Valorization of Agricultural Waste into Nutrient-Rich Functional Powders: Proximate, Phytochemical and Microbial Assessment

Sahul Hameed Rajamohamed [*], BharathRaj Mohan, Mathumitha Agaramuthan, Naveena Santha Kumar, Buvaneswari Eshwaramoorthi, Pavithra Ramakrishnan

Department of Home Science, the Gandhigram Rural Institute (Deemed to be University) Gandhigram, Dindigul District, Tamil Nadu, India

HIGHLIGHTS

- Developed powders showed low moisture contents, indicating effective dehydration.
- Selected leafy vegetable powders exhibited higher ash contents than pumpkin seed powders.
- Most developed powders showed crude fiber contents above 10%, except selected vegetable residues.
- Refrigerated powders showed acceptable microbial loads during the 30-day storage period.

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Abbreviations
AOAC= Association of Official Analytical Chemists
APHA= American Public Health Association
FSSAI= Food Safety and Standards Authority of India
TPC= Total Plate Count
CFU/g= Colony-forming units per gram

ABSTRACT

Background: Agricultural waste generated from fruits and vegetables is often underutilized despite its potential as a source of valuable nutrients and bioactive compounds. This study aimed to evaluate the proximate composition, phytochemical profile, and microbiological quality of powders developed from selected agricultural waste materials to explore their potential as sustainable functional food ingredients.

Methods: Agricultural residues, including cauliflower leaves, cauliflower stem, cabbage leaves, cassava peel, beetroot peel, white pumpkin seed, yellow pumpkin seed, banana peel, and orange peel were collected and processed into dried powders using standardized techniques. The prepared powders were analyzed for proximate composition, phytochemical characteristics, and microbial quality using standard analytical techniques.

Results: Significant nutritional variations were observed among the developed powders. Cabbage leaf powder exhibited the highest carbohydrate content (61.58 g/100 g), while yellow pumpkin seed powder showed the highest protein (30.37 g/100 g) and fat contents (45.00 g/100 g). Cassava peel powder recorded the highest crude fiber content (15.41 g/100 g), whereas cauliflower leaf powder contained the highest ash content (15.50 g/100 g), indicating greater mineral availability. Phytochemical analysis confirmed the presence of bioactive compounds such as flavonoids, tannins, saponins, steroids, and alkaloids, highlighting their potential functional and therapeutic significance. Microbiological evaluation showed low total plate count (TPC) values ranging from 1.0×10^3 to 2.8×10^3 colony-forming units per gram (CFU/g), indicating acceptable microbial safety and storage stability.

Conclusion: The findings demonstrate that agricultural waste materials can be effectively converted into nutrient-rich functional powders with promising nutritional, phytochemical and microbiological properties. Their utilization may support food waste valorization, development of sustainable functional food ingredients, environmental protection, and circular economy approaches.

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[*] Corresponding author (R. Sahul Hameed)
E-mail: syedfsn@gmail.com
ORCID ID: https://orcid.org/0000-0002-4126-9706

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Introduction

Agriculture remains a key driver of economic growth and food security in many developing countries. India is one of the largest agricultural producers in the world, with the sector supporting nearly 50–55% of the population and contributing about 18–20% to the national Gross Domestic Product (Government of India, 2024). The global demand for food products has risen significantly due to population growth, the expansion of food industry, and advances in agricultural practices and production levels. This growth has also generated large quantities of agricultural residues and by-products as waste. Globally, billions of tonnes of agricultural waste are generated each year during cultivation, harvesting, processing, and post-harvest operations (Ufitikirezi *et al.,* 2024). India generates substantial quantities of crop residues annually, creating opportunities for sustainable waste valorization and bioresource utilization (Yadav *et al.,* 2024). Based on the origin, these wastes are classified into primary and secondary residues. The wastes generated during field operations, such as cultivation and harvesting, are referred to as primary residues, which include leaves, stalks, stems, and husks. Secondary residues are produced during post-harvest processes such as cleaning, grading, storage, transportation, and industrial processing, and include peels, seeds, pomace, bran, and shells (Yadav *et al.,* 2024; Ufitikirezi *et al.,* 2024). Both primary and secondary residues, despite their potential value, are often discarded or disposed. The most common disposal methods are open-field burning, landfilling, and indiscriminate dumping due to their low cost and convenience (Sadh *et al.,* 2018).

The accumulation of agricultural waste has serious environmental consequences that extend beyond immediate pollution concerns. One of the most critical issues is the disruption of ecological balance caused by improper waste disposal practices. It has a profound impact on air pollution and climate change, mainly as a result of open-field burning of agricultural waste where harmful gases such as carbon dioxide, methane, nitrous oxide, sulfur dioxide, and particulate matter are released, causing respiratory illnesses (Sadh *et al.,* 2018). In addition to atmospheric pollution, the accumulation of agricultural waste also affects soil quality. Continuous deposition or burning of residues leads to alterations in soil pH, reduction in organic carbon content, and depletion of essential nutrients. This ultimately results in reduced agricultural productivity and increased dependency on chemical fertilizers (Mohanta *et al.,* 2025; Sadh *et al.,* 2018). Landfilling and improper disposal of waste can also lead to soil and groundwater contamination (Mohanta *et al.,* 2025). Furthermore, water bodies are increasingly threatened by agricultural runoff and leachate from waste. These contaminants can introduce excess nutrients such as nitrogen and phosphorus into aquatic ecosystems, leading to eutrophication. This process causes excessive algal growth, oxygen depletion, and eventual loss of aquatic biodiversity (Thiagarajan and Devarajan, 2025). Modern technological advancements have introduced innovative approaches for efficient agricultural waste management. Sustainable management and valorization of agricultural residues have gained considerable attention due to their potentials to support environmental sustainability and resource recovery (Bhardwaj *et al.,* 2025; Nosova *et al.,* 2025). Among these, agricultural waste valorization has emerged as a sustainable strategy for converting agricultural residues into value-added products, thereby minimizing environmental pollution and promoting resource utilization (Yadav *et al.,* 2024).

The valorization of agricultural waste involves converting low-value waste into high-value products using physical, chemical, biological, or biotechnological methods (Yadav *et al.,* 2024). This approach is closely linked to the circular economy, which promotes the reuse, recycling, and regeneration of resources rather than the traditional linear 'take–make–dispose' model. Several researchers have emphasized that agricultural waste valorization plays a crucial role in the development of a circular bioeconomy and sustainable food systems (Campos *et al.,* 2020; Leong and Chang, 2022; Subbiah *et al.,* 2025). Agricultural wastes are widely studied for their potential to be used in the production of biodegradable materials and bioplastics, offering eco-friendly alternatives to conventional plastics, and for bioenergy production, including biogas, bioethanol, and biohydrogen, contributing to renewable energy development and reduced dependence on fossil fuels (Yadav *et al.,* 2024). The researchers found that agricultural wastes are particularly suitable for valorization and the development of functional food ingredients due to their rich biochemical composition. Fruit and vegetable processing residues are considered promising sources of bioactive compounds, antioxidants, and nutraceutical ingredients for functional food applications (Carvalho *et al.,* 2020; Khaled *et al.,* 2025). The major constituents of waste were found to be carbohydrates, proteins, fats, and dietary fiber (essential macronutrients) as well as vitamins and minerals (micronutrients) (Correia et al., 2012; Khoozani et al., 2019; Mia et al., 2025). Various studies have demonstrated that agricultural residues such as fruit peels, vegetable leaves, and seeds can be processed into powders and extracts to enhance the nutritional quality, dietary fiber content, and antioxidant capacity of food products (Correia et al., 2012; Khoozani et al., 2019; Mia et al., 2025). The recovery of dietary fiber and phytochemicals from food processing by-products has also been widely explored for improving nutritional quality and

health-promoting properties of food products (Gullón *et al.*, 2018). In addition to nutrients, agricultural residues are rich in phytochemicals, including phenolics, flavonoids, tannins, alkaloids, terpenoids, saponins, and carotenoids. These compounds exhibit various biological activities such as antioxidant, antimicrobial, anti-inflammatory, and anticancer properties (Patel, 2013; Yadav *et al.*, 2024).

The growing demand for functional foods has led to increased interest in agricultural waste as a source of nutritionally rich ingredients. Recent studies have highlighted that sustainable utilization of food waste can significantly contribute towards functional ingredient development and food industry sustainability (Subbiah *et al.*, 2025). Fruit and vegetable by-products are rich in dietary fiber, antioxidants, and essential nutrients. Incorporation of these materials into food products not only escalates the nutritional value but also aids in various health promoting effects such as reduced cholesterol, improved gut and immune function (Khoozani et al., 2019; Campos et al., 2020; Yadav et al., 2024). Although extensive research has been conducted on agricultural waste valorization, there remains a lack of comprehensive studies that combine the evaluation of nutritional, phytochemical, and microbial characteristics of agricultural residues. Hence, the present study aimed to address these gaps by evaluating agricultural waste from multiple perspectives. This research will contribute to sustainable waste management, development of functional food ingredients, reduction of environmental pollution, and promotion of circular economy.

Materials and methods

Collection and storage of raw materials

Agricultural residues, including peels, leaves, stems, and seeds, were collected from the fruit shops and a weekly market in Dindigul District, Tamil Nadu, India, during winter season (January to February 2026). The raw materials collected were cassava (*Manihot esculenta*) peel, banana (*Musa paradisiaca*) peel, beetroot (*Beta vulgaris*) peel, orange (*Citrus sinensis*) peel, cauliflower (*Brassica oleracea* var. *botrytis*) leaves and stems, cabbage (*Brassica oleracea* var. *capitata*) leaves, white pumpkin (*Cucurbita maxima*) seeds, and yellow pumpkin (*Cucurbita moschata*) seeds.

The residues were collected fresh and immediately transported to the laboratory in clean, food-grade containers. The samples were sorted to remove any foreign matter, and damaged portions were discarded. The fresh peels, leaves, and stems were sterilized and then placed in clean containers and stored under refrigerated conditions at 4 ± 1 °C to minimize deterioration until further processing. The pumpkin seeds were cleaned thoroughly and stored separately in clean, airtight containers at room temperature (25 ± 2 °C) under dry conditions until required for analysis.

Preparation of agricultural waste powders

The collected waste materials were treated with 1% (w/v) citric acid solution to enhance safety and reduce surface microbial contamination. They were then blanched at 90 °C for 3 min to inactivate enzymes and reduce microbial load. After blanching, the waste materials were dried in a cabinet drier (Biotronics Instrument, Madurai) at 70 °C for 6 h to ensure adequate moisture removal. The dried materials were ground into fine powders and sieved through a 100 µm sieve to obtain a uniform particle size. The prepared powders were packed in airtight containers and stored under refrigerated conditions at 4 ± 1 °C until further analysis.

Powder yield and recovery percentage

The powder recovery percentage was calculated using the following formula:

Powder recovery (%) = (Powder weight / Raw material weight) × 100

Proximate analysis

The proximate composition, namely moisture, carbohydrate, crude protein, crude fat, mineral and crude fiber contents of the prepared agricultural waste powders were determined using standard analytical procedures. Moisture content was determined by oven drying method according to Association of Official Analytical Chemists (AOAC) Method 925.10 (AOAC International, 2019). Carbohydrate content was calculated by the difference method as described by Ranganna (2010). Crude protein content was estimated by Kjeldahl method according to AOAC Method 979.09 (AOAC International, 2019) using a nitrogen conversion factor of 6.25. Crude fat content was determined by the Soxhlet extraction method according to AOAC Method 920.39 (AOAC International, 2019). Mineral content was estimated by dry ashing in a muffle furnace at 550°C, according to AOAC Method 923.03 (AOAC International, 2019). Crude fiber content was determined by acid–alkaline digestion method according to AOAC Method 962.09 (Sadasivam and Manickam, 2008).

Phytochemical screening

Qualitative phytochemical screening of the prepared agricultural residue powders was carried out following standard procedures described by Harborne (1998). An aqueous extraction procedure was employed, since the study was intended to assess the presence of selected water-extractable phytochemical groups. For each sample, 1 g of each powdered sample was weighed into a clean beaker, and 10 mL of distilled water was added. The mixture was extracted in a shaking water bath at 40 °C for

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2 h. The resulting suspension was filtered through Whatman No. 1 filter paper, and the filtrate was used for the qualitative phytochemical tests. The same extraction procedure was followed for all samples to ensure uniformity and consistency.

The confirmatory qualitative phytochemical screening of plant extracts was performed to identify the main classes of compounds (tannins, saponins, flavonoids, alkaloids, and phenols) present in the extracts following standard protocols. Flavonoids were detected by using lead acetate test, in which 1 mL of the extract was treated with 1 mL of 10% w/v lead acetate solution; the formation of a yellow precipitate was considered indicative of flavonoids. Saponins were detected using foam test, in which 1 mL of extract was mixed with 5 drops of distilled water, followed by vigorous shaking (persistent foam formation was considered a positive reaction). Steroids were detected using the concentrated sulphuric acid test in which 1 mL of the extract was admixed with 1 mL of concentrated sulphuric acid and allowed to stand, with the development of the characteristic color change indicating the presence of steroids. Alkaloids were detected using Mayer's test, in which 1 mL of the extract was mixed with 1 mL of the Mayer's reagent, and the formation of a cream-coloured precipitate was considered positive for alkaloids. Tannins were detected using the ferric chloride test, treating 3 mL of the extract with three drops of 5% w/v ferric chloride ($FeCl_3$) solution; the development of a deep blue color was considered indicative of tannins. The observations were recorded as positive (+) or negative (−) based on the characteristic reactions obtained.

Microbiological analysis

The total plate count (TPC) of the prepared agricultural residue powders was determined to assess their microbiological quality following the standard procedures described by American Public Health Association (APHA) (2015) and Food Safety and Standards Authority of India (FSSAI) (2019). Ten grams of each powder sample on days 0, 15, and 30 was aseptically transferred into 90 mL of sterile diluent and homogenized to obtain the initial 10^{-1} dilution. Serial ten-fold dilutions up to 10^{-6} were subsequently prepared using sterile diluents. Dilutions of 10^{-4} and 10^{-5} were inoculated onto sterile petri plates and plated using the pour plate technique with sterile molten nutrient agar. The plates were allowed to solidify and aerobically incubated at 37 ± 2 °C for 48 h under anaerobic conditions. Plates containing countable colonies were selected, and the results were expressed as colony-forming units per gram (CFU/g) of sample.

Statistical analysis

All experiments were carried out in triplicate and the results were expressed as Mean ± Standard Deviation. Statistical analysis was performed using IBM SPSS Statistics version 25.0. One-way Analysis of Variance followed by Tukey's post hoc test was used to determine the level of significance among the samples at $p<0.05$.

Results and discussion

The powder yield and recovery percentage of the agricultural waste materials are presented in Table 1. Yellow pumpkin seed powder showed the highest powder recovery percentage (91.00%), followed by white pumpkin seed powder (90.00%). Cabbage leaf powder recorded the lowest recovery percentage (8.50%). The higher recovery percentage observed in seed powders may be attributed to their lower moisture loss during drying and having higher dry matter content.

Table 1: Powder yield and recovery percentage from agricultural waste materials

Kind of powder	Raw weight (g)	Dried weight (g)	Powder Weight (g)	Powder recovery (%)
Cauliflower leaves	1000.25	115.13	105.03	10.50
Cauliflower stem	999.85	145.48	132.98	13.20
Cabbage leaves	1000.20	95.02	85.02	8.50
Cassava peel	999.75	239.94	224.94	22.50
Beetroot peel	1000.10	135.21	122.01	12.20
White pumpkin seed	999.90	919.91	899.91	90.00
Yellow pumpkin seed	1000.15	930.14	910.14	91.00
Banana peel	999.80	184.96	169.97	17.00
Orange peel	1000.05	220.12	205.01	20.50

The powder yield and recovery percentage from agricultural waste materials in Table 2 and the proximate composition of powder prepared from different agricultural waste are represented in Figure 1. Significant differences ($p<0.05$) were observed among the developed powders with respect to moisture, carbohydrate, crude protein, crude fat, mineral and crude fiber contents. The moisture content of all developed powders ranged between 9.00 ± 0.09 and 10.50 ± 0.15%, indicating adequate dehydration and improved storage stability. Lower moisture content in dehydrated products is considered important for minimizing microbial growth and enhancing shelf life. Among powders, cauliflower stem powder recorded the highest moisture content (10.50 ± 0.15%), while white

pumpkin seed powder and banana peel powder exhibited the lowest moisture content (9.00 ± 0.09%) and (9.00 ± 0.10%), respectively. Similar moisture levels below 12% were reported in dehydrated vegetable residue powders by Mia *et al.* (2025), who stated that reduced moisture content improves microbial stability and storage quality of dehydrated food products. In particular, the moisture content of banana peel powder was consistent with values (9.97 ± 0.85%) reported by Deb *et al.* (2022), and that of cauliflower stem powder was comparable with 8.9% reported by Sharma and Prasad (2018) for dehydrated cauliflower stem powder. The close agreement with these earlier findings suggests that the moisture levels obtained in the present study are within the range previously reported for dehydrated plant-derived by-products. The relatively small differences among studies may be attributed to variations in the initial moisture content and physical characteristics of raw materials, together with differences in drying conditions, sample preparation and particle size, all of which can affect moisture removal during dehydration. Thus, the observed variation among the present samples and previously reported values is likely to reflect differences in processing and raw-material characteristics rather than a fundamental inconsistency in the effectiveness of dehydration.

Table 2: Proximate analysis of powders prepared from agricultural waste

Kind of powder	Proximate content (g/100 g)					
	Moisture (%)	Carbohydrate	Crude protein	Crude fat	Minerals	Crude fiber
Cauliflower leaves	10.00 ± 0.12^{b}	45.59 ± 0.34^{e}	11.43 ± 0.21^{e}	7.48 ± 0.16^{e}	15.50 ± 0.28^{a}	10.00 ± 0.19^{e}
Cauliflower stem	10.50 ± 0.15^{a}	57.92 ± 0.42^{b}	17.27 ± 0.25^{c}	1.31 ± 0.08^{f}	8.00 ± 0.14^{c}	5.00 ± 0.11^{f}
Cabbage leaves	9.50 ± 0.11^{c}	61.58 ± 0.39^{a}	13.47 ± 0.20^{d}	1.66 ± 0.07^{f}	9.00 ± 0.16^{b}	4.79 ± 0.10^{f}
Cassava peel	9.30 ± 0.10^{c}	38.96 ± 0.31^{f}	30.10 ± 0.33^{a}	1.23 ± 0.05^{f}	5.00 ± 0.12^{f}	15.41 ± 0.24^{a}
Beetroot peel	10.00 ± 0.13^{b}	54.30 ± 0.00^{d}	13.57 ± 0.22^{d}	0.80 ± 0.04^{g}	7.00 ± 0.13^{d}	13.97 ± 0.20^{b}
White pumpkin seed	9.00 ± 0.09^{d}	5.00 ± 0.10^{g}	28.00 ± 0.30^{b}	42.00 ± 0.45^{b}	4.00 ± 0.08^{g}	12.00 ± 0.18^{c}
Yellow pumpkin seed	9.70 ± 0.11^{b}	0.93 ± 0.05^{h}	30.37 ± 0.35^{a}	45.00 ± 0.48^{a}	4.00 ± 0.09^{g}	10.00 ± 0.16^{e}
Banana peel	9.00 ± 0.10^{d}	54.94 ± 0.37^{d}	6.20 ± 0.14^{f}	12.37 ± 0.19^{c}	6.00 ± 0.12^{e}	11.49 ± 0.17^{d}
Orange peel	9.50 ± 0.12^{c}	56.38 ± 0.40^{c}	6.13 ± 0.13^{f}	10.98 ± 0.17^{d}	6.00 ± 0.11^{e}	11.01 ± 0.15^{d}

Note: Values are expressed as Mean ± Standard Deviation of triplicate determinations. Means with different superscripts within a column differ significantly ($p<0.05$).

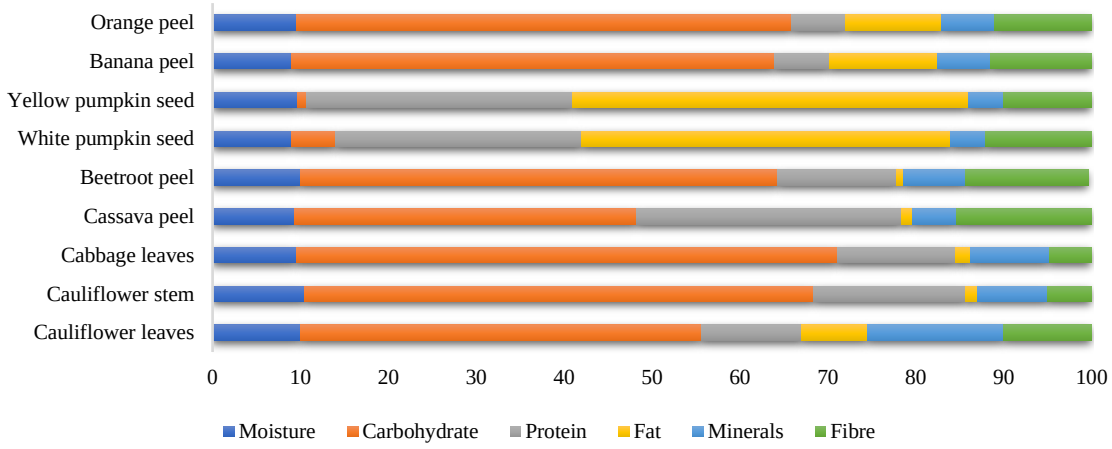


Figure 1: Proximate composition of powder prepared from different agricultural waste

The carbohydrate content varied considerably among powders, ranging from 0.93 ± 0.05 to 61.58 ± 0.39 g/100 g. Cabbage leaf powder showed the highest carbohydrate content (61.58 ± 0.39 g/100 g), followed by cauliflower stem powder (57.92 ± 0.42 g/100 g), orange peel powder (56.38 ± 0.40 g/100 g) and banana peel powder (54.94 ± 0.37 g/100 g). The higher carbohydrate content observed in leafy and peel powders may be attributed to the presence of structural polysaccharides and soluble sugars. Yellow pumpkin seed powder exhibited the lowest carbohydrate content (0.93 ± 0.05 g/100 g), which may be due to its higher fat and protein composition. Comparable observations were reported by Yadav et al. (2024), who observed lower carbohydrate levels in pumpkin seed-derived powders due to the predominance of lipids and proteins. The higher carbohydrate content observed in cabbage leaf powder was unexpected, as cassava peel is generally considered a carbohydrate-rich agricultural residue (Otache *et al.*, 2017). Baloch *et al.* (2015) also found high carbohydrate content in cabinet- and sun- dried cabbage leaves of 42.44% and 38.37%, respectively, compared with fresh cabbage leaves (4.42%) due to

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removal of moisture and concentration of dry matter content of leaves. Oladimeji *et al.* (2022) reported that reduction of the particle size of cassava peel resulted in lower moisture content of cassava peel products. It also lowered crude protein and crude fiber of the cassava peel products which was below the previously reported range of 4.90-5.60% (crude protein) and 10.46-16.26% (crude fiber) for oven dried cassava peel of sweet and bitter cassava varieties. The differences in processing methods can also affect the composition of cassava peel. Processes such as washing, blanching, drying temperature, duration, and grinding may have an influence on the accuracy of carbohydrate estimation by affecting moisture content and the distribution of soluble and insoluble components. Therefore, the lower carbohydrate content observed in the cassava peel powder in the present study may be attributed to variations in raw material composition and processing conditions (Diarra, 2018).

The crude protein content of developed powders ranged from 6.13 ± 0.13 to 30.37 ± 0.35 g/100 g. Yellow pumpkin seed powder (30.37 ± 0.35 g/100 g) and cassava peel powder (30.10 ± 0.33 g/100 g) recorded significantly higher protein content than the remaining samples, followed by white pumpkin seed powder (28.00 ± 0.30 g/100 g). Banana peel powder and orange peel powder showed comparatively lower protein contents (6.20 ± 0.14 and 6.13 ± 0.13 g/100 g, respectively). The elevated protein content in seed powders may be associated with the presence of storage proteins in seeds. Fruit and agricultural wastes constitute the major global environmental concerns and also contain abundant protein. The wastes are used in value-added products, like animal feed, pharmaceuticals, and other useful compounds (Zhou *et al.,* 2023). The present findings indicate that selected agricultural residues could serve as alternative protein-rich ingredients for food formulations. Similar protein values ranging from 25 to 32 g/100 g in pumpkin seed flour were reported by Polyzos et al., (2024), supporting the nutritional potential of seed-based agro-residues. The high protein content of yellow and white pumpkin seed powders suggests their potential for protein fortification of bakery products such as bread, biscuits, and cakes to improve their nutritional value (Arshad *et al.,* 2025; Galenko *et al.,* 2024). Pumpkin seed proteins also possess good functional properties and biological value, supporting their use in various food applications, such as meat analogues, protein supplements, and functional food additives (Xie *et al.,* 2025).

Considerable variation was observed in crude fat content among the powders. Yellow pumpkin seed powder exhibited the highest fat content (45.00 ± 0.48 g/100 g), followed by white pumpkin seed powder (42.00 ± 0.45 g/100 g), whereas beetroot peel powder showed the lowest fat content (0.80 ± 0.04 g/100 g). The high fat content observed in pumpkin seed powders may be attributed to the natural oil-rich nature of seeds, while vegetable peels and leafy residues generally possess lower lipid levels. Similar fat contents ranging from 40 to 50 g/100 g in pumpkin seed flour were previously reported by Patel (2013). The high crude fat content observed in yellow and white pumpkin seed powders was similar to that reported for pumpkin seed flour, reflecting the naturally oil-rich composition of pumpkin seeds (Oupathumpanont *et al.,* 2025).

The mineral content of developed powders ranged from 4.00 ± 0.08 to 15.50 ± 0.28 g/100 g. Cauliflower leaf powder exhibited the highest mineral content (15.50 ± 0.28 g/100 g), followed by cabbage leaf powder (9.00 ± 0.16 g/100 g) and cauliflower stem powder (8.00 ± 0.14 g/100 g). White and yellow pumpkin seed powders showed comparatively lower mineral contents (4.00 ± 0.08 and 4.00 ± 0.09 g/100 g, respectively). The higher mineral content in leafy vegetable residues may contribute significantly towards micronutrient enrichment when incorporated into food products. Comparable ash and mineral contents in leafy vegetable waste powders were also reported by Yadav *et al.* (2024), indicating their potential for mineral supplementation in functional foods. The higher mineral content observed in cauliflower leaf powder was similar to that reported for leafy vegetable materials, which are recognized as important sources of minerals and other nutrients (Jeon *et al.,* 2024). The relatively higher mineral content observed in the leafy residues compared with the pumpkin seed powders may be associated with differences in inherent mineral accumulation and compositional characteristics of respective plant tissues. The overall agreement with previous reports supports the observation that leafy vegetable residues can retain appreciable quantities of inorganic nutrients after processing. However, variation in mineral content among studies may arise from differences in plant variety, maturity stage, growing conditions, soil mineral availability, plant tissue examined, and processing or dehydration conditions. Such factors can affect the concentration and retention of mineral constituents in dehydrated plant materials and may explain differences in magnitude of mineral content reported across studies.

Crude fiber content ranged from 4.79 ± 0.10 to 15.41 ± 0.24 g/100 g. Cassava peel powder recorded the highest crude fiber content (15.41 ± 0.24 g/100 g), followed by beetroot peel powder (13.97 ± 0.20 g/100 g), white pumpkin seed powder (12.00 ± 0.18 g/100 g), banana peel powder (11.49 ± 0.17 g/100 g), and orange peel powder (11.01 ± 0.15 g/100 g). The higher fiber content observed in peel-based powders may be attributed to the abundance of cellulose, hemicellulose, and lignin in outer plant tissues. Dietary fiber plays an important role in improving gastrointestinal health, reducing cholesterol levels and

regulating blood glucose levels. Therefore, these powders could be effectively utilized in the development of functional and fiber-enriched food products. Similar fiber values in banana peel and cassava peel powders were reported by Yadav *et al.* (2024), who highlighted their applicability in fiber-enriched food formulations. The fiber content observed in banana peel powder was similar to that reported for banana peel, which is recognized as a rich source of dietary fiber (Khoozani *et al.*, 2019). The agreement of the present banana peel result with previous literature supports the suitability of banana peel as a fiber-rich plant by-product and is consistent with the reported abundance of structural fiber components in banana peel. However, differences in fiber values reported among studies may occur because of variations in cultivar, maturity stage, proportion of peel tissue, growing conditions, drying and processing conditions, and the analytical method used for fiber determination. Thus, the variation observed between the present study and previous reports may reflect differences in raw-material characteristics and analytical or processing conditions rather than a fundamental inconsistency in the fiber-rich nature of these plant by-products.

The phytochemical screening results are presented in Table 3, showing the existence of a number of important bioactive compounds in the developed powders. Tannins and flavonoids were widely distributed across most samples, indicating potential antioxidant activity. Saponins were present in cauliflower stem, cabbage leaves, cassava peel, beetroot peel, yellow pumpkin seed, and banana peel powders. Steroids were detected in cauliflower leaves, cabbage leaves, cassava peel, beetroot peel, white pumpkin seed, and yellow pumpkin seed powders. Alkaloids were identified in cauliflower stem, cassava peel, white pumpkin seed, and orange peel powders. The presence of these phytochemicals suggests that the developed powders possess potential health-promoting properties, including antioxidant, antimicrobial, and anti-inflammatory activities. Comparable phytochemical profiles containing flavonoids, tannins, and saponins in fruit and vegetable by-products were also reported by Patel (2013), indicating their functional and therapeutic potential. Similar findings on the presence of valuable bioactive compounds in agricultural and food-processing residues were reported by Carvalho *et al.* (2020) and Gullón *et al.* (2018), who highlighted their potential applications in functional food development.

Table 3: Qualitative phytochemical screening of powders prepared from agricultural waste

Kind of powder	Phytochemicals				
	Saponins	**Flavonoids**	**Steroids**	**Alkaloids**	**Tannins**
Cauliflower leaves	-	+	+	-	+
Cauliflower stem	+	+	-	+	-
Cabbage leaves	+	+	+	-	+
Cassava peel	+	-	+	+	+
Beetroot peel	+	-	+	-	+
White pumpkin seed	-	-	+	+	-
Yellow pumpkin seed	+	+	+	-	+
Banana peel	+	-	-	-	+
Orange peel	-	+	-	+	+

Note: + and – indicate the presence and absence of the phytochemicals, respectively.

The microbial load of the prepared agricultural waste powders is presented in Table 4. The TPC ranged from 1.0 × 10^3 to 2.8 × 10^3 CFU/g, with cabbage leaf powder showing the highest microbial count and white pumpkin seed powder showing the lowest. The microbial counts remained unchanged on days 0, 15, and 30 of storage for the respective powder samples. This consistent microbial count was considered to be associated with the low-moisture condition of the powders following drying at 70 °C and the maintenance of dry storage conditions in clean, airtight containers, which limited moisture availability and consequently restricted microbial multiplication during storage. Also, reduced water activity is known to inhibit or delay the growth of many microorganisms in dried food products (Alp and Bulantekin, 2021; Tapia *et al.*, 2020).

The washing and blanching treatments applied before drying would also have helped reduce the initial microbial load, while subsequent drying further reduced the moisture available for microbial growth. Therefore, the absence of an increase in microbial counts during the 30-day storage period suggests that the powders maintained their microbiological quality under the storage conditions used in this study. Thus, the combined effects of drying, low moisture availability, hygienic handling, and protection from moisture uptake during storage likely created conditions unfavorable for microbial multiplication.

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Table 4: Total count of powders prepared from agricultural waste

Kind of powder	Day 0 (CFU/g)	Day 15 (CFU/g)	Day 30 (CFU/g)
Cauliflower leaves	2.5×10^3	2.5×10^3	2.5×10^3
Cauliflower stem	2.0×10^3	2.0×10^3	2.0×10^3
Cabbage leaves	2.8×10^3	2.8×10^3	2.8×10^3
Cassava peel	1.5×10^3	1.5×10^3	1.5×10^3
Beetroot peel	1.7×10^3	1.7×10^3	1.7×10^3
White pumpkin seed	1.0×10^3	1.0×10^3	1.0×10^3
Yellow pumpkin seed	1.2×10^3	1.2×10^3	1.2×10^3
Banana peel	1.8×10^3	1.8×10^3	1.8×10^3
Orange peel	1.6×10^3	1.6×10^3	1.6×10^3

Note: Values are expressed as CFU/g.

Conclusion

The present study demonstrated that selected agricultural waste materials can be successfully converted into nutritionally valuable dehydrated powders through suitable processing techniques. The developed powders showed significant levels of carbohydrates, proteins, minerals, and dietary fiber, along with beneficial phytochemicals, such as flavonoids, tannins, saponins, steroids, and alkaloids, indicating their functional and health-promoting potential. Microbial analysis confirmed that the powders were microbiologically safe with acceptable TPC values. Among the samples, pumpkin seed powders showed higher protein and fat contents, while cassava peel and beetroot peel powders exhibited higher fiber levels. The findings highlight the potential of agricultural waste materials as low-cost and sustainable sources for the development of functional food ingredients. Utilization of these residues may contribute to waste reduction, environmental sustainability, value addition and the promotion of circular economy practices in food processing sector.

Author contributions

R.S.H. conceptualized, reviewed, and edited the manuscript. BR.M. investigated data analysis and prepared the original manuscript. A.M., S.N., E.B., and R.P. carried out sample preparation, laboratory analysis, and data compilation.

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Conflicts of interest

The authors declare no conflict of interest.

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Ethical consideration

Not applicable.

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