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The use of by-products for the improvement of techno-functional properties of dairy products

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Abstract: A significant challenge for the sustainable dairy sector is incorporating by-products generated during other food production and agricultural processes, such as fruit, vegetable, legume, oilseed, and grain production, into dairy products. In previous decades, by-products from these sectors were mainly used as feed for dairy cows and other animals. Currently, there is a trend to use these materials also in dairy production, for fortifying and developing novel dairy products. Additionally, their incorporation into dairy products offers the modification and enhancement of the techno-functional properties. This review summarises contemporary approaches and the current state of sustainable production in the dairy sector, with an emphasis on techno-functionality.

Keywords: valorisation of by-products; sustainable food chain; dairy science; texture; bioactive compounds

A novel approach to sustainable dairy production is the utilisation of by-products from the food sector to fortify the nutritional profile or enhance the texture of dairy products, thereby contributing to environmental benefits. Here, the by-products, such as processing residues from fruits and vegetables, or grains, can be considered, as they may also serve as materials for nutritional fortification and/or ingredients used to modify the texture of final dairy products (Lau et al. 2021). In general, the industrial processing of juicy fruits and vegetables generates a lot of residues, including leaves, peels, seeds, pulp, damaged or rejected fruits, and stones. These materials are often discarded directly, although they are often rich in valuable bioactive compounds, such as carotenoids and polyphenols (Carvalho et al. 2025). These bioactive compounds can support human health when used in their extracted forms or directly, as in the case of using the raw material for fortification. Several health benefits, like a lower chance of developing chronic heart disease, various types of cancer, type 2 diabetes, Alzheimer's, joint degeneration, and macular degeneration after the consumption of the mentioned bioactive compounds have been reported (He et al. 2023). Beyond the nutritional benefits, by-products can be used to modify the techno-functional properties of dairy products, potentially reducing the need for agents used for stabilisation and preservation of the final products since by-products, generated across various stages of agricultural and food processing operations, are typically composed of fibre, proteins, lipids, and other functional constituents (Klojdova et al. 2024). This review summarises the current possibilities, approaches, and goals for sustainable production in the dairy industry, with a focus on the nutritional and technological properties of the final products.

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BY-PRODUCTS WITH THE POTENTIAL USE IN THE DAIRY INDUSTRY

The valorisation of whey and buttermilk, the main by-products from the dairy industry, is a crucial way to effectively improve techno-functional properties and nutritional profile of final products. However, another important goal for sustainable dairy production and techno-functional improvement is the valorisation of by-products from other industries and their incorporation into the dairy industry. To date, the most utilised by-products in dairy manufacture are by-products from crop growing and processing, particularly from fruit and vegetable processing, as well as by-products from oilseed manufacturing, pulses, or grains (Lucera et al. 2018; Muiz et al. 2023).

By-products from fruit and vegetable processing. Since the fruit and vegetable sector generates the highest percentage of by-products, up to half of the global amount, the valorisation and utilisation of these materials is a key strategy for sustainable food production worldwide. Fruits and vegetables have a short shelf life in general and are therefore among the items most discarded in distribution chains and supermarkets. The common forms of fruit and vegetable by-products are peels, cores, and pomace. Further, immature and/or damaged fruits and vegetables are often wasted (Padayachee et al. 2017). Fruit and vegetable residues have been used as animal feed, fertilisers, or for anaerobic digestion. However, in recent decades, there has been a strong effort to valorise them in the food production chain (Gómez et al. 2025). Some examples of dairy products enhanced by fruit and vegetable by-products or their components/extracts are summarised in Table 1. In general, the incorporation of fruit and vegetable by-products in the manufacture of dairy products offers an improvement in the nutritional and/or textural profile of final products. Their incorporation possesses bio-functional properties like anticancer (Hashem et al. 2022; Verrillo et al. 2025), anti-inflammatory (Amorim et al. 2021) and antimicrobial (Sar et al. 2023) effects, as well as the possibility of enriching dairy products with natural colours, flavours, and antioxidants (Ramzan et al. 2025). The main bioactive compounds include vitamins, minerals, polyphenols, carotenoids, etc. Textural profile, other techno-functional properties, and stability, such as limited syneresis and phase separations, can be effectively improved if by-products with high fibre content or the extracted fibre itself are used as ingredients in the manufacture. Often, these incorporations also reduce the number of additives used (Usman et al. 2025). Fruit and vegetable by-products can be added in several forms, depending on their hydrophilicity/hydrophobicity, such as raw, air-dried, or freeze-dried materials, either directly or as an emulsion/gel phase after encapsulation. In recent years, encapsulation techniques have been very popular for delivering bioactive compounds, often extracted from by-products, since they provide effective protection of sensitive compounds during digestion, particularly during passage through the stomach. The basic idea of encapsulation is to incorporate a sensitive compound/extract within a wall of a protective material, often a biopolymer such as a polysaccharide. Additionally, colloidal and complex systems such as emulsions, multiple emulsions, gels (hydrogels, oleogels, and bigels) can be used for encapsulation (Klojdová et al. 2023). The advantage of the dairy industry is that some of the machines, such as homogenisers and mixers, are common equipment in the factories, and therefore, the encapsulation does not require additional investments (Klojdová et al. 2019). An example of the encapsulation process and its possible modification is shown in Figure 1. Despite all the benefits, by-products from fruit and vegetable processing may also contain antinutrients that can block the absorption or assimilation of essential nutrients, including lectins, oxalates, goitrogens, phytoestrogens, phytates, and tannins. However, other factors, such as amounts, crop variability (e.g. varying levels of antinutrients), manufacturing (e.g. heat treatment and/or other processing), and interactions with the food matrix, must be considered. On the other hand, some antinutrients can even act as therapeutic agents and have health-promoting effects (Petroski and Minich 2020). Lectins from plant sources are among the most discussed and studied groups, as they have shown antiviral and antifungal properties and may have potential for future cancer therapy (Fu et al. 2012; Ahmed et al. 2022).

Additionally, they have been reported to interfere with bacterial adhesion, thereby exerting an antimicrobial effect (Coutino-Rodriguez et al. 2001). In general, phytates are not found in fruits and vegetables in significant amounts, but they are abundant in seeds, which must be considered when using fruit waste for food fortification (Pires et al. 2023). Another group of antinutrients, saponins, is often extracted from seeds, leaves, flowers, and roots and offers emulsifying and foaming properties, and is also considered a source of pharmaceutical agents. They exhibit a range of biological properties, including antioxidant, antitumour,

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Table 1. Dairy products manufactured with the addition of fruit or vegetable by-products

Dairy product	By-product added	Benefit	Reference
Yoghurt	**fruit origin**		
	grape pomace extract	nutritional profile – increased total polyphenol content and antioxidant capacity	Olt et al. (2022)
	passion fruit pomace powder	nutritional profile – higher fibre levels (both soluble and insoluble) and mineral content (potassium, magnesium, and manganese), improved viscosity – preferred by panellists	de Toledo et al. (2018)
	grapefruit pomace powder	nutritional profile – monosaccharide composition, profile of metabolites after fermentation, improved texture – lower syneresis, higher gel strength and hardness	Qin et al. (2023)
	pomegranate and black grape seed powder	nutritional profile –polyphenols on antioxidants	Çalişkanlar et al. (2024)
	apple pomace powder	nutritional profile –polyphenols, improved texture – improved rheological properties	Klojdova et al. (2024)
	pumpkin peel powder	nutritional profile – carotenoids and antioxidant activity, improved texture – improved rheological properties	Gavril et al. (2024)
	pineapple pomace powder	nutritional profile – source of prebiotics	Sah et al. (2016)
	banana peel powder	nutritional profile – antioxidant and antidiabetic activity, source of phenolic compounds, extended shelf life	Kabir et al. (2021)
	vegetable origin		
	carrot pomace powder	improved texture – better gel strength, shorter fermentation period	McCann et al. (2011)
Cheese	**fruit origin**		
Spreadable cheese	red grape pomace white grape pomace	nutritional profile – phenolic content, flavonoids, and increased antioxidant activity	Lucera et al. (2018)
	orange peel	nutritional profile – antioxidant activity	Papagianni et al. (2021)
Whey cheese	apple pomace	nutritional profile – improved fermentation, higher counts of *Lactococcus lactis* LL16 strain	Mileriene et al. (2023)
Soft cheese	mango extracts	nutritional profile – antimicrobial effects, prolonged shelf life	Posseti et al. (2021)
	olive pomace	nutritional profile – antimicrobial effects, prolonged shelf life, increased content of polyphenols	Roila et al. (2019)
Cheese	**vegetable origin**		
Spreadable cheese	broccoli flour tomato peel	nutritional profile – phenolic content, flavonoids, and increased antioxidant activity	Lucera et al. (2018)
Whey cheese	red onion peel	nutritional profile – increased content of total polyphenols and higher antioxidant activity, improved texture – modified crosslinking of proteins	Lipșa et al. (2024)
Ice cream	**fruit origin**		
	pomegranate peel and seeds powder/extract	nutritional profile – phenolic content, and increased antioxidant activity	Çam et al. (2013)
	grape pomace	nutritional profile – phenolic content, and increased antioxidant activity	Vital et al. (2018)
	red pitaya powder	nutritional profile – increased antioxidant activity, improved texture - improved overrun and rheological behaviour	Utpott et al. (2020)
	vegetable origin		
	tomato peel extract	nutritional profile –carotenoids, colourants, improved texture, and melting profile	Rizk et al. (2014)

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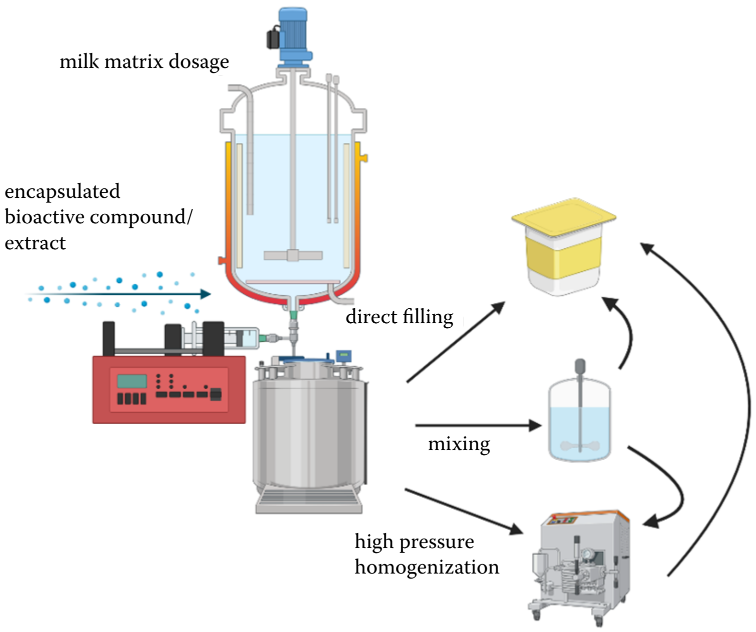

Figure 1. The possible ways of using encapsulated forms in the dairy industry

hypocholesterolemic, hypoglycemic, and anti-inflammatory activities (Sharma et al. 2021). Tannins are significant polyphenolic compounds with numerous and diverse health benefits, including helping to prevent cardiovascular disease, cancer, and diabetes while supporting gut microbiota and cognitive function (Kashi et al. 2019; Cosme et al. 2025).

Furthermore, because of a high water content and active metabolism, there is also a risk of microbial contamination since fruit and vegetable by-products can act as a potential carrier of foodborne pathogens (Mostafidi et al. 2020). Therefore, the appropriate treatment (heat treatment, drying steps, high-pressure treatment etc.) to ensure microbial safety must always be carried out (Routray et al. 2023).

Other by-products with a potential use in the manufacture of dairy products. Considering the use of by-products from cereal and legume processing in the dairy industry, a cost-effective approach is to use them as feed for dairy cows on farms (Pang et al. 2018). However, the use of by-products to produce new dairy products has become a popular and cost-effective approach in recent years (Nartea et al. 2023). This review focuses on their possible use in product development for human consumption, an approach that provides another sustainability benefit for plant-based products, and, here, for dairy products called hybrid products. Hybrid products combine both sources of nutrients, from animal (milk) and plant origin. Whereas by-products from fruit and vegetable processing are mostly used for dairy products fortification, by-products from legumes, grains, and oilseeds can more effectively replace and /or support milk proteins, providing the manufacturing of products at the boundary between conventional dairy products and their plant-based alternatives, offering benefits like higher protein and fibre contents (Ngasakul et al. 2025). Brito et al. (2025) provided a study on hybrid dairy products with 535 participants interested in a healthy diet. They reported interesting data showing that the most preferred hybrid products are ice creams and yoghurts. Other products, such as dairy beverages and milk substitutes, were the least desired. The most important message from this study is that the group of participants considered the most attractive products with nutritional claims such as 'high protein content', 'rich in fibre', or 'fortified with vitamins and minerals'. These findings support the potential of using by-products in the manufacture of dairy hybrid products. Recently, Nartea et al. (2023) summarised the potential valorisation of residues, such as seed coats, husks, hulls, pods etc., from legume processing. The authors highlighted the additional nutritional and technofunctional value of these materials, as well as the need for further clinical studies to evaluate the risks posed by antinutritional factors in legumes, which are the richest sources of such compounds. The levels of antinutrients are influenced by many factors, including genotype, environmental conditions, growth location, and seasonal variations. In general, they differ even within the plant material of the same species and include phytate, enzyme inhibitors (trypsin inhibitors, chymotrypsin in-

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hibitors, and α-amylase inhibitors), tannins, lectins, and saponins, as well as vicine and convicine (Patterson et al. 2017). During processing, there is also a risk of microbial contamination of seeds or by-products (due to inappropriate storage conditions, improper drying, long soaking times, or inadequate processing). This highlights the importance of good manufacturing practice (Lamonaca et al. 2025).

The new product development is also limited by disturbing sensory properties. However, they have great potential as main ingredients in vegan products and dairy alternatives because of their unique levels of protein, starch, fibre, lipids, minerals, and vitamins, which vary by variety. To date, they have been used mostly as ingredients in bakery products, where their sensory properties can be improved or modified (Bento et al. 2021). Due to the technofunctional properties, like emulsifying and foaming properties, of these residues, they could work as agents in dairy products. Dairy products are mostly based on emulsions in general, meaning that they contain droplets of fat within an aqueous phase (o/w emulsion) or water droplets within a fat phase (w/o emulsion). In both systems, there is an interfacial layer composed of proteins and, usually, other emulsifiers (such as lecithins, mono- and diacylglycerols etc.). Proteins are amphiphilic, allowing them to act as natural emulsifiers and effectively stabilise interfaces. (Lopez et al. 2024) reported a promising use of pea protein isolate for the stabilisation of o/w dairy emulsions. Therefore, research into a deeper understanding of the interactions between dairy proteins and by-product proteins from legumes, grains, and oilseeds remains a challenge.

For completeness, insect by-products can also be used in the manufacturing of dairy products, as there has been a trend toward increased consumption of insects due to their potential for a lower environmental impact. Insect-derived materials have been shown to have physicochemical and digestive benefits (Ribeiro et al. 2018). Since insects are rich in protein, essential amino acids, healthy fats, vitamins, and minerals, efforts to incorporate insect-derived materials into dairy products have increased over the last decade. In particular, the black soldier fly (*Hermetia illucens*) and the drone bee (*Apis mellifera*) have gained significant attention in recent years due to their relatively low environmental footprints. Additionally, they are rich in protein and, therefore, a promising ingredient for fortifying dairy products (Neves et al. 2024). Despite the benefits, concerns about consuming insects, especially in developed countries, persist, and a significant proportion of the population considers it unacceptable (Orsi et al. 2019). Insects and their by-products pose exogenous and endogenous risks to human health in three categories: chemical, biological, and allergenic (Murefu et al. 2019). Allergies to insect proteins, namely arginine kinase, α-amylase, and tropomyosin, can result in serious illness and, in some cases, death. Additionally, insects are related to crustaceans; their potential to cause food-related allergies must be considered as well (Nwaru et al. 2014; Francis et al. 2019). Other potential risks of insects are the presence of antinutrients (tannin, oxalate, hydrocyanide and phytate) (Meyer-Rochow et al. 2021), mycotoxins (mainly food spoilage moulds of mainly *Fusarium*, *Aspergillus* and *Penicillium* genera) (van der Fels-Klerx et al. 2018), pesticides (Imathiu 2020), heavy metals (such as cadmium, lead, mercury, and arsenic) were found to accumulate in insects (Malematja et al. 2023), microbial contamination, or even parasites (Akemu et al. 2025).

CONCLUSION

A significant approach to sustainable dairy production is the valorisation of by-products from other food sectors and agriculture, including those from fruit and vegetable processing, as well as from other production sources such as legume residues, in the development of novel dairy products or their modified recipes, often referred to as hybrid products. Studies reporting the successful incorporation of by-products to enhance the nutritional profile and techno-functional properties, such as texture and consistency, of dairy products like yoghurt, cheese, or ice cream, have been published. However, further studies should focus on the safety of plant-based by-products, as they can also contain antinutrients and pose a risk of microbial contamination.

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