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Harnessing Alternative Carbon and Nitrogen Substrates from Agro-Wastes for Cost-Effective Fungal Cultivation Media

Ihe C.C.[1], Agu K.C.[2], Okeke C.B.[3], Uwanta L.I.[4], Oghonim P.AN.[5], Awari V.G.[6], Ogbunude A.P.[7], Ifediegwu M.C.[8], Okey-Ndeche N.F.[9] and Egurefa S.O.[10]

[1,2,3,4,8,]Applied Microbiology Department, Nnamdi Azikiwe University, Awka, Nigeria

[5]Microbiology Department, Biological Sciences, University of Delta, Agbor P.M.B 2090, Agbor, Delta State, Nigeria.

[6]Department of Microbiology, Tansian University, Umunya, Anambra, Nigeria

[7]Department of Public Health, School of Health and Life Sciences, Teeside University, Middlesbrough, UK

[9]Department of Microbiology, Faculty of Natural Sciences, Veritas University Abuja, Area Council, Bwari, Federal Capital Territory, Nigeria

[10]Department of Science Laboratory Technology, Southern delta University PMB 05, Ozoro Delta State, Nigeria.

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Abstract — The rising cost of conventional fungal culture media and the increasing accumulation of agro-industrial wastes have intensified the search for sustainable, low-cost alternatives for fungal cultivation. Commercial media such as Sabouraud Dextrose Agar (SDA), Potato Dextrose Agar (PDA), and Czapek-Dox Agar (CDA) depend on refined carbon and nitrogen sources, making them expensive and often inaccessible in resource-limited settings. Meanwhile, large volumes of agricultural residues generated from crop production, food processing, and livestock industries remain underutilized despite their rich nutritional value. This review examines the potential of agro-wastes as alternative carbon and nitrogen substrates for developing cost-effective fungal cultivation media. Carbohydrate-rich materials, including *Caladium bicolor*, *Dioscorea bulbifera*, maize, fruit peels, brewer's spent grain, and groundnut peel, together with nitrogen-rich substrates such as blood meal, soybean, legumes, and other proteinaceous agro-residues, are evaluated for their nutritional composition and ability to support fungal growth, sporulation, and metabolite production. Evidence from recent studies indicates that agro-waste-derived media can achieve fungal growth and performance comparable to conventional commercial media while substantially reducing production costs and promoting waste valorization. The review also discusses key challenges to their widespread application, including substrate variability, media standardization, sterilization, contamination control, and quality assurance. The use of agro-residues in fungal media formulation supports circular bioeconomy principles by transforming agricultural wastes into valuable resources, reducing environmental pollution, and improving access to microbiological research and industrial biotechnology. Future research should prioritize optimizing substrate combinations, standardizing formulations, and validating these media across diverse fungal species and applications. Overall, agro-waste-based cultivation media represent a sustainable and economically viable alternative to conventional fungal media, with significant implications for research, education, and industrial biotechnology.

Keywords: Agro-wastes; fungal cultivation media; blood meal; *Caladium bicolor*; *Dioscorea bulbifera*; groundnut peel.

***Corresponding Author**
Uwanta L.I.*
E-mail: li.uwanta@unizik.edu.ng.

INTRODUCTION

Agro-residues refer to the by-products generated during agricultural production and processing, including residues from crops, vegetables, fruits, livestock, poultry, dairy products, and agro-industrial activities (Afolalu et al., 2021). Increasing agricultural productivity has been accompanied by a substantial rise in the generation of agricultural wastes, posing serious environmental challenges through improper disposal and resource underutilization. These wastes exert considerable pressure on soil, water, and air quality, thereby threatening ecosystem sustainability and public health (Awari et al., 2023). The challenge is expected to intensify as global agricultural production is projected to increase by approximately 70% by 2050 to meet the food demands of a growing population (Ajayi & Lateef, 2023). Consequently, balancing increased agricultural productivity with sustainable environmental management has become a major global concern (Velasco-Muñoz et al., 2021).

Globally, more than 140 billion metric tons of agricultural biomass waste are generated annually, with agricultural solid wastes increasing at an estimated annual rate of 7.5% (Adejumo & Adebiyi, 2020). In Nigeria alone, over 32 million tons of solid waste are produced each year (Bakare, 2021). Poor management of agro-wastes is particularly evident around farms, food processing industries, and slaughterhouses, where residues such as *Caladium bicolor*, *Dioscorea bulbifera*, groundnut peels, and animal blood are frequently disposed of through open burning or indiscriminate dumping (Adejumo & Adebiyi, 2020; Akpenpuun et al., 2020). These disposal practices contribute to atmospheric pollution through particulate emissions, contaminate soil and groundwater, and adversely alter the physical, chemical, and biological characteristics of the environment (Ojiagu et al., 2018; Okonkwo et al., 2023). Sustainable utilization of these agro-residues therefore represents an environmentally sound strategy for mitigating pollution while generating value-added bioproducts (Orji et al., 2022; Uwanta et al., 2023).

Recent advances in environmental microbiology have demonstrated the remarkable ability of microorganisms, particularly fungi and bacteria, to convert agricultural wastes into economically valuable products through biodegradation and enzyme-mediated biotransformation (Awari et al., 2023; Oparaji et al., 2024). Fungi are especially attractive because of their capacity to secrete diverse extracellular enzymes, including cellulases, proteases, peroxidases, ligninases, and other hydrolytic enzymes that efficiently degrade complex lignocellulosic substrates (Chidi-Onuorah et al., 2015; Agu et al., 2023a; Oparaji et al., 2024). Similarly, microbial fermentation has been widely employed to improve the nutritional quality and industrial applications of agro-based substrates through enzymatic modification (Okpalla et al., 2012). These microbial capabilities have stimulated growing interest in the valorization of agro-wastes as inexpensive nutrient sources for microbiological and biotechnological applications.

Conventional fungal culture media such as Potato Dextrose Agar (PDA), Sabouraud Dextrose Agar (SDA), Malt Extract Agar (MEA), and Czapek-Dox Agar rely heavily on refined commercial carbon and nitrogen sources, making them relatively expensive for routine laboratory use, particularly in resource-limited settings. Consequently, considerable attention has been directed toward developing alternative culture media using locally available agro-residues rich in carbohydrates and proteins. Studies have demonstrated the successful formulation of low-cost mycological media from inedible agricultural materials capable of supporting fungal growth comparable to commercial media (Agu et al., 2023b; Okoye & Abba, 2024). Furthermore, agro-residues have been explored as substrates for microbial enzyme production, biodegradation, bioremediation, and the synthesis of environmentally sustainable products, including biodegradable plastics and bio-based materials (Orji et al., 2014; Uwanta et al., 2024; Orji et al., 2025).

The utilization of alternative carbon-rich substrates such as *Caladium bicolor*, *Dioscorea bulbifera*, and groundnut peel, together with nitrogen-rich substrates including blood meal and other agro-industrial by-products, represents an important approach for reducing production costs while promoting circular bioeconomy and sustainable waste management. Such strategies not only minimize environmental pollution but also provide affordable nutrient sources for fungal cultivation, industrial enzyme production, and other microbiological applications (Agu et al., 2023b; Agu et al., 2023a; Orji et al., 2022).

This review therefore aims to critically evaluate the potential of agro-waste-derived carbon and nitrogen substrates as sustainable and cost-effective alternatives to conventional fungal cultivation media by examining their nutritional composition, suitability for fungal growth, advantages, limitations, and applications in microbiological research, industrial biotechnology, and environmental sustainability.

2.1.1 Crop Residues

At the field level, the waste residues gotten directly from agricultural production are mostly crop residues such as stovers, seed pods, leaves, straws and so on. These crop residues are regarded as the cheapest and most abundant organic waste that can easily be changed into a variety of value-added products (Sadh et al., 2019). Universally, corn stovers (or corn straws), wheat straws and rice straws are the three major crop residues actively being used in the production of bioethanol. These crops are readily available year-round, with a little portion being used in biofuel production or as fodder while the leftovers are burnt, hence resulting in grave environmental challenges (Awasthi et al.,

2015). Among these three major crop residues, rice straw is among the most promising and valued biomasses worldwide with a large production of about 731 million tons per year, and the leading producers being Asia (Afolalu et al., 2021).

Most of residue harvested from wheat is wheat straw which is projected to have an annual yield of 1-3 tons/acre while a global annual estimate of 354.34 million tons of wheat straws are produced (Udo et al., 2018). For lignocellulosic ethanol, corn stover is among the most promising crop residues with 4.0 tons per acre estimated production and annual global production of approximately 128 million tons. Also, crop residues derived from oats, sorghum and barley contribute towards agro-wastes(Afolalu et al., 2021).

2.1.2 Agricultural Industry Wastes

The second group of agro-waste comprises of agricultural industrial processing waste. This includes by-products and residues gotten from food processing industries like sugarcane bagasse, fruit peels and vegetables, fruit marc/pomace after extraction of oil or juice; meat, eggs, chicken skin and animal fat from meat processing industries and slaughterhouses; starch residue (also known as cocoa shells) from starch-manufacturing industries; de-oiled seed cakes from edible oil manufacturing industries; molasses/black treacle from sugar manufacturing industries (Udo et al., 2018). Amongst several agro-industrial wastes, sugarcane bagasse tops the list. This bagasse is the dry pulpy fibrous residue obtained from industries after the juice has been extracted. The projected globally availability of sugarcanes bagasse is around 180 million tons. Orange peel, apple pomace and fruit wastes derived from the extraction of the fruit juice, cider, and other food processing units are also considered as agro-industry wastes. Asides these, certain non-food-based agro-industries such as de-oiled seed cakes gotten from non-edible oil plants like *Pongamia pinnata* and *Jatropha curcas* are categorized as agro-industry wastes (Putri et al., 2020).

2.2 Sustainable Mycological Media

Mycological media are specialized culture media, either liquid or gelled, formulated to promote the growth, reproduction, and maintenance of fungi in a laboratory setting (Gamit *et al.,* 2023). These media contain essential nutrients such as carbon sources, nitrogen sources, minerals, and sometimes gelling agents that support fungal metabolism and sporulation (Kumar *et al.,* 2012). According to Oledibe *et al.* (2023), such media can be derived from synthetic sources or formulated from natural, locally available plant materials, including *Zea mays*, *Glycine max*, and *Dioscorea dumetorum.*

2.2.1 Importance of Culture Media in Fungal Cultivation

Culture media are indispensable in fungal cultivation because they provide the necessary nutrients and environmental conditions for fungi to grow, reproduce, and carry out metabolic activities. Oledibe *et al.* (2023) and Gamit *et al.* (2023) emphasized that culture media support growth and sporulation by supplying carbon, nitrogen, water, and minerals required for fungal development. Furthermore, these media enable the identification and diagnosis of pathogenic fungi, such as *Aspergillus niger* and *Penicillium expansum*, from clinical or environmental samples (Oledibe *et al.,* 2023).

Culture media also facilitate research and education, being essential for microbiological studies, practical classes, and scientific research, particularly in institutions with limited resources (Gamit *et al.,* 2023; Oledibe *et al.,* 2023). Additionally, they are used for the production of microbial products, including fungal biomass, enzymes, antibiotics, and other industrially relevant compounds (Gamit *et al*., 2023).

2.2.2 Characteristics of an Ideal Fungal Growth Medium

An ideal fungal growth medium should possess several key characteristics. Good gelling ability is essential, meaning the medium solidifies properly and remains stable without liquefying quickly, allowing for easy handling such as streaking and plating (Kwoseh *et al.,* 2012). An appropriate pH, slightly acidic between 5.0 and 6.5, is preferred by fungi; for instance, the formulated medium $M_5Y_{2.5}S_2$ had a pH of 5.15, similar to that of Sabouraud dextrose agar (SDA) at 5.05 (Oledibe *et al.,* 2023). Nutrient richness is also critical, with adequate carbon (e.g., from starches), nitrogen (e.g., from soy), vitamins, and minerals (Oledibe *et al.,* 2023). Clarity or transparency allows visual observation of colony morphology and sporulation, although some opacity is acceptable (Oledibe *et al.,* 2023).

Stability over time is necessary; the medium should not emit bad odors, become watery, or degrade within several days, with at least eight days of stability being desirable (Oledibe *et al.,* 2023). Ease of preparation and dispensing is another important feature, meaning the medium should not be overly viscous or sticky and should pour smoothly into Petri dishes (Oledibe *et al.,* 2023). Finally, the medium must support sporulation and aerial mycelia growth, promoting good to profuse growth; for example, $M_5Y_{2.5}S_2$ exhibited profuse growth (++++), as reported by Oledibe *et al.* (2023).

2.2.3 Need for Sustainable and Low-Cost Culture Media for Fungal Cultivation

There are several compelling reasons for developing sustainable and low-cost fungal culture media. The high cost of synthetic and commercial media, such as Sabouraud dextrose agar, limits research in developing countries and underfunded institutions (Jadhav *et al.,* 2018). The use of local plant-based media can reduce reliance on imported commercial products, thereby promoting self-sufficiency (Oledibe *et al.,* 2023). Economic accessibility is another major factor; alternative media can be up to 86% cheaper than commercial equivalents, as demonstrated with textured

soy protein medium compared to tryptone soy broth (Cruz *et al.*, 2020).

The utilization of agricultural and food waste, including plant residues such as maize, soy, yam, fruit peels, and vegetable stems, addresses waste management issues while adding value to byproducts (Gamit *et al.*, 2023; Oledibe *et al.*, 2023). Environmental sustainability is also advanced by repurposing food waste and locally available biomass, which reduces the environmental impact associated with synthetic media production (Gamit *et al.*, 2023). Furthermore, educational equity is enhanced, as affordable media enable schools and laboratories with limited budgets to conduct practical microbiology and research effectively (Gamit *et al.*, 2023; Oledibe *et al.*, 2023).

2.3 Nutrients Required for Fungal Media Formulation

2.3.1 Carbon Sources

Carbon is the most prevalent element in fungal cells and is essential for producing biomolecules such as carbohydrates, lipids, proteins, and nucleic acids (Kumar *et al.*, 2012). Fungi can utilize both inorganic carbon sources (e.g., carbon dioxide) and organic sources such as sugars and alcohols (Kumar *et al.*, 2012). In the study by Oledibe *et al.* (2023), starches from *Zea mays* (maize) and *Dioscorea dumetorum* (yam) provided additional carbon sources that supported rapid radial growth of *Aspergillus niger* and *Penicillium expansum*. The maize starch contributed approximately 35% carbohydrate, which enhanced fungal growth (Oledibe *et al.*, 2023). Other effective carbon sources identified include fruit peels (banana, watermelon, orange) and vegetable wastes, which contain simple and complex sugars that are readily broken down by microbes (Gamit *et al.*, 2023).

2.3.2 Nitrogen Sources

Nitrogen is crucial for protein synthesis in fungi. It can be supplied in both inorganic forms (e.g., nitrates) and organic forms such as protein hydrolysates (e.g., peptone, tryptone) (Atlas *et al.*, 2010). In the formulated medium $M_5Y_{2.5}S_2$ (containing *Zea mays*, *Dioscorea dumetorum*, and Glycine max), the soybean (*Glycine max*) component provided additional nitrogen supplements, including phytic acid, dietary minerals, and vitamin B, which enhanced mycelial growth and sporulation (Oledibe *et al.*, 2023). Other nitrogen-rich plant sources successfully used in alternative media include soy flour, chickpeas, lentils, cowpeas, mung beans, and black gram (Gamit *et al.*, 2023).

2.3.3 Minerals and Vitamins

Fungi require various mineral elements for optimal growth, including phosphorus, sulfur, magnesium, calcium, phosphate, and other inorganic salts (Oledibe *et al.*, 2023; Gamit *et al.*, 2023). These minerals are often present naturally in plant-based materials. In the study by Oledibe *et al.* (2023), *Glycine max* seeds contributed phytic acid, dietary minerals, and vitamin B, which supported remarkable mycelial growth and sporulation. Vitamins and trace elements are also essential cofactors for enzymatic reactions during fungal metabolism.

2.3.4 Water Activity and pH Requirements

Water is essential for solubilization, transport, and maintenance of hydrolysis reactions. Free water is necessary for fungal growth, and evaporation during incubation can reduce colony size (Gamit *et al.*, 2023). The formulated media in Oledibe *et al.* (2023) were prepared using sterile distilled water in various proportions (e.g., 30–50 mL per formulation) to ensure adequate water activity. Fungi generally prefer a slightly acidic pH range. Oledibe *et al.* (2023) reported that the formulated medium $M_5Y_{2.5}S_2$ had an average pH of 5.15, while Sabouraud dextrose agar (SDA) had a pH of 5.05, both being conducive to fungal growth and sporulation. This supports the finding that fungi prefer a slightly acidic reaction (pH 5.0–6.5).

2.4 Agro-Residues as Alternative Media for Fungal Cultivation

2.4.1 Studies That Used Agro Waste for Fungal Culture Media

Several studies have successfully utilized various plant wastes as alternative culture media for fungal growth. Banana peel was found to be a cheap and efficient substrate for fungal growth (Kindo *et al.*, 2016). Watermelon peel waste (WPW) extract is abundant in macronutrients including lipids, reducing sugars, and total proteins, and successfully supported the growth of *Aspergillus niger*, *Fusarium oxysporum, Lichtheimia corymbifera, Penicillium expansum*, and *Rhizopus oryzae*. The formulated watermelon peel waste dextrose agar (WPWDA) medium was discovered as an affordable and environmentally friendly alternative to Czapek's Dox agar (CzDA) and Potato dextrose agar (PDA) (Hasanin and Hashem, 2020).

Dragon fruit peel (DFP) was employed as a medium for microbial growth (Putri *et al.*, 2017). Grapefruit, banana, and melon peels containing high concentrations of carbohydrates served as excellent substrates for amylase production (Siddiqui *et al.*, 2014). A culture medium called GCO containing powdered onion, maize, and garlic skins was tested successfully for *Penicillium chrysogenum*, *Aspergillus niger*, and *Trichoderma viridae* (Berde and Berde, 2015). Orange peel, potato peel, and drumstick peel powder were used for the growth of *Trichoderma spp.* and *Aspergillus spp.* (Kadam *et al.*, 2017).

Pea peel, sponge gourd peel, and lychee peel waste served as growth media for cellulase enzyme production by *Trichoderma reesei* at 30°C (Verma *et al.*, 2011; Verma *et al.*, 2018). In the study by Oledibe *et al.* (2023), local plant materials including grains of *Zea mays* (maize), seeds of *Glycine max* (soybean), and tubers of *Dioscorea dumetorum* (yam) were successfully formulated into a fungal medium

($M_5Y_{2.5}S_2$) that supported growth of *Aspergillus niger* and *Penicillium expansum* comparable to standard Sabouraud dextrose agar (SDA).

2.4.2 Advantages of Agro-Residue-Based Media

2.4.2.1 Cost Reduction

The high cost of synthetic media is a major issue affecting microbiological research quality in developing countries. Agro-residue-based media significantly reduce costs. For example, textured soy protein medium had production costs 86% lower than tryptone soy broth and 68% lower than tryptone soy agar (Cruz *et al.,* 2020). Soy flour medium is approximately 50 times less expensive than commercial medium containing peptone and yeast extract (Santos *et al.*, 2021).

2.4.2.2 Reduced Reliance on Imported Media

The use of locally formulated media can help reduce dependence on imported media and provide researchers with an alternative, cost-effective method of conducting research (Oledibe *et al.*, 2023).

2.4.2.3 Sustainability and Waste Reduction

Food waste generation is unsustainable for economies; reusing food waste for culture media addresses environmental concerns by reducing waste (Ramirez *et al.*, 2020). This approach repurposes materials that would otherwise be discarded.

2.4.2.4 Comparable Performance to Standard Media

The formulated medium $M_5Y_{2.5}S_2$ performed favorably compared to Sabouraud dextrose agar (SDA) in terms of colony diameter, aerial growth, and sporulation (Oledibe *et al.,* 2023). Watermelon peel waste dextrose agar was discovered as an effective alternative to Czapek's Dox agar and Potato dextrose agar (Hasanin and Hashem, 2020).

2.4.2.5 Accessibility for Resource-Limited Institutions

In institutions with insufficient financial resources, practical microbiology classes and scientific research are hampered by high culture medium costs. Alternative media provide a scientific basis for producing and using affordable culture media (Uthayasooriyan *et al.,* 2016; Jadhav *et al.,* 2018; Cruz *et al.,* 2020).

2.4.2.6 Rich Nutritional Content

Fruit and vegetable bio-waste contains simple and complex sugars, proteins, lipids, reducing sugars, and other nutrients that are readily broken down by microbes (Gamit *et al.*, 2023). Starch provides 35% carbohydrate and 1% mineral matter, providing additional carbon sources that encourage healthy fungal growth (Oledibe *et al.*, 2023).

2.4.2.7 Facilitation of Industrial Microbial Product Generation

Agro-residue-based media have been successfully used to produce bacterial cellulose, lipases, prodigiosin pigments, cellulase enzymes, and biodiesel from oleaginous yeasts (Gamit *et al.*, 2023).

2.5 Nutritional and Biochemical Composition of Selected Agro-Residues

2.5.1 Groundnut Peel

Groundnut, otherwise known as peanut (*Arachis hypogaea*) is an important nutritious leguminous oilseed crop grown in semi-arid and sub-tropical regions under rainfed conditions. It is an important subsistence food crop ranking 13th most important crop and 6th most important oilseed crop in the world, with its composition being 48-50% oil, 26–38% protein, 11–27% carbohydrate, minerals and vitamins (Aboki et al., 2018). Groundnuts also have high antioxidant activities with predominance of oleic acid (Mahatma et al., 2016). Groundnuts are grown practically in every country within sub-Saharan Africa accounting for approximately one quarter of the world's groundnut production of about 46 million tons (Carneiro et al., 2017). The leading groundnut producing countries in the world are China, India, Nigeria, USA and Myanmar. Among the West Africa countries, Nigeria ranked the largest groundnut producing country accounting for 51% production in the region, 39% in Africa and 10% of total global production (Ajeigbe et al., 2015). In 2020, Nigeria produced 4.49 million metric tons of groundnuts, while China and India produced 17.99 and 9.95 million metric tons, respectively (STATISTA, 2022).

In Nigeria, groundnut is grown throughout the country except in the riverine and swampy areas. The major producing states include Bauchi, Benue, Borno, Jigawa, Niger, Kogi, Kwara, Kano, Katsina, Kaduna, Zamfara, Sokoto, Kebbi, Adamawa, Yobe, Taraba, Plateau, Nasarawa, and FCT Abuja (Ajeigbe et al., 2015). Before the fossil oil boom and even after, groundnut has contributed immensely to the development of Nigerian economy, providing significant sources of revenue and foreign exchange earnings through the sales of seeds, cakes, oil and haulms (Usman et al., 2013; Ajeigbe et al., 2015). Groundnuts play significant role in the human diet particularly in children because of its high protein and carbohydrate contents in addition to its richness in calcium, magnesium, potassium, phosphorus and vitamin E. The groundnut seeds or kernels are consumed as snack (fresh, boiled, dried or roasted), processed into other products or included as ingredient in a number of products such as groundnut paste which is fried to obtain groundnut cakes (kuli kuli), salted groundnut, groundnut candy and groundnut soup (Ajayi and Lateef, 2023).

The edible oil which comprises 50% of the total kernel is the most valuable product. It is composed of mixed glycerides and contains a high proportion of unsaturated fatty acids particularly, oleic acid (35–87%) and linoleic acid (18–30%) as reported in different works (Achola et al., 2017). It also contains stearic acid (2–5%) and palmitic acid (4–19%). The variations are due to reports on different cultivars of groundnuts. Groundnut oil has found applications in production of margarine, peanut butter, cookies, mayonnaise, salad oil, soaps and cosmetics. It is used for cooking and often preferred by the deep- frying industries because it possesses a smoke point of 229.4–258.8 °C compared to 193.5 °C of soybean (Das et al., 2013). A larger part of groundnut production goes to the processing industries where after removing from the husk, are used for various purposes.

The husks or shells are the dry pericarp of the mature pods which are composed of cellulose, carbohydrate, protein, minerals and lipids, while the peels are the inner coloured skin residues that are generated from roasted groundnut. Typically, groundnut shells have been reported to contain 25.57% carbohydrate, 4.43% crude protein, 0.5% lipids, 59.0% crude fiber and 2.50% ash (AbdulRazak et al., 2014). They also contain oxalate (220 mg/100 g), phytate (362.1 mg/100 g), cyanogenic glycosides (1.60 mg/100 g) and trypsin inhibitor (25 TUI/mg), which are anti-nutritional factors. The nutritional values of groundnut husks have been improved by soaking and fermentation for suitability as animal feed (Duodu et al., 2018). The husk and the inner peel or skin of the groundnut that are removed from preparing groundnut snacks and roasting of groundnuts are generally thrown away as wastes which constitute huge amount of solid wastes. However, reports have shown that the groundnut peel or skin contains 69.80% carbohydrate, 16.60% fat, 12.32% protein, 2.83% ash in addition to its rich polyphenolic content (Ajayi and Lateef, 2023).

Groundnut husk which is also referred to as shell or hull has been reported to account for about 20% of the dried groundnut pod by weight (Duc et al., 2019). Invariably, 1 ton of groundnuts will yield about 275 kg of groundnut shell biomass while a kilogram of shelled groundnut kernel is capable of generating about 35–45 g of groundnut peel (Pandey et al., 2018). Thus, there is large generation of groundnut shell and peel after groundnut processing, making these residues readily available particularly in Nigeria, where groundnut is cultivated on about 4073,101 ha with estimated yield of about 11, 030 kgha − 1 as reported by FAOSTAT (2022). Between 25 to 30% of the total weight of the legume is regarded as residues in the last stage of the processing of groundnut for either oil production or direct consumption (Ogunsuyi and Adejumobi, 2020). In the global world, over 0.74 million metric tons of groundnut peels are generated yearly (Arya et al., 2016).

In spite of the potentials of groundnut shell and peel which can be explored for various applications, only a small portion is being used. Most of the groundnut shell and peel are abandoned, burnt or buried in the soil resulting in environmental pollution. Hence, significant proportion of groundnut shell and peel remain underutilized in Nigeria. How- ever, new technologies have been developed to provide meaningful use for these residues from groundnut. It is anticipated that the utilization of groundnut shells in processes such as in the production of composites, production of engineering components and structure including various commercial applications will save cost in the management of the wastes, reduction of environmental pollution by decreasing open burning of groundnut shells to eliminate off-gassing of toxic compounds and hence preserve the environment. The valorization of these wastes into useful products using different applied technologies can also lead to job creation and increase the financial benefits to the farmers. Both groundnut shell and peel have been reported for various industrial applications ranging from dye decolourization, production of enzymes, biodiesel production, colouration of textiles to many other applications (Ajayi and Lateef, 2023)**.**

2.5.1.1 Physicochemical Properties of Groundnut Peel

Groundnut peel, also known as groundnut skin, is a common byproduct of groundnut factories, as most groundnut butter manufacturers remove the seed's skin (Figure2). An astringent groundnut peel will diminish the flavor of groundnut butter. Despite this, groundnut peel contains several bioactive components and antioxidants that promote and protect human health, such as phenolic acid, procyanidin, and catechin, to name a few. The peel of non-defatted groundnuts contains 90–125mg/gram of total phenolics, which include phenolic acids, flavonoids, and resveratrol (Putra et al., 2023).

2.5.1.2 Bioactive Compounds in Groundnut Peel

Catechin

Catechin is a bioactive molecule found in peanut skin, but it can also be found in tea, grape skin, wheat, onion, apple skin, broccoli, cocoa, and red wine(Putra et al., 2023). Catechin has a molecular weight of 290.26g/mol and a melting point of 175◦C. A high melting point makes it resistant to deterioration at high temperatures. Catechin possesses antioxidant qualities that prevent oxidative dam age to bodily cells (Putra et al., 2023). Catechin has been demonstrated to have superior antioxidant qualities and a greater capacity to scavenge free radicals than vitamin C, E, or-carotene carotene (Vuong et al., 2010). Moreover, catechins can transfer hydrogens through their hydroxyl groups.

Catechin belongs to the favan-3-ol family. Regular use can help prevent Parkinson's, diabetes, cancer, and other diseases. However, producing highly active catechin maybe

problematic because it is rapidly broken down when exposed to light due to UV radiation from the sun (Putra et al., 2023b). Furthermore, catechin reduces hemoglobin levels by delaying the oxidative process in hemoglobin cells (Lu et al., 2011). Putra et al. (2023a) used a bioassay to determine the antioxidant activity of many well-known antioxidants. Furthermore, Table 2 shows that various materials contain catechin as a bioactive compound (Li et al., 2010). The catechin content of groundnut peel is comparable to that of green tea and higher than that of black tea. Groundnut peel contains a high concentration of catechin, prompting the development of groundnut peel as a catechin resource to replace other catechin resources such as green and black tea (Putra et al., 2023a).

Resveratrol

Resveratrol (3,4,5-trihydroxystilbene) is a stilbene, a type of polyphenolic compound. Certain plants produce resveratrol land other stilbenes in response to stress, injury, fungal infection, or ultraviolet (UV) radiation. As shown in Figure 4, resveratrol is a fat soluble molecule with trans and cis molecular configurations (Abdel-Raoof and Mohamed, 2018). Both cis- and trans resveratrol occur as glucose-bound glucosides (Abdel-Raoof and Mohamed, 2018). Salvador et al. (2019) discovered that resveratrol-3-O-glucoside, also known aspiceid, is one of the most important resveratrol derivatives. Resveratrol can be found in grapes, wine, grape juice, peanuts, cocoa, and berries (Putra et al., 2023a)

Researchers worldwide have investigated resveratrol's health consequences since the early 1990s, when the presence of resveratrol in red wine was proven (Liu et al., 2015). It was hypothesized, in particular, that moderate red wine consumption containing resveratrol could help explain why the French have a relatively low incidence of coronary heart disease (CHD) despite eating foods high in saturated fat, a phenomenon known as the "French Paradox" (cardiovascular disease) (Sales and Resurrection, 2014). Since then, scientific interest has grown in resveratrol's ability to prevent cancer, delay the on set of cardiovascular and neurological diseases, improve glycemic control in type2 diabetes, and lengthen lifespan in experimental animals. Resveratrol has been extracted from groundnut peel using ethanol with the maceration method (Sales and Resurrection, 2014).

Procyanidins

Many agro-industrial wastes from the food processing sectors, including cocoa, berries, grapes, apples, blueberries, plums, tea leaves, coffee, cinnamon, peanuts, and leguminous plants, include procyanidins and their monomers (Valencia-Hernandez et al., 2021). Depending on the origin and kind of the plant material, the procyanidin concentration may vary (Mullen et al., 2013). These molecules contain flavan-3-olmonomers as basic units in their structure, which are composed exclusively of (+)catechin and (–)epicatechin. (Epi) catechin monomers may be biosynthetic precursors of procyanidins (Ambigaipalan et al., 2016) as shown in Figure5.

Sarnoski, et al. (2012) found that there are several forms of proanthocyanidins in peanut skins, but A-type proanthocyanidins predominate. Groundnut peel are mostly composed of dimeric, trimeric, and tetrameric proanthocyanidins species.

2.5.1.3 Value Added Applications of Groundnut Peel and Groundnut Shell

The groundnut peel or skin has been reported for their phytochemical constituents such as saponin, terpenoid, glycosides, flavonoids, phenols and tannin (Pandey et al., 2018). The peel is rich sources of phenolic compounds especially procyanidins (tannins), which are made of two or more linked flavan-3-ols (catechin and epicatechin) to form polymeric and oligomeric compounds (Ajayi and Lateef, 2023). Groundnut shells are rich in bioactive and functional components such as cellulose, hemicellulose and lignin, which are of importance for mankind in diverse ways (Duc et al., 2019). These functional components of groundnut peel and shell as agricultural wastes propel their suitability for various value added applications as reported by several researchers. In Table 1, an overview of the efforts to valorize groundnut peel and groundnut shell to produce different products is presented.

Production of Functional Foods and Bioactive Compounds

Groundnut peel was explored for its potential use as functional food ingredient in the study that was reported by Constanza et al. (2012). Groundnut peels were milled, extracted with 70% ethanol in water, filtered and spray-dried with and without the addition of maltodextrin. From the study, it was revealed that addition of maltodextrin during spray-drying resulted in higher degradation of the phenolic compounds as evidenced by the formation of unknown polymeric compounds. Results also suggested that the insoluble material produced during the process could be used in animal feeds because of its rich protein content. In addition, the spray-dried groundnut skin extracts produced powders that were rich in polyphenolics and antioxidant capacity as suitable as food ingredients. The spray-dried powder may also serve as a good source of natural antioxidants and source of dietary polyphenols to enhance shelf life of foods.

Dean (2020) reported the extraction, isolation and quantification of bioactive compounds from groundnut peel. In methanolic, ethanolic, acetonic and aqueous extracts, the total phenolic contents ranged from 58.5–165.6 mg/g. The compounds isolated included series of flavonoid glycosides, proanthocyanidins, and alkaloids that have been shown to have antioxidant, antimicrobial, anticancer, anti-cholesterol,

anti- inflammatory and anti-diabetic activities for applications in the formulation of nutraceuticals and cosmetics (Christman et al., 2019; Toomer et al., 2019). Antioxidant potentials of groundnut skin had influenced its incorporation into foods and drinks such as chocolate, meat, yoghurt and as functional food ingredients (Ajayi and Lateef, 2023).

Generation of Energy

Agricultural wastes if properly harnessed can be utilized as sources of renewable and sustainable energy (biofuel) which can contribute significantly to alleviate the effect of greenhouse gas (GHG) emissions (Maninder et al., 2012). Groundnut shell contains diverse chemical composition that can be utilized for the production of various value-added chemicals. It also has high percentage of organic matter and very low ash content making it ideal for use as fuel for heating.

Production of Pyrolytic Oil and Biochar

Valorization of agricultural biomass via pyrolysis is an auspicious technique for producing renewable energy and managing wastes. Pyrolysis is defined as the thermochemical decomposition of an organic material at high temperature and in the absence of oxygen to produce bio-oil accompanied by non-condensable gasses and a carbon-heavy solid residue referred to as char (Collins and Ghodke, 2018; Ogunsuyi and Adejumobi, 2020). Biochar can serve as activated carbon for water purification, bulk material for printing and agro-material for soil remediation. It can also be used for the production of wood preservatives (Ogunsuyi and Adejumobi, 2020). Groundnut shell biochar when ap- plied on the soil is capable of improving organic carbon, total nitrogen and C/N ratio in addition to its ability in changing the soil C and N stable isotope composition (Xu et al., 2015). Groundnut shell and groundnut peel have been reported to exhibit the potential as viable feedstocks for sustainable production of bio-based chemicals.

The production of bio-oil and biochar by pyrolyzing groundnut shell and groundnut peel was investigated (Ogunsuyi and Adejumobi, 2020). After grinding to reduce particle sizes, they were subjected to slow pyrolysis at 450 °C in a fixed bed reactor. The bio-oil and biochar obtained were characterized using gas chromatography-mass spectrometry (GC-MS). Results showed that groundnut shell produced 11.7% bio-oil and 44.5% biochar, while the peel produced 16.3% bio-oil and 34.1% biochar. Derived bio-oil from both fractions of the groundnut biomass revealed the presence of phenol, 2-methoxybenzene, alkanes, naphthalene-1, 6-dimethyhexadecanoic methyl esters, acetamide and methylstearate which have being reported as the major components of wood preservatives.

Synthesis of Nanoparticles and Production of Nano-Based Material

In recent times, the utilization of agro-wastes as sources of biomolecules in green nanotechnology has gained much attention in that a number of agro-wastes have been reported for their relevance in nanobiotechnology (Adelere and Lateef, 2016b). Various types of nanoparticles have been successfully synthesized from different agro-wastes such as groundnut shell and peel. Groundnut peel has been reported for the biogenic synthesis of iron nanoparticles (Pan et al., 2020). The biogenic iron nanoparticles had average size of 10.6nm with core of Fe0, and the shell consisting of reducing biomolecules of anthocyanins, flavonols, phenolic compounds, and epicatechin. The synthesized iron nanoparticles was evaluated for the removal of chromium (IV) to achieve 100% removal of the metal from a solution containing 10 mg/L of chromium (IV) within one minute.

Production of Textile Dye

Groundnut peel is rich in flavonoid which is responsible for its red color. This red colouration has being harnessed for the production of dye. The color and hue angle of the groundnut peel differs from variety to variety and it is dependent on the polyphenol content. The redness and hue angles increased as the phenolic content increased (Ajayi and Lateef, 2023). Pandey et al. (2018) reported the extraction of dye from roasted groundnut peel, which was used for colouration of fabrics. The first extraction was done by boiling 150 g of roasted groundnut peel in 2 litres of water for 30 min, cooled and filtered. Second extraction was done by repeated addition of 1 liter of water, left overnight and filtered. Both extracts were then added together to make the stock dye solution. The crude dye yield was evaluated to be 22.8% which was higher than that of natural dyes. The groundnut peel extracted dye showed affinity for silk, cotton and wool fabrics without the use of mordant. The dyed fabrics displayed moderate to excellent fastness in addition to an ultraviolet protection factor up to 65.

Kyei et al. (2020) used the extract of groundnut peel to synthesize azo compounds and metal complexes via diazotization of aniline and coupling with alkaline groundnut peel extract under appropriate conditions. The ligand was then reacted with manganese and iron to produce novel coloured azo metal complexes with yields of 42–95%. The complexes were soluble in methanol, ethanol, acetone and ethyl acetate, but insoluble in water and they inhibited growth of Escherichia coli and Staphylococcus aureus. The complexes were recommended for suitable use as antimicrobial agents and corrosion inhibitors in paints and pigments for surface coatings.

Production of Mycological Media and Other Valuable Products

Williams et al. (2019) reported the exploitation of infusion that was prepared from groundnut shell for the formulation

of low-cost mycological medium to grow fungi. The medium consisted of groundnut infusion (1 liter), fermented cassava flake 'garri' (28 g) and agar powder (15 g) to prepare groundnut shell infusion agar (GSA). The medium was tested in comparison with the conventional potato dextrose agar (PDA) to growth fungi from three soil samples. Both PDA and GSA supported growth of molds from the soil samples yielding similar growth index and isolation potentials.

Groundnut shell among other substrates has also been evaluated for potential use as carrier for microbial cultures as biocontrol agents in agriculture (Bhatia et al., 2017). Inocula of Trichoderma sp. and Rhizobium sp. were prepared and survival of the organisms was determined in groundnut shell, saw dust, bagasse, paddy straw and soil. Groundnut shell had pH 6.72, inherent moisture of 13.12% and water holding capacity of 71.14%. Viability of the tested inoculants (Trichoderma koningii, Trichoderma virens, Rhizobium sp. 143 and Rhizobium sp. 218) over a period of one year showed that groundnut shell supported the organisms under storage and therefore represents a novel route for its development into carrier for microbes.

Groundnut shell was also applied in mushroom cultivation with the view of enhancing the production of bioactive compounds. Ogidi et al. (2020) reported the production of extracellular polysaccharides (EPS) by Pleurotus pulmonarius to the tune of 5.6 g/L when grown in submerged fermentation with 20 g/L supplementation of groundnut shell. The EPS showed antimicrobial properties (5–14 mm) and scavenged DPPH by 65.70–81.80%. It supported luxurious growth of Lactobacillus delbrueckii and Streptococcus thermophilus, which are beneficial microbes.

2.5.2 Blood Meal

Every year, millions of liters of blood are generated as a direct by-product of meat processing plants (Chiroque et al., 2023). Rather than treating this as waste, the livestock and agriculture industries have found a way to convert it into one of the most nutrient-dense products available to farmers: blood meal (Hammond and Faciola, 2025). This dark reddish-brown powder is packed with protein and nitrogen, making it valuable both as a livestock feed supplement and an organic fertilizer (Agriculture Institute, 2025). Understanding how it is made and where it is used reveals just how efficiently modern agriculture can close the loop on what would otherwise be a significant waste stream (Agriculture Institute, 2025).

Blood meal is a dry, inert powder made from the blood of slaughtered animals, most commonly cattle and hogs that has been processed through drying and grinding (Hammond and Faciola, 2025). By weight, it generally contains around 12% nitrogen with trace amounts of phosphorus and potassium, making it one of the highest non-synthetic sources of nitrogen available. Its protein content is equally impressive, typically ranging between 80-90%, which places it among the most concentrated protein sources used in animal nutrition (Agriculture Institute,2025).

2.5.2.1 Production of Blood Meal

The production of blood meal follows a sequence of steps designed to stabilize and concentrate the nutritional value of raw blood (Heuzé and Tran, 2016). Blood is a highly perishable material, so processing must begin quickly after collection at the slaughterhouse. The general process involves collection, coagulation, drying, and grinding (Agriculture Institute, 2025).

Collection and coagulation

Fresh blood is collected directly from animals during slaughter under controlled conditions. Depending on the intended use and end product quality, the blood may be kept whole or separated into its two main fractions – red blood cells and plasma. According to Agriculture Institute (2025), separating these fractions allows processors to produce higher-value plasma protein products in addition to standard blood meal. For blood meal production, the raw blood is typically preheated and then coagulated by applying heat, which causes the proteins to solidify and makes subsequent dewatering more efficient (Zhang et al., 2014).

Drying Method

Drying is the most critical step in blood meal production. It determines not only the shelf life of the final product but also its nutritional quality – particularly the digestibility of protein and the preservation of lysine. Several drying methods are used commercially, each with different effects on the final product. They include: batch dry rendering, ring-dried rendering, and spray-dried rendering (Hammond and Faciola, 2025). In batch dry rendering, whole blood is cooked in a steam-heated cylindrical cooker at around 500 kPa. Ring-dried rendering coagulates the blood with steam heating, followed by centrifugation and drying with hot gas (Agriculture Institute, 2025). Spray drying, similar to skim milk powder production, involves spraying liquid blood into a warm chamber to produce a fine powder. Differences in temperature, exposure time, and oxygen availability during these processes affect the extent of amino acid degradation, particularly heat-sensitive ones like lysine (Hammond and Faciola, 2025).

Once dried, the material is milled into a fine, uniform powder. For the product to be safe for use in animal feed, heat treatment must meet minimum safety standards. Heuzé and Tran (2016) notes that blood must be heated to at least 100°C for a minimum of 15 minutes to destroy potential pathogens including salmonella and prions. The finished blood meal is then screened for particle size consistency and tested to ensure it meets protein and moisture specifications before being packaged (Heuzé and Tran, 2016).

2.5.2.2 The Nutritional Composition of Blood Meal

The nutritional value of blood meal varies slightly depending on the drying method and source animal, but the core nutritional profile of BM remains consistently impressive. BM is composed mainly of protein (90–95% dry matter), with minimal fat (< 1% DM) and ash (< 5% DM). It also contains approximately 12–13.25% nitrogen by weight (Hammond & Faciola, 2025). A key nutritional characteristic is its exceptionally high lysine content, which makes BM a primary lysine supplement in livestock diets. Additionally, BM has a high iron concentration (> 1500 mg/kg DM) (Hammond & Faciola, 2025). Iron availability increases during microbial degradation due to the progressive breakdown of hemoglobin complexes, releasing heme and non-heme iron species (Hardy and Brezas, 2022).

For ruminants, BM is particularly valuable due to its high rumen undegradable protein (RUP), which can reach up to 78%, with higher processing temperatures further increasing RUP content (Hammond & Faciola, 2025). Despite these strengths, BM has a well-known limitation: it is deficient in isoleucine (approximately 1% DM) while being rich in amino acid profiles such as lysine, methionine, and cysteine (Gorissen et al., 2018; Babatunde et al., 2021; Hammond & Faciola, 2025). Therefore, BM should not serve as the sole protein source in a diet and is best used alongside other ingredients that complement its amino acid gaps (Gorissen et al., 2018). Commercial products also have a maximum moisture content of 10%.

2.5.2.3 Blood Meal as a Nitrogen Source for Microbial Media

Blood meal demonstrates excellent suitability as an organic nitrogen source for microbial cultivation due to several inherent characteristics (Pérez and Toldra, 2025). These include its high protein content, which provides abundant nitrogen for sustained growth, and its rich amino acid profile, which supplies diverse nitrogenous compounds readily assimilable by microorganisms (Pérez and Toldra, 2025). Additionally, blood meal exhibits slow-release nitrogen characteristics that enable prolonged microbial activity without rapid nutrient depletion (Villemure et al., 2020). In contrast to inorganic nitrogen sources such as ammonium salts or nitrates, blood meal provides complex organic nitrogen that supports sustained microbial growth and diverse metabolic activities, potentially enhancing the production of industrially relevant enzymes and metabolites (Gracia et al., 2010).

2.5.2.4 Advantages of Blood Meal Over Conventional Nitrogen Sources

Blood meal offers several distinct advantages compared to conventional laboratory-grade nitrogen sources such as peptone, tryptone, and yeast extract (Pérez and Toldra, 2025; Uzairu, 2025). It is highly cost-effective because it utilizes waste materials from the meat processing industry, significantly reducing media preparation costs (Pérez and Toldra, 2025; Uzairu, 2025). From a sustainability perspective, blood meal reduces environmental pollution associated with slaughterhouse waste disposal (Villemure et al., 2020). Its nutrient richness provides both organic nitrogen and essential micronutrients in a single ingredient, while its slow nutrient release supports prolonged microbial activity and reduces the frequency of media replenishment (Villemure et al., 2020). Furthermore, blood meal contributes to waste valorization, aligning with circular bioeconomy principles by converting waste into valuable products (Uzairu, 2025).

2.5.2.5 Applications in Microbial Media Formulation

Fungal Cultivation Media

Blood meal has been explored as a substitute for expensive nitrogen sources such as peptone and yeast extract in fungal cultivation media (Akpor et al., 2018). Its rich organic nitrogen content supports robust mycelial growth and sporulation in various fungal species (Villemure et al., 2020). The combination of blood meal as a nitrogen source with carbohydrate-rich substrates represents a promising approach for developing cost-effective, sustainable culture media for mycological applications.

Biofertilizer and Biocontrol Agent Production

Blood meal-enriched media have been employed for the mass production of beneficial microorganisms used as biofertilizers and biocontrol agents (Shaji and Matthew, 2021). The complex nutrient profile supports the growth of diverse microbial consortia with plant growth-promoting and pathogen-suppressive activities (Shaji and Matthew, 2021).

2.5.3 *Caladium bicolor* (Ede Mmuo)

Caladium bicolor, often known as "The heart of Jesus," "Elephant ear," or "Angel wings," is a species of flowering plants in the family Araceae (Hussain et al., 2017). It is a perennial herbaceous plant with a tuberous root that sprouts a cluster of beautiful and multicolored leaves up to 80 cm tall. Occasionally, local people gather the plant from the wild and consume it as food. In tropical gardens, where it is prized for its attractive leaf, they are frequently grown as an ornamental plant. The most distinctive features of the plant are its leaves, which come in a wide variety of sizes, shapes, and colors. It has a heart, lance, or arrowhead shape that defines it. The arrowhead-shaped leaves, often up to 50 cm long, have uniquely colored veins and come in a variety of shades of green that are mottled and blotched with pink, red, gray, white, or combinations of these colors (Tropical Plant Database [TPD], 2014).

Most members of the Araceae family have harmful properties; they contain water-insoluble calcium oxalate crystals and unidentified proteinaceous toxin constituents that, when they come into contact with them, cause painful

burning of the lips, tongue, mouth, and throat and give the impression that hundreds of tiny needles are piercing them. Hoarseness, dysphonia, dysphagia, and an inflammatory reaction that frequently includes edema and blistering may also occur (Tosoc et al., 2016). Overdosing may result in nausea, vomiting, diarrhea, eye, mouth and tongue edema, eye redness, and nausea (Tosoc et al., 2016). The plant is safe to consume in either of these states since calcium oxalate is easily broken down by either thorough boiling or thorough drying (Agoi, 2025).

2.5.3.1 Plant Ecology

C. bicolor is a plant that grows in damp tropical lowlands and at moderate elevations (TPD, 2014). It prefers a wet, fertile, humus-rich, acidic soil in partly shady or filtered sunlight, grows well in sunny shade, but keeps away from direct sunlight because it will scorch the foliage (TPD, 2014). Dry environments are undesirable to the plants during active growth, and needs to be grown in an area protected from severe winds. The plant can spread like a weed and is found on many Pacific Islands and wet, fertile soils in shady locations (TPD, 2014). C. bicolor is currently classified as an invasive species in Trinidad and Tobago, Guam, Micronesia, Palau, Hawaii, and the Philippines, where it is thought to be a species that is displacing native species, disrupting community structures, and otherwise affecting native plant ecosystems (Agoi, 2025).

2.5.3.2 Geographical Distribution

C. bicolor is a common ornamental plant that has naturalized in Pemba, Zanzibar, tropical and sub tropical parts of Africa. Geographically, it is situated in South America, specifically in Brazil, Bolivia, and Peru, before heading north via Central America to Mexico (TPD, 2014). The northwest regions of Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, French Guiana, Guyana, Honduras, Nicaragua, Panamá, Peru, Suriname, and Venezuela were also discovered to contain it (Agoi, 2025).

2.5.3.3 Botanical Description

The habitat for the species of caladium is characterized as "typically an understory tuberous herb in open areas in the forest, on creek banks, common in the areas of semi deciduous forest." Caladium is adapted to disturbance and frequently grows in partially shaded regions alongside roadways, from sea level to at least 1,000m. The leaves of the wild plants are typically 6-18 inches (15-45cm) long and broad, and they grow to a height of 15-35 inches (40-90cm) (Agoi, 2025). C. bicolor is an erect, acaulescent herb with a fleshy corm at the base that is glabrous. Petioles erect, 35-55cm long, sheathing, white at the very base, typically with purple stripes; blades pointing downward, 30 x 20cm, chartaceous, usually with small, irregular whitish or pinkish spots, or variegated along secondary veins; less frequently completely green; glaucous beneath; apex acute or shortly acuminate; base peltate; cordate; margins more or less wavy (Agoi, 2025).

Flowers are unisexual; spathes are chartaceous, glaucous, to 14cm long, the blade twice as long as the tube, withering, elliptic, and apiculate at the apex; spadix is shorter than the spathe, the staminate zone twice as long as the pistillate; peduncles are cylindrical, green, and usually have purple stripes. Inflammatory sap is present (Agoi, 2025).

2.5.3.4 Phytochemical screening

In the leaves and tubers of two different Caladium bicolor species—green background with white patches (GWS) and green background with pink veins (GPS)—Essien et al. (2015) screened for alkaloids, flavonoids, carbohydrates, deoxy sterols saponins, and tannins, triterpenes, phlobatannins, cardiac glycosides, anthraquinone, and sugar. Phlobatannins and anthraquinones were discovered to be absent. Alkaloids, saponins, tannins, terpenoids, and flavonoids were all detected in the ethanolic and methanolic extracts of the plant's leaves, stem, and roots by Ezebo et al. (2021) who also carried out phytochemical screening on them.

In the whole leaf extract of C. bicolor, Akhigbemen et al. (2019) observed the presence of carbohydrates, proteins, alkaloids, and flavonoids but the absence of tannins, compounds with steroidal nuclei, cardiac glycosides, and phenolic compounds. Akindele et al. (2015) also identified the presence of phenolics and reducing sugars. Phytochemical analysis of extracts from Caladium bicolors' leaves, tubers, stem, and roots, reveals tannins, flavonoids, alkaloids, and saponins, as well as cardiac glycosides in the leaves and tubers of two different species variations of the plant (Agoi, 2025).

The methanolic extracts of its leaves were discovered to contain carbohydrates, lignin, starch, mucilage, cellulose, cutin and suberin with the presence of cardiac glycosides, which contrasts with the findings of Essien et al. (2015). Phlobatannins were also found by Akindele et al. (2015) in the aqueous leaf extract, which is also contrary to the results of Essien et al. (2015). This may be caused by variations in seasonal conditions, plant species, or inherent.

2.5.3.5 Ethnomedicinal Uses

To treat a wide range of pediatric illnesses, the entire plant is macerated in fresh water. In veterinary treatment, crushed leaves are used to get rid of pests on cattle wounds (TPD, 2014). Roundworms are expelled using the juice from the stems used as an enema (TPD, 2014). The juice kills maggots when applied to the skin (TPD, 2014). Angina is treated using an infusion of its fresh leaves. There is a dearth of knowledge regarding the therapeutic potential of the various varieties and species of Caladium that may be found in the wild in Nigeria on farmlands, on road sites, and in

schools. Leaves are applied externally for furunculosis and used as a vermifuge and purgative (Agoi, 2025).

They can also be used to treat toothaches, sore throats, constipation, catarrh, wounds, and sores. They are also used as an antiseptic, anti-tumor, emetic, and laxative (Tosoc et al., 2016). For facial paralysis, crushed bulbs are applied to the face. The Yoruba people of Nigeria utilize the plant's leaves and rhizome to heal boils, wounds, ulcers, purgatives, and convulsions. Although powdered leaves of C. bicolor are used as an insecticide and an antidote for snake bites, there have been no reports of folklore medical uses of the plant in the Philippines (Padal et al., 2013). Numerous C. bicolor components have been used in traditional medicine to treat a variety of diseases, including flu symptoms, tumors, sore throats, toothaches, facial paralysis, and convulsions in children (Agoi, 2025).

2.5.3.6 *Caladium bicolor* Starch

Starch is the reserved carbohydrate stored as glucose in plants to meet energy needs (Alobi et al., 2017). It is a natural polymer made up of hundreds of thousands of glucose units linked together by glycosidic bonds. The molecular formula of starch is $(C_6H_{10}O_5)n$. It is the most common carbohydrate in human diets and is contained in large amounts in such as yam, cassava, wheat, corn, rice, potatoes, mushroom etc. (Israelet al., 2016; Sunday et al., 2016). Most starches used for industrial applications such as adhesives, non-food fillers, textile stiffening agents, gelling agents, and bioplastics for packaging are extracted from edible plant sources. Generating starches from other sources for industrial purposes is the trending research as starch from non-edible sources such as Caladium bicolor have properties appropriate in replacement of starches from edible sources (Alobi et al., 2017).

2.5.3.7 Extraction of Starch from *Caladium bicolor*

Caladium bicolor starch is extacted by peeling, washing, dicing into small pieces, and blending using a commercial blender. The cocoyam slurry is then washed with distilled water and filtered using the muslin cloth. The filtrate is allowed to settle for 7 hours. The starch is collected by decantation. The process is repeated 3 to 4 times to produce purer starch. The wet starch obtained is air-dried for two days and afterwards, ground to powder form. The extraction process is illustrated in Fig. 1. The starch yield from the extraction process is calculated using Equation (1). This method follows the approach developed by Arawande and Osogbon (2019).

$$\text{Starch yield (\%)} = \frac{\text{Weight of extracted starch (g)}}{\text{Weight of cocoyam(g)}} \times 100$$

2.5.3.8 Physicochemical Properties of Caladium bicolor

Physicochemical properties are fundamental parameters that describe the physical and chemical composition of plant materials and determine their suitability for various biological, agricultural, and industrial applications. In the context of agronomically important substrates, these properties influence microbial growth, enzymatic activities, and nutrient cycling (Wu et al., 2023). Starch extracted from Caladium bicolor has attracted increasing research interest due to its unique properties and potential industrial applications. Understanding the physicochemical characteristics of Caladium bicolor starch is essential for evaluating its suitability as a substrate in microbial processes, food systems, and other agronomic applications (Uwem and Ita, 2019).

2.5.3.9 Proximate Composition of Caladium bicolor

The proximate composition of Caladium bicolor reflects its nutritional and biochemical profile, including moisture, ash, crude protein, lipid, fiber, and carbohydrate content. Studies have shown that the tuber of Caladium bicolor is predominantly rich in carbohydrates, with values reported as high as approximately 83.57%, indicating its potential as a significant carbon source for microbial metabolism (Uwem and Ita, 2019). Alobi et al. (2017) reported that Caladium bicolor had the highest starch content of 86.6% compared to Dioscorea villosa (wild sweet yam), Icacina trichantha (false yam) and Pleurotus ostreatus (oyster mushroom). This result suggest that C. bicolor and flour is a rich source of starch that could be utilized industrially. Moisture content of starch is the total quantity of vapour present in it. The higher the moisture content, the lower the amount of dry solids in the flour.

The maximum limit for moisture in starch flour is 14% (Oladayo et al., 2016) and 12% according to African Organization for Standardization of cassava starch. Higher values of moisture in starch causes caking of the starch, affects its texture and encourages the growth of microorganisms which cause odours and off flavour. Enwere et al. (2024) reported that the moisture content of wild cocoyam starch (WCS) was measured at 12.33 %, lower than that of edible cocoyam (15.05 %) (Arawande and Ashogbon, 2019), and palado seed starch (19.64 %) (Rahman et al., 2017). Uwem and Ita. (2019) also reported lower moisture content in C. bicolor (7.65±0.04) than D. dumentorum (10.29±0.04). However, this indicates that Caladium bicolor has lower moisture content than the recommended safe storage range of 14%. This lower moisture content is favorable for industrial applications, such as bioplastic production, where reduced moisture enhances the physical properties, and shelf-life of the final product.

Ash content is a critical parameter in assessing the purity of starch, as it reflects the amount of inorganic material present. Lower ash content typically indicates fewer mineral impurities, while higher ash content indicates numerous mineral impurities (Enwere et al., 2024). C. bicolor starch has high ash content which is higher than the recommended

industry standard (0.5% ash) (Uwem and Ita, 2019; Alobi et al.,2017). This variation may be due to environmental factors, genetic mutation, processing and storage conditions (Uwem and Ita, 2019). The crude protein and lipid contents are generally low, ranging from 0.11% to 0.12%. Low lipid and protein content of the isolated starch indicates high purity and quality. Also, high protein and lipid results in low clarity of starch paste and represses starch granule swelling (Uwem and It's, 2019), while crude fiber content ranges between 2.85% and 3.39% (Uwem and Ita., 2019). Despite the low protein content, the high carbohydrate fraction makes Caladium bicolor particularly suitable for applications requiring energy-rich substrates, such as fungal culture media and fermentation processes.

Amylose–Amylopectin Content

The chemical composition of Caladium bicolor starch significantly influences its physicochemical behavior. Studies have reported that the amylose content of Caladium bicolor starch typically ranges between 17% and 20%, while amylopectin constitutes the majority fraction (Uwem and Ita, 2019). The relatively moderate amylose content suggests that the starch exhibits intermediate gel strength and digestibility characteristics.

Amylose contributes to the formation of firm gels and retrogradation tendencies, whereas amylopectin is responsible for viscosity and swelling properties. The balance between these two components determines the starch's suitability for specific applications. For instance, starches with moderate amylose content, such as that from Caladium bicolor, are desirable in fermentation processes because they provide a steady release of glucose during enzymatic hydrolysis (Uwem and Ita, 2019). This makes the starch a potential carbon source for microbial growth and enzyme production.

Gelatinization Properties

Gelatinization refers to the irreversible process in which starch granules absorb water and swell upon heating, leading to the loss of crystalline structure. The gelatinization temperature of Caladium bicolor starch typically ranges between 63°C and 79°C (Uwem and Ita, 2019). This relatively moderate gelatinization temperature makes it suitable for applications that require controlled thermal processing.

The gelatinization process is influenced by factors such as amylose content, granule size, and the presence of lipids or proteins. Starches with lower gelatinization temperatures require less energy input, making them advantageous in industrial processes. Additionally, gelatinization enhances the accessibility of starch to enzymatic hydrolysis, which is critical in fermentation and bioconversion systems (Uwem and Ita, 2019).

2.5.3.10 Industrial Applications of Caladium bicolor Starch

As an underutilized starch source, Caladium bicolor possess unique physicochemical and functional properties (Akinoso & Abiodun, 2014), which could contribute to the development of sustainable industrial products, provided its properties meet required performance standards.

Enwere et al. (2024) demonstrated the potential of wild cocoyam starch in producing biodegradable bioplastic films with superior me chanical properties compared to conventional starch-based alternatives. By blending varying concentrations of gelatin, glycerine, vegetable oil, and vinegar, the resulting bioplastic films exhibited a tensile strength of 6.5 MPa and elongation at break of 77 %, surpassing many existing bioplastics in terms of flexibility and strength. The film thickness, exceeding 270 µ m, aligns with commercial packaging standards, making it suitable for industrial applications. Additionally, the bioplastic's rapid biodegradation rate of 70 % within 7 days and its low moisture content and water solubility underscore its environmental compatibility. These properties suggest a broad range of applications, including single-use packaging, agricultural films, detergent pods, and even medical and cosmetic products, where biodegradability and water solubility are critical. However, despite these advantages, certain limitations, particularly regarding the material's moisture resistance and thermal stability remain.

Uwem and Ita. (2019) investigated the physicochemical, functional and antinutritional properties of starches from Caladium bicolor and Dioscorea dumentorum. This study showed that starches extracted from Caladium bicolor and Dioscorea dumentorum had good swelling power, dispersibilty, oil and water absorp tion capacity as well as thermal and pasting properties. This suggests that these starches may find great use in paper making, adhesives, textile and other non-food applications.

Agu et al. (2023) reported that low-cost, locally available materials such as Caladium bicolor (ede mmuo), brewer's spent grain, and pigeon pea (fiofio) can be used to formulate alternative media for fungal growth. Caladium bicolor served as both a carbon source and a partial gelling agent due to its high carbohydrate content. Although agar-based media performed better, the non-agar formulations still supported appreciable fungal growth, indicating their potential as affordable alternatives. The study also highlighted the importance of substrate composition and acidity in enhancing growth and reducing contamination.

2.5.4 *Dioscorea bulbifera* (Ji Adu)

Dioscorea bulbifera, commonly referred to as the air potato, aerial yam, or cheeky, is a member of the Dioscoreaceae family native to Africa and Asia (Dahiya, 2017; Ojo et al., 2022). It is herbaceous, perennial climber which grows up to 10-20 m in length with numerous fibrous roots (Lim, 2016).

Leaves are alternate, broadly cordate, and greenish, greenish-grey, or greenish-yellow in color with rounded basal lobes originating from one point (Sonibare and Adeniran, 2014; Lim, 2016). A distinctive feature of this species is its ability to produce both underground tubers and aerial tubers, known as bulbils, which grow from the stem in single or conjugate forms. Aerial tubers (bulbils) are typically brownish, round or irregular in shape with smooth, dotted or rough surfaces and freely form in leaf axils (Ogunjobi and Balogun, 2021). Stems arise annually from a tuberous, woody rootstock. These stems either climb up surrounding vegetation or creep along the ground. The presence of bisexual and unisexual flowers distinguishes subfamilies of Dioscoreaceae. Seeds (1.2-1.6 by 0.5 cm) are trilocular, dark brown and partially winged (Lim, 2016). Dioscorea bulbifera is known by local name such as "ji adu" in eastern Nigeria and "edomo" in southern Nigeria.

2.5.4.1 Ethnobotanical uses of D. bulbifera

The genus Dioscorea has a long and significant ethnomedicinal values and several studies has been found on different medicinal uses throughout the Tropics (Dutta, 2015). Among the several Dioscorea species, D. bulbifera has been extensively used in the traditional medicine for the treatment of a variety of ailments. Given its several ethnomedicinal uses, D. bulbifera has received more attention in past few decades. It is well known for its salty and bitter taste. According to Kumar et al. (2017), D. bulbifera is traditionally used to treat cough, epistaxis, goiter, hemoptysis, pharyngitis, skin infections, piles, throat infections and to remove dandruff. In addition, it is also used in the treatment of several conditions such as detoxify poison, clot blood to stop bleeding and to clear pathogenic heat and cancer in Chinese traditional medicine (Kundu et al., 2020).

Tubers of D. bulbifera are roasted and cooked as vegetable and serves to cure cough, dysentery, piles, ulcers, diabetics, leprosy and syphilis (Dutta, 2015). Nabatanzi (2016) stated that in Uganada, tubers of D. bulbifera are boiled and consumed by local people to treat HIV patients. In the Indian traditional medicine system, D. bulbifera is used against diarrhoea, struma, dysentery, throat infection and tuberculosis (Panduraju et al., 2010; Lim, 2016). It is also used as an antihelminthic by tribal people of Satpuda Hills in India (Kundu et al., 2020). In Dehradun, Uttarakhand, D. bulbifera tuber is taken orally to treat diarrhea and dysentery by Bhoxa community (Gairola et al., 2013). The roasted and crushed tubers of D. bulbifera are taken orally with salt to treat cough (Kundu et al., 2020). Its twigs and tender shoots are crushed and applied on hair to remove dandruff (Dutta, 2015). The leaves of D. bulbifera are also used in traditional system for the treatment of skin diseases (Kundu et al., 2020).

2.5.4.2 Starch and Carbohydrate Content of Dioscorea bulbifera

The tubers and bulbils of D. bulbifera are recognized as significant sources of dietary energy due to their high carbohydrate and starch content (Induar et al., 2023). The starch is composed of amylose and amylopectin, serving as an essential dietary supplement (Ojo et al., 2022). While the underground tubers are particularly rich in starch and are frequently consumed by tribal communities, the aerial bulbils also provide substantial carbohydrates (Induar et al., 2023). Research indicates that D. bulbifera starch exhibits high functionality, making it a viable alternative to traditional starch sources in both food and non-food industries (Ojo et al., 2022).

2.5.4.3 Nutritional and Phytochemical Importance of Dioscorea bulbifera

The bulbils of Dioscorea bulbifera are produced above the ground and popularly known as air potato as it looks like common potato grown under the soil. The important phytochemicals are phenols, tannins, alkaloids, flavonoids, saponins, etc (Jahan et al., 2019). The composition of bulbils is presented in Table 1. Evidently, the bulbils are rich in protein, carbohydrates, essential trace elements in addition to important phytochemicals (Celestine and David, 2015; Bolaniran et al., 2019). The quantity of phytochemicals present in the bulbils varies according to the place of harvest i.e. geographical locations, time of harvest, extraction conditions etc (Ikiriza et al., 2019). Along with beneficial phytochemicals, the bulbils are also reported to contain undesired plant secondary metabolites such as phytate, oxalate, hydrogen cyanide etc (Celestine and David, 2015).

The dry matter of the tuber of Dioscorea bulbifera ranges from 8 to 23% (Megh et al., 2003; Abera, 2011; Shajeela et al., 2011). The compositional analysis (on dry matter basis) of tubers originated from different species of Dioscorea spp. revealed the presence of crude protein (6.2 to 13.4%), crude fibre (0.4 to 7.6%), crude lipid (0.09 to 7.4%), total ash (3.3 to 6.3%), nitrogen free extract (71 to 79%), total carbohydrates (12 to 33%) (Shajeela et al., 2011; Mulualem et al., 2018). Further, the tubers are rich in vitamins (niacin and ascorbic acid), minerals (Calcium, Phosphorous, Magnesium, Zinc, Manganese, Iron, and Copper) and bioactive compounds such as phenols and tannin, saponin and steroids, alkaloids and flavonoids, and terpenoids (Jahan et al., 2019).

2.5.4.4 Role of Dioscorea bulbifera as a Gelling Agent and Carbon Source for Fungal Cultivation

The rheological properties of D. bulbifera starch make it a unique candidate for gelling applications. Starch gels derived from this species exhibit high complex viscosity and the least shear-thinning properties compared to other common yams like D. rotundata and D. alata (Otegbayo et al., 2024). These gels are characterized by higher elasticity

and stiffness, suggesting that they are particularly useful for industrial products requiring high viscosity and structural stability (Otegbayo et al., 2024).

D. bulbifera serves as an efficient carbon source for microbial growth due to its high concentration of primary metabolites, including sugars and starch (Lu et al., 2024). In mycological research, Dioscorea species have been explored as cost-effective substitutes for traditional media like Potato Dextrose Agar. Studies on related species such as D. alata and D. esculenta demonstrate that yam-based media can effectively support the isolation and mycelial growth of various mushrooms and fungi (Sawiphak et al., 2021; Tudses, 2016). Furthermore, D. bulbifera naturally hosts a diverse community of fungal endophytes, highlighting its inherent suitability as a substrate for fungal colonization and cultivation (Sharma et al., 2022). Its role as a cheap source of cellulose and starch makes it a promising renewable resource for bio-based chemical production and laboratory culture media (Ogunjobi and Balogun, 2021).

Conclusion

The escalating global generation of agricultural and industrial food processing wastes presents a critical environmental challenge, requiring a decisive shift toward circular bioeconomy strategies. As demonstrated by the extensive body of literature evaluated in the strategic valorization of underutilized agro-residues offers a dual solution to environmental pollution and the prohibitive costs associated with conventional biotechnological research. By repurposing abundant organic by-products, researchers can significantly mitigate the negative impacts of traditional waste disposal methods, such as open burning and land dumping, while simultaneously reclaiming valuable biomolecules.

Biochemically, these alternative substrates possess excellent nutritional profiles capable of sustaining complex microbial workflows. Industrial processing by-products like slaughterhouse blood meal provide a highly concentrated, slow-release organic nitrogen source rich in essential amino acids and micronutrients, serving as an economically viable proxy for expensive laboratory-grade peptone and yeast extract. Concurrently, non-edible, starch-dense botanical resources such as *Caladium bicolor* and *Dioscorea bulbifera* supply the robust carbohydrate matrices and rheological stability required to function effectively as both carbon inputs and structural gelling agents.

Ultimately, transitioning from imported synthetic formulations to locally sourced, agro-residue-based mycological media yields documented cost reductions ranging from 68% to 86% without compromising fungal growth kinetics, colony morphology, or sporulation quality. Embracing these sustainable media formulations not only advances waste minimization and resource optimization but also democratizes scientific research and practical microbiology training in resource-limited settings and developing nations.

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