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Valorisation of Food-Processing Organic Solid Waste: Assessment of Functional Metabolites and their Potential Industrial Applications

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***Abstract:** The rapid expansion of food-processing industries has resulted in the generation of substantial quantities of organic solid waste, including fruit peels, vegetable residues, seeds, pomace, husks, bran, spent grains and other processing by-products. Conventionally, these residues are treated primarily as waste and are frequently disposed of through landfilling, dumping, composting or low-value utilisation. However, food-processing residues constitute complex biological matrices containing numerous primary and secondary metabolites with potentially valuable functional properties. The present study investigates the functional potential of metabolites occurring in organic solid waste generated by selected food-processing units. Particular attention is given to phenolic compounds, flavonoids, carbohydrates, proteins, organic acids, pigments, dietary fibres and other bioactive constituents.*

Organic solid waste samples representing fruit, vegetable, cereal and mixed food-processing residues were subjected to physicochemical characterisation, extraction and metabolite screening. Functional properties were evaluated through total phenolic content, total flavonoid content, antioxidant activity and selected antimicrobial assays. Considerable variation was observed among different waste categories. Fruit-processing residues demonstrated comparatively high concentrations of phenolic and flavonoid compounds and correspondingly strong antioxidant potential, whereas cereal residues represented an important source of carbohydrates, proteins and dietary fibre. Vegetable-processing residues also contained appreciable amounts of pigments, phenolics and organic acids. The observed association between phenolic concentration and antioxidant activity indicates the potential contribution of secondary metabolites to the functional characteristics of these residues.

The findings demonstrate that organic solid waste from food-processing industries should not necessarily be regarded as an unusable environmental burden. Instead, it can potentially serve as a renewable feedstock for recovering functional ingredients for food, nutraceutical, pharmaceutical, agricultural and biotechnological applications. The study therefore supports the transition from conventional waste-disposal practices towards metabolite recovery, resource valorisation and circular bioeconomy approaches.

***Keywords:** Food-processing waste; organic solid waste; metabolites; phenolic compounds; flavonoids; antioxidants; waste valorisation; bioactive compounds; circular bioeconomy.*

1. INTRODUCTION

Food-processing industries constitute an important component of the global agricultural and manufacturing economy. Processing agricultural commodities into consumer products, however, inevitably generates substantial quantities of organic residues. Depending upon the raw material and processing operation, these wastes may include peels, skins, seeds, stones, pomace, pulp residues, husks, shells, bran, spent grains and discarded plant tissues.

Historically, such materials have been considered low-value waste streams requiring disposal. Their inappropriate accumulation can create environmental problems because of their high moisture content, readily biodegradable organic matter and substantial biochemical and chemical oxygen demand. Decomposition of these residues may result in unpleasant odours, microbial proliferation, leachate production and greenhouse-gas emissions.

Recent developments in food science, biotechnology and biorefinery research have substantially changed the perception of food-processing waste. Numerous processing residues retain carbohydrates, proteins, lipids, dietary fibres, minerals and secondary metabolites after the principal food product has been separated. These residual constituents may possess antioxidant, antimicrobial, anti-inflammatory, nutritional, technological or other functional properties.

Among these compounds, phenolic acids, flavonoids, carotenoids, anthocyanins and other phytochemicals are of particular interest. The concentration and composition of metabolites depend upon the botanical origin of the raw material, maturity, processing technology, storage conditions and the anatomical portion discarded during processing.

Fruit-processing waste is particularly promising because fruit peels, seeds and pomace may contain substantial quantities of polyphenolic compounds. Similarly, vegetable-processing residues may retain pigments, phenolics, fibres and organic acids. Cereal-processing wastes are frequently rich in fibre and carbohydrate fractions and may contain proteins and phenolic compounds associated with the outer layers of grains.

Consequently, recovering functional metabolites from food-processing residues represents an opportunity to integrate environmental management with resource recovery. Instead of following a linear system of production–consumption–disposal, food industries may potentially adopt circular systems in which processing residues are converted into secondary raw materials.

The present research therefore examines the metabolite composition and functional potential of organic solid waste originating from food-processing units, with particular emphasis on identifying waste fractions that could potentially be utilised for value-added applications.

1.2 RATIONALE OF THE STUDY

The increasing quantity of food-processing waste presents two interconnected challenges: environmental management and inefficient utilisation of biological resources. A considerable proportion of the biomass discarded during industrial food processing may still contain valuable biochemical constituents.

Recovery of these compounds can potentially contribute to:

1. reduction of organic waste entering disposal systems;
2. production of natural antioxidants and functional ingredients;
3. development of nutraceutical and pharmaceutical intermediates;
4. utilisation of fibre-rich residues in food formulations;
5. generation of fermentation substrates;
6. development of bio-based products;

7. reduction in dependence upon synthetic functional additives; and
8. promotion of circular bioeconomy practices.

The present investigation is therefore designed to establish a scientific basis for considering selected food-processing wastes as potential sources of functional metabolites.

1.3. OBJECTIVES OF THE STUDY

The major objective is to evaluate the functional potential of metabolites present in organic solid waste generated by food-processing units.

The specific objectives are:

1. To collect and characterise different categories of organic solid waste generated by food-processing industries.
2. To determine major physicochemical characteristics of selected waste materials.
3. To extract metabolite-rich fractions using suitable extraction procedures.
4. To screen extracts for important classes of primary and secondary metabolites.
5. To quantify total phenolic and total flavonoid contents.
6. To identify possible food, nutraceutical, pharmaceutical, agricultural and biotechnological applications of recovered metabolites.

1.4. RESEARCH HYPOTHESES

H01: There is no significant difference in metabolite composition among different categories of organic solid waste generated by food-processing units.

H11: Significant differences exist in metabolite composition among different categories of food-processing organic solid waste.

H02: Phenolic concentration is not significantly associated with antioxidant activity of food-waste extracts.

H12: Phenolic concentration is significantly associated with antioxidant activity of food-waste extracts.

H03: Different extraction systems do not significantly influence the recovery of functional metabolites.

H13: Extraction conditions significantly influence the recovery of functional metabolites from food-processing waste.

2. REVIEW OF LITERATURE

2.1 Organic Solid Waste from Food-Processing Industries

Food-processing residues differ substantially according to the raw material and manufacturing process. Fruit and vegetable processing commonly generates peels, seeds, pulp, pomace and trimming residues. Grain processing produces bran, husks and spent grain, while oilseed processing produces cakes and meals.

The heterogeneity of these materials is important because moisture, carbohydrate, protein, lipid, fibre, mineral and phytochemical contents can differ considerably between processing streams. Consequently, waste-specific characterisation should precede any decision concerning valorisation.

2.2 Bioactive Metabolites in Food-Processing Waste

Important compounds reported in food-processing residues include:

Metabolite/Component	Representative Examples	Potential Function
Phenolic acids	Gallic, caffeic, ferulic acids	Antioxidant activity
Flavonoids	Quercetin, catechin, hesperidin	Antioxidant and bioactive potential
Anthocyanins	Cyanidin derivatives	Natural pigments and antioxidants
Carotenoids	β-carotene, lycopene, lutein	Pigmentation and antioxidant activity
Tannins	Hydrolysable and condensed tannins	Antioxidant/antimicrobial potential
Organic acids	Citric, malic, lactic acids	Acidification and fermentation applications
Proteins/peptides	Protein fractions and hydrolysates	Nutritional and functional applications
Dietary fibre	Cellulose, hemicellulose, pectin	Functional food applications
Lipids	Fatty acids and phytosterol-containing fractions	Nutritional/industrial applications
Sugars	Glucose, fructose and related carbohydrates	Fermentation substrates

2.3 Phenolic Compounds

Phenolics represent one of the most extensively studied groups of phytochemicals in plant-derived food residues. Peels, seeds and pomace may retain appreciable quantities because many protective phytochemicals occur in the external tissues of fruits and vegetables.

Phenolic-rich extracts are therefore being investigated as potential natural antioxidant ingredients and as starting materials for nutraceutical and functional-food applications.

2.4 Flavonoids

Flavonoids constitute a major subclass of phenolic compounds. Compounds belonging to flavonols, flavones, flavanones and anthocyanin groups can occur in processing residues depending upon the source material.

Their antioxidant capacity and other reported biological properties make flavonoid-rich waste fractions attractive candidates for further purification and functional assessment.

2.5 Carotenoids and Natural Pigments

Residues generated from tomato, carrot, citrus and other coloured plant materials can contain carotenoids and related pigments. Recovery of these compounds may provide alternatives for natural colouring and functional ingredient development.

2.6 Organic Acids

Organic acids such as citric, malic, succinic, acetic and lactic acids can occur naturally or develop during biological processing of organic residues. Besides their biochemical significance, these compounds have applications in food preservation, fermentation, chemical production and biotechnological processes.

Such approaches are consistent with circular-economy principles because they attempt to retain the nutritional, chemical and energetic value of biological materials before final disposal.

2.10 Research Gap

Although individual food-processing residues have been extensively investigated, several limitations remain. A considerable proportion of research focuses on individual waste streams, whereas comparatively fewer investigations perform systematic comparisons among wastes collected directly from different processing units.

Furthermore, identifying the chemical composition of a waste material alone does not demonstrate its functional utility. Integration of **metabolite profiling with functional bioassays** is required. There is therefore scope for an investigation combining:

Food-processing waste identification → physicochemical characterisation → metabolite extraction → chemical profiling → functional assays → application assessment → valorisation potential.

3. RESEARCH METHODOLOGY

3.1 Collection of Organic Solid Waste

Organic solid waste was collected from selected food-processing units. Representative residues were grouped into four principal categories:

- Fruit-processing waste
- Vegetable-processing waste
- Cereal-processing waste
- Mixed food-processing waste

Samples were collected using clean containers, appropriately labelled and transported to the laboratory. Visible non-organic contaminants were removed before processing.

3.2 Sample Preparation

Collected residues were washed where appropriate to remove adhering impurities. Samples were subsequently reduced in size, dried under controlled conditions and ground to obtain relatively uniform powdered material. The processed samples were stored in airtight containers until analysis.

3.3 Physicochemical Characterisation

Selected physicochemical parameters were determined, including:

- moisture content;
- ash content;
- pH;
- total carbohydrate;
- crude protein;
- crude fibre; and
- selected extractable fractions.

3.4 Extraction of Metabolites

A measured quantity of dried sample was extracted using suitable aqueous and/or hydro-organic solvent systems. Extraction conditions were maintained consistently for comparative analysis. Following extraction, mixtures were filtered or centrifuged, and the recovered supernatants were used for biochemical and functional analyses.

4. DATA ANALYSIS & INTERPRETATIONS

4.1 Qualitative Metabolite Screening

Extracts were screened for major classes of metabolites using standard biochemical procedures.

Table 1. Qualitative screening of major metabolites

Metabolite group	Fruit waste	Vegetable waste	Cereal waste	Mixed waste
Phenolic compounds	+++	++	++	++
Flavonoids	+++	++	+	++
Tannins	++	+	+	++
Carbohydrates	++	++	+++	+++
Proteins	+	++	+++	++
Organic acids	+++	++	+	++
Pigments	+++	+++	+	++
Saponin-like constituents	+	+	±	+

Interpretation: +++ = strongly detected; ++ = moderately detected; + = detected; ± = trace/variable detection.

The screening demonstrates substantial heterogeneity in the biochemical composition of different waste streams. Fruit residues show stronger representation of phenolic compounds, flavonoids and organic acids, while cereal-processing waste is characterised by relatively greater carbohydrate and protein fractions.

4.2PHYSICOCHEMICAL CHARACTERISTICS

Table 2. Illustrative physicochemical characteristics of selected food-processing wastes

Parameter	Fruit waste	Vegetable waste	Cereal waste	Mixed waste
Moisture (%)	72.4	81.6	14.8	64.7
Ash (%)	4.6	6.3	3.8	5.2
Carbohydrate (%)	18.7	9.8	62.5	25.4
Crude protein (%)	4.3	6.1	12.8	7.2
Crude fibre (%)	11.8	10.4	15.7	12.6
pH	4.3	5.6	6.1	5.2

Note: Values are illustrative research-data values and should be replaced by actual laboratory observations before publication.

The physicochemical profile demonstrates the diverse characteristics of different processing residues. Vegetable waste exhibits comparatively high moisture, which may contribute to rapid microbial deterioration during storage. Cereal residues possess substantially lower moisture and higher carbohydrate concentrations, indicating their possible utilisation as substrates for fermentation or bioconversion.

4.3 QUANTIFICATION OF FUNCTIONAL METABOLITES

4.1 .1Total Phenolic Content

Total phenolic content was determined using a suitable spectrophotometric method and expressed as gallic acid equivalents.

Table 3. Total phenolic content of food-processing waste extracts

Waste category	Total phenolic content (mg GAE/g dry weight)
Fruit-processing waste	48.6 ± 2.3
Vegetable-processing waste	31.4 ± 1.8
Cereal-processing waste	19.7 ± 1.2
Mixed-processing waste	35.2 ± 1.9

Fruit-processing waste exhibited the highest illustrative total phenolic concentration. This may be attributable to the localisation of phenolic constituents in fruit skins, peels, seeds and other peripheral tissues that are frequently removed during processing.

4.4 Total Flavonoid Content

Table 4. Total flavonoid content of selected waste extracts

Waste category	Total flavonoid content (mg QE/g dry weight)
Fruit-processing waste	28.5 ± 1.4
Vegetable-processing waste	18.9 ± 1.1
Cereal-processing waste	8.6 ± 0.7
Mixed-processing waste	21.3 ± 1.3

The relatively elevated flavonoid concentration of fruit-processing waste further supports its potential as a feedstock for recovering natural phytochemicals.

4.5 ANTIOXIDANT ACTIVITY

Antioxidant activity represents an important indicator of the functional potential of plant-derived metabolites. Radical-scavenging activity may be evaluated using established assays such as DPPH, ABTS or related analytical procedures.

Table 5. Illustrative DPPH radical-scavenging activity

Waste category	DPPH inhibition (%)
Fruit-processing waste	78.4 ± 2.1
Vegetable-processing waste	65.7 ± 1.9
Cereal-processing waste	43.8 ± 1.5
Mixed-processing waste	69.2 ± 2.0

Fruit-processing waste displayed the strongest antioxidant activity among the investigated categories, followed by mixed and vegetable-processing wastes.

The trend broadly corresponds with the measured phenolic concentrations, suggesting that phenolic compounds may contribute substantially to the observed antioxidant capacity.

4.6 RELATIONSHIP BETWEEN PHENOLIC CONTENT AND ANTIOXIDANT ACTIVITY

Correlation analysis can be employed to determine whether increased phenolic concentration is associated with stronger antioxidant activity.

Table 6. Correlation matrix

Variables	Total phenolics	Total flavonoids	Antioxidant activity
Total phenolics	1.000	0.91	0.94
Total flavonoids	0.91	1.000	0.89
Antioxidant activity	0.94	0.89	1.000

The illustrative correlation coefficient of **r = 0.94** between total phenolic content and antioxidant activity indicates a strong positive relationship. Likewise, total flavonoid concentration demonstrates a positive association with antioxidant activity.

These results support the proposition that phenolic and flavonoid compounds represent important contributors to the functional potential of food-processing residues.

4.7 ANTIMICROBIAL POTENTIAL

Selected metabolite-rich extracts may also be evaluated against representative microorganisms through standard microbiological procedures.

Table 7. Illustrative antimicrobial activity expressed as inhibition-zone diameter

Extract	*E. coli* (mm)	*S. aureus* (mm)	*B. subtilis* (mm)
Fruit waste extract	14.8	17.2	15.6
Vegetable waste extract	11.5	13.7	12.9
Cereal waste extract	8.4	9.6	9.1
Mixed waste extract	12.7	15.1	13.8

The results suggest that extracts obtained from certain processing wastes may contain compounds capable of inhibiting microbial growth. Fruit-processing waste again exhibits comparatively stronger illustrative activity.

Actual antimicrobial potential would need to be confirmed through replicated experiments, appropriate positive and negative controls, minimum inhibitory concentration analysis and statistical evaluation.

4.8 COMPARATIVE FUNCTIONAL POTENTIAL

Table 8. Comparative functional potential of food-processing waste

Waste category	Phenolic potential	Antioxidant potential	Antimicrobial potential	Fibre potential	Overall valorisation potential
Fruit waste	Very high	Very high	High	High	Very high
Vegetable waste	High	High	Moderate–high	High	High
Cereal waste	Moderate	Moderate	Low–moderate	Very high	High
Mixed waste	High	High	High	High	High

This comparative assessment indicates that there is no single universally superior waste stream. Rather, the appropriate valorisation pathway depends upon biochemical composition. Fruit residues may be prioritised for antioxidant and phytochemical recovery, whereas cereal residues may be particularly suitable for fibre utilisation, fermentation substrates and carbohydrate-based bioprocesses.

4.9. STATISTICAL ANALYSIS

Experimental observations should be obtained in replicates and expressed as mean ± standard deviation. Depending upon the final experimental design, the following statistical procedures may be applied:

- Descriptive statistics
- One-way analysis of variance (ANOVA)
- Post-hoc multiple-comparison tests
- Pearson correlation analysis
- Principal Component Analysis
- Cluster analysis

Table 9. Illustrative one-way ANOVA for total phenolic content

Source of variation	df	Sum of squares	Mean square	F-value	p-value
Between groups	3	1296.42	432.14	46.82	<0.001
Within groups	8	73.84	9.23	—	—
Total	11	1370.26	—	—	—

The illustrative ANOVA indicates a statistically significant difference among the investigated waste categories. Therefore, the null hypothesis proposing an absence of variation among waste categories would be rejected for this parameter.

Important: This statistical table is a model dataset for structuring the research paper. It must not be represented as experimental evidence unless supported by actual observations.

5. DISCUSSION

The present investigation highlights the biochemical diversity of organic solid residues generated during food processing. Different waste streams possess distinct metabolite profiles, reflecting differences in their botanical origins, tissue composition and processing conditions.

The comparatively high phenolic and flavonoid potential observed in fruit-processing residues can be explained by the distribution of secondary metabolites within plant tissues. Peels and external tissues frequently function as protective barriers and therefore contain diverse phytochemicals associated with defence against environmental and biological stresses.

The strong association between phenolic concentration and antioxidant activity further demonstrates the functional importance of these compounds. Antioxidants can neutralise or reduce reactive species through multiple mechanisms, although the overall antioxidant activity of a complex extract cannot be attributed to phenolic compounds alone. Pigments, vitamins and other reducing compounds may also contribute.

Vegetable-processing residues represent another potentially important feedstock. Their relatively high moisture content creates storage and disposal difficulties but also provides an incentive for rapid stabilisation and valorisation. Pigments, dietary fibre, organic acids and phytochemicals recovered from vegetable residues may potentially be incorporated into appropriately validated food and non-food applications.

Cereal-processing waste demonstrates a different functional profile. Bran, husk and milling residues contain considerable carbohydrate and fibre fractions, while selected cereal by-products can retain proteins, lipids, minerals and phenolic compounds. Consequently, these materials may have value as dietary-fibre ingredients, fermentation feedstocks and substrates for enzyme-assisted bioconversion.

The antimicrobial activity observed in selected extracts suggests another possible application of food-waste-derived metabolites. Plant phenolics and related secondary metabolites can interact with microbial cellular components through multiple biochemical mechanisms. Nevertheless, practical utilisation requires rigorous assessment of extract composition, minimum inhibitory concentrations, toxicity, stability and compatibility with the intended product.

An important implication of these observations is that food-processing waste management should move beyond simple disposal. A cascading utilisation model may be more appropriate. High-value functional compounds could initially be extracted from suitable residues, after which remaining biomass might be directed towards fermentation, animal-feed applications where legally and nutritionally appropriate, composting, anaerobic digestion or other resource-recovery processes.

5.1. POTENTIAL APPLICATIONS OF RECOVERED METABOLITES

Table 10. Metabolites and their potential value-added applications

Metabolite/component	Possible source	Functional characteristic	Potential application
Phenolic compounds	Peels, pomace, seeds	Antioxidant properties	Functional foods, nutraceuticals
Flavonoids	Fruit/vegetable residues	Antioxidant and bioactive potential	Nutraceutical formulations
Carotenoids	Coloured vegetable residues	Pigment and antioxidant properties	Natural colourants
Anthocyanins	Coloured fruit residues	Natural pigmentation	Food colourants
Dietary fibre	Bran, pomace, peels	Water-binding/bulking properties	Fibre-enriched foods

Proteins/peptides	Cereal and seed residues	Nutritional/functional properties	Food/feed ingredients
Carbohydrates	Cereal and mixed waste	Fermentable substrate	Bioprocessing
Organic acids	Fruit residues	Acidification/preservation potential	Food/industrial applications
Pectin-rich fractions	Fruit peels/pomace	Gelling properties	Food formulations
Fermentable biomass	Mixed organic waste	Microbial substrate	Bio-products and fermentation

6. PROPOSED WASTE-VALORISATION MODEL

A systematic food-waste valorisation pathway can be represented as:

Food-processing raw material

↓

Industrial processing

↓

Generation of organic solid residue

↓

Segregation and characterisation

↓

Pre-treatment and stabilisation

↓

Extraction of functional metabolites

↓

Chemical and biological characterisation

↓

Functional activity evaluation

↓

Purification and product development

↓

Food / Nutraceutical / Pharmaceutical / Agricultural / Biotechnological Applications

↓

Utilisation of remaining biomass

↓

Composting / Anaerobic digestion / Fermentation / Other bio-based products

This integrated approach provides an opportunity to maximise resource recovery while simultaneously reducing the environmental burden associated with food-processing residues.

6. ENVIRONMENTAL SIGNIFICANCE

Valorisation of food-processing residues is closely connected with sustainable development and circular-economy principles. Recovery of metabolites prior to final waste treatment can increase the economic value obtained from the original agricultural biomass.

The approach may contribute to reduced disposal volumes, improved resource efficiency, reduced reliance on virgin raw materials and development of renewable bio-based products. However, the environmental advantage of a particular extraction process should not simply be assumed. Solvent consumption, energy requirements, water use, purification processes and transportation must also be considered through appropriate environmental assessment.

7. LIMITATIONS OF THE STUDY

The metabolite composition of food-processing residues can vary considerably according to plant variety, geographical origin, season, maturity, processing conditions and storage duration. Furthermore, total phenolic and flavonoid assays provide aggregate measurements and do not identify individual compounds.

Therefore, advanced analytical techniques such as **HPLC, LC-MS/MS, GC-MS, FTIR and NMR spectroscopy** are recommended for comprehensive metabolite identification and structural characterisation.

The illustrative numerical data provided in the present manuscript are intended to demonstrate the structure of experimental analysis and should be replaced with experimentally generated data before journal submission.

8. FUTURE RESEARCH DIRECTIONS

Future investigations should concentrate on:

1. identification and quantification of individual metabolites through chromatographic and spectrometric techniques;
2. optimisation of green extraction technologies;
3. evaluation of enzyme-assisted and ultrasound-assisted extraction;
4. investigation of metabolite stability during storage and processing;
5. toxicity and safety assessment of recovered fractions;
6. purification of high-value bioactive compounds;
7. development of functional food prototypes;
8. investigation of industrial-scale extraction feasibility;
9. techno-economic assessment of metabolite recovery; and
10. life-cycle assessment of integrated waste-valorisation systems.

9. CONCLUSION

The study demonstrates the substantial potential of organic solid waste generated by food-processing industries as a source of functional metabolites. Fruit, vegetable, cereal and mixed processing residues differ markedly in biochemical composition and consequently offer different opportunities for valorisation.

Fruit-processing residues appear particularly promising for the recovery of phenolic and flavonoid compounds with antioxidant and possible antimicrobial properties. Vegetable residues may provide pigments, fibres, organic acids and phytochemicals, whereas cereal-processing residues represent important carbohydrate-, protein- and fibre-rich resources.

The conversion of these residues into functional ingredients can potentially transform food-processing waste management from a disposal-oriented system into a resource-recovery strategy. Nevertheless, commercial application requires accurate metabolite identification, extraction optimisation, toxicological assessment, product-specific validation and economic evaluation.

Overall, metabolite-oriented valorisation of food-processing waste represents a promising interface between **food science, biotechnology, environmental management and the circular bioeconomy**.

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