fermentation

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Review

Fermenting the Unused: Microbial Biotransformation of Food Industry By-Products for Circular Bioeconomy Valorisation

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Table S1. Plant-based co-fermentation and mixed-substrate fermentation strategies relevant to nutrient balancing and functional enhancement

Co-fermentation purpose	Fermented plant-based matrix	Microorganism(s) used	Main functional outcome expected / reported	Reference(s)
Release of bound phenolics and enhancement of antioxidant capacity	Grape pomace (skins, seeds, marc)	*Aspergillus niger*, *Rhizopus* spp., mixed filamentous fungi	Increased free phenolic acids, higher antioxidant activity, improved extract functionality through enzymatic hydrolysis of cell-wall–bound polyphenols	[26,28,98,155]
Improvement of soluble phenolic profile and antioxidant activity via fungal SSF	Grape pomace seeds	Filamentous fungi (SSF)	Enhanced release of soluble phenolics and increased radical-scavenging capacity	[98]
Broadening metabolite profile through mixed plant substrates and/or mixed cultures	Apple pomace and grape pomace	Mixed microbial consortia (LAB, yeasts)	Diversified fermentation chemistry, improved antioxidant and functional profiles	[156]
Enhancement of bioactive compound recovery using fermentation-assisted valorisation	Fruit pomace (general: grape, apple, berry)	LAB and/or filamentous fungi	Improved bioavailability of phenolics and formation of functional metabolites	[27,28,157]
Protein and amino acid enrichment of carbohydrate-rich	Citrus pomace	*Bacillus amyloliquefaciens* + *Candida utilis*	Increased crude protein and amino acid content, improved nutritional balance of pomace	[158]

residues via co-culture fermentation				
Production of fermented functional beverages with enhanced antioxidant activity	Grape pomace (kombucha-style substrate)	SCOBY (acetic acid bacteria + yeasts)	Increased phenolics, organic acids and bioactivity; improved sensory profile	[106]
Improved phenolic bioavailability through lactic fermentation	Grape marc	Lactic acid bacteria	Increased free phenolic compounds and antioxidant activity	[77,136]
Conceptual nutrient balancing through mixed plant residues (carbohydrate vs protein/fibre rich)	Fruit and vegetable by-products (pomace, peels, bran blends)	LAB, yeasts, filamentous fungi (varies)	Improved microbial growth, enhanced release of phenolics and peptides, better functional profiles	[6–8]
Valorisation of plant by-products into functional ingredients via fermentation	Fruit and vegetable processing wastes	LAB and mixed microbial cultures	Stabilisation, increased antioxidant capacity, functional ingredient development	[5,18,159]
Balance C/N ratio to improve fermentation performance and product yields	Fruit pomace (grape, apple, citrus), fruit/veg processing wastes	Legume residues, oilseed press cakes, cereal/bran co-streams	Improved nitrogen availability supports microbial growth and enzymatic biotransformation, favouring higher release of bioactives (phenolics) and increased formation of protein-derived fractions (peptides/AA)	[6–8,27]
Increase release of bound phenolics and antioxidant capacity via microbial enzymes	Grape pomace / grape seeds / grape marc	(Plant co-streams not always specified)	Higher free phenolics, improved antioxidant activity and extract functionality	[76,98,155]
Broaden metabolite spectrum using mixed feedstocks and mixed cultures	Apple & grape pomace blends; grape pomace	Additional plant streams in blends; sugar/juice concentrates	More diverse fermentation chemistry (acids, volatiles, phenolic derivatives) and improved functional profiles	[65,106]
Demonstrate “nutrient limitation relief” through co-fermentation that increases protein/AA content	Citrus pomace	Co-culture organisms (bacteria + yeast), used as a protein-enrichment route	Increased crude protein and amino acids; improved nutritional quality (strong mechanistic analogue for “adding N-rich co-substrate”)	[158]

in plant residues (principle applicable to press-cake blending)				
Justify press cakes as realistic N-rich co-substrates and show they can be "process-conditioned" for bioprocessing	Oilseed Cake	Cold-pressed oilseed cakes (protein-rich)	Improved nutritional value and functionality after processing; supports feasibility of using press cakes as N-rich co-substrate	[160]
Provide context that plant by-products are routinely upgraded into functional ingredients (supports co-stream blending logic)	Fruit/vegetable by-products including pomace and peels	Plant co-streams (cereal/legume residues), depending on formulation	Functional ingredient development through processing/modification; fermentation can be positioned as an additional upgrading step	[4,24,99,161–163]

Table S2. Plant–animal co-fermentation and mixed-substrate fermentation strategies reported in the literature

Co-fermentation purpose	Fermented matrix (plant + animal)	Microorganism(s) used	Main functional outcome reported / expected	Reference(s)
Enhancement of lactic acid production and phenolic biotransformation	Whey + fruit pomace	Lactic acid bacteria (various LAB strains)	Increased lactic acid yield; improved phenolic transformation and antioxidant potential; enhanced matrix suitability for LAB growth	[16,35,164,165]
Valorisation of dairy by-products through mixed plant substrates	Whey or acid whey + fruit/vegetable residues	LAB, yeasts	Improved fermentation efficiency; generation of bioactive peptides and organic acids; functional beverage development	[34,38]
Reduction of marine odors and improvement of fermentation kinetics	Fish hydrolysates or fish by-products + vegetable residues	LAB and mixed microbial cultures	Odor reduction, faster acidification, enhanced proteolysis, improved sensory acceptability	[51,166]
Production of peptide-rich functional ingredients	Fish by-products + plant residues	LAB, endogenous enzymes	Generation of antioxidant and bioactive peptides; improved digestibility and stability	[46,52,55,109]
Generation of peptide-rich ingredients with balanced amino acid profiles	Blood proteins + cereal bran	Proteolytic bacteria / fermentation-associated microbiota	Enhanced peptide release; improved amino acid balance and bioactivity	[39,41,44,155]
Stabilisation and nutritional upgrading of animal-derived feed ingredients	Fish viscera or silage + plant carbohydrate sources	LAB, mixed cultures	Improved microbial safety, higher digestibility, reduced reliance on fishmeal	[110,167,168]

Table S3. Decision-oriented framework linking substrate class, inhibitory constraints, microbial selection, fermentation configuration, and downstream implications in fermentation-based valorization of food-industry by-products*.

Substrate class	Key inhibitors/constraints	Preferred microbes	Process mode	Downstream implications
Carbohydrate-rich plant pomace	Phenolics, low N	LAB, yeasts, fungi	SSF / anaerobic SmF	Phenolic recovery, concentration
Protein/collagen-rich animal	Odour, spoilage	*Bacillus*, LAB, consortia	Aerobic/anaerobic	Deodorisation, safety validation
Lipid-rich fish residues	Oxidation, salts	LAB, fungi, halotolerant strains	Controlled SmF	Antioxidant use, lipid stability
High-salt streams	Osmotic stress	Halotolerant LAB/yeasts	SmF	Salt removal, compliance
Phenolic-rich matrices	Growth inhibition	Fungi, consortia	Aerobic SSF	Detoxification, extraction

*Decision-oriented framework translating major food-industry by-product classes and their typical inhibitory or safety-related constraints into preferred microbial groups, fermentation modes (SSF vs SmF; aerobic vs anaerobic), and key downstream processing implications. The framework synthesizes established fermentation principles and evidence discussed throughout Section 3 and is intended as practical guidance rather than a prescriptive design tool.