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Posted Date: 4 July 2025

doi: 10.20944/preprints202507.0340.v1

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From Discard to Resource: Unlocking the Environmental and Nutritional Value of Bambara Groundnut Waste

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Abstract

Global food security is increasingly threatened by population growth, environmental degradation, and climate change, making resilient and nutrient-rich alternative crops like Bambara groundnut vital. This underutilized legume, native to sub-Saharan Africa, boasts drought tolerance and nitrogen-fixing properties, offering a valuable asset for food and nutrition security. However, its processing generates substantial waste, contributing to environmental harm and greenhouse gas emissions through current disposal methods like landfilling and open burning. This review explores integrated valorization pathways for Bambara groundnut waste, transforming these discards into valuable commodities and aligning with circular economy principles. Key pathways include bioenergy production (biogas and bioethanol), soil amendments (compost and biochar), bio-based materials (bioplastics and adsorbents), and nutrient extraction (dietary fiber, proteins, and bioactive compounds). While similar initiatives for other legume wastes show promising environmental, nutritional, and economic benefits, widespread adoption faces technical, economic, regulatory, and socio-cultural challenges. Overcoming these necessitates collaborative efforts encompassing supportive policy measures, dedicated research, strong stakeholder partnerships, and effective community education, ultimately realizing opportunities for sustainable development, enhanced food systems, and economic empowerment within Africa's agricultural sector.

Keywords: food security; Bambara groundnut; waste valorization; bioenergy; circular economy

1. Introduction

 doi:10.20944/preprints202507.0340.v1

Food security still remains a burning issue globally due to the rapid increase in human population, which requires more mouths to be fed, causes environmental degradation, as well as the negative impact of climate change resulting in poor crop yield. The global dependence on a few staple crops with increased dietary energy and improved global yield over the years cannot sustain the current dietary needs of man, and make food available, accessible and affordable to the vulnerable populations [1]. This heightens food insecurity and environmental strain, underscoring the need for crop diversification. Moreover, this dependence does not guarantee the nutritional quality of the food we consume. Poor quality soil and environmental factors often affect most staple crops (such as cereals like wheat and maize, and tuber crops), which hinders their yield. This calls for more focus on alternative sources of food that are rich in nutrients (and capable of providing equity in food availability and affordability), thus enhancing food and nutrition security. This is essential if we are to achieve the sustainable development goals (SDGs) of the United Nations on no poverty, zero hunger, and good health and well-being by 2030.

Bambara groundnut (*Vigna subterranea* (L.) Verdc.), is an underutilized leguminous crop native to West Africa, and regarded as an opportunity crop, due to its abundant untapped potential to enhance food and nutrition security in the context of climate change [2]. The legume is recognized for its adaptability to marginal environments and its nutrient-rich profile. Thriving in semi-arid regions with poor soils, this crop contributes to food security through its drought tolerance and nitrogen-fixing properties. The world's greatest producer of Bambara groundnut (BG) is sub-Saharan Africa (SSA). Reports have shown that annual production of BGS in Africa is approximately 0.3 million metric tonnes, with an average yield of 0.85 t/ha. Nevertheless, the yield potential is estimated to be over 3 t/ha [1,3,4]. Nigeria produces 0.1 million tonnes of BGS on average, which is more than any other country. Burkina Faso comes in second with 44,712 tonnes, and Niger with 30,000 tonnes [1,3]. The primary centre of genetic diversity of Bambara groundnut is considered to be north-eastern Nigeria and Cameroon [5].

1.1. Importance and Challenges of Bambara Groundnut

Bambara groundnut is an income-generating and food security crop, having the ability to produce good yields in marginal soils that are poorly drained or lacking nutrients, and withstand harsh environmental conditions (such as extreme heat and drought). Due to the beneficial microbes in its root nodules, Bambara groundnut cultivation does not require the use of fertilizers. as it naturally fixes nitrogen in the soil, which reduces the cost of fertilizer application by farmers and enhances agricultural and environmental sustainability. Bambara groundnut when consumed, gives the whole complement of nutrients. as the grains contain a good balance of carbohydrates, proteins, oils and amino acids [6]. The seeds are a valuable source of carbohydrates (~60–65%), proteins (~20–25%), fats (~5–7%) and micronutrients, such as iron, potassium and calcium; thus, supporting its role in combating malnutrition [7]. Bambara is often intercropped with other crops (such as maize, millet, sorghum, cassava and yam), because of its nitrogen-fixing roots that aid in replenishing soil nutrients.

Despite its agronomic and nutritional benefits, Bambara groundnut remains underutilized, due to limited research investment, underdeveloped markets and cultural perceptions linking it to subsistence agriculture, particularly among women farmers [8]. Farming systems result in the production of huge amounts of wastes after processing. Leguminous crop waste is the most prevalent and includes 50% of all biomass waste, of which more than 90% are lignocelluloses, with an estimated yearly global production of 200×10^9 tonnes [9]. These agricultural wastes could be useful for the development of bio-products. A critical challenge is the management of waste streams from shells, haulms and processing the by-products of BGS that are often discarded, contributing to environmental degradation and resource loss [4]. Addressing these issues aligns with sustainable agricultural systems and circular economy principles.

1.2. Bambara Groundnut Waste as a Prospective Asset

Bambara by-products include the stalks, shells, haulms and offal that are often disposed during processing. In Nigeria, the waste product of Bambara groundnut is the offal that is obtained from the milling of the Bambara groundnut seeds [10]. However, these wastes have found usefulness in biofuel production and biofertilizers, and are essential ingredients in animal feeds, due to their nutritional and high fibre content. The waste streams present opportunities for environmental and nutritional benefits. These by-products contain valuable compounds (such as dietary fiber, proteins, and bioactive molecules) that can be channelled for food, feed, or industrial applications [11]. The rich protein content of the offal makes it suitable as an alternative energy source of poultry feeds, which will reduce the cost of producing the feeds and lessen environmental degradation from disposal of the wastes. Valorizing these materials reduces waste, mitigates pollution and supports nutritional security. This aligns with the SDGs of the United Nations [12].

Bambara groundnut is a legume prevalent in sub-Saharan Africa, recognized for its remarkable adaptability to harsh climatic conditions, particularly drought-prone environments. Bambara thrives in marginal soils with minimal inputs, making it a resilient crop suited for regions where climate change is exacerbating agricultural vulnerabilities. The seeds of Bambara groundnut are nutritionally dense, comprising high levels of carbohydrates, quality protein, crucial minerals and fatty acids, thereby positioning it as a potential candidate for addressing food and nutrition insecurity [13].

Despite these attributes, it remains underutilized when compared to other legumes, such as soybean and cowpea. This underutilization extends not only to its seeds but also to the crop's by-products and residues generated during harvesting and processing. The primary wastes include shells, haulms (stems and leaves), and residual biomass. In many rural areas, these waste products are thrown, burnt, or left to degrade, resulting in environmental deterioration, greenhouse gas emissions, as well as lost economic possibilities.

In the wake of growing global awareness around sustainable food systems, climate change mitigation and resource efficiency, the concept of waste valorization has gained prominence. Waste valorization is the process of transforming waste resources into more usable commodities, including energy, bio-based materials, soil amendments and nutritional supplements. When applied to Bambara groundnut, such strategies present an opportunity to enhance the crop's value chain, minimize environmental impact and improve livelihoods, especially within the operational zones of the International Institute of Tropical Agriculture (IITA).

The circular economy framework offers a transformative lens through which Bambara groundnut waste can be viewed, not as refuse, but as a valuable input into new production cycles. By harnessing these by-products for bioenergy, compost, bioplastics and food or feed additives, it is possible to contribute simultaneously to environmental sustainability and nutritional security. This review explores integrated valorization pathways for Bambara groundnut residues and outlines the enabling conditions required for their successful implementation.

This review is focused on Africa, particularly regions within the operational scope of the International Institute of Tropical Agriculture (IITA), headquartered in Nigeria. IITA's extensive collection of over 2,000 Bambara groundnut accessions facilitates research into genetic diversity and sustainable practices [14]. By focusing on these regions, this article explores localized strategies for waste valorization, enhancing food security and environmental sustainability in African agricultural systems.

2.0. . Current Environmental Impacts of Bambara Groundnut Waste

Maintaining a pristine environment is paramount, as Earth is the only inhabited planet in our solar system. Unfortunately, human activities are accelerating waste accumulation, encompassing everything from organic and plastic materials to industrial byproducts. A foundational step towards fostering a sustainable existence on Earth involves mitigating this escalating waste problem. While the complete eradication of certain waste streams (such as plastics, electronic waste and other industrial refuse) presents considerable challenges, the effective management of organic waste offers numerous opportunities during disposal. These opportunities extend beyond mere reduction,

 doi:10.20944/preprints202507.0340.v1

encompassing the potential to transform these discarded materials into eco-friendly products of significant economic interest, thereby promoting both environmental stewardship and sustainable development.

However, it is crucial to recognize that current approaches to waste disposal impose considerable ecological pressures. Several factors primarily influence these pressures: the sheer volume of waste generated, its original point of generation, the specific type of organic waste involved and the timing of its generation (whether during the dry or wet seasons), as environmental conditions vary. Presently, numerous landfills and open waste disposal sites are in operation, often without adequate consideration for their far-reaching impacts on both human and overall environmental health.

Within these anaerobic environments, organic matter decomposes, releasing considerable amounts of methane. This is a potent greenhouse gas with a far greater global warming potential than carbon dioxide, which is also released during the incomplete combustion of some discarded wastes over shorter timeframes. Open burning any waste materials, they pollute the atmosphere directly. This combustion liberates harmful particulate matter, carbon monoxide, other greenhouse gases and toxic compounds. This leads to localized air quality deterioration, contributes to smog and poses serious respiratory and cardiovascular health risks to nearby communities. Therefore, seeking alternative means of waste management appears to be the sole viable path for a better and more sustainable environment. After all, waste generation is an unavoidable aspect of human activity; thus, its management is paramount.

This leads us to the transformative principle of "From waste to wealth"; quite simply, the way forward. By adding value to a material, irrespective of how worthless it may appear, transforms it into a valuable commodity, generating economic gains. Value addition represents the new strategic approach for converting waste into economic products that ensures the materials are no longer left to decompose on the Earth's surface; instead, they are removed to create economic value. Bambara groundnut wastes, in particular, present a useful economic material for establishing a value chain that can lead to wealth and prosperity, especially among smallholder farmers, traders, and crop processors.

Substantial quantities of Bambara groundnut waste produced annually contribute to growing landfill burden. Annually, throughout Africa, more than 300,000 tonnes of Bambara are produced [5]. Although the majority of Bambara groundnuts are produced in sub-Saharan Africa, West Africa is the core of production in this region. In Nigeria, for example, reports show that production has reached over 100,000 tonnes, thus making it Africa's primary producer of the underutilized crop [1,2]. This information suggests that Bambara generates a significant volume of waste annually, particularly in key producing regions like Nigeria. Majority of the wastes generated range from plant stalks, residues from processing, haulage, offal (which include broken or damaged seeds), and the shells and husks that are usually lignocellulosic and high in fibre. Disposing these, therefore, constitutes a huge challenge; no wonder they will easily be found in open dumpsites and landfills. Over time they decompose, thus releasing potent greenhouse gases like methane. The continuous influx of such agricultural waste rapidly consumes available landfill space. In metropolitan areas like Lagos, Benin, Onitsha, Kano, Kaduna and Enugu, the challenge of availability of spaces for siting landfills is increasingly becoming untenable. Moreover, securing new landfill locations is often met with strong public opposition, owing to concerns over environmental pollution, health risks and land devaluation, making effective waste management a perpetual urban and rural challenge across the continent [15,16].

When unmanaged in open landfills, Bambara groundnut waste produces greenhouse gases. The primary culprit is methane, which forms as these wastes decompose due to microbes in oxygen-deprived conditions. Additionally, burning Bambara groundnut waste creates carbon monoxide from incomplete combustion, along with other pollutants like volatile organic compounds (VOCs) that increase vapour pressure and decrease water solubility. These VOCs are often human-made chemicals that are used and produced in the manufacture of paints, and so on. Global temperature rise as a result of the strong greenhouse gases (such as carbon monoxide and methane) trapping heat in the atmosphere. This temperature increase, in turn, accelerates the melting of Arctic ice, significantly contributing to higher sea levels. A substantial increase in sea level can impact ocean currents, which in turn typically influence global climatic conditions and patterns. Consequently, a significant and sustained global rise in temperature is fundamentally linked to global climatic change. Also, importantly, is the release of particulate matter (PM2.5). Beyond environmental degradation, these waste disposal practices inflict severe adverse health effects on nearby communities, ranging from respiratory disorders [17] to heart disease (American Heart Association, undated). Compounding these threats, the presence of carcinogens like dioxins and polycyclic aromatic hydrocarbons in burn emissions elevates the risk of various cancers among exposed populations [18,19]. Therefore, this paradigm shift from disposing of waste to actively pursuing "waste to wealth" strategies, which involve adding value to discarded materials like Bambara groundnut waste for economic gain, is not only environmentally imperative but also crucial for safeguarding public health and fostering sustainable development.

Beyond the direct environmental harm, current waste disposal practices lead to a significant loss of beneficial nutrients and squandered resource reclamation. Critically, the removal of organic matter and essential nutrients from the agricultural cycle, rather than their natural return to the soil, depletes soil fertility over time. This depletion, consequently, drives an increased reliance on synthetic fertilizers to maintain crop yields. Moreover, there is a considerable lost economic value associated with this waste. If these by-products were converted into valuable commodities like compost, biochar or bioenergy, they could generate substantial alternative income streams for farmers and local communities, fostering a more sustainable and economically viable agricultural system.

The continuous removal of organic matter and nutrients from the agricultural cycle, instead of their beneficial return to the soil, perfectly illustrates the shortcomings of a linear economy. This approach fundamentally misses a crucial opportunity for efficient environmental management within a circular economy framework. In a linear model, resources are extracted from the environment, processed into products, consumed or used, and then ultimately discarded as waste. This is particularly evident when agricultural residues, such as Bambara groundnut stalks and shells, are simply sent to landfills or burned, and by-products are washed away or otherwise discarded. Given that these are organic materials, valuable nutrients—the very building blocks for soil improvement and a sustainable factor for food security—that are simply lost from the system.

On the other hand, by extending the life of resources, a regenerative economy seeks to reduce waste, as well as optimizes resource use. Under this model, agricultural by-products are not viewed as waste but are instead channelled into valuable resources. This perfectly embodies the "waste to wealth" principle.

3.0. Potential Valorization Pathways Integrating Environmental and Nutritional Perspectives

The issues raised regarding the impacts of waste generation during production are relevant. The importance of waste valorization, therefore, cannot be overemphasized, serving both as a means of gain for human populations and benefit for the environment. Imagine a scenario where wastes are also used as feedstock for the generation of the same products for which primary raw materials would be required. That would reduce reliance on imports and thus help manage exploitation. The aim of this section is to explore specific pathways that not only mitigate environmental harm but also leverage the inherent nutritional components of Bambara groundnut waste for resource recovery and benefit. The concept of waste valorization, which effectively manages waste streams, is important particularly for mitigating environmental impact, reducing greenhouse gases and enhancing soil conditions through soil nutrient amendments [20].

3.1. Bioenergy Production from Bambara Groundnut Waste

 doi:10.20944/preprints202507.0340.v1

In a world already grappling with the threats of over-reliance on fossil fuel-based energy, alternative sources are crucial. Such sources should not only be sustainable, relying on readily available organic materials (particularly wastes), but also generate substances less detrimental to the environment than their fossil-fuel counterparts. Given this, encouraging reliance on the wastes generated from the production, processing and consumption of Bambara groundnut is beneficial, emphasizing both environmental gain and the nutritional value of these by-products.

One of the most promising uses for Bambara groundnut residues lies in bioenergy generation. The lignocellulosic content of their haulms and shells makes them suitable for anaerobic digestion and bioethanol production. Anaerobic metabolism, the microbial decomposition of organic material in the absence of oxygen, produces biogas (mostly carbon dioxide and methane) and digestate (the liquid and solid residue left after digestion). The biogas can then serve as a clean energy source for cooking or electricity, while the digestate can be applied to agricultural fields to enhance soil fertility [21].

In a study on valorization of agro-industrial wastes for biorefinery process and circular bioeconomy, Yaashikaa and Kumar [22] showed the relevance of Bambara groundnut in the development of strategies for generation of biogas. They reported that Bambara groundnut possessed adequate nutrients (fat and carbohydrate) for biogas generation. Moreover, Bambara groundnut is known for its high crude protein and nitrogen levels, which indicates its suitability for development of biofertilizers for providing adequate nitrogen to the soil. **W**hile carbon is converted to methane, essential plant nutrients (nitrogen, phosphorus, potassium and micronutrients) remain in the digestate. Crucially, these nutrients are often in a more plant-available form (e.g., ammoniacal nitrogen) compared to raw organic matter, making them effective as a bio-fertilizer.

Production of bioethanol from the fermentable sugars extracted from Bambara groundnut shells offers another route for renewable energy. Technologies, such as simultaneous saccharification and fermentation (SSF), can be employed to maximize ethanol yield. These bioenergy solutions align with global efforts to lessen reliance on fossil fuels, mitigate carbon emissions and promote rural energy self-sufficiency.

Ofoefule *et al.* [23] reported another specific study on Bambara groundnut chaff in the production of biogas. Ofoefule *et al* [23] also supported claims on Bambara groundnut waste suitability for anaerobic digestion and the general nutrient content of organic waste for biogas production. However, while they found blending, as is most times required, failed to significantly improve biogas yield, and reiterated that potentially, all organic waste materials contain adequate quantities of the nutrients essential for the growth and metabolism of anaerobic bacteria in biogas production.

Orok *et al*. [24] emphasize that anaerobic digestion of Bambara groundnut wastes produces methane, which is a major combustible constituent in biogas, in addition to carbon dioxide. By diverting significant volumes of organic waste, anaerobic digestion directly tackles landfill issues, thereby preventing methane emissions that would otherwise occur in dumps. The process yields a nutrient-rich digestate along with biogas. The resulting biogas and organic fertilizer generated from anaerobic digestion can economically offset challenges associated with the process. Notably, applying digestate back to agricultural land replenishes soil fertility, reduces the need for synthetic fertilizers and indirectly supports the nutritional quality of future crops by ensuring healthy soil. This effectively completes a circular nutrient loop.

3.2. Soil Amendments from Bambara Groundnut Waste

Ikhajiagbe *et al* [25] used bio-organic fertilizer developed from food wastes to enhance the growth, resilience and yield of *Amaranthus hybridus* after amendment. Ikhajiagbe *et al*. [26] also reported improved remediation indices and enhanced plant indices of oil-polluted soil amended with plant waste-prepared composts. They also reported improved growth of okra (*Abelmoschus esculentus*). Composts are usually generated from aerobic decomposition of organic materials.

The application of soil amendments enhances soil physicochemical characteristics, improving its structure, organic content, as well as microbial population. Compost is one of most prominent materials for soil improvements [27]. According to the TNAU Agritech Portal [28], application of composts improves the physical, chemical and biological properties of the soil, thus sustaining soil fertility. Apart from soil fertility, application of amendments has been reported to enhance remediation of contaminated and degraded soils. Composting plays a pivotal role in sustainable waste management by addressing several critical environmental concerns, including the diversion of a large volume of wastes from collection centres, landfills, open dumpsites, as well as homebased collection points [29,30].

Composting is a low-tech, low-cost valorization pathway especially suited to rural communities. When properly composted, Bambara groundnut shells and haulms decompose into humus-rich organic matter that can be applied to soils to improve their chemical, biological and physical properties. Waqas *et al*. [31] reported that composts from leguminous residues are typically rich in nitrogen, potassium and phosphorus. These elements are central for soil microbial activity and plant growth. In regions suffering from soil degradation, organic amendments derived from Bambara groundnut waste can restore soil fertility, lessen dependence on synthetic fertilizers and enhance water retention. Moreover, composting contributes to carbon sequestration and provides a means of managing agricultural waste sustainably.

Composting, through its controlled aerobic decomposition, is effective at preserving the nutritional value of organic materials. During this process, nearly all of the initial essential plant nutrients, such as major macronutrients like nitrogen (N), phosphorus (P) and potassium (K), alongside crucial micronutrients (e.g., iron, manganese, zinc, copper), are retained [26,28]. What sets composting apart from simply discarding raw organic waste is its ability to transform these nutrients. Composting breaks down complex organic compounds into simpler, more stable structures. This vital change ensures that the nutrients become progressively more accessible for absorption by plants over time, providing a gradual rather than a sudden effect. Organic materials, such as Bambara groundnut haulms, shells, as well as foliage, constitute a significant portion of municipal solid waste. By channelling these materials to composting facilities instead of landfills, we dramatically reduce the sheer amount of refuse that needs to be buried.

Beyond the use of compost, certain organic wastes undergo pyrolysis to produce biochar. The potential for Bambara groundnut shells to be used as a biochar material has also been explored [32], providing information on its elemental composition and optimal pyrolysis parameters. Biochar, a carbon-rich and porous material, is known for enhancing soil fertility, promoting crop productivity and contributing to environmental sustainability. In addition to its immediate benefits for soil health, biochar acts as a long-term carbon sink. It sequesters atmospheric carbon for centuries, sometimes even millennia, thereby aiding in the mitigation of greenhouse gas emissions. Consequently, biochar is a vital tool in developing resilient and sustainable agricultural systems better equipped to adapt to the impacts of a changing climate. Moreover, biochar has been successfully applied to enhance crop resilience and nitrogen use capacity in bananas [33].

Utilized as substrates for soil amendments, organic wastes, including Bambara groundnut, are capable of playing pivotal roles in: improving crop growth and resilience in stressed environments [34]; supporting soil remediation efforts [35,36]; and enhancing soil structure, thereby stimulating the soil seed bank, and consequently, promoting weed biodiversity [37,38].

3.3. Bio-Based Materials

Lignocellulosic biomass, such as Bambara groundnut shells, can be processed into bio-based materials, including bioplastics, biochar and adsorbents for water treatment. The cellulose and lignin components in the shells can be extracted through chemical or thermal processes and used to synthesize biodegradable plastics. This innovation is gaining momentum as societies seek to reduce plastic pollution and transition to sustainable packaging materials [39]. In environmental applications, pyrolyzed Bambara groundnut shells can serve as adsorbents to remove heavy metals

 doi:10.20944/preprints202507.0340.v1

or organic pollutants from water. This low-cost solution is particularly relevant in resource-limited settings where access to clean water remains a challenge.

3.4. Nutrient Extraction for Food/Feed Applications

Bambara groundnut residues are not waste; they contain nutritionally significant compounds that can be extracted for food and feed enrichment. Defatted shells, for example, retain high levels of dietary fibre and polyphenolic antioxidants [40]. These can be processed into dietary supplements or incorporated into animal feeds to improve digestibility and health outcomes.

Furthermore, recent advancements in food science allow for the extraction of protein hydrolysates, peptides and phytochemicals from agricultural residues. These bioactive components can function as anti-inflammatory, antioxidant and antimicrobial agents, enhancing the nutritional value of processed foods or animal feeds. By adopting a cascading use model—where higher-value products, such as food additives, are extracted before composting or energy recovery, communities can maximize the utility of Bambara groundnut waste streams.

The shells of Bambara groundnut, which are frequently thrown away as waste, are rich in nutrients and can be used for a variety of things, including animal feed. They may include health-promoting substances and are high in fibre, especially pectin. The major product of processing Bambara groundnut is flour, which is then cooked and eaten by the Ibo people of Nigeria in a dish known as *okpa* [41]. To make the flour, the seeds are split in an attrition mill, the loosened testa are winnowed, and the cotyledon is covered with fine flour by repeatedly milling it in a hammer mill or any other kind of mill, followed by sieving. When Bambara groundnuts are processed, a sizeable amount of their inedible component is thrown away as trash. This inedible part had been used as soil waste and given to animals without discrimination. Weaner pigs can withstand up to 10% of toasted Bambara groundnut offal in their diet, as per a 2007 study by Onyimonyi and Okeke [42]. The fact that *okpa* is still a staple protein meal in the majority of Eastern Nigerian households guarantees the accessibility of Bambara groundnut waste as a possible feeding ingredient.

Table 1. The main valorization pathways of Bambara groundnut waste along with their associated environmental and nutritional/economic benefits.

Valorization pathway	Environmental benefits	Nutritional/economic benefits
Bioenergy (biogas, bioethanol)	Reduces reliance on fossil fuels; lowers GHG emissions	Provides renewable energy to rural communities
Composting and soil amendment	Improves soil structure and fertility; sequesters carbon	Boosts crop yields; reduces need for chemical fertilizers
Bio-based Materials (Bioplastics, adsorbents)	Reduces plastic pollution; treats wastewater	Creates sustainable packaging; supports green jobs
Nutrient Extraction (food/feed additives)	Minimizes waste; reduces pressure on natural resources	Enhances food/feed value; offers income from by-products

An important feed component for rabbit nutrition in Nigeria is raw Bambara groundnut waste, a by-product of processing Bambara groundnut (V. subterranea). Bambara groundnut waste is appropriate for use in cattle diets, because it provides a reasonably high source of protein with a crude protein concentration of 16–17%. Because of its nutritional richness, accessibility and affordability, it is frequently used as a baseline or control diet component in experimental studies looking into alternate sources of rabbit feed [43]. The viability of feeding rabbits Bambara groundnut waste has been investigated in a number of studies. According to Ani (2007) [43], up to 30% of raw

Bambara groundnut waste was added to rabbit feed. Results showed that growth performance was unaffected by inclusion rates as high as 20%, suggesting that the waste could be a good partial replacement for conventional feed ingredients like soybean meal or maize. However, performance decreased when inclusion levels surpassed 20%, possibly as a result of dietary imbalances or the presence of anti-nutritional substances [44].

Amaefule *et al*. [44] investigated the use of raw Bambara groundnut offal in place of maize offal in full rabbit diets in a different study. The results showed promise when this offal was incorporated at up to 20%. When compared to the control diet that contained maize offal, all experimental diets demonstrated better growth performance. Notably, the diet that included 15% Bambara groundnut offal produced the greatest growth enhancement, with the growth rate rising by 58% compared to the control group. This noteworthy improvement demonstrates the potential of Bambara groundnut offal as a feed element that could increase rabbit farming output in addition to being a reasonably priced alternative [45]. This review lends credence to the notion that Bambara groundnut waste and offal may be essential for raising feed efficiency and lowering feed expenses in rabbit production systems, particularly in areas with expensive or limited feed supplies. It is also critical to take into account issues such as eating a balanced diet, potential anti-nutritional substances and the necessity of processing (such drying or heat treatment) to increase nutrient availability and digestibility.

4.0. Nutritional Composition of Bambara Groundnut Waste Streams

We provide a concise overview of the potential nutritional composition found within the various waste streams produced from Bambara groundnut; specifically, the primary constituents present in the shells (e.g., fibre, minerals), haulms (e.g., protein, fibre), and processing leftovers (e.g., remaining protein, carbohydrates, micronutrients). This overview should establish the initial nutritional value contained in these by-products before examining possible extraction or improvement techniques.

4.1. Overview of BGS Waste Streams

Bambara groundnut processing generates substantial waste, including shells, haulms and processing residues (such as seed coats and milling by-products called offal). Though traditionally underutilized or discarded, these wastes are nutritionally rich, which makes them valuable for food, and inclusion in animal feeds and other bio-based products. Instead of discarding the shells after harvesting the nuts, they could be channelled to other beneficial uses. Agricultural industries produce huge amounts of biomass waste, which can be used for the production of biological products and polymer compounds that will advance sustainable technologies [46].

4.2. Primary Constituents of Waste Streams

Bambara groundnut shells (BGS) are primarily composed of dietary fibres that support digestive health in food or feed applications. The BGS are naturally lignocellulosic, consisting of a polymer of cellulose (42.4%) and hemicellulose (27.8%), lignin (13%) and a minor proportion of extractives (16.8%) [15,16]. BGS is also composed of a considerable quantity of volatile matter (69.1%) and low moisture (4.4%). The low moisture content is significant for the usefulness of BGS for polymeric composite development, since high moisture impairs the properties of fabricated composites by reducing the strength of the bonds at the edge of the matrix, which could destabilize the dimensions thereby making the mechanical properties of the composites of low quality [47].

Yang and Lü [48] observed that the proximate analysis before and after the treatment of BGS with *Pleurotus ostreatus* oyster mushroom showed an elevation in crude fibre of 52.32 vs 28.8%, crude protein 9.30 vs 11.03%, ash content 10.90 vs 13.50%, and fat and oil content 3.78 vs 3.78%, respectively. The BGS had high amounts of crude fibre and ash content before the treatment, which increased by the addition of 10 g of *P. ostreatus* spawn. The BGS ash content of 10.9% observed before treatment was slightly higher from the 8.4% obtained in the study of Ncube et al. [47]. The offal from the milling

 doi:10.20944/preprints202507.0340.v1

of the seeds is composed of 17.90– 21.16% crude protein, 5.29 – 21.50% crude fibre and 12.44 MJ/kg gross energy [10].

Haulms, encompassing stems and leaves, are rich in crude protein (10–15%) and fibre, making them suitable for livestock feed or composting substrates [49]. They also contain secondary metabolites (such as flavonoids) with potential health benefits, including anti-inflammatory effects. Although the leftovers of BGS (which include the leaves and chaff) are often thrown away, thereby causing environment degradation, they can be put into better use by blending them for poultry feed. These residues, often discarded during flour production or traditional food processing, can be enhanced through techniques like fermentation to improve nutrient bioavailability, making them viable for human consumption or fortified feed. Nevertheless, efforts have been made to use this waste in biogas production by blending with animal wastes to maintain methanogens.

5.0. Case Studies and Examples

Initiatives to valorize agricultural waste from legume crops (such as peanut, cowpea and soybean) demonstrate the viability of combining environmental sustainability objectives with the recovery of important nutritional components. These case studies shed light on tactics that might guide comparable efforts to value Bambara groundnut waste.

5.1. Soybean (Okara) Valorization

In East Asia, *okara*— the insoluble residue left over after creating soy milk or tofu—is a significant agro-industrial by-product. As a significant source of protein, soybeans are prized and frequently used in Asian desserts and cuisine [50]. However, a significant amount of the soybean is unused in the finished product via procedures like soy milk extraction. As a result, a large quantity of *okara* is produced. Actually, about 45% of each kilogramme of processed soybeans is turned into the finished product, with the remaining 55% becoming *okara* [51]. Because of its negative qualities, including its short shelf life, gritty texture and bland flavour, *okara* is frequently burned or thrown in landfills despite its nutritional value. The plant-based proteins found in soybeans have a comparatively high biological value, making them an excellent supply of dietary protein in both human and animal diets. Soy protein is economical and is a viable answer to the world's feed and agricultural problems. Also, bioactive peptides with anticancer, antihypertensive, antioxidant, antibacterial and antidiabetic qualities are abundant in soybean by-products like *okara*. Proteolytic enzymes are usually required to remove these advantageous peptides from the intricate *okara* matrix [52,53].

After being processed to remove fibre and oils, soy has comparatively high protein content (40%) and is a great ingredient for food. Including soy proteins in a diet that is comparatively low in cholesterol and saturated fatty acids decreases the risk of coronary heart disease. Along with its rich protein level, soy also has fibre, which improves glucose tolerance in diabetics and decreases fat, and has beneficial isoflavones that are important in reducing heart disease. In addition to its anti-inflammatory and anti-carcinogenic properties, the fibre in soy helps with inflammation, and diarrhoea [54]. However, soy contains antinutritive substances like raffinose, phytic acid, stachyose and trypsin inhibitors that pose a hazard. Certain antinutritional substances are disappearing as a result of technological processing [55]. *Okara* is raw material that is produced as a by-product from the production of soy milk and tofu [53]. One tonne of tofu yields approximately 1.1 to 1.2 tonnes of *okara*, which can reach over 3,000,000 tonnes annually in Asia where *okara* is mostly used as an agricultural fertilizer or animal feed [56]. Soy milk, which has a protein level of 20 to 27% by dry matter and a fibre content of 52 to 58%, contains dried *okar*a, a high-fibre residue left over from the production process, and good amino acid profiles. After adding *okara* to maize tortillas, they measured the amino acid composition of the tortillas and the changes in their flavour and texture at different fortification levels. Higher levels of fortification with *okara* were judged inappropriate by the expert panelists who assessed the product, because of its unpleasant flavour and scent. Even when up to 10% more *okara* was added to maize flour, there was still no discernible difference in flavour between traditional corn tortillas and tortillas enhanced with *okara*.

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Japanese culinary innovators and SMEs have used *okara* to create value-added products in fermented drinks, health snacks and baked good [56]. Notably, meat substitutes and dietary fibre supplements made from *okara* have gained popularity in regions where consumers are concerned about their health. These initiatives have decreased methane emissions from landfilling wet biomass and organic waste. Furthermore, *okara* is being used more and more as a feed component for monogastric animals, which helps livestock systems use fewer resources.

Financial benefits can result in the conversion of food sector wastes (including biological waste) to natural fertilizers, which can effectively lessen adverse environmental effects [57, 58]. Biologically-derived digestates can be applied to non-agricultural land [59], for example, as a top layer when municipal trash dumps are closed [60] or for soil rehabilitation once they are turned into biochar. Biodegradable wastes from the food industry may also be used for refining processes, which should yield valuable goods, including colouring, nutrients, enzymes and natural acids, in addition to fertilizer and supply of energy [61].

5.2. Cowpea Husk and Pod Utilization in West Africa

In West African nations like Nigeria and Ghana, the cowpea (*Vigna unguiculata*) is a popular legume crop that yields large amounts of husks and pods after harvest. The whole cowpea grain is typically consumed with cereals or added to soups or stews in West and Central Africa, whereas the milled cowpeas are primarily used to produce steamed cakes or fritters [62]. In addition to the traditional famous *gari* as well as beans, the dry grains are processed into cowpea flour to make *agawu* and *koos*, both of which are nutritious and a common meal in Ghana when combined with millet or maize porridge. The vitamins and mineral elements found in the roots, green pods, young leaves and seeds provide human nutrition [63]. These residues were previously burned or disposed of as waste, but national agricultural extension programmes and projects run by the International Institute of Tropical Agriculture (IITA) have helped to valorize them [64].

The goal of value-adding initiatives is to turn cowpea shells (as well as pods) into animal feed, especially in dry seasons when there is a shortage of fodder in numerous parts of the globe. A significant source of high-quality hay for animal feed is cowpea leaves [65,66]. Cowpea forage is an essential ingredient for livestock in Nigeria's desert regions. Cowpea fodder production helps supply feed for both big and small grazing animals. Preparation involves drying in the sun, crushing and pelletizing wastes into feed blocks rich in fibre and remaining protein. Because it may replenish soil fertility for subsequent non-leguminous crops cultivated in rotation with it [67] or as an intercrop, cowpea is an important part of farming systems in many places. Green manure is made from seedlings and organic manure is made from plant waste that remains after harvest. In addition to improving organic farming for organic production, cowpeas are used as a soil-building cover crop to assist prevent erosion [68]. Composting these items also improves soil fertility, which supports sustainable farming practices. An initiative's dual benefits of waste reduction and livestock nutritional recovery highlight how well it aligns with environmental and food security objectives.

5.3. Peanut Hull (PH) Valorization

Global priorities include lowering food waste and refining human food systems' efficiency to end hunger. Upcycling important byproducts, such as peanut hulls, would increase the amount of food available to humans given existing land usage and resource inputs, because peanuts are produced in enormous amounts and generate a lot of waste. By raising the quantity of sellable harvests, this will not only aid in the fight against hunger but also perhaps increase farmers' profit margins and cost-benefit ratio [69,70]. Peanut production requires a lot of energy or fuel, fertilizer or other soil changes, and water, all of which contribute to substantial greenhouse gas emissions, eutrophication and other ecological externalities that increase proportionately as farming efficiency decreases and change depending on the growing region and farming practices used globally [71,72]. Due to the high percentage of peanut waste and the desire to increase the value of such a plentiful resource stream, there have been multiple initiatives to reuse peanut hulls. Peanut hulls are most

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commonly used in animal feed, although they can also be used as a dry composite material for packaging and industrial fillers. Newer sectors have also looked at the possibility of using peanut hulls for commercial filtration systems and biofuel [73-75].

The value addition of peanut hulls to human food may have special advantages for human nutritional health. Perhaps an increase in the total supply of shelf-stable and nutrient-dense foods through effective retention in the human food supply may support better food and nutrition safety. Repurposing peanut byproducts (such as hulls) for human consumption also offers farmers financial advantages, since it raises the market value of peanut hulls that can be sold for more than cheap animal fodder [76]. Furthermore, by exploiting each peanut harvest and encouraging greater byproduct salvaging, peanuts' ecological influence in relation to the quantity of human food items may be diminished, and the effects of food waste itself could be declined [77,78]. Other nut hulls and nut by-products (such as those of coconut hull, hazelnut shells, almond and walnut shells), are widely valued [79-81]. In culinary applications, these flour substitutes contribute beneficial bioactive compounds, raise the percentage of calories from protein and decrease net carbs by adding dietary fibre. Hazelnut, almond and Bambara groundnut shells are recognized to be edible to humans, much like peanut hulls, and there has been some early development of nutrition items made with these ingredients. Notably, hazelnut hulls have continued to be used in commercially available snack foods and almond hulls have been added to bread with favourable ratings of flavour and satisfaction [81-83]. The production of mycoprotein from almond hulls for alternative protein diets has also been the subject of preliminary research. The examples of peanut husks, cowpea leftovers and *okara* show how the value-adding of legume by-products can have both nutritional and environmental advantages. These programmes attest to the viability of combining nutrient recovery, emissions mitigation and waste reduction in sustainable food systems. Through creative, bio-circular solutions, these case studies promise both ecological and financial benefits for the value-adding of Bambara groundnut waste.

6.0. Policy and Implementation Challenges

At the moment, no evidence exists of suitable technological strategies being deployed to manage Bambara groundnut waste. Our concerns have been that agricultural engineers will enable the deployment of suitable innovations that would support the required infrastructure that would be generally acceptable to all.

As such, the Society for Underutilized Legumes (SUL), Nigeria, with its headquarters at the Genetic Resources Center, International Institute of Tropical Agriculture (IITA), has increased advocacy for the adoption of Bambara groundnut as a mandate crop in research institutions across sub-Saharan Africa, particularly in Nigeria. This is coming in the wake of the adoption of the crop by the CGIAR as evident during the Science Week held in Nairobi, Kenya in April 7-12, 2025. Furthermore, the foremost national research institutes in Nigeria (such as the Institute for Agricultural Research, Ahmadu Bello University, Zaria) have indicated interest to lead the development of varieties that would be adaptable for the greater use and commercialization in the country and Africa as a whole.

Nigerian governmental bodies like the Federal Ministry of Agriculture and Food Security, the Ministry of Innovation, Science and Technology, and the Federal Ministry of Health, alongside non-governmental organizations, are prepared to drive essential government policies. Their aim is to foster economic incentives, boost consumer demand for sustainable and nutritious products, and ensure the availability of research and development expertise. Key research-focused agencies, such as the Agricultural Research Council of Nigeria (ARCN), Nigerian Stored Products Research Institute (NSPRI) and the National Biotechnology Development Agency (NABDA) are also integral to these efforts.

Despite the scientific and practical promise of Bambara groundnut waste valorization, several challenges hinder widespread adoption. These barriers span technical, economic, institutional and socio-cultural domains.

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6.1. Technical and Infrastructure Barriers

The valorization processes often require specialized equipment and skilled labour, which are scarce in many rural areas. Composting can be done manually, but bioethanol production and bioplastic synthesis demand more sophisticated facilities (See Table 1). The deficiency in infrastructure for collection of waste, segregation, as well as transportation also limits the feasibility of centralized processing plants.

6.2. Economic Constraints

Start-up costs for valorization enterprises can be prohibitive, especially for smallholder farmers. Market uncertainty around eco-products (such as bioplastics and biofertilizers) may deter private investment. Moreover, many communities lack access to microcredit or development finance that could enable them to establish such ventures.

6.3. Regulatory and Policy Gaps

In many countries, there is a lack of coherent policies promoting the circular bioeconomy. Regulatory uncertainty concerning the classification and safe use of agricultural waste for food and feed purposes can stall innovation. For instance, standards for compost quality, bioplastic certification and food safety are often fragmented or non-existent in developing economies [84].

6.4. Socio-Cultural Factors

In some contexts, cultural perceptions of waste may pose barriers. Using agricultural residues in food or feed might be seen as unsafe or undesirable, despite scientific evidence to the contrary. Awareness campaigns and community engagement are needed to shift these attitudes and promote behavioural change.

6.5. Opportunities and Recommendations

Despite these barriers, several opportunities can be leveraged to support the valorization of Bambara groundnut waste:

Governments can implement enabling policies, such as tax incentives for green enterprises, subsidies for composting and renewable energy projects, and public procurement of bio-based products.

Institutions (such as IITA) can play a central role in developing low-cost, scalable valorization technologies, and in providing technical assistance to farming communities.

Collaboration between farmers, NGOs, governmental bodies and private companies can encourage resource pooling, the sharing of risks, and enhance market access for valorized products.

Training programmes for farmers, processors and extension workers on waste valorization techniques can empower communities and create green jobs.

7.0. Conclusion

Transforming Bambara groundnut waste into valuable resources presents a game-changing opportunity for sustainable development. This approach not only mitigates pollution and enhances soil fertility through the production of bioenergy and compost, but also tackles malnutrition and supports food security by extracting nutritious compounds. Adopting circular economy principles that merge environmental and nutritional goals can revolutionize agricultural waste management in Bambara groundnut-producing regions. This dual-focus model aligns with global sustainability goals and provides a framework for resilient food systems, resource efficiency and economic empowerment. Instead of being discarded into the environment, Bambara groundnut wastes can be used as valuable resources for developing bio-products. By harnessing Bambara groundnut residues for biofuel and animal feed, resource efficiency is optimized, reflecting circular economy principles.

 doi:10.20944/preprints202507.0340.v1

This valorization approach reduces environmental harm and boosts livestock nutrition, ultimately contributing to more resilient and sustainable food systems.

Author contributions: Conceptualization – ML and BI**;** Methodology – ML and BI**;** Original Draft Preparation – ML, OBO, EBO, BPM, LO, FAI, AU, TTA, and BI ; Review & Editing – ML and BI; Supervision – ML and BI; Funding Acquisition:; Approval of final draft of manuscript – ML, OBO, EBO, BPM, LO, FAI, AU, TTA, and BI
Funding: This study received no external funding
Informed Consent Statement: Not applicable.
Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare no conflicts of interest.

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