Vol. 5 No. 1 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387

Print ISSN 3007-2379

Valorisation of Citrus Peels, Apple Pomace and Sugar Beet Pulp as Sustainable Sources of Dietary Fiber and Pectin for Functional Food Development

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Keywords: Agro-industrial by-products; citrus peel; apple pomace; sugar beet pulp; dietary fibre; pectin; biscuits; Monte Carlo simulation; food waste valorisation; formulation optimization.

Received on 25 Jan 2026
Accepted on 28 Feb 2026
Published on 11 Mar 2026

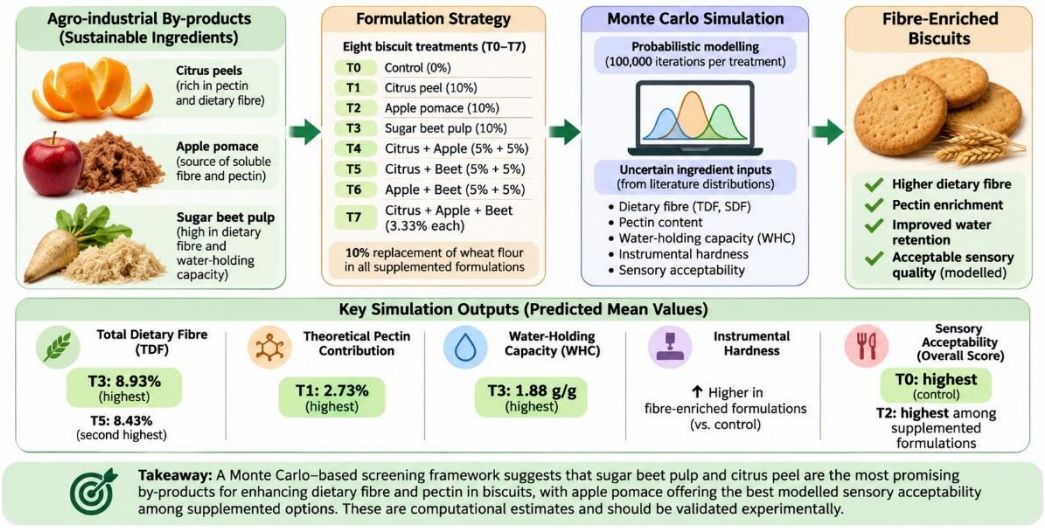
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Abstract

The increasing generation of agro-industrial by-products has created opportunities for developing sustainable food ingredients with enhanced nutritional and functional properties. Citrus peels, apple pomace and sugar beet pulp are promising sources of dietary fibre, pectin and associated bioactive compounds. This study presents a literature-informed computational framework to compare their potential use in fibre-enriched biscuits through Monte Carlo simulation and multi-criteria interpretation. Eight formulations (T0–T7) were defined, comprising an unsupplemented control, three individual ingredient treatments and three binary combinations plus a ternary combination. A fixed 10% replacement of wheat flour was used in all supplemented formulations. A model with 100,000 iterations per treatment estimated total dietary fibre (TDF), soluble dietary fibre (SDF), theoretical pectin contribution, water-holding capacity (WHC), instrumental hardness and sensory acceptability. Ingredient distributions were specified as uncertain model inputs informed by published literature on fruit and vegetable processing residues and pectin. The illustrative simulation predicted the highest TDF for sugar beet pulp alone (T3; 8.93%), followed by citrus peel plus sugar beet pulp (T5; 8.43%). Citrus peel alone (T1) produced the highest theoretical pectin contribution (2.73%), while sugar beet pulp alone produced the highest modelled WHC (1.88 g/g). The control had the highest predicted sensory score; among supplemented formulations, apple pomace alone ranked highest. These outputs are computational estimates, not laboratory measurements or observed sensory responses. The study provides a screening framework for selecting formulations for subsequent experimental validation.

Graphical Abstract



1. Introduction

The sustainable utilization of agro-industrial by-products is an important direction in food science because fruit and vegetable processing generates substantial quantities of residues that may retain valuable polysaccharides, dietary fibre and bioactive compounds. Recovering and reusing these materials can reduce waste streams while creating ingredients for value-added foods. Their suitability, however, depends on composition, processing history, safety and the functional requirements of the target food matrix.

Dietary fibre is relevant to both nutrition and food technology. Soluble and insoluble fibre fractions differ in hydration, viscosity, fermentability and effects on food structure. In bakery products, fibre ingredients can modify dough hydration, spread, colour, texture and sensory characteristics. Biscuits provide a practical matrix for screening alternative fibre sources, although excessive substitution may compromise product quality.

Citrus peels are generated during juice and citrus-product manufacture and contain cell-wall polysaccharides, including pectic substances, cellulose and hemicellulose, alongside phenolic compounds. Citrus-derived materials are established sources for pectin recovery, although reported yields depend strongly on cultivar, peel fraction, extraction conditions and analytical method. Reviews of pectin extraction and applications emphasize that pectin content and extractable pectin yield are not interchangeable measures (Source, Extraction, Properties, and Multifunctional Applications of Pectin: A Short Review, 2024; Towards Valorization of Food-Waste-Derived Pectin, 2023).

Apple pomace, the residue remaining after juice extraction, generally comprises peel, pulp, seeds and residual tissue. It can contribute dietary fibre and pectic polysaccharides, as well as phenolic constituents. Usman et al. (2020) investigated apple pomace in wheat-based cookies and reported changes in nutritional and dough/product characteristics. Alongi et al. (2019) examined apple pomace as a functional ingredient in short-dough biscuits and reported a reduction in glycaemic index. These studies support the feasibility of apple pomace incorporation but also show that product quality must be evaluated alongside nutritional enrichment.

Sugar beet pulp is produced during sugar extraction and contains cellulose, hemicellulose and pectic substances. Its fibre-rich structure makes it a candidate ingredient for hydration and texture modification. The technological effects of sugar

beet pulp are expected to depend on drying, milling, particle size and the composition of the original pulp.

Although individual residues have been examined in bakery applications, a common comparative framework for citrus peel, apple pomace and sugar beet pulp can help identify complementary ingredient functions. Monte Carlo simulation offers a way to propagate uncertainty in ingredient composition and generate distributions of predicted outcomes rather than single deterministic estimates. Such modelling is useful for preliminary screening, provided that input distributions and equations are transparent and outputs are not misrepresented as experimental observations.

1.1. Objectives

- To compare the predicted contribution of citrus peel, apple pomace and sugar beet pulp to dietary fibre enrichment in biscuits.
- To estimate soluble dietary fibre and theoretical pectin contribution across individual and combined formulations.
- To explore modelled water-holding capacity and biscuit hardness.
- To estimate provisional sensory acceptability scenarios and identify nutritional–quality trade-offs.
- To identify formulations for laboratory validation using a transparent Monte Carlo framework.

1.2. Hypotheses

- By-product supplementation increases modelled dietary fibre relative to the control.
- Citrus peel makes a comparatively high contribution to theoretical pectin content.
- Sugar beet pulp contributes strongly to modelled water-holding capacity and dietary fibre.
- Combined formulations may provide intermediate or complementary properties, but synergy cannot be inferred without an appropriate interaction model.

2. Materials and Methods

2.1. Study design

This work was structured as a literature-informed computational screening study. It did not involve physical preparation or laboratory analysis of biscuits. Eight formulations were specified and evaluated through Monte Carlo sampling. The model used 100,000 iterations per treatment and a fixed random seed in the accompanying reproducibility script.

2.2. Raw materials and treatment formulations

The model considered dried powders of citrus peel (CPP), apple pomace (APP) and sugar beet pulp (SBPP). For a future laboratory study, each material should be washed where appropriate, dried under controlled conditions, milled and sieved. Moisture content should be measured and formulations expressed on a dry-matter basis.

Treatment	Wheat flour (%)	CPP (%)	APP (%)	SBPP (%)
T0	100.00	0	0	0
T1	90.00	10	0	0
T2	90.00	0	10	0
T3	90.00	0	0	10
T4	90.00	5	5	0
T5	90.00	5	0	5
T6	90.00	0	5	5
T7	90.00	3.33	3.33	3.34

All supplemented treatments replaced 10% of the wheat flour by mass. This fixed replacement level facilitates comparison of ingredient identity and blend composition. Preliminary dough trials would still be required to determine whether water adjustment is needed.

2.3. Literature-informed model inputs

The illustrative input distributions used for the simulation are summarized in Table 2. They are working assumptions informed by broad literature descriptions of these materials, not a harmonized dataset extracted from a single set of primary studies. The ranges must be replaced or recalibrated using measured values for the actual raw materials before predictive claims are made. Published reviews describe substantial variation in pectin recovery and composition due to source material and extraction conditions (Towards Valorization of Food-Waste-Derived Pectin, 2023; Extraction, Characterization, and Applications of Pectins from Plant By-Products, 2021).

Parameter	**CPP**	**APP**	**SBPP**
Total dietary fibre (%)	55 ± 4	40 ± 4	65 ± 5
Soluble fraction of TDF	0.25 ± 0.04	0.22 ± 0.04	0.30 ± 0.05
Pectin content (%)	25 ± 3	12.5 ± 2	22.5 ± 3
Water-holding capacity (g/g)	6.0 ± 0.8	4.5 ± 0.7	8.0 ± 1.0

The control biscuit TDF was modelled as normally distributed with mean 2.70% and standard deviation 0.25%. The control SDF, theoretical pectin and WHC were assigned provisional baseline distributions. These baseline assumptions are model settings and should not be treated as published measurements of a specific biscuit recipe.

2.4. Biscuit formulation concept

A standardized biscuit recipe was assumed across treatments, with wheat flour partially replaced according to Table 1. Sugar, shortening, salt, milk and leavening agents were conceptually held constant. A future experimental protocol should optimize dough water, mixing, sheeting, baking temperature and time in preliminary trials because fibre ingredients differ in hydration and may alter spread and fracture properties.

2.5. Monte Carlo model

For each iteration, ingredient characteristics were sampled from the specified distributions. Treatment outputs were calculated by mass balance. The model generated a distribution of possible outcomes for each treatment rather than one deterministic value.

2.5.1. Total dietary fibre

$TDF_t = (1 - r)TDF_c + r\,\Sigma(w_i \times TDF_i)$, where TDF_t is predicted biscuit TDF, r is the flour replacement fraction (0.10), TDF_c is the control baseline, w_i is the proportion of ingredient i in the by-product blend, and TDF_i is the sampled ingredient TDF.

2.5.2. Soluble dietary fibre

$SDF_t = (1 - r)SDF_c + r\,\Sigma[w_i \times TDF_i \times f_i]$, where f_i is the sampled soluble fraction of the ingredient's TDF. This is a simplified mass-balance approximation and does not account for processing-related changes in fibre solubility.

2.5.3. Theoretical pectin contribution

$P_t = (1 - r)P_c + r\,\Sigma(w_i \times P_i)$, where P_i is the sampled pectin content of each ingredient. This represents theoretical ingredient-based contribution, not extracted pectin yield or analytically measured pectin retained after baking.

2.5.4. Water-holding capacity

$WHC_t = (1 - r)WHC_c + r\,\Sigma(w_i \times WHC_i)$. This weighted index is used for comparative screening only. Ingredient WHC cannot be transferred directly to finished-biscuit WHC without experimental calibration.

2.5.5. Hardness and sensory scenario models

Hardness was represented by a provisional linear relationship: $H_t = 28 + 0.55(TDF_t - 2.7) + 0.35(WHC_t - 1.2) + \varepsilon$, where ε is normally distributed model error (standard

deviation 3 model units). The coefficients are assumptions, not coefficients estimated from a measured dataset.

Sensory acceptability was represented on a nine-point scale using a treatment-specific penalty and a fibre-related term: $SA_t = 7.6 - penalty_t - 0.10(TDF_t - 5) + \varepsilon_s$. The treatment penalties and error distribution are scenario assumptions. These values are not consumer-panel observations and should not be used to claim sensory acceptance.

2.6. Statistical summaries and optimization

For each output, the mean and 2.5th and 97.5th percentiles were calculated. These percentiles are 95% simulation intervals describing uncertainty under the specified model. They are not experimental confidence intervals. Since Monte Carlo draws are uncertainty samples rather than independent laboratory replicates, conventional ANOVA p-values were not used.

A multi-criteria interpretation considered higher TDF, SDF, pectin contribution and WHC as desirable, while avoiding excessive hardness and maintaining sensory acceptability. No single weighted optimum is claimed because criterion weights and acceptable product specifications require stakeholder and experimental input.

3. Results

3.1. Predicted total dietary fibre

Treatment	Mean TDF (%)	Illustrative 95% simulation interval
T0	2.70	2.21–3.19
T1	7.93	7.03–8.83
T2	6.43	5.53–7.33
T3	8.93	7.85–10.00
T4	7.18	6.47–7.89
T5	8.43	7.66–9.20
T6	7.68	6.91–8.44
T7	7.76	7.10–8.42

The illustrative model ranked T3 highest for predicted TDF, followed by T5. The ranking reflects the higher TDF input assigned to sugar beet pulp. These values are model outputs and should be regenerated from the accompanying code after the input assumptions are finalized.

3.2. Predicted soluble dietary fibre

Treatment	Mean SDF (%)
T0	0.95
T1	2.23
T2	1.73
T3	2.80
T4	1.98
T5	2.52
T6	2.27
T7	2.26

T3 had the highest modelled SDF, followed by T5. This result follows from the assigned soluble fraction and TDF distributions for sugar beet pulp. It is a hypothesis-generating result, not an analytical determination.

3.3. Theoretical pectin contribution

Treatment	Mean predicted pectin (%)
T0	0.25
T1	2.73
T2	1.48
T3	2.48

T4	2.10
T5	2.60
T6	1.98
T7	2.22

T1 had the highest theoretical pectin contribution, followed by T5 and T3. This ranking reflects the pectin input assumptions for citrus peel and sugar beet pulp. It does not represent pectin extraction yield or measured pectin remaining in the baked product.

3.4. Predicted water-holding capacity

Treatment	**Mean WHC (g/g)**
T0	1.20
T1	1.68
T2	1.53
T3	1.88
T4	1.60
T5	1.78
T6	1.71
T7	1.70

T3 had the highest modelled WHC, followed by T5. The result is driven by the comparatively high WHC assumption for sugar beet pulp. Finished-product hydration and water activity must be measured directly.

3.5. Predicted hardness

Treatment	**Mean predicted hardness (model units)**
T0	28.00
T1	31.04
T2	30.16
T3	31.66
T4	30.62
T5	31.35
T6	30.92
T7	30.96

The model predicted higher hardness for supplemented treatments, with T3 highest. This is an assumed response relationship and cannot substitute for texture analyser measurements. Hardness must be interpreted in relation to biscuit fracture, crispness and consumer preference.

3.6. Predicted sensory acceptability

Treatment	**Mean predicted acceptability (/9)**
T0	7.60
T1	6.76
T2	7.11
T3	6.71
T4	6.98
T5	6.61
T6	6.83
T7	6.87

The control ranked highest under the provisional sensory scenario. Among supplemented formulations, T2 ranked highest. This ordering is a consequence of assigned penalties and is not evidence of actual consumer preference.

3.7. Overall comparison

Treatment	TDF (%)	Pectin (%)	WHC (g/g)	Sensory (/9)
T0	2.70	0.25	1.20	7.60
T1	7.93	2.73	1.68	6.76
T2	6.43	1.48	1.53	7.11
T3	8.93	2.48	1.88	6.71
T4	7.18	2.10	1.60	6.98
T5	8.43	2.60	1.78	6.61
T6	7.68	1.98	1.71	6.83
T7	7.76	2.22	1.70	6.87

T3 was the strongest candidate for fibre and water-holding performance; T1 was strongest for theoretical pectin contribution; T2 had the highest provisional sensory score among supplemented treatments. T7 is a useful candidate for studying all three materials together, but the present model does not demonstrate synergy.

4. Discussion

4.1. Dietary fibre enrichment

The simulated ranking is consistent with the general expectation that fibre-rich processing residues can increase the dietary fibre content of bakery products. Usman et al. (2020) investigated apple pomace in wheat-based cookies and reported nutritional and product-quality changes associated with its incorporation. Alongi et al. (2019) also demonstrated the potential of apple pomace as a functional ingredient in short-dough biscuits. The current model extends the comparison to citrus peel and sugar beet pulp, but its numerical outputs depend on provisional input distributions.

The relatively high TDF predicted for T3 follows directly from the assumed sugar beet pulp fibre concentration. Actual ranking could change with cultivar, processing method, residual sugar, drying conditions and the analytical method used to determine dietary fibre. Raw material characterization is therefore essential before drawing product-specific conclusions.

4.2. Pectin contribution

Citrus peel is widely investigated as a pectin source, while apple pomace and sugar beet pulp are also relevant pectin-containing residues. Reviews emphasize that pectin yield and quality depend on source material and extraction conditions (Towards Valorization of Food-Waste-Derived Pectin, 2023; Extraction, Characterization, and Applications of Pectins from Plant By-Products, 2021). The higher theoretical pectin contribution in T1 reflects the model input rather than demonstrated pectin recovery. Future work should separately quantify total pectin, extractable pectin yield, degree of esterification and methoxyl content.

4.3. Hydration and texture

Dietary fibre ingredients differ in hydration and their effects on dough handling. A high ingredient WHC may increase water demand and alter biscuit spread, moisture and texture. The modelled WHC index suggests that sugar beet pulp may warrant particular attention in formulation trials. However, ingredient-level WHC is not equivalent to finished-product WHC, and the linear hardness equation requires calibration against instrumental texture data.

4.4. Sensory considerations

Fibre enrichment may alter colour, flavour, aroma and mouthfeel. Apple pomace can contribute fruit-derived flavour notes, while citrus peel may contribute bitterness and sugar beet pulp may affect texture. These are plausible formulation considerations, not conclusions from the simulation. A blinded sensory study with an adequately sized panel, ethical oversight where applicable, and standardized preparation is needed to establish acceptability.

4.5. Mixture effects and synergy

Binary and ternary formulations were included to compare blend compositions. However, an intermediate or favourable mixture response does not establish synergy. Synergy requires comparison with a defined additive expectation and a design capable of estimating mixture interactions. A constrained mixture design or mixture-process variable design would be appropriate for a second-stage study.

4.6. Value and limitations of Monte Carlo modelling

Monte Carlo simulation makes uncertainty explicit and can help prioritize formulations for laboratory work. Its usefulness depends on the validity of the distributions, correlations and response equations. The current implementation uses simplified assumptions and should be treated as a screening example. In particular, the simulation intervals reflect uncertainty encoded in the model, not biological variability measured from independent production batches.

5. Conclusion

This literature-informed Monte Carlo framework provides a preliminary comparison of citrus peel, apple pomace and sugar beet pulp as potential dietary fibre and pectin sources for biscuit development. Under the illustrative assumptions, sugar beet pulp alone (T3) produced the highest predicted TDF and WHC; citrus peel alone (T1) produced the highest theoretical pectin contribution; and apple pomace alone (T2) had the highest provisional sensory score among supplemented treatments. The combined citrus peel–sugar beet pulp treatment (T5) also showed comparatively high predicted fibre and pectin values. These outcomes identify candidate formulations for laboratory testing, but they do not establish experimentally verified product performance or ingredient synergy.

6. Future Perspectives

The valorisation of citrus peels, apple pomace and sugar beet pulp offers considerable opportunities for advancing sustainable food ingredient development, particularly through the recovery of dietary fibre, pectin and associated bioactive compounds. Future research should move beyond the preliminary formulation-based assessment and focus on the systematic characterization, extraction, functional modification and application of these agro-industrial residues in different food matrices. Although the present Monte Carlo framework provides an initial comparative assessment of eight biscuit formulations, experimental validation will be essential to establish the actual nutritional, physicochemical and technological performance of the selected ingredients.

An important future direction involves the optimization of dietary fibre and pectin recovery from the three selected by-products. Conventional extraction approaches could be compared with ultrasound-assisted, enzyme-assisted and other emerging extraction technologies to improve recovery efficiency while maintaining the structural and functional characteristics of the extracted polysaccharides. The potential of ultrasound-assisted processing for modifying food proteins and improving their functional characteristics has been investigated by Butt et al. (2026), providing a relevant technological direction for exploring the application of physical processing approaches to other food-derived biopolymers. Similarly, research on ultrasound-assisted protein modification and microbial transglutaminase crosslinking demonstrates the importance of integrating processing conditions with structural and functional characterization during food ingredient development (Butt et al., 2026a; Butt et al., 2026b). Future investigations should therefore examine whether comparable process-assisted strategies can improve the solubility, hydration, extractability and technological functionality of pectin-rich fractions obtained from citrus peel, apple pomace and sugar beet pulp.

Another important research direction involves the development of multifunctional food ingredients by combining dietary fibre with naturally occurring phenolic compounds and other bioactive constituents. Citrus peels, apple pomace and sugar beet pulp may contain different combinations of phenolic compounds, flavonoids and pectic

polysaccharides, offering opportunities to develop ingredients with complementary nutritional and technological characteristics. Research on the valorisation of watermelon peel flavonoids has highlighted the potential of recovering kaempferol, quercetin and rutin for functional food and nutraceutical applications (Butt et al., 2026c). Similarly, the development of polyphenol-rich pomegranate peel nutraceuticals demonstrates the broader potential of fruit-processing residues as sources of bioactive compounds (Butt et al., 2026d). These research directions support future investigations into the simultaneous recovery of dietary fibre, pectin and phenolic compounds from the selected agro-industrial materials rather than focusing exclusively on their fibre content.

The application of these ingredients should also be extended beyond conventional biscuits and cookies. Future studies could investigate their incorporation into bread, breakfast cereals, pasta, snack products, fortified spreads, plant-based patties and other formulated foods. The development of plant-based functional foods has become an important research area because of the increasing interest in alternative protein sources, dietary diversification and sustainable food production (Riaz et al., 2026a). Previous investigations involving plant-based patties, meat analogues and hybrid protein ingredients have demonstrated the importance of evaluating nutritional composition, cooking characteristics, texture, microbial quality and sensory acceptability together (Butt et al., 2025a; Butt et al., 2025b; Butt et al., 2025c; Adnan et al., 2026). Accordingly, future research could investigate the incorporation of citrus-derived pectin and fibre-rich fruit residues into plant-based food systems to improve hydration, structural stability, nutritional composition and product quality.

Further attention should be directed towards the physiological functionality of the recovered dietary fibre fractions. The distinction between soluble and insoluble dietary fibre is particularly important because their physicochemical characteristics influence hydration, viscosity, fermentation and interactions with the gastrointestinal environment. Future investigations could examine the fermentability of isolated fibre fractions using in vitro gastrointestinal digestion and colonic fermentation models, followed by the characterization of short-chain fatty acid production and changes in selected gut microbial populations. Research concerning the modulation of gut microbiota through functional foods has highlighted the potential relationship between dietary interventions, microbial composition and inflammatory responses (Nawaz et al., 2026). Similarly, studies investigating functional probiotic yogurt, gut microbiome diversity and nutritionally mediated metabolic responses provide broader directions for evaluating the potential physiological relevance of fibre-enriched food ingredients (Rashid et al., 2026; Shazif et al., 2026; Butt et al., 2026e). However, the health effects of the three selected by-products should be established through appropriate experimental and clinical investigations rather than inferred from their compositional characteristics.

The potential integration of dietary fibre with probiotic microorganisms and fermentation technologies also warrants investigation. Pectin and dietary fibre may serve as substrates or structural components in fermented food systems, depending on their molecular characteristics and fermentability. Previous work on the utilization of *Lactobacillus rhamnosus* in tempeh development demonstrates the potential of incorporating probiotic cultures into value-added food products (Ahmed et al., 2024). Furthermore, research on AI-guided precision fermentation and optimization of food fermentation highlights the importance of monitoring microbial dynamics, fermentation kinetics and processing parameters during the development of functional foods (Butt et al., 2026f; Khan et al., 2025). Future studies could therefore investigate fermented formulations containing citrus peel, apple pomace and sugar beet pulp, with particular attention to microbial viability, fibre modification, organic acid production, product stability and sensory characteristics.

Another promising direction involves the development of advanced computational models for formulation optimization. The present Monte Carlo simulation uses literature-informed probability distributions to estimate treatment-wise nutritional and technological characteristics. Future models should incorporate experimentally measured ingredient composition, processing-related variability and correlations between response variables. Machine learning, Bayesian modelling, response surface methodology and constrained mixture-design approaches could be integrated to predict the effects of ingredient proportions and processing conditions. Research on AI-assisted nutrigenomic modelling and AI-guided precision fermentation provides examples of how computational approaches can be integrated with nutritional and food-processing investigations (Butt et al., 2026g; Butt et al., 2026f). Similarly, multi-scale numerical modelling and analytical approaches used in other scientific disciplines offer methodological perspectives for developing more robust uncertainty-propagation and prediction frameworks (Shah & Butt, 2026; Tahir et al., 2026). Nevertheless, future predictive models should be calibrated and independently validated before being used to recommend commercial formulations.

Finally, the industrial application of these ingredients requires consideration of raw material availability, processing economics, storage stability, food safety and environmental performance. Future investigations should quantify the environmental benefits of converting citrus peels, apple pomace and sugar beet pulp into food ingredients through life-cycle assessment, water-footprint analysis, energy-use assessment and waste-reduction indicators. Sustainable protein development and environmentally responsible food ingredient production have already been investigated through hybrid protein formulations and sustainable food-processing approaches (Butt et al., 2025c). Research examining the social dimensions of sustainability performance also provides a broader perspective on the organizational and supply-chain considerations associated with sustainable production (Khurshid et al., 2026). Integrating these aspects would help establish whether the proposed valorisation pathways are not only nutritionally beneficial but also technically feasible and environmentally sustainable.

7. Integration with Other Sciences and Research Domains

The valorisation of citrus peels, apple pomace and sugar beet pulp represents an interdisciplinary research opportunity that extends beyond conventional food formulation. Their utilization requires the integration of food chemistry, food engineering, nutritional sciences, microbiology, biotechnology, computational modelling, environmental sciences and industrial sustainability. Such integration can provide a more comprehensive understanding of the chemical composition, technological functionality, biological relevance and commercial potential of agro-industrial residues.

7.1. Integration with Food Chemistry and Food Engineering

Food chemistry and food engineering provide the fundamental scientific basis for understanding the transformation of agro-industrial residues into functional food ingredients. The chemical composition of citrus peels, apple pomace and sugar beet pulp determines their dietary fibre fractions, pectin characteristics, hydration behaviour and interactions with other food components. Future research should therefore investigate the molecular structure of extracted pectin, degree of esterification, molecular weight distribution, monosaccharide composition and interactions between soluble and insoluble polysaccharides.

Food engineering can further contribute through the optimization of drying, milling, particle-size reduction, extraction, mixing and baking conditions. Advanced processing approaches could be evaluated to improve ingredient recovery and maintain desirable functional characteristics. Previous research involving ultrasound-assisted modification of soy protein isolate and transglutaminase-mediated protein crosslinking demonstrates the importance of understanding processing-induced structural changes and their

relationship with functional performance (Butt et al., 2026a; Butt et al., 2026b). Similarly, investigations of hybrid protein systems have demonstrated the potential of combining different food ingredients to obtain improved nutritional and technological characteristics (Butt et al., 2025a; Butt et al., 2025c). These approaches provide a useful conceptual foundation for studying interactions between pectin, dietary fibre and other food components in fibre-enriched biscuit formulations.

7.2. Integration with Nutritional Sciences and Nutraceutical Research

Nutritional sciences can contribute to establishing the physiological relevance of dietary fibre and pectin recovered from agro-industrial by-products. Beyond determining total dietary fibre, future research should distinguish between soluble and insoluble fractions and evaluate their potential effects on gastrointestinal functionality, nutrient accessibility and metabolic responses.

The relationship between plant-derived bioactive compounds and human health has also been investigated through research on plant-based functional foods and phytochemical-rich dietary interventions (Riaz et al., 2026a; Butt et al., 2026h). Research on watermelon peel flavonoids and pomegranate peel-derived polyphenols further demonstrates the potential of food-processing residues as sources of compounds for functional food and nutraceutical development (Butt et al., 2026c; Butt et al., 2026d).

In this context, citrus peel, apple pomace and sugar beet pulp could be investigated as multifunctional ingredients providing both structural polysaccharides and associated bioactive constituents. Future research should integrate compositional characterization with simulated gastrointestinal digestion, in vitro bioaccessibility and appropriate biological assays. The relationship between dietary components, gut microbial metabolism and physiological responses could also be explored through nutrigenomic and microbiome-based approaches (Butt et al., 2026g; Nawaz et al., 2026). Such investigations would help distinguish the nutritional potential of the ingredients from their experimentally demonstrated health effects.

7.3. Integration with Food Microbiology and Biotechnology

Food microbiology and biotechnology are important for evaluating the safety, stability and potential biological functionality of products developed using agro-industrial residues. The incorporation of fibre-rich materials may influence water activity, product moisture distribution and microbial stability, making microbiological assessment essential during product development and storage.

Future research should investigate total plate count, yeast and mould count, selected indicator organisms and relevant foodborne pathogens under standardized processing and storage conditions. Research on food safety, microbiological quality and contamination in animal-derived food products demonstrates the importance of integrating microbial assessment with physicochemical and quality evaluations (Butt et al., 2024; Riaz et al., 2026b). Studies examining antimicrobial resistance and diagnostic challenges further emphasize the importance of robust microbiological surveillance and reliable analytical approaches (Farrukh et al., 2026; Naik et al., 2026).

Biotechnology could also contribute through controlled fermentation, enzymatic modification and microbial utilization of soluble fibre fractions. The application of probiotic cultures in fermented food systems, as demonstrated in tempeh and yogurt research, provides a foundation for investigating fibre-containing fermented products (Ahmed et al., 2024; Rashid et al., 2026). Furthermore, AI-guided fermentation approaches could facilitate the optimization of microbial growth conditions, fermentation duration and product functionality (Butt et al., 2026f; Khan et al., 2025). These integrations may expand the applications of recovered polysaccharides beyond conventional bakery products.

7.4. Integration with Agricultural Biotechnology and Crop Sciences

The availability and composition of agro-industrial residues are influenced by crop variety, cultivation conditions, geographical origin, maturity and agricultural practices.

Therefore, agricultural biotechnology and crop sciences can contribute to understanding the variability of raw materials before their incorporation into food systems.

Future investigations could examine the influence of cultivar selection, environmental stress and postharvest handling on the dietary fibre and pectin composition of citrus fruits, apples and sugar beet. Research on CRISPR-Cas-mediated crop improvement and the modification of stress-response pathways demonstrates the potential of agricultural biotechnology for improving crop performance under changing environmental conditions (Jabeen et al., 2025; Fatima et al., 2026). Similarly, studies examining trehalose-mediated alleviation of salinity stress in cauliflower provide an example of the relationship between crop stress physiology and agricultural productivity (Shafeeq et al., 2026).

These research directions may indirectly contribute to the availability and consistency of agro-industrial raw materials. In the longer term, integrating crop science with food ingredient characterization could help identify agricultural production systems that provide both desirable primary products and valuable processing residues.

7.5. Integration with Computational Biology, Artificial Intelligence and Data Science

Computational modelling and artificial intelligence offer opportunities to improve formulation design, ingredient characterization and process optimization. The present Monte Carlo framework provides an initial method for propagating uncertainty in ingredient composition and predicting nutritional and functional outcomes across eight biscuit treatments.

Future research could combine Monte Carlo simulation with machine learning and Bayesian inference to develop more reliable predictive models. Experimentally measured data could be used to train models for predicting dietary fibre content, pectin recovery, water-holding capacity, biscuit hardness, colour and sensory performance under different formulation and processing conditions.

Research on AI-guided precision fermentation and nutrigenomic modelling provides relevant examples of integrating computational methods with food technology and nutritional sciences (Butt et al., 2026f; Butt et al., 2026g). The application of multi-omics approaches in environmental and biological investigations further demonstrates the potential of integrating complex datasets to understand interactions between biological systems and external factors (Ullah et al., 2026a).

In future studies, data from proximate composition, dietary fibre analysis, pectin characterization, antioxidant assays, texture profile analysis and sensory evaluation could be integrated into a common predictive framework. This would allow formulation optimization based on multiple response variables rather than relying exclusively on dietary fibre concentration.

7.6. Integration with Environmental Sciences and Circular Bioeconomy

The proposed research is closely associated with environmental sustainability because it focuses on converting processing residues into value-added food ingredients. Citrus peels, apple pomace and sugar beet pulp can otherwise contribute to waste-management challenges when generated in large quantities without suitable utilization pathways.

Their conversion into dietary fibre and pectin ingredients may support resource efficiency, waste minimization and the development of circular food-processing systems. However, the environmental benefits of these approaches should be quantified rather than assumed. Future studies should incorporate life-cycle assessment, energy consumption, water utilization, processing emissions, transportation requirements and residual waste generation.

Research on sustainable hybrid protein development and sustainability performance provides broader perspectives on resource-efficient production and the organizational dimensions of environmental responsibility (Butt et al., 2025c; Khurshid et al., 2026). Environmental monitoring studies involving emerging contaminants and aquatic

ecosystems also demonstrate the importance of considering environmental quality when evaluating industrial and agricultural production systems (Ullah et al., 2026a; Ullah et al., 2026b).

Furthermore, environmental DNA-based biodiversity monitoring can provide methodological perspectives for assessing environmental changes associated with agricultural and industrial activities (Iqbal et al., 2024). Integrating these approaches with food-waste valorisation could help establish a more comprehensive sustainability framework connecting agricultural production, food processing, residue recovery and environmental protection.

7.7. Integration with Food Safety, Toxicology and Regulatory Sciences

The development of functional ingredients from agro-industrial residues requires careful consideration of food safety and regulatory compliance. Although citrus peels, apple pomace and sugar beet pulp originate from food-processing operations, their suitability for direct food incorporation cannot be assumed without appropriate safety assessment.

Future studies should evaluate pesticide residues, heavy metals, mycotoxins, microbial contamination and other relevant chemical or biological hazards. The safety of recovered ingredients should also be assessed following drying, extraction, concentration and storage.

Previous research examining heavy metal-associated risks in raw milk and toxicological responses to microplastic and nanoplastic exposure demonstrates the importance of analytical surveillance and toxicological evaluation in food and environmental systems (Riaz et al., 2026b; Ullah et al., 2026b). Similarly, research on nutritional and biosafety assessment of modified hybrid proteins provides a relevant example of integrating nutritional evaluation with safety-oriented investigation (Butt et al., 2025a).

Future research should also distinguish between food-grade fibre ingredients, isolated pectin and concentrated bioactive extracts because their processing requirements, exposure characteristics and regulatory considerations may differ.

7.8. Integration with Industrial Processing, Economics and Sustainable Manufacturing

The transition from laboratory-scale formulation to industrial application requires integration with food manufacturing, process economics and supply-chain management. The availability of citrus peels, apple pomace and sugar beet pulp may vary according to season, geographical location and processing capacity. Therefore, future studies should examine raw material collection, transportation, drying, storage, processing costs and the economic feasibility of ingredient recovery.

The development of standardized fibre powders and pectin-rich ingredients could support their incorporation into existing food manufacturing operations. Their commercial potential should be evaluated through cost-benefit analysis, ingredient recovery efficiency, product stability and consumer acceptance.

Research on sustainable food manufacturing and hybrid ingredient development demonstrates the importance of integrating nutritional performance with processing feasibility (Butt et al., 2025c; Adnan et al., 2026). Furthermore, investigations of AI-guided optimization and strategic decision systems provide broader methodological perspectives for evaluating complex production processes and resource-allocation decisions (Butt et al., 2026f; Naeem et al., 2026a).

Ultimately, the successful valorisation of these by-products will depend on developing economically feasible processing systems that deliver consistent ingredient quality while minimizing environmental burdens.

7.9. Integration with Systems Modelling and Multi-Criteria Decision Science

A further opportunity involves connecting food formulation with systems modelling and multi-criteria decision science. The present research considers dietary fibre, soluble

dietary fibre, theoretical pectin contribution, water-holding capacity, hardness and sensory acceptability as interconnected response variables.

Future studies could expand this framework by integrating nutritional quality, processing performance, microbial stability, economic feasibility and environmental indicators into a single decision-support model. Constrained mixture designs, response surface methodology, probabilistic modelling and sensitivity analysis could be used to identify formulations that balance competing product-development objectives.

Research applying computational investigation, numerical modelling and simulation-based decision frameworks in other domains provides methodological examples of how complex systems can be evaluated through integrated analytical approaches (Shah & Butt, 2026; Tahir et al., 2026; Naeem et al., 2026a). However, the application of such approaches to functional food development requires food-specific experimental calibration and independent validation.

The integration of these methods could eventually support the development of predictive formulation platforms capable of estimating nutritional enrichment, technological functionality, sensory performance and environmental implications before large-scale manufacturing.

7.10. Overall Interdisciplinary Research Perspective

The future development of citrus peel-, apple pomace- and sugar beet pulp-based functional ingredients will require coordinated contributions from several scientific disciplines. Food chemistry will establish their molecular and compositional characteristics; food engineering will optimize extraction and processing; nutritional sciences will investigate dietary fibre functionality; microbiology and biotechnology will assess microbial stability and fermentation potential; agricultural sciences will address raw material variability; and computational modelling will facilitate formulation optimization.

Environmental sciences and industrial sustainability will further establish the feasibility of integrating these ingredients into circular food-processing systems. Such interdisciplinary collaboration could transform agro-industrial residues from underutilized processing materials into standardized, multifunctional ingredients for sustainable food development.

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Appendix A. Reproducible Python implementation

The following code provides a reproducible implementation of the principal mass-balance simulation. It writes a CSV file containing treatment-level summaries. The code should be run after confirming the model assumptions and should be considered a computational screening tool, not a validated predictive model.

```
import numpy as np
    import pandas as pd

    rng = np.random.default_rng(20261115)
    N = 100_000
    replacement = 0.10
```

```
params = {
   "CPP": {"tdf": (55, 4), "sdf": (0.25, 0.04),
         "pectin": (25, 3), "whc": (6.0, 0.8)},
   "APP": {"tdf": (40, 4), "sdf": (0.22, 0.04),
         "pectin": (12.5, 2), "whc": (4.5, 0.7)},
   "SBPP": {"tdf": (65, 5), "sdf": (0.30, 0.05),
          "pectin": (22.5, 3), "whc": (8.0, 1.0)}
}

treatments = {
   "T0": {},
   "T1": {"CPP": 1},
   "T2": {"APP": 1},
   "T3": {"SBPP": 1},
   "T4": {"CPP": 0.5, "APP": 0.5},
   "T5": {"CPP": 0.5, "SBPP": 0.5},
   "T6": {"APP": 0.5, "SBPP": 0.5},
   "T7": {"CPP": 1/3, "APP": 1/3, "SBPP": 1/3}
}

rows = []
for treatment, blend in treatments.items():
   control_tdf = np.clip(rng.normal(2.7, 0.25, N), 1.8, 3.5)
   if treatment == "T0":
      tdf = control_tdf
      sdf = np.clip(rng.normal(0.95, 0.12, N), 0.5, 1.4)
      pectin = np.clip(rng.normal(0.25, 0.05, N), 0.05, 0.5)
      whc = np.clip(rng.normal(1.2, 0.15, N), 0.7, 1.8)
      hardness = rng.normal(28, 3, N)
      sensory = rng.normal(7.6, 0.35, N)
   else:
      mix_tdf = np.zeros(N)
      mix_sdf = np.zeros(N)
      mix_pectin = np.zeros(N)
      mix_whc = np.zeros(N)
      for ingredient, weight in blend.items():
         p = params[ingredient]
         tf = np.clip(rng.normal(*p["tdf"], N),
                  p["tdf"][0]-3*p["tdf"][1],
                  p["tdf"][0]+3*p["tdf"][1])
         sf = np.clip(rng.normal(*p["sdf"], N), 0.08, 0.5)
         pc = np.clip(rng.normal(*p["pectin"], N), 1, None)
         wh = np.clip(rng.normal(*p["whc"], N), 0.5, None)
         mix_tdf += weight * tf
         mix_sdf += weight * tf * sf
         mix_pectin += weight * pc
         mix_whc += weight * wh

      tdf = 0.9 * control_tdf + replacement * mix_tdf
      sdf = 0.9 * 0.95 + replacement * mix_sdf
      pectin = 0.9 * 0.25 + replacement * mix_pectin
      whc = 0.9 * 1.2 + replacement * mix_whc
      hardness = 28 + 0.55*(tdf-2.7) + 0.35*(whc-1.2) + rng.normal(0, 3, N)
```

```
        penalties = {"T1":0.55, "T2":0.35, "T3":0.50,
                     "T4":0.40, "T5":0.65, "T6":0.50, "T7":0.45}
        sensory = 7.6 - penalties[treatment] - 0.10*(tdf-5) + rng.normal(0, 0.4, N)

    outputs = {"TDF":tdf, "SDF":sdf, "Pectin":pectin,
               "WHC":whc, "Hardness":hardness, "Sensory":sensory}
    row = {"Treatment": treatment}
    for name, values in outputs.items():
        row[name+"_mean"] = np.mean(values)
        row[name+"_2.5%"] = np.quantile(values, 0.025)
        row[name+"_97.5%"] = np.quantile(values, 0.975)
    rows.append(row)

results = pd.DataFrame(rows)
results.to_csv("Monte_Carlo_Biscuit_Results.csv", index=False)
print(results.round(3).to_string(index=False))
```