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Valorization of agri-food waste and by-products in cheese and other dairy foods: An updated review

Ines Tarchi[a,b], Sofiane Boudalia[c], Fatih Ozogul[d,e], José S. Câmara[f,g], Zuhaib F. Bhat[h], Abdo Hassoun[i], Rosa Perestrelo[f], Mohamed Bouaziz[a,j], Siti Nurmilah[k], Yana Cahyana[k], Abderrahmane Aït-Kaddour[b,k,*]

[a] Laboratoire D'Electrochimie et Environnement, Ecole Nationale D'Ingénieurs de Sfax (ENIS), Université de Sfax, BP 1175, 3038, Sfax, Tunisia
[b] Université Clermont-Auvergne, INRAE, VetAgro Sup, Unité Mixte de Recherche sur le Fromage UMRF, 89 Avenue de L'Europe, France
[c] Laboratoire de Biologie, Eau et Environnement, Faculté des Sciences de La Nature et de La Vie et Sciences de La Terre et de L'Univers, Université 8 Mai 1945 Guelma, P. O. Box 4010, Guelma, 24000, Algeria
[d] Department of Seafood Processing Technology, Faculty of Fisheries, Cukurova University, Adana, Turkey
[e] Biotechnology Research and Application Center, Cukurova University, Adana, Turkey
[f] CQM - Centro de Química da Madeira, NPRG, Campus da Penteada, Universidade da Madeira, 9020-105, Funchal, Portugal
[g] Departamento de Química, Faculdade de Ciências Exatas e Engenharia, Campus da Penteada, Universidade da Madeira, 9020-105, Funchal, Portugal
[h] Division of Livestock Products Technology, SKUAST-J, India
[i] Sustainable AgriFoodtech Innovation & Research (SAFIR), F-62000, Arras, France
[j] Institut Supérieur de Biotechnologie de Sfax, Université de Sfax, BP1175, 3038, Sfax, Tunisia
[k] Faculty of Agro-Industrial Technology, UniversitasPadjadjaran, Sumedang, Indonesia

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ABSTRACT

Food waste and by-products have attracted attention in recent years due to the reduction of food resources and the negative impact on the environment of current production and consumption systems. However, food waste and by-products can be transformed into new products that can be useful for human consumption because they represent a source of nutritional and technological (e.g., preservative, colorant, fibres) added-value compounds. Those compounds of interest can be extracted using several advanced and/or emerging extraction techniques, which follow the green chemistry principles, and incorporated into food products. This is true for many types of foods; even dairy products of which cheese is one of the most appreciated and consumed worldwide. Therefore, cheese and dairy products can be effective vehicles for food waste and food by-products valorization.

This review focuses on the opportunities for valuing various food wastes in the dairy sector, especially in cheese. It also highlights the contributions of recovered bioactive added-value compounds in enhancing the nutritional, technological, and sensory properties of dairy products. It is expected that food wastes could be used to improve functionalities of dairy products in the future, leading to innovative functional dairy food products to decrease the environmental footprint and simultaneously contribute to improve sustainability in the food sector.

1. Introduction

The United Nations has estimated that the world population will reach nearly 10 billion people by 2050 and approximately 11 billion by 2100 (UN, 2019, pp. 8–12). As the population increases, a parallel growth in the production of raw materials, processed foods, and goods is inevitable. Besides being a clear economic problem for agri-food industries (e.g., high processing costs, low energy efficiency), food waste and by-products increase environmental pollution (Fig. 1) and contribute to an unbalanced relationship between the scale of wastes and the malnutrition and hunger crisis facing a large part of the human population (Zhang et al., 2020). Regarding the environmental impact, food waste and by-products were evaluated as contributing to more than 20% of the total global production of greenhouse gases, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (emission of 3.3 billion tons of CO_2 per year), which contribute significantly to

* Corresponding author. Université Clermont-Auvergne, INRAE, VetAgro Sup, Unité Mixte de Recherche sur le Fromage UMRF, 89 Avenue de L'Europe, 63370, Lempdes, France.
E-mail address: abderrahmane.aitkaddour@vetagro-sup.fr (A. Aït-Kaddour).

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climate changes (Murugesan, Raja, Dutta, Moses, & Anandharamakrishnan, 2022; Peydayesh, Bagnani, Soon, & Mezzenga, 2023). Concerning the hunger crisis, it has been stated that about 805 million people are already suffering from hunger worldwide (FAO, 2021), while it is estimated that approximately 1.3 billion tonnes of waste are produced annually worldwide during the supply chain (30%–40% of food production wasted). In Europe, over 58 million tonnes of food waste (131 kg/person) are produced yearly representing a market value estimated to be worth 132 billion € (Eurostat, 2023).

Therefore, it is nowadays mandatory to implement alternative strategies to decrease and mitigate these negative effects on the economy, ecosystems, and population well-being, by proposing more sustainable ways of managing the negative impact of human waste and by-products (FAO, 2022). Solutions to the problems caused by food waste and by-products can focus on decreasing their production through better management of the supply chain (from farm to fork) or their valorization as a sustainable way of exploring and converting food waste and by-products into value-added products limiting by this way the disposal of food wastes in landfills and decreasing greenhouse gas emissions (Mak, Xiong, Tsang, Yu, & Poon, 2020). Several strategies can be implemented to decrease the environmental impact related to the food industry. Implementing water, and energy-efficient technologies (solar, wind, and hydropower), supporting the use of products made from sustainable materials, and encouraging initiatives based on circular economy practices, may contribute to a significant reduction in the overall environmental footprint.

Fruits and vegetables have the highest wastage rate (~45%) among different consumable food products in the world (FAO, 2021). However, waste and by-products such as peels, trimmings, shells, seeds, and bran constitute rich sources of primary and secondary health-promoting compounds that can be valorized. Primary compounds refer to sugars, amino acids, proteins, and chlorophyll; while secondary compounds involve alkaloids, flavonoids, saponins, tannins, carotenoids, and phenolic compounds, among others (Poiroux-Gonord et al., 2010; Rodríguez-Pérez, Quirantes-Piné, Fernández-Gutiérrez, & Segura-Carretero, 2013; Sepúlveda et al., 2012; Shi et al., 2015). Value-added compounds, such as complex polysaccharides, carbohydrates, proteins, polyphenols, and vitamins, can also be obtained from agri-food waste and by-products (Vodnar et al., 2019; Yusuf, 2019). These bioactive compounds can be incorporated into foods to involve a wide range of functions such as enrichment, coloring, stability against oxidation, and microbial proliferation (Marcillo-Parra, Anaguano, Molina, Tupuna-Yerovi, & Ruales, 2021). Moreover, as can be observed in Fig. 2, these bioactive compounds exhibit a wide range of biological activities including antioxidant, antidiabetic, antihypertensive, anti-Alzheimer, antiproliferative, and antimicrobial activity, among others. This gives them significant preventive potential in the development of chronic diseases mediated by oxidative stress including cardiovascular, oncologic, and neurodegenerative diseases. Furthermore, they represent an obvious potential market due to their affordable price, availability, and accessibility (Tylewicz, Nowacka, Martín-García, Wiktor, & Gómez Caravaca, 2018; Villacís-Chiriboga, Vera, Van Camp, Ruales, & Elst, 2021).

Milk is an important food product in the diet of approximately 6 billion people worldwide (OECD/FAO, 2023). In addition to milk, several milk-derived products such as cheese, yogurt, ice cream, and butter, among others, are widely produced and consumed. Therefore, milk and dairy products may be a strategic choice and an easy way to valorize agri-food waste and by-products to strengthen their nutritional and techno-functional characteristics and to provide new ingredients for the formulation of innovative dairy foods (El-Messery, Aly, López-Nicolas, Sánchez-Moya, & Ros, 2021). However, fortification of such dairy products must not alter their sensory or physical characteristics in order to preserve the finished product's consumer acceptability and palatability. Therefore, agri-food waste and by-product valorization in milk and dairy products and their impact on their characteristics (e.g., nutritional quality, physical and sensory properties) have been a focus of considerable research over the last 10 years (Fig. 3). To the best of our knowledge, no review gathering the findings of different research publications in this field has been found in the literature. Therefore, this review aims to gather and discuss the latest scientific research, dealing with the valorization of food waste and by-products into dairy products, especially in cheese.

2. research methodology

The Scopus bibliographic database was used to identify and select publications. The Scopus platform was explored due to its high journal coverage compared to similar database platforms such as Web of Science, PubMed, and Medline (Baykoucheva, 2010; Falagas, Pitsouni, Malietzis, & Pappas, 2008). The criteria used to select articles were title, abstract, keywords, as well as year of publication spanning over almost 10 years (from 2013 to August 2023). The search took place in August 2023 using the terms.

i. '*Food* AND *byproducts* AND *in* AND *milk*';

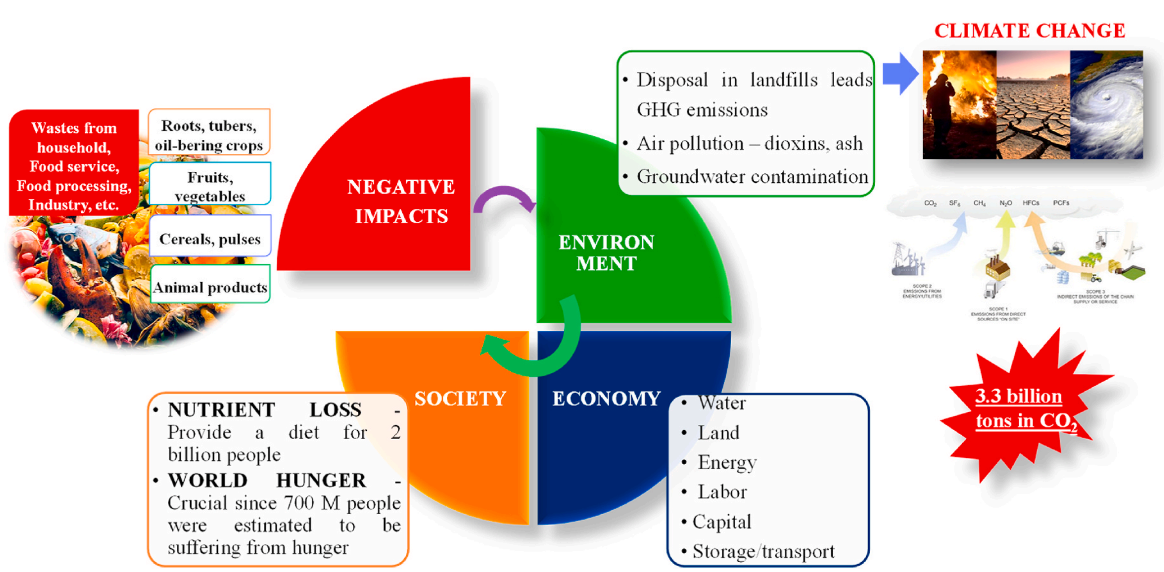

Fig. 1. Potential impacts of food waste and by-products.

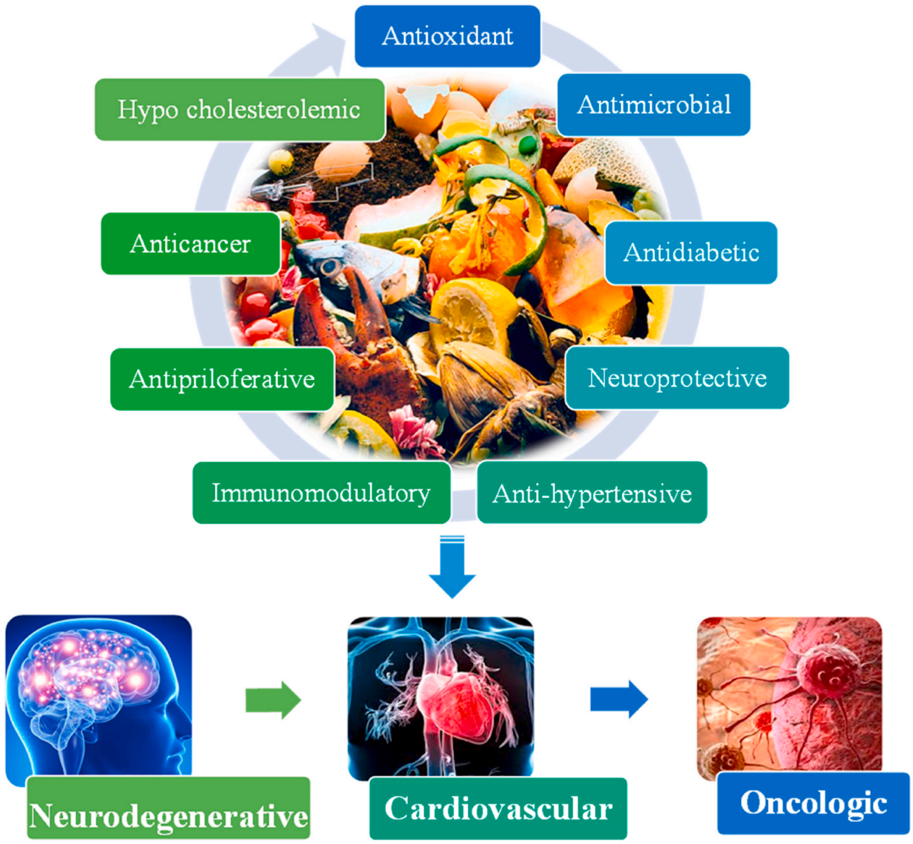

Fig. 2. Biological properties of bioactive compounds recovered from food waste and by-products.

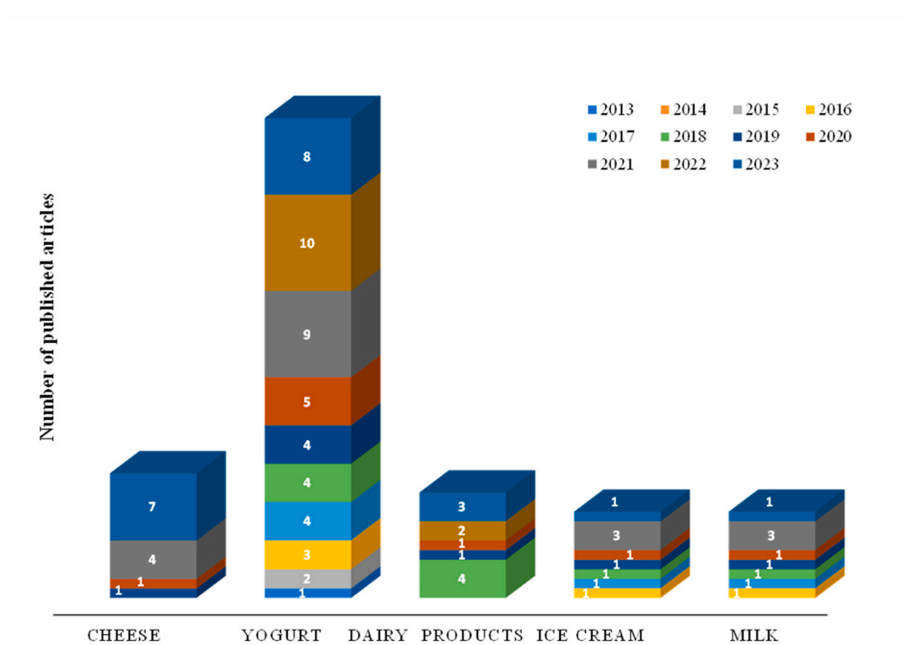

Fig. 3. Distribution of the number of articles per year on the recovery of food waste and by-products in dairy products.

ii. '*Food* AND *wastes* AND *in* AND *milk*';
iii. '*Food* AND *wastes* AND *in* AND *cheese*';
iv. '*Food* AND *byproducts* AND *in* AND cheese';
v. '*Food* AND *wastes* AND *in* AND *yogurt*';
vi. '*food* AND *byproducts* AND *in* AND *yogurt*';
vii. '*Food* AND *byproducts* AND *in* AND *dairy* AND *products*';
viii. '*Food* AND *wastes* AND *in* AND *dairy* AND *products*';
ix. '*Food* AND *byproducts* AND *in* AND *ice* AND *cream*';

By including all the types of publications (i.e., articles, reviews, book, book chapters), the initial number of papers extracted contained 33 duplicate items, which were removed. Of the remaining 101 articles, 10 were eliminated due to their year of publication, which fell outside the temporal spectrum defined in this study. The 91 remaining articles were examined.

These publications selected were published in esteemed journals, including the Journal of Food Processing and Preservation, with an impact factor of approximately 2.93, along with Foods (IF = 5.42), LWT (IF = 6.91), and Food Chemistry (IF = 10.07) (Table 1).

Fig. 3 shows that the exploration of food waste and by-products utilization was predominantly centered on yogurt, with a substantial number of papers, n = 51, dedicated to this topic. In contrast, cheese gathered attention in only 17 articles, while dairy products, milk, and ice cream received 12, 11, and 10 articles, respectively. This distribution accurately reflects the current research landscape in this field.

3. Composition of the main sources of waste and by-products

3.1. Fruits and vegetables

In the human diet, fruits are a source of several bioactive components such as fiber, phytosterols, acids, minerals, polyphenols, provitamin A, amino acids, aromatic compounds, carotenoids, and water-soluble vitamins (such as C and B complex). Fruits have low levels of lipids in their pulp and peel, but the majority of these substances are found in their seeds, which are rarely eaten. Fruits vary and are not always high in protein (Maheshwari, Kumar, Bhadauria, & Mishra, 2022; Pereira, Berenguer, Andrade, & Câmara, 2022). Furthermore, fruits have a high fiber content, which helps with digestion and is associated with a lower risk of cancer, cardiovascular disease, and gastrointestinal disorders. Additionally, fruits provide adequate amounts of oligosaccharides that encourage lactobacilli and bifidobacteria to colonize the colon (Fernandez & Marette, 2017). Therefore, when mixed with dairy products (yogurt, cheese, ice cream), fruit waste and by-products may increase their health benefits. In addition to meeting the body's needs for essential nutrients, it would assist people in overcoming nutritional inadequacies and enhancing sensory qualities (such as color, taste, and aroma).

Table 1
The bibliometric information of the first 18 journals presenting the high number of articles or reviews.

Journal title	N° of articles	Impact factor	h-index	SJR[a]	Ranking
Journal of Food Processing and Preservation	8	2.93	56	0.494	10429
Foods	6	5.42	73	0.771	6289
LWT	6	6.91	158	1.173	3202
Food Chemistry	4	10.07	302	1.624	1871
Journal of Dairy Science	3	3.70	216	1.179	3177
Journal of Food Science	3	4.03	170	0.711	6983
Journal of Microencapsulation	3	3.99	85	0.511	10136
Antioxidants	2	7.07	83	1.084	3679
Applied Biochemistry and Biotechnology	2	3.38	127	0.514	10073
Biomolecules	2	5.61	89	1.074	3733
Biotechnology and Applied Biochemistry	2	3.01	78	0.467	10961
Brazilian Journal of Food Technology	2	1.08	16	0.268	16206
Fermentation	2	3.85	43	0.518	10015
Food and Function	2	6.51	102	1.103	3581
International Journal of Food Science	2	3.95	32	0.625	8184
Journal of Agricultural and Food Chemistry	2	6.21	328	1.099	3603
Nutrients	2	6.01	178	1.291	2754
Pakistan Journal of Biological Sciences	2	1.01	49	0.239	17320

[a] SJR: Scientific Journal Ranking.

Vegetables constitute a crucial source of essential vitamins, with a notable presence of Vitamin C, A, B1, B6, B9, and E. Additionally, they provide a rich array of minerals, particularly potassium, calcium, and magnesium, along with dietary fiber (Górska-Warsewicz, Rejman, Kaczorowska, & Laskowski, 2021). Within vegetables, diverse bioactive compounds contribute to their nutritional value. Polyphenols, primarily concentrated in leaves and flowers, and carotenoids, present in vegetables displaying yellow, orange, red, or purple pigmentation, are among these beneficial compounds (Górska-Warsewicz et al., 2021; Lombardelli, Benucci, Mazzocchi, & Esti, 2022; Nabi et al., 2023). Vegetables contain also phytosterols, contributing to their overall nutritional profile. Regarding macronutrients, specific vegetables, such as green peas, fresh broad beans, and Brussels sprouts, may contain substantial amounts of protein. Carbohydrates are present in notable quantities in vegetables like beets, sweet kernel corn (non-dried), baby corn, and parsnips. This comprehensive nutritional composition underscores the importance of vegetables in promoting a balanced and healthy diet (Górska-Warsewicz et al., 2021).

Vegetables serve as excellent additions to food products, not only due to their nutritional value but also for the desired taste, color, and aroma they impart. Various vegetables and fruits, or derivatives thereof, have found their way into diverse food items such as cheese and yogurt (Fernandez & Marette, 2017). Incorporating these products into yogurt offers additional benefits, as vegetables contribute diverse nutritional profiles that may not be present in yogurt alone, such as dietary fiber.

Several food items, including ice cream, cheese, and flavored milk, have undergone testing and preparation with the inclusion of vegetables (Saleh et al., 2018). While fruits are more commonly employed for fortification, vegetables and their derivatives have been tested, and some have been optimized for the industrial production of vegetable-based products.

3.2. Cereals

The Gramineae family of cereals including wheat, rice, corn, rye, millet, and sorghum among others, are the most popular and widely consumed food products around the world (Patra et al., 2023), because they are rich in carbohydrates, protein, fiber, and micronutrients like zinc and magnesium as well as vitamin E and B. Carbohydrates are generally representing 75% of the cereal composition with a ratio of amylose to amylopectin in starch granules varying between varieties (wheat, rice and maize). Non-starch polysaccharides are present in all grains. According to Saini, Saxena, Samtiya, Puniya, and Dhewa (2021) oats, and rye exhibit higher levels of beta-glucans and arabinoxylans compared to wheat, with percentages on a dry weight basis of 3%–7%, 1%–2%, and less than 1%, respectively. The lipid content of cereals varies from 1% to 3% for barley, rye, rice, and wheat to 5%–9% for maize, and 5%–10% for oats. Cereals range in protein content from 6% to 15%. Except for yellow maize, cereals lack beta-carotene, vitamins C and B12 (Saini et al., 2021). However, cereals provide a great source of B vitamins like niacin, riboflavin, and thiamin (Baniwal, Mehra, Kumar, Sharma, & Kumar, 2021). Additionally, grains are packed with minerals, phytochemicals, or plant bioactive substances. Similar to other plant-based diets, grains are low in salt and high in potassium. Significant amounts of magnesium, iron, and zinc are also present in whole grain cereals, along with a reduced amount of certain trace elements, such as selenium that can have health-promoting properties. Grain also contains other antioxidants including tocotrienols, tocopherols, and carotenoids, however, flavonoids are only found in trace amounts (Belobrajdic & Bird, 2013).

In view of the nutritional and technological value of fruits, vegetables, and cereals and their waste or by-products they have been used in numerous research projects to enrich cheese and other dairy products (Table 2). The fortification of those products was generally investigated to increase their antioxidant properties, dietary fiber content, microbial quality, and functionality (e.g., sensory, texture).

Table 2
Valorization of food waste in cheese and other dairy products.

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
Mango skin or kernel	Substitute partially milk fat with mango kernel flour	–	Mango kernel fat	5%, 10%, 15% and 20%	Gouda cheese	Fortified cheeses exhibited: - higher antioxidant properties, - higher concentration of unsaturated fatty acids - higher oxidative stability	Khan et al. (2018)
White and red grape pomace powder, tomato peel, broccoli, corn bran, artichokes	Assess how the addition of various by-products affects the sensory and physicochemical characteristics of cheese	–	Phenolic and flavonoids compounds	5% (w/w)	Spreadable cheese	Fortified cheese presented: - higher total phenolic content, - higher flavonoids, - higher antioxidant activity	Lucera et al. (2018)
Grape pomace powder (GPP)	Produce a novel fresh ewes' milk pressed cheese Selected Lactococcus lactis strains resistant to the main grape phenolic compounds	–	–	1% (w/w)	Fresh ovine “primosale” cheese	Fortified cheese exhibited: - lower fat content, - higher protein content, - higher secondary lipid oxidation - higher antioxidant activity	Gaglio et al. (2021a)
Grape pomace powder	Assess the practicality of incorporating grape pomace powder into cheese Determine how this addition impacts the cheese's ripening process	–	Phenolic compounds	0.8% and 1.6 % (w/w)	Semi-hard and hard cheeses	Supplemented cheese presented: - higher total phenolic content - higher radical scavenging activity	Marchiani et al. (2016)
Red grape pomace powder	Improve the functional properties of cheese typology	–	–	1% (w/w)	Italian Vastedda cheese	Fortified cheese presented: - higher antioxidant activity - higher lipoperoxyl radical scavenger capacity	Gaglio et al. (2021b)
Asparagus powder	Enhance the nutritional qualities of processed cheese (PC) by examining the impact of incorporating asparagus powder on the rheological and physicochemical properties of fortified PC	–	–	0.5%, 1%, and 1.5% (w/w)	Processed cheese	Suppplemented cheese presented: - lower pH - lower lipolysis indexes - higher phenolic content - higher antioxidant activity - higher proteolysis - lower spreadability and higher elastic and rigidity behavior	Solhi et al. (2020)
Pomegranate rind extract	Examine the feasibility of using pomegranate (*Punica granatum*) peel extract as a new natural preservative for cheese Investigate the impact of varying levels of the extract on the lipid oxidative stability and storage characteristics of the cheese	–	–	1%, and 2%	Buffalo cheese “Kalari”	Supplemented cheese presented: - higher oxidative stability - lower values for total plate, psychrophilic yeast and mold counts - better sensory properties	
Olive oil mill by-product extracts	Enhance the shelf life of "Fior di latte" cheese during storage	Solid phase extraction	Polyphenolic compounds	250 and 500 μg/mL	Cheese	Fortified cheese presented: - a limited growth of the spoilage microorganisms - an extended the shelf life	Roila et al. (2019)
Wheat bran	Investigate the impacts of supplementing cheese with wheat bran (as a prebiotic) on	–	Fibers	0.1%, 0.2%, 0.3%, 0.4% and 0.5% milk	Egyptian cheese “Kariesh”	Fortified cheese exhibited: higher	Abd Elhamid (2016)

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Table 2 (*continued*)

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
	its physicochemical, rheological, and sensory characteristics					yield and moisture content - lower pH and protein content. - lower texture characteristics	
Chinese common dairy industry byproduct	Extend the shelf life of Eastern European curd cheese	–	Cinnamon carbon dioxide	0.3%	Eastern European curd cheese	Supplemented whey protein film: - increase the shelf of cheese curd - improved functional value of cheese curd.	Mileriene et al. (2021)
Tomato pomace	Assess the effect of lycopene, as a natural colorant, on the storage stability of ice cream	Solid-liquid extraction using alkaline solution	Lycopene	70 mg/kg	Ice-cream, butter and mayonnaise	Fortified ice cream exhibited and butter during storage: - lower development of off-flavor and off-odors - lower changes of color.	Kaur et al. (2011)
Pomegranate seed oil & pomegranate peel	Fortify ice cream with pomegranate peel phenolics Replace milk fat with pomegranate seed oil	Soxhlet technique (hexane).	Phenolics and punicic acid	0.2% and 0.4% (w/w)	Ice cream	Supplemented ice cream presented: - an increase in antioxidant - higher antidiabetic properties - higher phenolic content. - increase in conjugated fatty acid - an increase in perceived oxidized flavor.	Çam et al. (2013)
Orange by-products: peel, bagasse, and seed	Develop a reduced-fat lemon ice cream	–	Fibers	1.0%	Ice cream	Fortified ice cream exhibited: - lower fat content, - higher fiber and carotenoids contents - higher hardness, gumminess, and springiness parameters. - lower melting rate - no changes in acceptance by consumer.	Crizel et al. (2014)
Tomato peels	Improve the properties of ice cream using natural colorants and antioxidants	Solid-liquid extraction (ethanol)	Carotenoid (lyco-red)	0%, 1%, 2%, 3%, 4% and 5%	Ice cream	Fortified ice cream presented: - higher radical scavenging activity, - higher ferric reducing antioxidant power - higher scores for flavor, body and texture, melting and color.	Rizk et al. (2014)
Quince seed powder (QSP)	Improve the textural and melting properties of ice cream	–	Dietary fiber, polysaccharides and proteins	0.25%, 0.50% and 0.75%	Ice cream	supplemented ice cream presented: - reduced melting rate - enhanced the first dripping and complete melting times, - higher smoothness - lower hardness - higher overall acceptability	Kurt and Atalar (2018)
Rice byproduct	Create a prebiotic ice cream	Solid-liquid extraction (water)	Water-soluble extract from rice byproduct and long and medium-chain inulins	5%	Ice cream	Fortified ice cream exhibited: - higher antioxidant, anti-hypertensive,	da Silva et al. (2020)

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Table 2 (*continued*)

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
						anti-diabetic activities, - better health indexes.	
Grapefruit peel	Development of fat-reduced ice cream	Soxhlet technique	Nanofibrillated cellulose	0%–0.8%	Ice cream	Fortified ice cream presented high: - textural quality and an elastic behavior - lower fat content lower gross energy dropped - lower fat digestibility	Yu et al. (2021)
Coconut residue	Assess the effect of coconut residue fiber on the properties of probiotic ice cream throughout storage	–	Fibers	0.01 g/mL −0.03 g/mL	Ice cream	Supplemented ice cream showed: - stable probiotic viability, - soft texture, - low melting rate, - high protein, - low-fat, - appropriate pH for probiotics - acceptable sensory properties - that 0.02 g/mL of coconut residue was the best formulation for probiotic ice cream	Hanafi, Kamaruding, and Shaharuddin (2022)
Date fiber that remains after syrup extraction	Determine the amount of date fiber that could be incorporated into yogurt without affecting sensory quality and acceptability	Solid-liquid extraction	Phenolic compounds (Gallic acid, Procyanidin, Gallocatechingallate, 3-Coumaric acid, 2-Coumaric acid, Rutin)	1.5%, 3.0%, and 4.5%	Yogurt	Fortified yogurt presented: - higher pH - higher hardness - darker color (lower L* and higher a*) - acceptable sensory properties (with 3% fibers)	Hashim et al. (2009)
Dried grape and pomegranate seeds powder	Evaluated the effect of phenolic compounds extracted from grape seed and pomegranate seed on milk sheep yoghurts	Soxhlet technique	Phenolic compounds	2.5 ml/kg 10% solution	Sheep milk yogurt	Supplemented yogurt showed: - lower sensory properties (flavor, consistence and general acceptance) - lower physicochemical characteristics (total solids, titrable acidity, pH, total nitrogen, water soluble nitrogen and acetaldehyde) - lower peroxide and tyrosine values - lower *Lactobacillus bulgaricus* count at 14 days storage - decrease in *L. bulgaricus* and *S. thermophilus* counts during storage (14 days)	Ersöz, Kinik, Yerlikaya, and Açu (2011).
Olive and grape pomace	Develop a new probiotic food containing natural phenolic compounds	Solid-liquid extraction	Polyphenol	100 mg/L of milk	Fermented milk	Fortified fermented milk presented: - Phenolic compounds remain stable during the fermentation process - Phenolic compounds are not detrimental to the production process	Aliakbarian et al. (2015).

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Table 2 (*continued*)

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
Pineapple peel	Develop antioxidant and antimutagenic yogurts containing *Lactobacillusacidophilus*, *Lactobacilluscasei*, and *Lactobacillusparacasei* ssp. *Paracasei*	–	–	1% (wt/vol)	Yogurt	Supplemented yogurt exhibited: - higher degree of proteolysis that increase with time storage - stronger antimutagenic and antioxidant activities	Sah, Vasiljevic, McKechnie, and Donkor (2015).
Pineapple peel	Investigate the influence of incorporating pineapple peel on the physicochemical, textural, rheological, and microstructural properties of set-type yogurt during storage	–	Fibers	1% (w/v)	Yogurt	Fortified yogurt presented: - reduced fermentation time for milk co-fermented with probiotics - lower firmness and storage modulus.	Sah et al. (2016)
Powdered skin hazelnuts	Assess the feasibility of utilizing hazelnut skin as a source of dietary fiber and antioxidants in yogurt	–	Fibers	3% and 6%	Yogurt	Fortified yogurt showed: - higher total polyphenol content - higher antioxidant capacity. - that Georgia hazelnut skin presented the highest values for all the previous parameters - a decrease in consumer preference - for with 3% San Giovanni and Tonda Gentile Trilobata hazelnut skins the highest consumer preference.	Bertolino et al. (2015)
Apple pomace powder	Examine the impact of adding apple pomace powder on the acid milk coagulation process, as well as the texture and stability of the fermented product during storage	–	Phenolic compounds	0.1%, 0.5% and 1% (w/w)	Yogurt	Fortified yogurt presented: an early milk gelation stage (with 1% fortification), - firmness and cohesiveness - a uniform cellular structure	Wang et al. (2019)
Apple pomace powder	Investigate the effect of apple pomace powder as a natural stabilizer as well as a source of dietary fiber source in stirred-type yogurts and yogurt drinks	–	Phenolic compounds	1%, 2%, and 3%	Yogurt	Fortified yogurt showed: - higher firmness and cohesiveness, - higher viscosity - lower whey release during cold storage.	Wang et al. (2020)
Papaya peel powder	Develop a functional yogurt with reduced syneresis and improved nutritional value and antioxidant properties	–	Fibers	1.5% and 3.0% (w/w)	Yogurt	Fortified yogurt exhibited: higher viscosity - lower pH after storage - darker color, more yellowish color. - higher sensory scores (with 1.5% papaya peel powder).	Manzoor et al. (2019)
Banana peel fiber extract	Study the influence of various concentrations of banana fiber and banana peel fiber on the chemical and rheological characteristics of symbiotic yogurt made from camel milk	Solid-liquid extraction (water)	Fibers	0%, 0.2%, 0.5%, and 1%	Camel milk yogurt	Fortified yogurt presented: lower values for pH, hydration, surface tension - lower overall acceptability, color, and flavor - higher viscosity	Safdari et al. (2021)

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Table 2 (*continued*)

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
						- higher survival of probiotic - higher texture acceptance - lower syneresis	
Barley bran	Investigated the effect of barley bran on the quality characteristics of yogurt	–	Fibers	0.3%–1.2%	Yogurt	Fortified yoghurt presented: - a higher level of L. *acidophilus* - higher viscosity - lower sensory properties (at a level of 1.2%) - optimum properties for a 0.6% level of bran	Hasani et al. (2017)
Rice bran	Compared effects of adding rice bran before and after fermentation on the stability of yogurt Investigate the effect of rice bran on other properties of yogurt, with a focus on the optimal method of fortifying yogurt with rice bran	–	Phenolic compounds (gallic acid, protocatechuic acid, *p*-hydroxybenzoic acid, vanilic acid, chlorogenic acid, caffeic acid, syringic acid, *p*-coumaric acid, ferulic acid and sinapic acid)	2.0% and 3.0%	Yogurt	Fortified yoghurt with addition of bran before fermentation presented: - low syneresis - increased *p*-hydroxybenzoic acid, *p*-coumaric acid, ferulic acid and sinapic acid contents. Fortified yoghurt with addition of bran after fermentation presented: - Higher syneresis. All the yoghurts presented: - higher pH - lower firmness, consistency, cohesiveness, - lower viscosity and gel strength.	Wu et al. (2023)
Cheese whey-spent coffee ground powder	Assess the practicality of enriching a type-set yogurt with a recently developed ingredient containing cheese whey and spent coffee ground powder	–	–	100/0% (w/w), 75/25% (w/w), 25/75% (w/w), and 0/100% (w/w)	Greek-style yogurt	Fortified yoghurt showed: a decrease in water holding capacity depending on the level of fortification. - a decrease in hardness - a decrease in shear-thinning behavior.	Osorio-Arias et al. (2020)
Quince seed mucilage powder	Enhance the textural and rheological attributes of yogurt by incorporating quince seed mucilage powder, Explore a novel substitute stabilizer to replace existing synthetic or natural stabilizers that may have health consequences	–	–	0.15% and 0.2% (w/v)	Yogurt	Fortified yogurt showed: - lower syneresis - lower firmness, consistency, cohesiveness, compacity, cohesion - thinner gel structure - decreased sensory attributes.	Gürbüz, Erkaya-Kotan, and Şengül (2021)
Fermented durian seed powders	Examine the utilization of fermented durian seed powder as a functional ingredient in yogurt, and its impact on the physicochemical characteristics, LAB count, antioxidant properties, and consumer acceptance of set-type yogurt during refrigeration	Solid-liquid extraction (water) Soxhlet method (ethanol)	Phenolic compounds	–	Yogurt	Fortified yogurt presented: - redder hue - higher total phenolic content - higher antioxidant activity - higher syneresis - the best sensory properties with the MFDS extracted by ethanol.	Srianta et al. (2022)

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Table 2 (*continued*)

Wastes/by-products	Objective of the study	Extraction technique	Bioactive components or main component	Concentration of bioactive extracts	Dairy products fortified	Main conclusions	Reference
Carrot wastes extract	Create a practical symbiotic yogurt utilizing carrot wastes. Investigate the influence of microsphere production techniques on the viability of probiotics and the physicochemical characteristics of the product throughout storage	Solid-liquid extraction (ethanol)	Phenolic compounds	6% (w/w)	Yogurt	Fortified yogurt exhibited: better physicochemical properties - higher antioxidant quality - better survival of probiotic bacteria.	Sharifi et al. (2023)
Encapsulated carotenoid extracts from carrot wastes	Encapsulate natural β-carotene from carrot wastes in alginate beads using the electrostatic extrusion technique Investigate the possibility of developing fortified yogurt by including encapsulated natural β-carotene in the traditional formulation	Solid-liquid extraction	β-carotene	2.5% and 5% (w/w)	Yogurt	Fortified yogurt presented: better physico-chemical and microbiological characteristics during storage time. - higher antioxidant properties.	Šeregelj et al. (2021)

4. Food waste and by-product valorization in cheese and other dairy foods

4.1. Valorization in cheese

Cheese has been a popular dairy product for centuries, with its production dating back to 5200 BC (Salque et al., 2013). The process of making cheese typically involves curdling milk from various animal species (e.g., cow, sheep, goat, camel, buffalo) and separating the whey. This is achieved by fermenting the milk with a lactic acid bacteria starter and adding rennet enzyme, leading to changes in the proteins (predominantly casein), carbohydrates, and lipids. After removing the whey by heating, pressing, and/or addition of salt, the remaining product is left to mature by selected microorganisms for a varying period depending on the cheese category (e.g., fresh or matured) (Ferreira & Santos, 2023; Zheng, Shi, & Wang, 2021). Several factors play an essential role in the cheese-making process, depending on the production step, such as acidification, coagulation, whey separation, salting, shaping, and ripening (Boukria et al., 2020a). These factors can affect end-product characteristics, such as flavor and texture (Sachan & Karnwal, 2022).

Currently, numerous advancements have been made and utilized for the industrial production of cheese (Christaki, Moschakis, Kyriakoudi, Biliaderis, & Mourtzinos, 2021), such as using waste and by-products as a natural biosource of beneficial added-value compounds (e.g., proteins, lipids, carbohydrates, micronutrients, polyphenols, glucosinolates, carotenoids, and dietary fibres). These compounds can both enhance nutritional value and decrease environmental negative impacts caused by food waste and by-products (Fig. 4) (Torres-León et al., 2018). Therefore, different studies have shown interest in cheese fortification through the incorporation of different bioactive compounds from food waste and by-products.

In this context, dried powdered mango peel has been studied by Serna-Cock, García-Gonzales, and Torres-León (2016) for the development of cheese as a source of dietary fibre and to enhance antioxidant activity. Additionally, mango skin or kernel can be used to replace fat in cheese. Partial replacement of fat with mango kernel in Gouda cheese has been shown to improve sensory characteristics, total phenolic

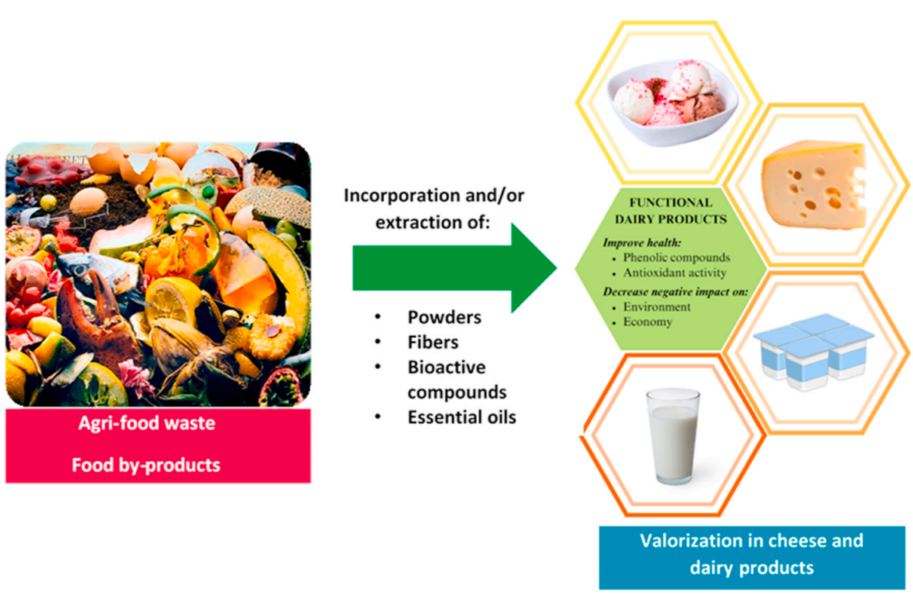

Fig. 4. Functional dairy products fabrication with the use of food waste and by-products.

contents, 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging activity, total flavonoids, and concentrations of trans fatty acids (e.g., C18:1, C18:2, and C18:3). Moreover, the presence of added-value compounds, such as mangiferin, caffeic acid, catechin, quercetin, and chlorogenic acid, has been documented in cheese fortified with mango kernel (Khan, Nadeem, Imran, Ajmal, & Ali, 2018).

Lucera et al. (2018) found that cheese enriched with grape pomace powder exhibited a significantly higher increase in total phenolic content, flavonoids, and antioxidant activity compared to the control cheese. Other natural biosources, such as broccoli, artichokes, corn bran, and tomato peel, were also found to increase these activities. These results were confirmed by Gaglio et al. (2021a), who used grape pomace powder to fortify fresh ovine "primosale" cheese. The cheese was produced using pasteurized ewes' milk and enriched with 1% (w/w) of grape pomace powder and selected *Lactococcus lactis* strains resistant to the main grape polyphenols. Results showed that fortification reduced fat content and increased protein and secondary lipid peroxidation. Moreover, following *in vitro* simulation of human digestion, antioxidant capacity, evaluated as radical scavenging activity, and inhibition of membrane lipid peroxidation were significantly improved. Marchiani, Bertolino, Ghirardello, McSweeney, and Zeppa (2016) observed that the addition of grape pomace powders (Barbera, Chardonnay) to semi-hard cheeses (Italian Toma-like) at a concentration of 1.6% (w/w) significantly improved phenolic content, radical scavenging activity, and antioxidant activity. Similarly, Italian Vastedda cheese fortified with 1% (w/w) of red grape pomace powder and produced using four lactic acid bacteria and ovine milk showed a decrease in fat content, an increase in protein content, and higher values of secondary lipid oxidation.

It is believed that powdered asparagus contains high amounts of beneficial compounds, such as flavonoids, phenolic compounds, hydroxyl cinnamic acids, and dietary fibers. As a result, adding varying amounts of asparagus powder to cheese (0.5%, 1%, and 1.5% w/w) led to a decrease in the pH and lipolysis indices and an increase in the phenolic content, antioxidant activity, and proteolysis. The addition of asparagus powder led to a cheese structure that was more elastic, less spreadable, and had increased rigidity (Solhi, Azadmard-Damirchi, Hesari, & Hamishehkar, 2020).

Lucera et al. (2018) reported that the use of flour developed from artichoke external leaves at 5% (w/w) level increased the total phenolic content (from 0.66 to 1.20 mg GAEs/g in dry weight) and the fiber content of cheese produced from pasteurized skimmed cow milk (0.1% fat), although it added a bitter taste.

Some studies have also analyzed the possibility of using by-products from fruits, vegetables, and edible oilseeds as well as their extracts for adding value to cheese. For example, grape seed and pomegranate peel extracts have been demonstrated to retard lipid oxidation in cheese during storage, while lycopene extracted from tomato by-products protected milk derivatives from spoilage (Kaur, Wani, Singh, & Sogi, 2011). These protective properties were attributed to the presence of value-added molecules in agri-food wastes. After 28 days of storage at 4 °C, Mahajan, Bhat, and Kumar (2015) showed that the use of pomegranate rind extract (2000 mg/100 mL) as a natural preservative in buffalo cheese "*Kalari*" caused a reduction of thiobarbituric acid reacting substances (−15%), and a decrease in free fatty acid content (−24%) compared to control. Strawberry by-products contain ellagic acid and phenolic antioxidants that could potentially be used to preserve cheese (Ariza et al., 2018). Meanwhile, liquid chromatography in tandem with mass spectrometry (LC-MS) was used to analyze the *Arbutus unedo* L. extract and revealed that quinic acid and catechin were the main phenolic compounds present at a level of 0.3 g/L, which showed antioxidant activities in the enriched soft cheese (Masmoudi, Ammar, Ghribi, & Attia, 2020). Roila et al. (2019) investigated the use of a polyphenolic extract derived from olive oil by-products to improve the storage stability of "Fior di latte" cheese during storage. The extract was added to two batches of cheese at concentrations of 250 and 500 μg/mL. Results showed that the extract reduced the growth of *P. fluorescens* and *Enterobacteriaceae,* leading to a delay in reaching the microbial limit, thus extending the cheese's shelf life by 2 and 4 days for the two applied concentrations, respectively. The addition of the extract significantly increased the total phenolic content of the cheese, increasing its functional value and health-promoting properties.

Waste and by-products from the dairy and cereal industries for improving storage quality and functional value of cheese were also reported. For instance, Abd Elhamid (2016) found that incorporating wheat bran into traditional Egyptian cheese "Kariesh" (up to 0.4%) increased its fiber content, although this resulted in a significant decrease in its rheological properties, such as hardness, adhesiveness, springiness, cohesiveness, gumminess, chewiness, and resilience. Mileriene et al. (2021) utilized a common dairy industry by-product, liquid whey protein, for the development of an edible coating enriched with 0.3% Chinese cinnamon extract to extend the shelf life of Eastern European curd cheese. The coating reduced yeast and mold counts and improved the cheese's color and appearance without affecting its sensory characteristics.

The studies identified in the literature showed that different types of cheeses have been investigated from fresh ones to hard ones (e.g., spreadable, fresh, semi-hard, and hard). Moreover, studies focused mostly on cheese fortification by direct incorporation of waste and by-products in a powder form (e.g., mango peel, red and white grape pomace, tomato peel, broccoli, corn bran, and artichokes) or after extraction of their fibre or antioxidant compounds. Food waste and by-products powder and extract are generally used to increase shelf life, nutritional value (total flavonoids and phenolic compounds, lower fat, and increase fibers contents) without compromising safety goals and sensory properties and its acceptance by consumers (Baker, Lu, Parrella, & Leggette, 2022; Picciotti, Massaro, Galiano, & Garganese, 2022). Therefore, several important issues that can impact the previous concerns, need to be considered. It will be important that the original/traditional characteristics of cheeses (mainly texture, flavor, and taste) are not significantly changed with the fortification. In addition, the stability of fortified cheeses remaining their nutritional value, and the bioavailability and safety of the incorporated bioactive compounds must be ensured throughout the fortified cheeses' shelf-life (Picciotti et al., 2022). The costs associated with fortification and the minimal concentration of the added compounds to achieve the desired effect must also be considered (Dwyer et al., 2015).

4.2. Valorization in other dairy products

4.2.1. Yogurt

Yogurt is a dairy product that results from the simple acid coagulation of milk. Typically, lactic acid bacteria, such as *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *Bulgaricus,* are commonly used to coagulate the milk. During this process, lactose is fermented into lactic acid, which decreases the electrostatic repulsion between casein micelles and reduces their calcium phosphate content. These two phenomena lead to the precipitation of the micelles, which form a gel network that gives yogurt its desirable taste and texture (Boukria et al., 2020b). Set, stirred, and sipping yogurts are generally the three existing categories of yogurts (Rashwan, Osman, & Chen, 2023). The consumption of yogurt has been on the rise worldwide due to its human's health benefits, therapeutic effects, and functional properties (Abdi-Moghadam et al., 2023). Because of the fermentation and manufacturing processes, yogurt contains a variety of nutrients (e.g., vitamins, calcium, riboflavin, zinc) (Hadjimbei, Botsaris, & Chrysostomou, 2022). In most cases, yogurt is made using traditional industrial production techniques, but process development has made it possible to change the technologies and procedures, especially when yogurt is combined with other ingredients to make it more nutritious or improve its physicochemical properties, sensory as well as marketability (Bankole, Irondi, Awoyale, & Ajani, 2023). Therefore, researchers as experienced the potential of yogurt to be fortified with waste, by-products, or their extracts. For example, Bertolino et al. (2015) studied the effect of adding hazelnuts powder directly in yogurt (3000 mg/100 g). They observed an increase in radical scavenging capacity and total phenolic content on average by 96 and 31%, respectively, in fortified yogurt when compared to the control. In addition, total dietary fibre increased from undetectable levels in controls to about 9.5 g/100 g in enriched yogurt. In another study, Wang, Kristo, and LaPointe (2019) investigated the impact of incorporating freeze-dried apple pomace powder (at a concentration of 1%) on the quality and structure of the yogurt gel matrix. Results indicated that the addition of the powder increased the aggregation of casein micelles, leading to earlier gelation onset at a higher pH (5.9) compared to controls (5.3). Furthermore, yogurt fortified with increasing concentrations of apple pomace powder (0%–1%) exhibited greater firmness and cohesiveness during storage, indicating a reinforcing effect on the structure of casein gels. These findings were supported by a subsequent study by Wang, Kristo, and LaPointe (2020), which found that stirred yogurt fortified with 3% (w/w) apple pomace powder exhibited reduced syneresis and improved firmness, viscosity, and cohesiveness. In the same context, Manzoor et al. (2019) suggested using papaya peel powder in the yogurt formulation to develop a functional yogurt with reduced syneresis and improved nutritional value and antioxidant properties. However, they observed that the addition of the peel powder decreased the total number of viable bacterial counts and the shelf life of yogurts. A study was carried out by Safdari, Vazifedoost, Didar, and Hajirostamloo (2021) to investigate the effect of different concentrations (0%, 0.2%, 0.5%, and 1%) of banana peel fiber extracts on the rheological and sensory properties of probiotic camel milk yogurt. The results showed that the addition of 1% fiber improved the growth of probiotics (*L. casei* and *L. gasseri*), reduced syneresis, increased viscosity, and lowered the pH of the product. However, the sensory quality of the product was adversely affected by the increase in concentration of banana peel fibers.

Hasani, Sari, Heshmati, and Karami (2017) investigated the effect of barley bran (0.3%–1.2%) on the quality characteristics of yogurt. The addition of bran powder improved the population and viability of probiotic bacteria (*L. acidophilus*) while a concentration of up to 0.6% bran did not affect the physicochemical properties, but a higher level (1.2%) negatively affected the product characteristics. Rheological properties were also modified by rice bran incorporation into yogurt before and after fermentation. Another study by Wu, Deng, Luo, Liu, and Hu (2023) used rice bran to investigate its impact on yogurt quality. They discovered that yogurt syneresis increased when rice bran was added after fermentation but was significantly lowered if added before fermentation at levels of 2.0% and 3.0%. Additionally, the yogurt gel was denser and had higher contents of free *p*-hydroxybenzoic acid, *p*-coumaric acid, ferulic acid, and sinapic acid with rice bran added before fermentation, whereas it was more porous when rice bran was added after fermentation.

Osorio-Arias, Pérez-Martínez, Vega-Castro, and Martínez-Monteagudo (2020) showed that Greek-style yogurt enriched with a cheese whey-spent coffee ground powder improved rheological properties by decreasing the shear-thinning behavior and the water-holding capacity as a function of the fortification level. Gürbüz et al., (2021a) reported that the use of quince seed mucilage powder as a stabilizer at 0.15% and 0.2% (w/v) for yogurt could accelerate the growth of *Lactobacillus bulgaricus* and improve the textural properties by decreasing syneresis, viscosity, firmness, and gel thickness. Srianta et al. (2022) found that the addition of fermented durian seed powders significantly improved the color, total phenolic content, and radical scavenging potential of yoghurt, increasing its health-promoting properties during refrigerated storage for two weeks.

Hashim, Khalil, and Afifi (2009) proposed to incorporate date fiber after syrup extraction in the yogurt. They noted that the extract at levels up to 3% did not have any significant impact on the physicochemical characteristics of the final product, such as acidity and pH. However, the yogurt enriched with date fiber had a harder texture with higher hardness values and a deeper Hue value compared to the control, while maintaining similar consumer acceptance. Similarly, Sah, Vasiljevic, McKechnie, and Donkor (2016) reported that fortified yogurt with 1% (w/v) pineapple peel, used as a source of dietary fiber, reduced yogurt-making time, increased yellow color intensity, and increased storage modulus but decreased firmness during 28 days of storage.

Sharifi, Jebelli Javan, Hesarinejad, and Parsaeimehr (2023) evaluated the use of carrot waste extract obtained using a multi-stage extraction process (extracted overnight with 80% ethanol in a ratio of 1:15 (w/v) and dried using a freeze dryer) for the development of functional symbiotic yogurt. The addition of the extract improved its physicochemical properties and increased the survival rate of *Lactobacillus plantarum* (which played the role of prebiotic). The extract increased the total phenolic content, DPPH free radical scavenging activity, and functional value of the product. In a similar study, Šeregelj et al. (2021) used encapsulated carotenoid extracts from carrot wastes (2.5 and 5% w/w) for yogurt development. The encapsulated β-carotene remained stable throughout the 28-day storage at refrigeration temperature and enhanced the antioxidant activity of the yogurt. The stability and microbiological profile of the fortified yogurt remained unchanged during storage. This implies that the use of encapsulation of bioactive components of waste and by-products could improve the effectiveness of the extracts (Christaki et al., 2021).

Since most bioactive compounds are sensitive to several food characteristics (pH, oxygen, light, and moisture) which can determine their solubility, stability, bioavailability, and controlled release in the medium, there is a need to encapsulate these compounds to improve their functionality, bioavailability, and long-term stability (Martins, Pintado, Morais, & Morais, 2022). There are several encapsulation mechanisms depending on the properties of bioactive compounds and target application. Among the physical encapsulation mechanisms, the most commonly used are spry-drying, extrusion, and freeze-drying, whilst chemical crosslinking, polymerization, and liposome formation are the most used chemical encapsulation processes (Řepka, Kurillová, Murtaja, & Lapčík, 2023).

The valorization chain of dairy products can face several issues related to sustainability, safety, and quality concerns, in addition to regulatory compliance, technical challenges, and also with the competition with traditional products that are well-established in the market, which may be overcome through educational efforts, innovation, and collaboration involving the scientific community, dairy producers, consumers, and regulatory authorities (Rao, Bast, & de Boer, 2021).

4.2.2. Ice cream

Ice cream, which originated in Europe and was later imported to the United States, is generally produced from a mixture of eggs, milk products, sweeteners, stabilizers, colorants, and flavors (Deosarkar, Kalyankar, Pawshe, & Khedkar, 2016). Currently, it has become very popular across the globe, and it is eaten both after and in between meals. Global sales are expected to be 75 billion US Dollars by 2024 (Genovese, Balivo, Salvati, & Sacchi, 2022). Despite its popularity, ice cream is nutritionally high in sugar and fat, which makes it a high-calorie food that increases the risk of obesity and metabolic disorders (Krystyjan, Gumul, Ziobro, & Sikora, 2015). These health issues, as well as negative environmental impacts, have increased consumer demand for low-calorie, high-fibre diets, driving the development of functional ice cream.

Kaur et al. (2011) used food waste and by-products to improve the quality of ice cream. To reduce the development of off-flavors, off-odors, and color changes during storage of dairy products, the authors used lycopene crystals extracted from tomato pomace as an antioxidant agent and incorporated it into ice cream (70 ppm), butter (20 ppm), and mayonnaise (50 ppm). The results showed that fortification improved the antioxidant activities and shelf life of ice cream without affecting its organoleptic acceptability. Çam, Erdoğan, Aslan, and Dinç (2013) tried to substitute milk fat with pomegranate seed oil (a source of conjugated fatty acid, especially punicic acid) and added pomegranate peel as a source of phenolic compounds to the ice cream formulation. The results revealed an increase in antioxidant and anti-diabetic properties. At a concentration between 0.1% and 0.4% of pomegranate peel, the authors noted a significant increase in the total acidity, a decrease in pH, alteration in the color, and an increase in the sour and astringent score attributes. They reported that formulations with 0.4% (w/w) pomegranate peel and 2.0% (w/w) pomegranate seed oil appeared to be the most suitable for the development of functional ice creams. Similarly, Crizel, Araujo, Rios, Rech, and Flôres (2014) reduced the total fat content of ice cream by 70% by adding orange by-products such as peel, bagasse, and seed, which also improved the phenolic compounds and carotenoids content of the ice cream. Additionally, carotenoid compounds, such as lycopene, phytoene, phytofluene, β-carotene, *cis*-lycopene, and lutein obtained from tomato peels were used as natural colorants and antioxidants to improve the properties of ice cream, resulting in increased radical scavenging activity, iron-reducing antioxidant power, and organoleptic properties with increasing amounts of carotenoids (Rizk, El-Kady, & El-Bialy, 2014).

Kurt and Atalar (2018) discovered that the incorporation of quince seed powder at levels of 0.5% and 0.75% led to an enhancement in the texture and melting properties of ice cream. The product's crystallization and hardness were significantly reduced, in addition to a reduction in the complete melting time. Recently, da Silva et al. (2020) proposed the development of prebiotic ice cream by utilizing a water-soluble extract from rice by-products along with long-chain and medium-chaininulins. The product exhibited superior functionality, including anti-hypertensive, antioxidant, and anti-diabetic activities, as well as better health indices. Yu, Zeng, Wang, and Regenstein (2021) utilized nano-fibrillated cellulose (0%–0.8%) extracted from grapefruit peel as a fat substitute in their ice cream formulations. The incorporation of cellulose led to a reduction in gross energy (calories), protein, and fat digestion during simulated digestion, and an increase in cellulose concentration, which improved product hardness and miscibility. Moreover, the addition of cellulose improved the melt, texture, and sensory properties of the ice cream, with the optimal sensory scores being obtained at 0.4% cellulose.

Hanafi et al. (2021) evaluated the use of coconut residue dietary fiber (0.01–0.03 g/mL) in the development of probiotic ice cream (*Lactobacillus plantarum*) and evaluated the quality characteristics of the product during 60 days of storage. The inclusion of 0.03 g/mL of the fiber significantly improved the quality characteristics of the product throughout the storage time, resulting in a high protein content, low-fat content, stable probiotic viability, and high sensory acceptability.

The sensory properties of foods in general and dairy products in particular, are impactful on the acceptance by consumers of food products fortified with bioactive compounds. The health benefits of the added bioactive compounds, the taste and flavor potentially induced in the food (positive notes and off-flavors), and cultural considerations, are key factors to be considered. In addition, if the bioactive compounds are from natural biosources and aligned with clean label trends and sustainability goals, it can positively impact consumers' perception of the food (Abdul Hakim, Xuan, & Oslan, 2023).

4.2.3. *Exploring the potential of microbial enzymes from agro-industrial biomass for cheese and dairy production*

The utilization of microbial enzymes produced from various types of agro-industrial biomass as raw materials is a possibility for the food industry, particularly in the dairy and cheese sectors, as noted by Raina, Kumar, and Saran (2022). For instance, cassava bagasse was studied as a substrate for generating extracellular proteases and bioactive hydrolysates during *Bacillus* sp. Cultivation, which could be used for the enzymatic hydrolysis of dietary proteins (Clerici, Lermen, & Daroit, 2021). Alternative sources of enzymes derived from agri-food wastes could be used as milk coagulation enzymes in the cheese industry. Proteases with milk coagulant activity were identified in sunflower seeds (*Helianthus annuus*) (Nasr, Mohamed Ahmed, & Hamid, 2016), hairy root cultures of cardoon (*Cynara cardunculus*) (Folgado, Pires, Figueiredo, Pimentel, & Abranches, 2020), artichoke (*Cynara scolymus*) flower extract (Bueno-Gavilá et al., 2020), and moringa (*Moringa oleifera*) seed extract (Sánchez-Muñoz et al., 2017). A recent study conducted on proteases extracted from *Morindacitrifolia* L seeds, which possess milk-clotting activity, showed that these enzymes exhibit high milk-clotting activity (3.891 U/mL) at a temperature of 65 °C. This suggests that under specific conditions, 1 mL of the extract can coagulate 3.8 L of milk in 40 min (Oliveira & Siqueira Junior, 2022). In another study, a protein precipitation approach using carrageenan to extract cucumisin enzymes from melon peels resulted in a recovery yield of 0.17 g/100 g by-products, while maintaining its proteolytic properties (4.24 U/mg protein) (Gómez-García, Campos, Aguilar, Madureira, & Pintado, 2021a). These enzymes have proteolytic and milk-clotting activities. They may be utilized to create vegetable rennet for the cheese-making industry as an alternative to animal rennet. However, they still have various issues related to low consumer acceptability and high production costs (Ben Amira, Besbes, Attia, & Blecker, 2017). Thus, the analytical technique used to evaluate coagulation enzymes from agro-wastes is critical. Analytical techniques can be performed by measuring the recovery yield of enzyme activity related to milk clotting and proteolytic activity compared with commercial microbial or animal rennet (Ben Amira et al., 2017; Gómez-García, Campos, Aguilar, Madureira, & Pintado, 2021b; Lombardi, Woitovich Valetti, Picó, & Boeris, 2013).

5. Final remarks and future trends. Emerging opportunities

To improve the environmental sustainability of the food industry, a crucial step is to recover secondary side streams instead of disposing them in a landfill or incinerator. This approach offers both ecological and economic benefits and addresses the challenges of value-added production and waste management. The valorization of secondary side-stream products, such as milk, meat, fruit and vegetable skins, eggshells, seafood shells, oil, and bread resulting from food preparation or processing, is essential to the sustainability of the food sector. The industry is currently focusing on reducing water and energy consumption and exploring energy recovery from waste.

The use of secondary stream products can be accelerated by better collaboration between food researchers and the various players in the food sector. This collaboration can promote the adaptation and use of available technologies and resources for the recovery of biomolecules from secondary side-stream products. In addition, reducing the cost of fortified foods and improving their sensory qualities will encourage consumers to choose products containing recovered biomolecules.

The exploration of new strategies for the recovery of secondary side-stream products from the meat, eggshell, and dairy industries is a line of research that needs to be explored further.

Moreover, the use of food waste from fruit, vegetables, and cereals offers considerable potential for improving a variety of dairy products, including cheese, yogurt, and ice cream. Researchers have skillfully used waste from these sources to enrich dairy products with dietary fiber, antioxidant compounds, and bioactive components, enhancing their nutritional value, and health-promoting properties.

In particular, the exploration of enzymes derived from agri-food waste for the dairy and cheese industry is an interesting trend. These enzymes, derived from various biomasses, can coagulate milk and break down proteins, paving the way for alternatives to non-animal rennet. Overcoming challenges such as consumer acceptance and production costs, these enzymes offer a promising path to sustainable, animal-friendly cheese production. In addition, the principles of the circular economy and sustainability will stimulate research and development into the efficient use of food waste and by-products. This approach enables the dairy industry to embrace waste recovery, improve sustainability, and align with consumers' environmental concerns. The integration of innovative technologies, such as encapsulation techniques, could revolutionize the incorporation of bioactive compounds from food waste into dairy products. Encapsulation could make dairy products healthier and more stable, by ensuring controlled release and accessibility of these beneficial compounds. Moreover, advanced technologies, such as those associated with Industry 4.0 are being progressively implemented in the dairy sector, from farm to fork, as can be noticed from recent publications. For example, we have recently argued that the use of robotics, artificial intelligence, the Internet of Things, big data, and blockchain, among others, could make a significant transformation in the production of milk, cheese, and other dairy products (Hassoun et al., 2023).

In the world of ice cream, the search for healthier, more functional variants is set to continue. Scientists could create ice creams with reduced sugar and fat content, making the most of the antioxidants, fibers, and bioactive compounds in waste products.

The dairy industry is at the dawn of many untapped opportunities when it comes to valorizing waste and by-products. By fully using the potential of these materials (food wastes), dairy products could not only become more nutritious and attractive but also more sustainable, perfectly aligned with changing consumer preferences.

It is important to note that, despite the benefits to human health, the economy, and the environment that come from utilizing agri-food waste and by-products, their incorporation into cheese and dairy products is constrained by potential health-hazardous compounds. These hazards can include physical and chemical contaminants that pose a threat to human health. However, safety evaluation and determination of toxic contaminants have been conducted only in a limited number of studies (Socas-Rodríguez, Álvarez-Rivera, Valdés, Ibáñez, & Cifuentes, 2021).

In grape crops, 90% of mycotoxin Ochratoxin A during processing steps was retained in the by-product. Consequently, if grape pomace is used as the ingredient, it can represent a health hazard due to the possible presence of ochratoxin A, which is considered carcinogenic. Moreover, its thermal stability even at temperatures up to 250 °C makes it difficult for elimination in heat-processed food (Dachery et al., 2019). Other compounds might be present during crop growth, such as pesticide residues (Cyprodinil, Dimethomorph, and Famoxadone) and heavy metals (Moncalvo et al., 2016), or generated during vegetable by-products drying such as toxic furans (Makarova et al., 2015). These Agri-food waste and by-products must adhere to legal requirements and undergo evaluations to assess the risks for human health. Their toxicity must be considered before they are introduced to the market (Vilas-Boas, Pintado, & Oliveira, 2021).

6. Concluding remarks

By-products from the food sector contain valuable compounds such as phenolic compounds, vitamins, complex polysaccharides, carbohydrates, proteins, and bioactive compounds, giving them antioxidant and antimicrobial potential. Phenol-rich by-products hold special significance for the food industry. They offer cost-effective sources of bioactive compounds while also tackling environmental issues through the reuse of food by-product residues. This, in turn, leads to an enhanced competitive edge for the sector.

This review focuses mainly on the nutritional and antioxidant effects of food by-products in dairy products, examining the effects of incorporating them in powder or extract form. It is essential to consider the quantity of by-products used and potential side effects, such as changes in taste and texture, before implementing them. The stability of food by-products in dairy products is an essential aspect for their optimal use, as it enables the extraction of high nutritional value. *In vivo*, experiments are needed to better understand the real impacts of these practical molecules when added to foods for human consumption. Overall, the data gathered underline the significant potential of food by-products for a variety of beneficial activities. However, the integration of phenolic compounds into food products comes with challenges that limit their overall usefulness. These include complexities related to their chemical composition, stability, bioavailability, taste, and consumer understanding.

The use of food waste and by-products in cheese and other dairy products has attracted attention. Incorporating these by-products improves the dietary fiber content, antioxidant properties, microbial quality, and functional attributes of dairy products such as cheese, yogurt, and ice cream. Cheese production, in particular, has seen advances in the use of by-product powders and extracts from sources such as mango peel, grape pomace, and tomato rind, which improve phenolic compound content, antioxidant activity, protein content, and texture. Yoghurt production also benefits from the incorporation of food waste and by-products, which enhances antioxidant activity, improves texture, and increases phenolic compound content. Waste utilization is also being explored in the ice cream field, with ingredients such as tomato pomace, pomegranate seed oil, orange and rice by-products being used to create functional ice creams with reduced fat content and enhanced health-benefiting properties. Agro-industrial biomass-derived enzymes from sources such as sunflower seeds, cardoon, and moringa seeds offer potential alternatives to traditional milk coagulants in the dairy and cheese industry, intending to develop a plant-based rennet. However, challenges relating to consumer acceptance and production costs need to be overcome.

In conclusion, incorporating food waste and by-products into dairy products not only improves their nutritional value and functional properties but also contributes to waste reduction and the overall sustainability of the food industry. This approach benefits both consumers and the environment, promoting a healthier and more environmentally friendly food ecosystem.

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CRediT authorship contribution statement

Ines Tarchi: Writing – review & editing, Writing – original draft. **Sofiane Boudalia:** Writing – original draft. **Fatih Ozogul:** Writing – review & editing, Writing – original draft. **José S. Câmara:** Writing – review & editing. **Zuhaib F. Bhat:** Writing – original draft. **Abdo Hassoun:** Writing – review & editing. **Rosa Perestrelo:** Writing – review & editing. **Mohamed Bouaziz:** Visualization. **Siti Nurmilah:** Writing – original draft. **Yana Cahyana:** Writing – original draft. **Abderrahmane Aït-Kaddour:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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