temperature, heating rate, residence time, particle size, moisture, and reactor design (Jerzak; Acha and Li, 2024; Sharma; Pareek and Zhang, 2015; Bridgwater, 2012). For agricultural biochar production, slow pyrolysis at 350–500 °C is generally preferred, as it favors solid yield, fixed carbon content, alkaline pH, and greater stability, although higher temperatures may enhance surface area and carbonization for adsorption applications (Awogbemi and Kallon, 2023; Ighalo et al., 2025; Waheed et al., 2025; Rambhatla et al., 2025). Cassava residues require careful pretreatment, including drying, particle-size standardization, and control of mineral-rich ashes, since their starch, holocellulose, potassium, and calcium contents affect thermochemical behavior and biochar reproducibility (Weligama Thuppahige et al., 2023; Thuppahige et al., 2023; Wijitkosum and Sriburi, 2021). Thus, optimized pyrolysis conditions can enhance the sustainable valorization of cassava waste into stable biochar for soil conditioning and environmental applications.

4.3.2 Applications for improving soil fertility and carbon sequestration

Biochars produced by slow pyrolysis of cassava residues exhibit agronomic properties typical of alkalizing, structuring, and nutrient-retaining inputs, capable of improving fertility in weathered tropical soils (pH<5.5; low organic matter) and simultaneously stabilizing carbon in the soil. In terms of agronomic performance, studies with cassava stem biochar show increases in corn productivity in infertile soils when biochar is incorporated alone or in combination with usual fertilizer doses, with gains in seed mass, number of ears, and optimal productivity observed in the biochar+fertilizer co-application (2.5–3.0 kg m⁻²) in field designs in Southeast Asia. These results were accompanied by a significant increase in specific surface area ($\approx 200 \text{ m}^2 \text{ g}^{-1}$) and a reduction in the O/C and H/C atomic ratios of the material, indicators of greater stability of the fixed carbon after pyrolysis (H/C ≈ 0.39 ; O/C ≈ 0.65) (Wijitkosum and Sriburi, 2021).

Mechanistically, the cation exchange capacity (CEC) of biochar and surface alkalinity raise soil pH (the “liming effect”), mitigate exchangeable Al³⁺, and improve phosphorus (P) availability and ammonium (NH₄⁺) retention, reducing losses through leaching; porosity and aromatic/oxygenated functional groups favor micro-habitats and soil aggregation, with positive effects on available water and aggregate stability. In global meta-analyses, biochar application increased, on average, soil organic carbon (SOC) and labile components (microbial, particulate, and easily oxidizable carbon), with stronger responses in tropical regions, acidic soils (pH<5.5), coarser texture, and conditions of low initial fertility (SOC<5 g kg⁻¹). The syntheses also highlight that moderate pyrolysis temperatures ($\approx 550\text{--}650 \text{ }^\circ\text{C}$) favor the accumulation of SOC and that moderate doses combined with nitrogen fertilization are more economically and environmentally efficient than very high applications (Zhang *et. al.*, 2023).

Specifically for cassava, the composition of the residues (residual starch, relevant K and Ca contents, and low lignin content) influences the quality of the biochar and, therefore, the

effects on the soil: biochars from husk/bagasse tend to have a neutral to alkaline pH, cation exchange capacity, and appreciable K and Ca contents, desirable agronomic attributes in highly weathered Ultisols and Latosols. Recent studies characterizing husk and bagasse (focused on biodegradable packaging, but analytically useful here) show K and Ca contents that help explain the “liming” effect observed after pyrolysis, in addition to highlighting the need for standardization of drying and particle size to ensure reproducibility of biochar properties (Adekanye *et. al.*, 2025; Zhang *et. al.*, 2023).

In terms of ecosystem services, biochar contributes to carbon sequestration both by adding recalcitrant pyrogenic C (low H/C_{org} and O/C ratios associated with greater aromaticity and a half-life exceeding decades) and by inducing increases in native SOC via improved soil physicochemical conditions (pH, CEC, aggregation). A rapid review with global meta-analysis reported an average increase of 61% in soil carbon stock (CI 36–90%) after biochar application, with effects modulated by application rate, feedstock type, and pyrolysis temperature; the study also pointed out that, although the total soil CO_2 flux may increase in some scenarios (probable priming and microbial respiration associated with the labile fraction of biochar), the sequestration balance remains positive (Bekchanova *et. al.*, 2024).

There are also relevant collateral agronomic benefits: (i) synergies with organic sources and amendments, such as combined use with poultry litter or composted manure, which increase total N and available P and accelerate the recovery of degraded soils; (ii) contextual phytosanitary effects, for example, formulations with cassava peel biochar and organic fertilization helped manage root-knot nematodes (*Meloidogyne incognita*) in okra, reducing severity in endemic soils; and (iii) potential reductions in N losses through volatilization and leaching, with repercussions on nutrient use efficiency. Although evidence on phytosanitary effects with cassava-based biochars in food crops is still emerging and heterogeneous, the results suggest a promising line of applied research (Tian *et. al.*, 2024).

From a technical recommendation point of view, evidence converges on moderate doses and integration with mineral/organic fertilization according to the cropping system. In maize under low fertility soil, levels of 2.5–3.0 kg m⁻² of stem biochar, combined with NPK, maximized productivity and grain quality; in acidic tropics, SOC responses and crop yield tend to be greater than in temperate zones, and peaks of benefit appear with biochars produced at intermediate temperatures (~550–650 °C), which balance solid yield and stability/aromaticity. Such general trends in the biochar literature are consistent with the specific properties of cassava residues (Zhang *et. al.*, 2023).

Thus, the literature shows that biochars obtained from cassava residues are technically suitable as multi-purpose soil conditioners in tropical environments, as they increase pH, Cation Exchange Capacity (CEC), and nutrient availability, improve soil structure and water retention, and add stable pyrogenic carbon, contributing to carbon sequestration and productive resilience. Fine-tuning should consider the pyrolysis temperature (to modulate stability and ash content), the type of residue (peel, bagasse, stems), and integration with fertilization and local management. Research priorities include dose-response curves by crop/soil, effects on GHG (greenhouse gases; N_2O/CH_4) emissions in the field, durability of Soil Organic Carbon (SOC) gains over multiple cycles, and quality protocols for cassava-based biochar oriented towards CEC, ash content, H/C_{org} ratio, and the presence of reactive minerals.

5. Implementation framework: economic feasibility, biosafety, regulation, and monitoring

The implementation of cassava residue valorization depends not only on technical feasibility, but also on economic scale, logistics, residue availability, regulatory compliance, and local adoption capacity (Cruz et al., 2021; Oghenejoboh et al., 2021; Olukanni and Olatunji, 2018; Andrade et al., 2023). Low-complexity routes such as drying, ensiling, fermentation, composting, and treated fertigation are more suitable for smallholder systems, while anaerobic digestion and pyrolysis are better suited to cooperatives, starch industries, or regional valorization centers due to their higher investment and technical requirements (Adetunji et al., 2015; Pujaningsih; Mukodiningsih and Pakpahan, 2017; Souza et al., 2019; Andrade Cruz et al., 2022). Quality and biosafety control must include parameters such as residual cyanogenic compounds, pH, electrical conductivity, BOD/COD, moisture, C/N ratio, germination index, pathogens, toxic elements, and biochar stability indicators (Duarte et al., 2012; He et al., 2023; Ediene and Iren, 2025; Wijitkosum and Sriburi, 2021). Scaling up these technologies requires cooperative processing models, regulatory frameworks, public incentives, technical training, techno-economic and life cycle assessments, and digital monitoring tools to ensure traceability, safety, environmental benefits, and economic viability (BRASIL, 2020; BRASIL, 2024; Cruz et al., 2021; Andrade Cruz et al., 2022).

Conclusions

The valorization of cassava residues is a technically feasible and strategic approach for integrating circular bioeconomy principles into agro-industrial systems. Solid and liquid residues, including peels, bagasse, aerial biomass, and cassava wastewater, can be converted into animal feed, biofertilizers, digestate, compost, biochar, and renewable energy, provided that toxicity, nutritional limitations, and environmental risks are properly managed. Pretreatments such as drying, fermentation, ammoniation, anaerobic digestion, composting, and pyrolysis are essential to improve safety, nutrient recovery, and product quality. However, the most suitable valorization route depends on residue characteristics, local infrastructure, regulatory requirements, and producer organization. Scaling up these strategies requires standardized quality and biosafety protocols, techno-economic and life cycle assessments, long-term field validation, public incentives, technical training, and cooperative implementation models. Under these conditions, cassava residues can become valuable resources for animal nutrition, soil fertility, carbon management, renewable energy, and rural development.

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