Review

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Review

Cultivating Value from Waste: Creating Novel Food, Feed and Industrial Applications from Bambara Groundnut By-products

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Abstract

Bambara groundnut (*Vigna subterranea*), a vital yet underutilized African legume, significantly boosts food security due to its nutritional value and adaptability to harsh climates and soils. However, its processing yields substantial waste like husks, shells, and haulms, which are often carelessly discarded, causing environmental damage. This paper highlights the urgent need to valorize these waste streams to unlock sustainable growth and economic development. Given their lignocellulosic composition, Bambara groundnut residues are ideal for generating biogas and bioethanol. Beyond energy, these wastes can be transformed into various bio-based products, including adsorbents for heavy metal removal, activated carbon for water purification, and bioplastics. Their inherent nutritional content also allows for the extraction of valuable components like dietary fiber, protein concentrates, and phenolic compounds for food products or animal feed. The nutrient-rich organic matter can also be composted into fertilizer, improving soil fertility. These valorization strategies offer multiple benefits: reduced waste, less environmental contamination, and lower greenhouse gas emissions, alongside new revenue streams for agricultural producers. This integrated approach aligns perfectly with circular economy principles, promoting resource efficiency and maximizing agricultural utility. Despite challenges like anti-nutritional factors and processing costs, strategic investments in technology, infrastructure, and supportive policies can unlock Bambara groundnut's potential for sustainable innovation, job creation, and enhanced food system resilience across Africa and globally. Ultimately, valorizing Bambara groundnut waste presents a transformative opportunity for sustainable growth and improved food systems, particularly within African agriculture.

Keywords: bambara groundnut; waste volarization; sustainable development; bio-products; *Vigna subterranean*; agricultural waste

1. Introduction

Bamabara groundnut (BGN) (*Vigna subterranea* (L.) Verdc.) is an important underutilized legume crop native to Africa and grown around the regions of semi-arid sub-Saharan Africa [1]. BGN is a complete food source containing adequate macronutrients required in a balanced diet, especially when protein from animals is unaffordable [2]. Seeds of BGN contain 64.4% carbohydrate, 23.6% protein, 6.5% fat and 5.5% fibre. as well as mineral elements [3,4]. It is a key ingredient of different local food products, thus significantly contributing to the dietary needs of both rural and urban communities by alleviating malnutrition and micronutrient deficiency [5]. Climate change threatens the production and productivity of the common major legumes (cowpea, soybean and groundnut), prompting a search for more resilient crops [6]. The exceptional ability of BGN to thrive in semi-arid climate and poor soils, combined with its rich nutritional contents, has positioned it as a promising future crop [1].

In spite of the benefits of BGN, the processing of its seeds into valuable food products leads to the generation of wastes (such as husks, shells, haulms and offal), which are disposed of into the environment, thus, creating an inconvenience. There is a growing interest in adding value to the wastes generated from BGN and converting them to products that are useful for industrial purposes, as well as food and feeds.

The leguminous Bambara groundnut (BGN) is a nutritious, drought-resistant crop indigenous to Africa, where it thrives in marginal soils with minimal inputs [7]. Despite its impressive nutritional profile, including high protein content, carbohydrates, dietary fibre, essential minerals and vitamins, Bambara groundnut (BGN) has yet to receive attention proportional to its agricultural value. It remains under-researched and underutilized in comparison to more widely cultivated legume crops, particularly in the areas of breeding, agronomic development and large-scale commercialization. The crop's rich genetic diversity also remains untapped. A key reason for this neglect is the global over-reliance on a small number of major legume species [8].

In Africa, Nigeria has been recognized as the major producer of BGN and the crop is extensively cultivated in other parts of Africa, particularly in West and Southern Africa, for its versatile seeds [9]. The seeds serve a varied choice of culinary purposes, including local delicacies and more recently, plant-protein based milk alternatives [10]. In Nigeria, particularly in the Eastern regions, BGN is a vital food crop with diverse traditional uses. The seeds are often roasted, ground into powder and incorporated into soups [11]. It can also be roasted and chewed alongside palm kernel nuts as a snack. Beyond human consumption, the seed haulms serve as valuable fodder for livestock and poultry, contributing to sustainable agricultural practices in the region [12].

Holistic value addition involves the comprehensive utilization of all parts or components of a crop, including not only the edible seeds but also the various residual materials generated during harvesting, processing and consumption. Beyond its primary role as a nutrient-rich food source, BGN possesses numerous untapped applications that extend into its by-products and waste streams. For instance, the seed hulls and pods of BGN, often regarded as waste, are in fact rich in bioactive compounds, such as flavonoids, alkaloids and tannins, among others. Studies have shown that these by-products display antioxidant assets [8,13]. Likewise, the haulms (aerial parts) of BGN are excellent sources of phosphorus and can be utilized as livestock feed, thereby contributing to improved animal feed nutrition [14].

In addition, BGN by-products have been explored as raw materials for plant-based milk alternatives [15]. Its residues also positively impact soil health by enhancing nutrient cycling and enriching soil organic matter [8]. Furthermore, Harris [16] reported that extracts from BGN seed coats and other residues inhibit pathogens, indicating potential for use as natural food preservatives and plant-based antimicrobials.

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The untapped by-products obtainable from BGN offer a wide range of economic and social benefits. For example, the development of local agro-processing enterprises that utilize BGN by-products can create employment opportunities, particularly for women and unemployed youths in rural communities. By diversifying income sources and encouraging broader participation in the value chain and bioeconomy, food security and socio-economic resilience are enhanced [16].

Additionally, BG crop residues have been identified as promising raw materials for bioethanol and biogas production [14], thereby adding economic value while promoting the use of renewable energy and reducing the environmental burden of agricultural waste. BGN by-products also hold potential for the development of novel plant-based concentrates, flours and food additives. These innovations can support the growing demand for sustainable and alternative protein sources, align with global protein trends and contribute to efforts to combat malnutrition by enhancing the nutritional value of food products.

Wastes from BGN seeds are unsuitable for consumption by humans, however, they can be used in the preparation of livestock feeds or as soil conditioners [18]. Reports have also shown that leguminous residues from groundnut, soybean and pigeon pea are promising alternatives as fertilizer sources for enhancing soil fertility in tropical regions [19,20].

2. Potential Value-Added Products and Markets

Disposal of legume by-products could hinder the adoption and integration of these crops into the current farming system. However, exploring and using residues from underutilized crops (such as Bambara groundnut shells) offers a solution to waste management and facilitates the introduction of the crop into new growing regions [21].

2.1. Animal Feed

Among the major concerns in livestock farming is the high cost of animal feed [22]. Therefore, research and development focus on identifying novel feed ingredients that lower production costs. Low-cost agro-industrial by-products offer a solution to reducing feed expenses, as they attract little pricing [23]. Bambara groundnut offal, a waste product from the milling of BGN seeds, is a readily available but often overlooked resource [24].

The study of Oyeagu *et al.* [25] revealed broiler chick diet consisting of a maximum of 10% toasted Bambara offal along with enzyme supplementation had no detrimental effect on the chick's haematological and growth performance. Similarly, the report of Ironkwe and Amaefule [26] revealed that the inclusion of 15% BGN offal into weaner rabbit diets yielded the highest result in respect of weight gain and final live weight of rabbit Due to their high phosphorus and protein contents, the he haulm and leaves of BGN are used as fodder for cattle [27].

2.2. Biofertilizers and Soil Amendments

Because it has the capacity to fix nitrogen in the soil, BGN can function as a soil conditioner [1]. Soil amendments made from charred plant materials are known as "biochar" [28]. Biochar derived from BGN shells can enhance soil quality and improve nutrient absorption in crops. The BGN shell biochar improves the soil's physical conditions and also retains nutrients, making them more available to plants [29]. Biochar from BGN shells has been used for the growth of sweet corn [30]. Jeffery *et al.* [31] reported that the use of biochar from BGN for crop production led to increased root length, volume and surface area in crops, a benefit attributed to enhanced soil conditions in the root zone.

2.3. Novel Food Ingredients: Dietary Fibre, Antioxidants, and Bioactive Compounds as Probiotics

BGN is rich in bioactive compounds like flavonoids, saponins and alkaloids that support overall human well-being. Therefore, BGN can help prolong the shelf life of fat-containing products, thereby

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enhancing health and nutrition [32]. The antioxidants present in BGN are capable of reducing lipid oxidation in food items, which in turn extends their shelf life [33–35].

Additionally, Bambara groundnut has been used in the development of nutraceuticals and functional foods, as well as an ingredient in probiotic drinks [36]. Bambara milk derived from BGN, can be used as a probiotic for reducing the growth and activity of pathogenic microorganisms [37]. Also, extracts from BGN grains have demonstrated antimicrobial properties against bacteria and fungi, which is attributed to the presence of flavonoids, anthocyanins and tannins present in the seed hulls [38,39]. Fermentation of BGN using lactic acid bacteria produces a probiotic drink that helps to combat malnutrition [40].

3. Nutritional Profile and Extraction Methods

The African Orphan Crop Consortium lists Bambara groundnut as an important crop, because of its enormous nutritional potential. It contains enough nutrients to make up a balanced diet. With dietary fibre (55-70%), proteins (17-25%), fat (5.2-6.4) and carbohydrates (1.4-12%), respectively, Bambara groundnut has a high nutritional value [41]. While the protein and fat profile of Bambara groundnut is comparable to that of soybeans, it is equivalent to frequently used legumes, including cowpea, kidney beans, broad beans, as well as chickpea in terms of protein (20.8%) and carbohydrate (61.9%) [42]. Research shows that the vital amino acids lysine (2%) with methionine having (3%) are relatively abundant in Bambara groundnut protein [40]. Another research documented that Bambara groundnut proteins composition is higher than that of groundnut, one of the most popular legumes, in terms of leucine, isoleucine, lysine, methionine, phenylalanine, threonine, as well as valine [43]. Because of its high lysine content, it can be used to boost low-lysine cereals such as rice and wheat [44]. Additionally, due to its high protein content (17–25%), Bambara groundnut is a great source of protein for people who avoid animal protein and those from lower socioeconomic backgrounds that are unable to afford meat-derived protein [7,12,45]. A study by Shanmugasundaram showed that minerals such as calcium (30–128 mg/100 g), magnesium (32–335 mg/100 g), potassium (1545–2200 mg/100 g), iron (2–9 mg/100 g) and phosphorus (81–563 mg/100 g) are among the other minerals found in Bambara groundnut [46]. Bambara groundnut fat is a healthier substitute for animal-based fats, since it naturally has low levels of saturated fatty acids and no cholesterol [47]. Its content of fatty acids promotes nutritional benefits that include lowering blood cholesterol, supporting weight loss, as well as minimizing the risk of cardiovascular disease. According to Yao et al. [47], the three main fatty acids included in Bambara groundnut shells are palmitic (21%), oleic (23%) and linoleic (36%). Furthermore, Bambara groundnut contains omega-3 and omega-6 fatty acids, as well as other polyunsaturated fatty acids [48], which means that it may have a positive result on health outcomes related with polyunsaturated fatty acids consumption.

Bambarra groundnut can be compared to popular legumes like peas, broad beans and soybeans that normally have soluble dietary fibre levels between 3.3 and 13.8% [49]. Given that soluble fibre is crucial for supporting digestive health and may help treat illnesses like constipation, obesity, diabetes, cardiovascular problems, haemorrhoids, as well as some types of cancer, this demonstrates the greater nutritional benefit of Bambara groundnut [49]. Furthermore, by slowing down the absorption of glucose and cholesterol into the bloodstream, soluble fibre helps to improve glucose homeostasis, reduce blood cholesterol levels, and minimize blood sugar spikes after meals [49]. Condensed tannins (polyphenolic compounds found in many legumes), in particular, are antinutritional agents that can impair nutrient absorption and digestion. BGN contains 0.01–2.37 mg g^{-1} of condensed tannins, [16,48]. By inhibiting protease activity and generating insoluble complexes with proteins, they reduce the availability of amino acids and hence inhibit the utilization of proteins. Similarly, trypsin inhibitors prevent digestive enzymes from doing their work. Thankfully, the tannin in BGN seeds is significantly reduced by both home and commercial processes, such as boiling, roasting, sprouting and soaking [43,47].

Protein has been extracted from the plant using a variety of methods, including alkaline extraction followed by isoelectric precipitation, alcohol and isoelectric precipitation and a

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combination of both [50]. To extract protein from Bambara groundnuts, isoelectric precipitation has been used in conjunction with various physical and chemical conditions [51]. The gel-forming properties of proteins extracted by isoelectric precipitation, either alone or in combination with alcohol precipitation, were the best among these techniques [50]. Using the isoelectric precipitation process, the protein isolate was achieved and Bambara groundnut flour was made from whole seeds [51] without defatting [52]. As Bambara groundnut (BGN) seeds contain oil, more research is being conducted on them. Oils and fats are essential for optimal health and are used extensively in edible products (e.g., salads, cooking oil, margarine, confections). Nigerian industries currently rely on palm, groundnut, and beniseed (sesame) oils for manufacturing vegetable cooking oil, soap, cream, and margarine. To diversify sources for these enterprises, other oil-producing options, like Bambara groundnut seed, need to be made available. Using a Soxhlet extractor and solvent extraction is the main technique for removing fat from Bambara groundnuts. This entails dissolving the fat from the crushed seeds with a solvent (such as benzene), then distilling the mixture to separate the solvent and oil [53]. Dietary fibre extraction from legumes, including chickpeas, lentils and cowpeas, has been researched [54]. Although the principles of dietary fibre extraction are identical, the methods differ according to the equipment, fibre source and desired result. They all employ fractionation to isolate certain components [55]. Common methods include chemical, enzymatic, dry, wet and microbiological retting [56].

According to Dalgetty and Baik [54], a modified wet milling technique that uses α-amylase to eliminate leftover starch works better than conventional wet techniques, because it improves the purity of the fibre. Wet milling has been used to extract dietary fibre from Bambara groundnut, and information about the characteristics and applications of Bambara groundnut dietary fibre is available [41]. It is critical to comprehend the physicochemical characteristics for applications in food, non-food and digestion. For Bambara groundnut dietary fibre, Diedericks [57] employed an enzymatic-gravimetric technique that was expensive and time-consuming. Wet milling, on the other hand, is easier and less expensive [44].

Bambara groundnut shows great promise as a nutritious, sustainable legume with major health and financial advantages. Beyond macronutrients like proteins, carbohydrates, dietary fiber, and good fats, it's rich in vital micronutrients including potassium, calcium, iron, and magnesium. Its high protein concentration in essential amino acids makes it a beneficial crop. High levels of soluble dietary fibre further strengthen its ability to help manage a number of illnesses, such as diabetes, obesity and cardiovascular disease. Simple processing methods can lessen the effects of antinutritional elements like tannins and trypsin inhibitors, increasing the bioavailability of nutrients. Bambara groundnut is a desirable raw material for food, medicinal and industrial uses, because of the effective extraction techniques for its protein, fibre and fat, including isoelectric precipitation, wet milling and Soxhlet solvent extraction. To improve these extraction methods and increase the commercial use of Bambara groundnut, more research is necessary, particularly to replace traditional sources of plant oil, fibre and protein. All things considered, Bambara groundnut shells has enormous potential to improve industrial innovation, nutrition and food security in Africa and beyond.

4. Economic Feasibility and Market Analysis

Historically, managing vast amounts of waste, especially organic waste, posed a significant challenge. However, this changed with the advent of waste valorization, which transformed these burdens into economic opportunities. The potential for substantial waste generation from Bambara groundnuts in countries like Nigeria is particularly noteworthy. Nigeria, being sub-Saharan Africa's leading producer, accounts for over 30% of the continent's total annual output of 300,000 tonnes [12,58]. To optimize the economic benefits of Bambara waste valorization, it is essential to conduct a thorough analysis of economic factors, market demand and long-term sustainability.

To determine the overall operational costs of Bambara waste valorization, it is crucial to understand all associated expenses. These include raw material acquisition, transportation and logistics, processing costs, energy consumption (especially critical in regions with unreliable energy

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supply and distribution), and indirect costs. A thorough grasp of these expenditures is vital for accurate financial projections.

Equally important is market demand. A low market demand directly impacts the value chain, leading to reduced waste generation and diminished economic returns. Therefore, the ability to assess the current and future market appetite for Bambara-derived products becomes paramount. This also raises the question: How can farmers, processors or even traders, effectively present these commodities to buyers in an appealing manner?

Another pivotal factor is profitability. A guarantee of a substantial return on investment (ROI) is essential to ensure the continued production of Bambara, regardless of evolving market dynamics.

The volume of surplus Bambara waste is directly linked to its production scale. Although the crop is substantially grown by subsistence and smallholder farmers, the enormous quantity of waste generated primarily consists of by-products, such as shells, husks, broken seeds and foliage. Additionally, packaging materials used for transporting the crop sometimes contribute to this waste stream.

Bambara groundnut waste can be sourced primarily from farmers or processors. A third group, traders, also contributes to the available waste stream. Traders often collect foliage used as cushioning during packaging, along with broken or crushed seeds that lack direct economic value for those purchasing seeds free from blemishes. Sourcing from processing plants, though less common for Bambara compared to other major crops, offers a significant advantage: It provides a more centralized and potentially higher-volume collection point for the waste. As the Bambara value chain matures and more commercial processing hubs emerge, these facilities are expected to generate larger and more consistent quantities of waste, simplifying collection efforts.

For Bambara farmers, traders and processors, managing waste can be a significant hurdle. They often resort to environmentally harmful burning practices, and the costs associated with transportation and disposal are considerable. Fortunately, waste valorization offers a beneficial alternative, transforming Bambara waste into value-added products that provide substantial economic benefits.

Establishing a Bambara waste valorization business necessitates careful consideration of critical operational expenditures related to energy, labour and transportation. Energy costs will constitute a major component of overall expenses, as power is required at every stage of waste processing, from electricity consumption for machinery to fuel for transportation. Labour costs are another key factor, encompassing wages for both skilled and unskilled personnel, along with expenses for training and retraining staff on improved valorization technologies. Furthermore, transportation and logistics pose significant challenges. The movement of raw Bambara waste, as well as the distribution of finished products, incurs substantial transportation costs, which also include expenses for conveying labour to and from operational sites.

The agricultural sector has always been the pillar of the African economy, particularly in Nigeria, with the great groundnut pyramids of the North, the cocoa of the West, the rubber plantations of the South, and the oil palms of the East. With the economy's reliance on oil, less attention was paid to agricultural development for economic growth. However, today, with the need for a green economy and the push to help develop strategies for global climate change mitigation, the world is gradually looking back at agriculture and its attendant products, by-products and wastes for the earth's sustenance. With a population soaring over 200 million, the internal market in Nigeria alone for agricultural products, by-products, and valorized agricultural wastes is immense. This huge population will also provide an affordable labour force that can drive mass production to meet global demands [59]. A deliberate investment in the youth population of Nigeria, which constitutes over 70% of its demographics, will be a good starting point.

The biofertilizer market, though still developing, shows significant promise for economic growth. Picture sub-Saharan African farmers, with their rapidly increasing numbers, relying on organic fertilizers instead of synthetic ones. Since conventional fertilizers often pose environmental sustainability challenges, this shift is crucial.

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Farmers are increasingly recognizing the environmental harm and rising expenses associated with chemical fertilizers, prompting a growing interest in organic and sustainable farming methods [60]. In response, the Nigerian government, alongside universities and research bodies, such as the International Institute for Tropical Agriculture (IITA), the Nigeria Institute for Oil Palm Research (NIFOR) and the Projects Development Agency (PRODA), are actively championing biofertilizers to boost food security and rejuvenate soil health [60].

Global energy consumption, particularly of fossil fuels, is steadily increasing, largely due to the expanding global population, notably in Africa. While fossil fuels currently meet over 85% of the world's energy demands [62,65], their reliance exacerbates greenhouse gas levels, posing a continuous threat to global sustainability through climate change. As a result, the world is now turning its attention to renewable energy as the next significant market. The market for sustainable energy is gradually rising. Currently, there has been a surge in the diversion to the use of solar panels to meet the growing needs for energy, whether in the manufacturing and industrial sectors or others, including health, food and agriculture. Bioenergy now contributes to electricity generation and transportation inputs. This situation creates substantial opportunities for those involved in agro-commodities, including Bambara, to invest in bioenergy development. Achieving UN SDG 7 (affordable and clean energy) by 2030 relies heavily on renewable and sustainable energy solutions [61]. The bioenergy market possesses immense potential if effectively managed. For instance, in Nigeria, Yusuf et al. [62] reported that municipal solid waste in 2015 produced an estimated 491,000 tonnes of methane emissions, which could have generated 3 billion kWh of electricity. They further projected that by 2030, methane emissions from solid waste in the country could reach 670,000 tonnes, yielding 4.74 billion kWh of electricity if converted to energy.

The understanding that fossil fuel dependency is unsustainable is likely propelling the biofertilizer market, which is projected to reach USD 6.34 billion by 2032 with a 12.21% Compound Annual Growth Rate (CAGR) from 2025 [63]. Concurrently, the global bioenergy market is also seeing rapid expansion, valued at USD 199.46 billion in 2024 and expected to hit USD 387.9 billion by 2033, with a 7.67% CAGR. This growth can be enhanced by policy incentives that foster a market economy focused on creating a sustainable environment.

Assessing the Financial Viability and Long-Term Economic Benefits of Turning Bambara Waste into Valuable Products

Determining the economic feasibility and lasting benefits of valorizing Bambara waste demands significant effort. This assessment requires evaluating profitability, long-term sustainability and ROI, all while factoring in market conditions, input expenses, production capacity and product pricing. The profitability of Bambara waste valorization is tied to managing operational costs versus revenue. Challenges include accurately determining the pure Bambara waste in mixed streams and ensuring consistent supply due to irregular generation and crop output. Despite this, higher profits are expected, particularly when Bambara waste products displace more expensive alternatives. Improving processing efficiency and logistics for waste collection will further enhance profit margins.

The enduring economic vitality and robustness of Bambara waste valorization depend on a combination of mutually reinforcing actions. These include building market adaptability to adjust to fluctuations in supply, demand and competition. Crucially, continuous investment in R&D drives product improvement, new applications and enhanced processing. Furthermore, stable raw material sourcing is ensured through strong relationships with farmers and suppliers. Lastly, delivering clear environmental and social advantages fosters community acceptance and regulatory support, which are vital for sustained operations.

5. Business Models and Entrepreneurial Opportunities

The recent global focus on issues of climate change, particularly in agriculture, is becoming so intense and real that things need to be done differently for sustainability to be ensured. Sub-Saharan Africa, particularly West Africa, needs to look inward to solve these crises with a focus on the

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abundant, environmentally smart, adaptable, though indigenous, crop species in a bid to solve this peculiar climate effect. SDG 7 centres on clean, affordable energy and its sustainability, 11 on sustainable cities and communities and 13 on climate action, and with these come the need to ensure product availability for all, irrespective of any natural or unnatural circumstances. Bambara groundnut readily comes to mind at solving this peculiar problem, given its wide adaptability and cultivation in many countries of sub-Saharan Africa. Away from its various usages as food and food products, significant wastes (inclusive of shell and husk are usually discarded). These products have been studied and observed to be rich in lignocellulosic materials, giving them chances to be further explored as valuable additional products beyond their food and other environmental advantages. The potential resiliency of Bambara groundnut, with its abilities to produce yields on marginal lands [10,11,64], thus positioned it to be available for an all-year-round supply of its by-products. Despite the low-income generation from the main seed products of Bambara groundnuts, the use of the various wastes can also add value, thus creating additional revenue streams to augment the initial lost production cost. The various Bambara groundnut by-products include the seed coats, seed hulls and the husk. These by-products can be value-added to give products like animal feed, compost or biochar.

5.1. Biofuel Production

Bambara groundnut shell residues for possible production of biofuel will largely be dependent on the amount of oils that can be extracted from it while this will in turn be dependent on the diverse genetic accessions. This shell residue for biofuel represents a 2nd generation lignocellulosic biomass option that comes with the benefit of not competing with food, but potentially with other uses as animal feed or industrial uses [65]. A recent report by Ibrahim et al., [66], identified a particular BGS-G1 Bambara genotype as a suitable option for pyrolysis among the three genotypes studied, which is a pointer that Bambara shell will be readily available as a sustainable biofuel. The study on soybean had helped showcase that Bambara shell can be a major source for biodiesel production through the approach of pyrolysis or transesterification. The pyrolysis method is a known thermochemical method process involving the use of heat and chemical reactions to convert these shells to bio-oils through the intermediate pyrolysis approach. Intermediate pyrolysis will often use a temperature range of 500-650^{0}C for the production of these bio-oils. Then transesterification will further convert the bio-oil to biofuel, which involves reacting the bio-oil with alcohol (particularly methanol) and a catalyst (e.g., KOH or sodium hydroxide) to produce biodiesel and glycerin. Notably, Bambara groundnut shells have been converted to biodiesel at a conversion rate of up to 95% [67] emphasizing the practicability of this agricultural waste for biodiesel production. Both the bio-oil and biofuel yields will end up offering a sustainable energy source, thus giving an alternative to fossil fuels and also adding economic value to these agricultural residues.

5.2. Animal Feed

Bambara groundnut byproducts of focus will include the offal (the fibrous residue that remains after processing of Bambara seed), sievate (the extra fine powder that results after sieving), haulm (the above-ground parts of the plant that include the stems and leaves, seed coats (the external coatings of the Bambara that come in varied colour reflective of extensive protein content) and the seed hulls. Depending on the digestibility of the animals, these byproducts can serve the broad purpose of feed for both ruminants and poultry. Animals in this category include rabbits, fish, poultry, goats and cattle. Known for its high protein content, Okonkwo et al., [68] established that toasted Bambara groundnut is high in nutritional and health benefits as it contains 12 different proteins and 214 identifiable peptides. Evaluation of toasted Bambara groundnut offal on broiler chicks showed significant weight gain and efficient protein use [25]. Several research studies on rabbits have established that they can tolerate up to 50% inclusion of this byproduct in their diet. However, pigs may experience an adverse effect [69] from being fed over 30% of Bambara groundnut offal, which could be coming from the various antinutrients. Bambara groundnut and its varied

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byproducts are known to contain fibre, tannins and flavonoids [70,71], which as expected, reduces their nutritional quality. Despite this, it is recognized for its cheap nature, accessibility and availability for a broad category of animals.

5.3. Bio-Composites

Given the fibrous nature of Bambara groundnut shells and haulms, they are also readily available as an ideal inclusion as bio-composite materials. The typical conventional composites are usually made from exhaustible resources and non-decomposable materials, which contributes to pollution concerns, thus making bio-composites a promising option, as it uses renewable resources. These materials find applications in various industries, including packaging, construction (e.g., lightweight panels), and even automotive parts. Nwambu et al., [72], researched on the combination of Bambara nut shell and potato as a unique agricultural waste product opportunity for valorization as a reinforcement material. This outcome further indicated that contents of Bambara groundnut shell fillers in the epoxy matrix will determine to a great extent the mechanical and physical strength of the product.

This outcome indicated that the amount of Bambara groundnut shell fillers in the epoxy matrix has a significant impact on both mechanical and physical properties. The work of Ncube et al., [73], further found Bambara groundnut shell to contain a relatively high amount of cellulose and crystallinity that may result in bio-composites with improved mechanical properties. So, beyond its high nutritive value as a food product, Bambara groundnut shell as an agricultural waste can go on to becoming a full resource.

5.4. Activated Carbon

Through pyrolysis and activation, Bambara groundnut waste can be transformed into high-quality activated carbon. This product is effective for water filtration and purification, with an adsorption capacity typically ranging from 10-20% by weight for various pollutants, making it valuable for industrial and municipal water treatment plants.

5.5. Fertilizers

Composting or anaerobic digestion of the waste produces nutrient-rich organic fertilizers. These fertilizers can significantly improve soil health and crop yields. Post-composting, the NPK (nitrogen-phosphorus-potassium) content typically ranges around 2-1-2, thus providing essential macronutrients for plant growth.

5.6. Mushroom Cultivation

Bambara groundnut waste serves as an excellent substrate for cultivating various edible mushrooms, particularly oyster mushrooms (*Pleurotus* species). This method provides an additional income stream, with mushroom yields typically reaching 20-30% of the dry weight of the substrate, transforming low-value waste into a high-value food product.

5.7. Cost-Benefit Analysis

Presently there are challenges associated with establishing a Bambara groundnut by-product processing business in Nigeria, as a thorough cost-benefit analysis is crucial for evaluating the economic feasibility of waste conversion. The initial capital expenditure for biofuel production, animal feed, bio-composites, activated carbon, fertilizers or for mushroom cultivation, can be substantial. This investment typically covers processing equipment (such as bioreactors for biofuel production, composting units for fertilizer or specialized machinery for bio-composite manufacturing. There will also be the angle of the operating cost that represents perpetual daily expenses needed to run most of the conversion facilities. This will include running expenses of energy consumption, as well as the labour wages for the machine operations. Labour wages further extends

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to costs in relation to pre-processing of raw materials, like cleaning, winnowing and shredding, as the case may be.

Expectedly, revenues will be generated from the sales of the diverse value-added products. At the present time, market prices for biofuels, animal feed and bio-composites will be key determinants, while activated carbon and fertilizer prices will vary significantly by region, product quality and obvious market demands. In all of this, breaking even is essential to be able to ascertain if the production volume is matched up to cover all costs. Depending on the feasibility and potential prospects, this kind of business can benefit from government incentives through giving tax breaks, subsidizing goods, as well as giving grants particularly the ones available for sustainable waste management and renewable energy initiatives.

5.8. Market Analysis

The Nigerian market is well known for using the Bambara groundnut, stemming from its dense nutritional benefits but not to waste conversion and its various uses. Thus, the first point of action will be understanding the market landscape that expectedly will be diverse giving the range of possible value-added potentials. For biofuels, the local small-scale power generation and local transportation sector will be the main consumers. The livestock and poultry farms that seek to have a nutritious and cost-effective product will be the main consumers of the Bambara converted animal feeds. The consumers of the bio-composites will include industries like construction and packaging companies that are particular about sustainability. As water availability is still a challenge, a massive production of activated carbon will see solutions to the needed water treatment while also supplying various industrial users requiring filtration solutions. Given that we are in the era of sustainable agriculture, the organic fertilizers will be readily available to farmers interested in organic farming and home gardeners.

5.9. Risk Assessment

Just like any business, establishing businesses centered on Bambara groundnut waste conversion involves several inherent risks that must be systematically identified and mitigated.

Technological Risks: Inefficient conversion processes can lead to lower product yields or substandard quality, affecting profitability. Equipment malfunction or failure can cause significant operational downtime and increased maintenance costs.

Financial Risks: Fluctuating market prices for the output products (e.g., biofuels, bio-composites) can impact revenue stability. High operating costs, especially energy and labour, could erode profit margins if not managed effectively.

Supply Chain Risks: An inconsistent supply of Bambara groundnut waste, possibly due to seasonal variations in harvest or competition from other uses, can disrupt production. Logistical challenges in waste collection and transportation from dispersed agricultural areas can also increase costs and reduce operational efficiency.

Environmental Risks: Improper waste handling during collection or processing, such as leaching from composting piles or uncontrolled emissions from biofuel production, could lead to soil, water, or air pollution, resulting in regulatory penalties and reputational damage. Greenhouse gas emissions from certain processing methods must also be carefully managed.

To mitigate these risks, a multi-faceted strategy is advised. Diversifying the product portfolio can reduce reliance on a single market and provide stability. Securing long-term supply contracts with farmers or processors can ensure a consistent raw material flow. Implementing efficient waste management practices, including proper storage and processing technologies, can minimize environmental impact. Regular maintenance and investment in reliable equipment will reduce technological downtime.

6. Stakeholder Engagement and Collaboration

Realizing the full potential of Bambara groundnut waste valorization hinges on strong collaboration among key stakeholders. No single entity can achieve this alone; therefore, a concerted effort is ensuring the sustainable valorization of Bambara waste for national economic growth and development. Building robust partnerships, aggregating support from all disciplines and driving capacities for key policymaking and incentives are all crucial. Equally important is an environment that guarantees the transfer of technology and capacity from laboratories to industries. Research should be tailored towards the direct application of its findings.

Effective valorization of Bambara groundnut waste relies on developing collaborative networks that cenre around the initial sources of the waste: farmers and their cooperatives. In Nigeria, key organizations like the All Farmers Association of Nigeria (AFAN) and the National Association of Bambara Nut Producers, Processors and Marketers of Nigeria (NABAPPMAN) exemplify potential partners. These partnerships are crucial for teaching best practices in waste generation, collection, segregation and transport.

The collaborative framework should also include waste aggregators and processors, particularly those operating at the local government level. Local waste management companies and recycling enterprises are well-suited to bridge the gap between farmers and valorization facilities, leveraging their existing infrastructure and expertise in waste handling and initial processing. Furthermore, small and medium-sized enterprises (SMEs) involved in ag ro-processing are equally important contributors to this integrated network.

Effective collaboration for Bambara groundnut waste valorization must integrate research & development (R&D) institutions and their personnel, particularly those focused on Bambara groundnut research. In Nigeria, key examples include the Institute for Agricultural Research (IAR) in Samaru, the International Institute of Tropical Agriculture (IITA) in Ibadan, the Nigeria Stored Products Research Institute (NSPRI) in Ilorin and the numerous universities specializing in science and agriculture across the country. Private sector R&D divisions are also vital collaborators in this venture.

Furthermore, governmental bodies and financial institutions are essential stakeholders within the Bambara waste valorization value chain. These include the Federal Ministries of Agriculture and Rural Development, Environment and Investment, alongside financial institutions crucial for providing necessary business financing.

The role of end-users and industries is also paramount in ensuring an environment that facilitates the transfer of technologies and capacities from laboratories to practical industrial application. These crucial stakeholders include diverse sectors, such as animal feed producers, manufacturers of bio-composites and organic fertilizers, bioenergy companies and food processing industries. By fostering strong, multi-stakeholder partnerships across all these categories, the Bambara groundnut waste valorization initiative can overcome challenges and fully realize its potential for driving economic growth, promoting environmental sustainability and achieving significant social impact in Nigeria.

7. Challenges and Opportunities

The presence of anti-nutritional elements such tannins, phytates, as well as oxalates, which are primarily present in the seed coats and hulls, is a major obstacle to using Bambara groundnut waste streams [74–76]. These substances damage the bioavailability in addition to absorption of nutrients, particularly vital minerals like calcium, zinc, and iron [77]. To make these by-products fit for use in food, feed or nutraceuticals, efficient detoxification techniques like fermentation, enzymatic treatment or thermal processing are commonly essential [78,79]. However, implementing such procedures in low-resource contexts may be difficult, due to the need for specialized knowledge, processing equipment, as well as regulatory control. It frequently requires a significant capital investment in processing infrastructure to turn Bambara groundnut residues into profitable goods. Both operating and maintenance expenses are associated with processes that include extrusion, grinding and bioconversion (such as anaerobic digestion and composting) [80]. It is challenging to

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guarantee consistency, scalability and product quality in many areas, due to the lack of access to dependable utilities and transportation networks. Unless they get specific financial or policy support, these restrictions may discourage smallholder farmers or cooperatives from participating in waste valorization [80,81]. Food safety is still a major issue. Mycotoxins, including aflatoxins made by *Aspergillus flavus*, can contaminate Bambara groundnut waste if it is handled improperly [82]. This is particularly difficult in tropical, as well as, wet places where storage circumstances often promotes the growth of fungus [82]. Additionally, while not well examined in Bambara groundnuts, allergenic proteins may be harmful to health if not fully assessed across landraces [83]. Although it can be expensive and logistically challenging to implement, establishing safety and quality control mechanisms—through certified laboratories, certification procedures and frequent monitoring—is crucial for market adoption.

Notwithstanding these obstacles, treating Bambara groundnut waste offers significant opportunities for technological advancement. Novel techniques (such as microbial fermentation, enzymatic hydrolysis or the creation of bio-composites from husks as well as hulls, could produce value-added products with practical or environmental advantages [75,81]. For example, fermented by-products may have improved dietary or prebiotic qualities and biodegradable packaging materials made from seed coatings may be used as plastic substitutes [84]. Inclusive development can be promoted by scaling these technologies in a decentralized, cost-effective way. Reusing Bambara groundnut waste maximizes resource usage and reduces waste, which is consistent with the circular economy's tenets [81]. Sustainable farming methods can be supported by turning agricultural waste into organic compost or bio fertilizers. This method improves soil health, lessens reliance on artificial fertilizers, and makes farming systems more resilient to climate change. Furthermore, the carbon footprint linked to conventional waste disposal techniques is decreased by valorising these byproducts [80]. Rural economies can be stimulated by creating new value chains centred around Bambara groundnut trash. Local job possibilities can be generated by small businesses that specialize in turning leftovers into food components, animal feed, eco-packaging, or cosmetics. By selling both the main crop and its byproducts, farmers can increase their revenue and stability in the economy.

The Bambara groundnut's economic footprint can be increased by these businesses by accessing both domestic and international markets. By valuing waste streams, Bambara groundnuts can be fully utilised, greatly increasing resource efficiency. Environmental effect and overall production costs can be decreased by incorporating waste processing into current activities, such as combining food-grade processing with the creation of feed or fertilizer from by-products. Improved market accessibility, infrastructure, and knowledge of the advantages of Bambara groundnuts can further boost local value chains, promote increased planting, lower postharvest losses, and maintain year-round price stability [81]. The crop provides enormous promise for sustainable innovation as well as economic growth, despite the inherent challenges associated with using Bambara groundnut waste streams, such as anti-nutritional components, processing costs, and safety issues. Bambara groundnuts (BG) have the potential to provide resource-efficient growth, job creation, and increased food system resilience throughout Africa and beyond with the correct investments in infrastructure, technology, and policy support.

8. Conclusions

Transforming Bambara groundnut waste represents a crucial stride towards achieving sustainable development. Through the recovery of valuable nutrients and the creation of environmentally beneficial products like bioenergy and compost, efforts contribute to diminished pollution and enhanced soil fertility. Concurrently, the extraction of nourishing compounds addresses malnutrition and supports robust feed security. Embracing circular economy principles that integrate both environmental and nutritional objectives holds the potential to significantly improve agricultural waste management practices within regions cultivating Bambara groundnut. This dual-focus model aligns with global sustainability objectives, providing a framework for resilient food systems, heightened resource efficiency, and economic empowerment. Rather than being discarded, Bambara groundnut wastes offer valuable resources for bio-product development, thereby enhancing resource efficiency in line with circular economy principles. Furthermore, utilizing Bambara groundnut residues for biofuel production through valorization and incorporating them into animal feeds mitigates environmental degradation while improving livestock nutrition, thereby fostering resilient and resource-efficient food systems.

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