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# Incorporation of fruits or fruit pulp into yoghurts: recent developments, challenges, and opportunities

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The incorporation of fruits and/or fruit pulps into fermented dairy products has gained substantial interest in the food industry, driven by consumer demand for functional foods that combine health benefits with natural ingredients. This value addition enhances plain yoghurts with antioxidants, dietary fiber, bioactive compounds, and probiotics, delivering potential health benefits such as immune modulation, gut health improvement, and reduced risks of metabolic disorders. Fruit components interact with the macromolecular structure of yoghurt, influencing its physicochemical properties, texture, and sensory attributes. Organic acids modulate protein gelation and emulsification, polyphenols alter protein aggregation and antioxidant stability, and dietary fibers enhance water-holding capacity and probiotic viability. These interactions significantly impact yoghurt's structure, stability, and functional benefits, necessitating an understanding of their mechanisms. Fruits such as pomegranate, passion fruit, and açaí pulp have demonstrated antioxidative and cardioprotective properties, while innovations in incorporating fruit peels and seeds, such as passion fruit peel flour and grape skin, enhance physicochemical stability and nutrient density. Beyond these advantages, challenges such as increased syneresis, altered pH, reduced probiotic viability, and microbial contamination during storage persist. This review critically evaluates the impact of fruit incorporation into yoghurt, examining its effects on probiotic viability, physicochemical properties, sensory attributes, and microbiological stability. Achieving an optimal balance requires careful selection of fruit sources, processing strategies, and formulation techniques to sustain probiotic viability and yoghurt stability throughout its shelf life. By synthesizing recent research, this review highlights both the challenges and opportunities in developing fruit-enriched yoghurts, emphasizing strategies to optimize processing techniques and preserve key quality attributes. The findings offer a scientific framework for developing innovative, health-promoting, and shelf-stable fruit-enriched yoghurts, aligning with evolving market demands and functional food advancements.

KEYWORDS

**fermented milk, probiotics, fruit-flavoured yoghurt, antioxidative properties, prebiotics, textural stability, shelf-life enhancement**

## 1 Introduction

Yoghurt offers numerous health benefits, enhancing overall wellbeing when consumed regularly (Fernandez and Marette, 2017). Its nutritive value stems from milk's composition and the activity of lactic acid bacteria, *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* (Hadjimbei et al., 2022). Milk composition varies with factors such as breed, feed, geography, and season (Priyashantha and Lundh, 2021). The addition of probiotics like *Bifidobacteria* and *L. acidophilus* further enhances its biofunctional properties (Hadjimbei et al., 2022).

Yoghurt consumption supports bone health and reduces osteoporosis risk (Bridge et al., 2020; Rizzoli, 2014). It also addresses gut-related issues, including *Helicobacter pylori* infection, inflammatory bowel disease, and colon cancer (Han et al., 2023; Pannerchelvan et al., 2024), while lowering serum cholesterol (Pourrajab et al., 2020), reducing LDL and triglycerides (Hadjimbei et al., 2022), and aiding weight management (Abdi-Moghadam et al., 2023). Regular dairy intake is linked to a lower risk of type-2 diabetes, with probiotic yoghurt improving blood sugar levels in clinical trials (Mirjalili et al., 2023; Ejtahed et al., 2011; Asgharian et al., 2020). Probiotic yoghurt consumption during pregnancy has been associated with reduced insulin resistance and improved serum insulin levels (Mahdizade Ari et al., 2022). Additionally, yoghurt has been shown to alleviate allergy symptoms, modulate immune responses (Hadjimbei et al., 2022; Rivero-Pino et al., 2024) and various other health benefits as summarized in Figure 1.

The incorporation of fruits into yoghurt is gaining popularity due to their nutritional and functional properties. Fruits contribute antioxidants such as vitamin C, vitamin E, carotenoids, and dietary fibre, enhancing yoghurt's health benefits (Zainoldin and Baba, 2009). Beyond improving sensory attributes, fruit-fortified yoghurt serves as an effective probiotic carrier, promoting gut microbiota balance and immune function (Meybodi et al., 2020). However, maintaining probiotic viability during storage and digestion remains a challenge (Fazilah et al., 2018). Fruits and fruit pulps may help stabilize probiotics, exerting synergistic health effects (Yapa et al., 2023; Rahman et al., 2024).

The prebiotic effect of fruit components further enhances yoghurt's probiotic functionality. Prebiotics are indigestible carbohydrates that selectively support beneficial gut microbes, modifying the intestinal microbiota to improve host health (Fernández et al., 2016; Swanson et al., 2020). The combination of prebiotics and probiotics in synbiotic yoghurt can aid digestion and prevent conditions such as irritable bowel syndrome and colorectal cancer (Swanson et al., 2020). Thus, consuming synbiotic yoghurt enriched with fruits and probiotics enhances gut health and overall wellbeing (do Espírito Santo et al., 2012a; Meybodi et al., 2020).

Recent research has explored various fruit sources in yoghurt, considering factors such as flavour, functionality, seasonality, and cost (Hapuarachchi et al., 2024; Rahman et al., 2024; Kovsari et al., 2024). While fruit incorporation offers innovative product development opportunities, it also presents challenges in maintaining sensory and quality attributes. Achieving an optimal balance requires careful selection of fruit types, processing strategies, and formulation techniques to sustain probiotic viability and yoghurt stability throughout its shelf life.

This article critically evaluates the impact of incorporating fruits and fruit pulps into yoghurt, with a focus on their influence on

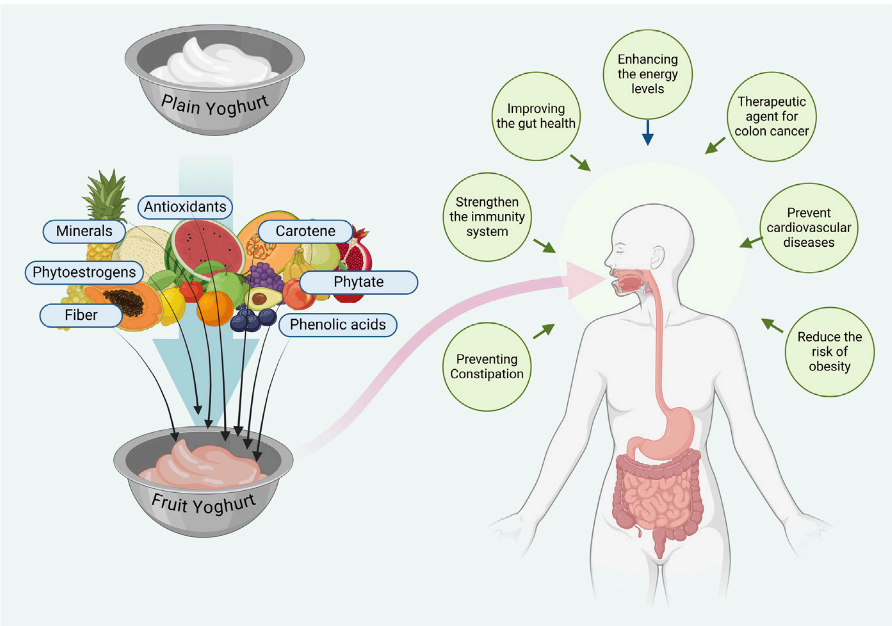


FIGURE 1
The incorporation of fruits and fruit pulp into yoghurt delivers various additional health benefits to the host owing to their nutritional versatility. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/w61a426.

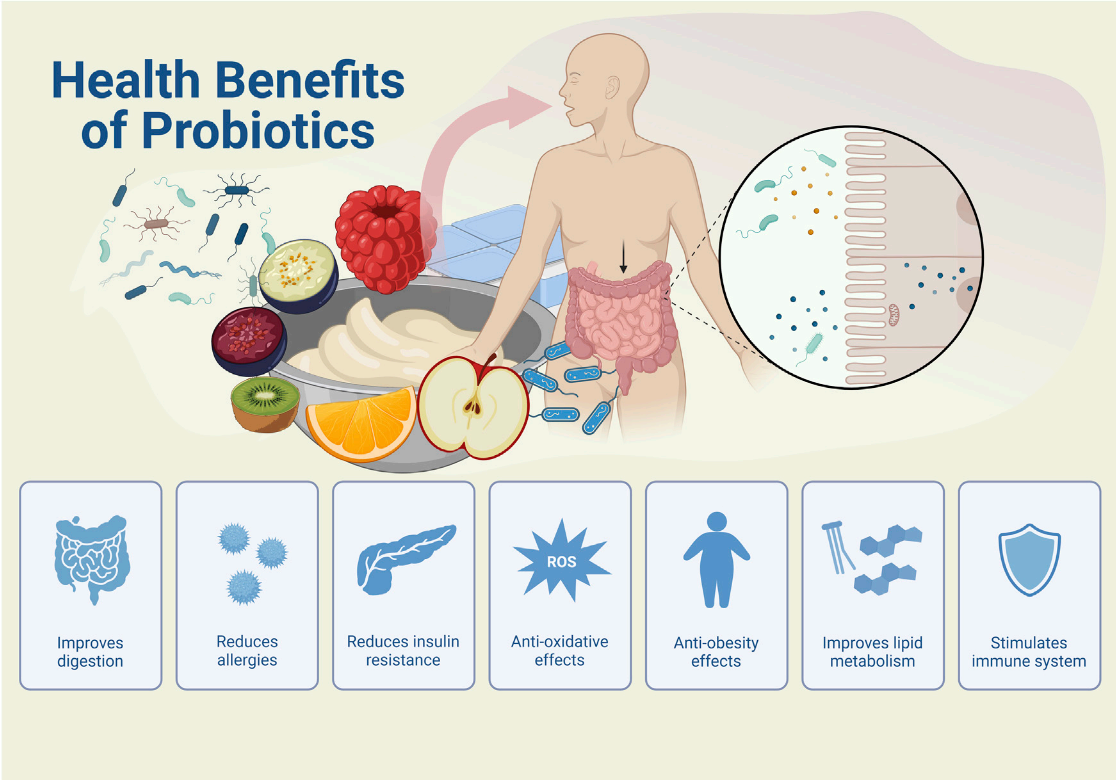


FIGURE 2
Health benefits of probiotics. Potential probiotic health benefits associated with the consumption of fruit or fruit pulp incorporated into dairy products, as identified in this study. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/r81n348.

probiotic viability, physicochemical properties, sensory attributes, and microbiological stability. By reviewing current research, this study aims to highlight the challenges and opportunities in developing fruit-enriched yoghurts, ensuring both functional and nutritional benefits. The integration of fruits into dairy yoghurt aligns with the growing consumer demand for natural, health-enhancing foods. By combining the nutritional benefits of yoghurt with the bioactive properties of fruits, this innovation represents a significant advancement in functional food development. Future success lies in addressing technical challenges while maintaining key quality attributes.

## 2 Methodology

This review synthesizes current knowledge on the incorporation of fruits and fruit pulps into dairy yoghurts, with a focus on their chemical, physical, sensory, and nutraceutical properties, as well as their impact on shelf-life stability. Special attention is given to the interaction mechanisms between fruit components and yoghurt components. A comprehensive literature search was conducted using databases such as PubMed, Scopus, and Google Scholar, covering peer-reviewed articles, scientific reviews, and relevant industry reports published within the last two decades. The selection criteria emphasized studies examining the effects of various fruits, their by-products, and incorporation methods on yoghurt quality parameters, probiotic viability, and consumer acceptability.

Key data were categorized into thematic areas: chemical properties (e.g., pH, acidity, total solids), physical properties (e.g., syneresis, viscosity), sensory attributes (e.g., color, flavor, texture), nutraceutical benefits (e.g., antioxidative and cardioprotective effects), and shelf-life stability. Emphasis was placed on summarizing trends, identifying challenges, and highlighting innovative approaches in fruit-incorporated yoghurt production. Insights were drawn from comparative analyses to provide actionable recommendations for future research and industry applications.

## 3 Results and discussions

### 3.1 Interaction mechanisms between fruit components and yoghurt components

The incorporation of fruits into yoghurt introduces a diverse range of bioactive compounds, including organic acids, polyphenols, dietary fibers, and pigments, which interact with the primary macromolecular components of the yoghurt matrix, namely, proteins and fats. These interactions significantly influence the physicochemical properties, texture, flavor, and nutritional profile of yoghurt, thereby modifying its overall functionality and stability, as detailed later in this article.

Organic acids, such as citric acid, malic acid, and tartaric acid, play a crucial role in altering the structural and rheological

TABLE 1 Effect of different fruits on the viability of probiotics in yoghurt.

| Fruit | Probiotic | Effect[a] | Reference |
|---|---|---|---|
| Fruit cocktail | *Saccharomyces boulardii* | + | Lourens-Hattingh and Viljoen (2001) |
| Açaí pulp | *Lactobacillus acidophilus*<br>*Bifidobacterium* | none<br>none | de Almeida et al. (2008) |
| Mango<br>Mixed berry<br>Passion fruit<br>Strawberry | *B. animalis* ssp. *lactis* LAFTI® B94<br>*L. acidophilus* LAFTI® L10 | none<br>none | Kailasapathy et al. (2008) |
| Orange fiber<br>Lemon fiber | *L. acidophilus* CECT 903<br>*Lactobacillus casei* CECT 475<br>*B. bifidum* CECT 870 | +<br>+<br>+ (except for lemon fiber) | Sendra et al. (2008) |
| Açaí pulp | *L. acidophilus* L10<br>*b. bifidum* subsp. *lactis* Bl04<br>*Bifidobacterium longum* Bl0 | +<br>+<br>+ | do Espirito Santo et al. (2010) |
| Apple (fiber)<br>Banana (fiber)<br>Passion fruit (fiber) | *L. acidophilus* L10<br>*B. animalis* subsp. *lactis* BL04<br>*B. animalis* subsp. *lactis* HN019<br>*B. animalis* subsp. *lactis* B94 | +<br>+<br>+<br>+ | do Espirito Santo et al. (2012a) |
| Passion fruit peel powder | *L. acidophilus* L10<br>*L. acidophilus* NCFM<br>*B. animalis* subsp. *lactis* Bl04<br>*B. animalis* subsp. *lactis* HN019 | none<br>none<br>+<br>none | do Espirito Santo et al. (2012b) |
| Fruit juice (mix of apple juice-45%, orange juice-44%, banana puree-5%, pineapple juice-4%, mango puree-1.3% and passionfruit juice-0.6%) | *L. acidophilus* LA-5<br>*B. animalis* subsp. *lactis* BB-12<br>*Propionibacterium jensenii* 702 | +<br>none<br>none | Ranadheera et al. (2012) |
| Cupuassu pulp | *L. acidophilus LA-5* | + | Costa et al. (2015) |
| Pineapple peel powder | *L. acidophilus (ATCC 4356)*<br>*L. bacillus casei (ATCC393)*<br>*Lactobacillus paracasei subsp. paracasei (ATCC BAA52)* | +<br>+<br>+ | Sah et al. (2016) |
| Seabuckthorn whole fruit<br>Seabuckthorn purified mucilage | *L. acidophilus*<br>*Bifidobacterium lactis* | +<br>+ | Gunenc et al. (2016) |
| Soursop pulp<br>Sweetsop pulp<br>Custard apple pulp | *B. animalis* subsp. *lactis* BB-12 | + | Senadeera et al. (2018) |
| *Siraitia grosvenorii* fruit | *L. casei*<br>*Lactobacillus bulgaricus*<br>*Streptococcus thermophilus* | +<br>+<br>none | Abdel-Hamid et al. (2020) |

[a]none, neither a negative nor a positive effect; +, significant positive effect on the viability of the probiotic.

properties of yoghurt. Their primary effect is the reduction of pH, which leads to the destabilization of casein micelles, thereby enhancing gel strength and improving texture. However, excessive acidification can promote protein aggregation and syneresis, while negatively affecting water-holding capacity (Asaduzzaman et al., 2021). Furthermore, these acids engage in electrostatic interactions with whey proteins, altering their solubility and influencing the viscosity and smoothness of the final product. Organic acids can also affect fat emulsion stability by interacting with the milk fat globule membrane (MFGM), which modulates fat distribution and contributes to variations in yoghurt consistency (do Prado Silva et al., 2021; Cui et al., 2024).

Polyphenols, abundant in fruits and vegetables, interact with both protein and lipid components of yoghurt, primarily through non-covalent interactions such as hydrogen bonding and hydrophobic interactions, as well as covalent modifications (Muntaha et al., 2025). The binding of polyphenols to casein and whey proteins affects protein aggregation, solubility, and gel formation, which in turn influences the structural integrity of yoghurt. Depending on the concentration and type of polyphenols, these interactions may either strengthen or weaken the yoghurt matrix. Additionally, polyphenols exhibit enzyme-inhibitory properties, modulating proteolytic activity and altering protein digestibility. Their role as natural antioxidants is particularly significant in protecting lipids from oxidation, thereby enhancing the shelf-life and maintaining the sensory quality of yoghurt (Wróblewska et al., 2023; Serra et al., 2021; Muntaha et al., 2025).

Dietary fibers derived from fruits and vegetables further contribute to the structural and functional properties of yoghurt.

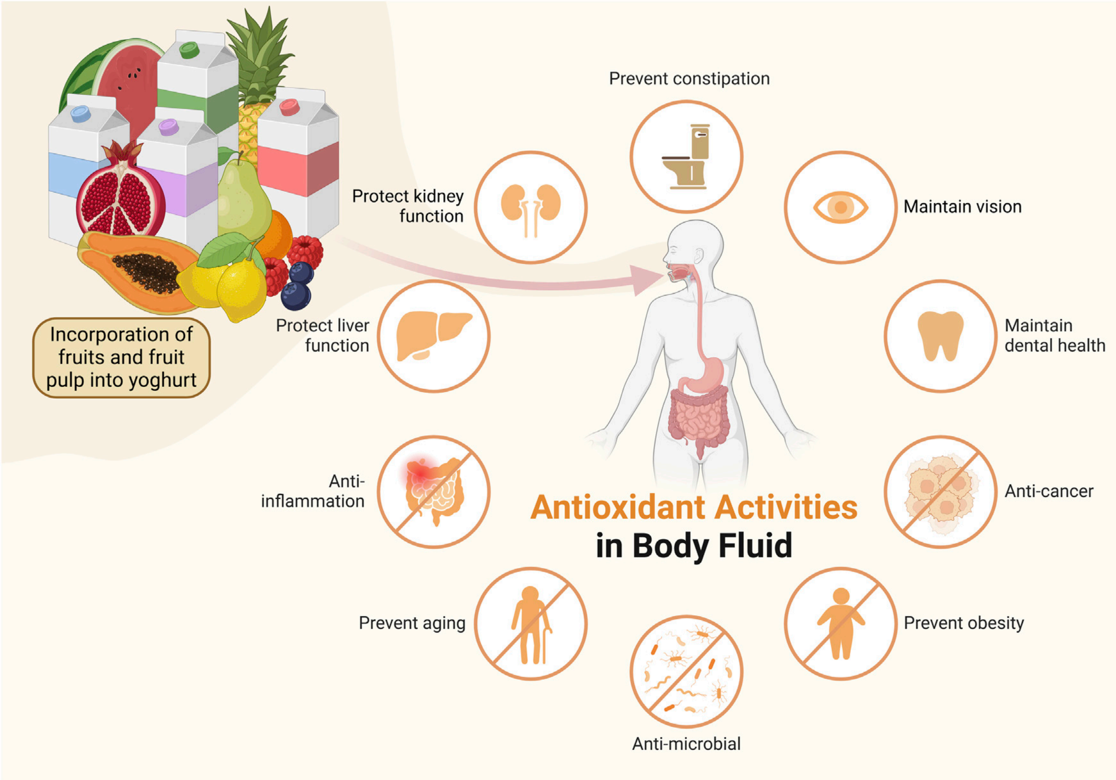


FIGURE 3
Potential health benefits and antioxidant activities of consuming fruit and fruit pulp-incorporated yoghurts. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/a36s464.

Soluble fibers, such as pectin and inulin, enhance water-holding capacity, reducing syneresis and improving mouthfeel. These fibers also interact with casein micelles, affecting gelation kinetics and viscosity, leading to a creamier and more stable yoghurt matrix. Additionally, dietary fibers act as prebiotics, promoting the growth and viability of probiotic bacteria such as *Lactobacilli* spp., thereby enhancing the functional properties of yoghurt and supporting gut health (Kieserling et al., 2019; Arab et al., 2023). Pigments, including carotenoids and anthocyanins, influence both the visual appeal and the biochemical stability of yoghurt. Carotenoids, such as β-carotene, dissolve in the lipid phase, enhancing color retention and improving oxidative stability by preventing lipid peroxidation. Anthocyanins, on the other hand, interact with casein proteins in a pH-dependent manner, modifying color intensity and stability. These interactions are crucial in determining the overall appearance and marketability of fruit-and fruit-pulp-enriched yoghurts (Molina et al., 2023; Rodriguez-Amaya et al., 2023; Khoo et al., 2017; Gavril et al., 2024). Therefore, the complex interactions between fruit and fruit pulp components and yoghurt matrix's macromolecules play a pivotal role in determining the texture, stability, antioxidant properties, and probiotic viability of the final product. These interactions are also being altered by the action of probiotics and prebiotics incorporated in yoghurt production. Hence, a deeper understanding of these mechanisms enables the development of optimized formulations for functional dairy products that offer enhanced sensory attributes, improved nutritional benefits, and prolonged shelf-life.

## 3.2 Chemical properties of fruit-incorporated yoghurt

### 3.2.1 Total Solids (TS)

Total solids (TS) are a key quality parameter in yoghurt production, influencing texture through a three-dimensional protein network (Sah et al., 2016). Fruits high in fiber and diverse cell wall components can impact TS content (Sah et al., 2016). Yoghurt enriched with 1% and 2% peeled and unpeeled Russian olive flour showed TS values of 16.05% (1% peeled), 17.21% (2% peeled), 16.10% (1% unpeeled), and 17.26% (2% unpeeled), all higher than the control (15.34%) (Öztürk et al., 2018). Additionally, the highest fat content was observed in yoghurt enriched with 2% unpeeled Russian olive flour (3.5%), followed by 2% peeled (3.4%), with lower values in 1% treatments compared to plain yoghurt.

Similar findings were reported for xique-xique jam in goat-milk yoghurt, where TS increased, leading to reduced moisture (83.5 g–82.3 g/100 g) and higher lipid (2.5–3.0 g/100 g) and protein (3.5–3.98 g/100 g) contents, while lactose decreased (3.8–3.5 g/100 g) (Bezerril et al., 2021). Likewise, passion fruit peel and seed flour increased protein (8.7%) and fat (9.9%) in drinkable yoghurt (Morais et al., 2017). Passion fruit seeds contain unsaturated fatty acids, mainly oleic (4.2%) and linoleic acid (16%), while their fiber content (64%) lowered moisture levels compared to commercial yoghurt. Furthermore, its incorporation increased ash and mineral content, including phosphorus (13.5%–17.7%), potassium (2.8%–6.7%), calcium (9.5%–16.4%), magnesium

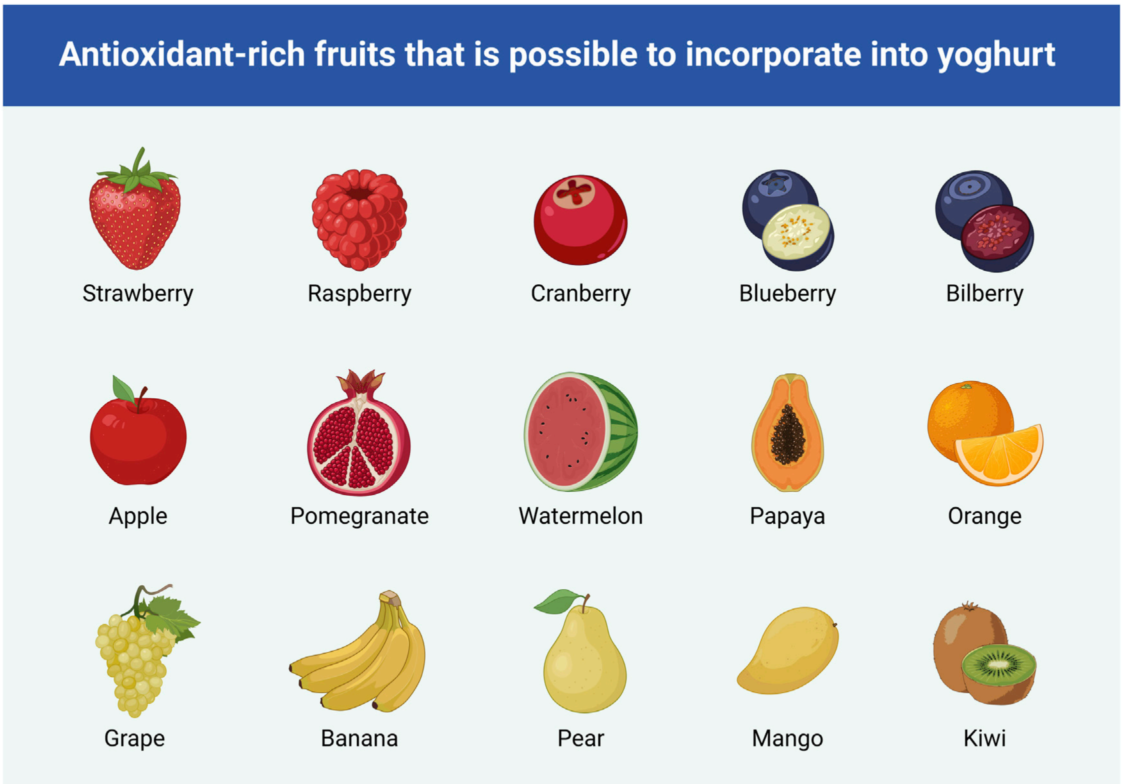


FIGURE 4
Possible fruits to incorporate in the production of dairy yoghurt. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/n28m236.

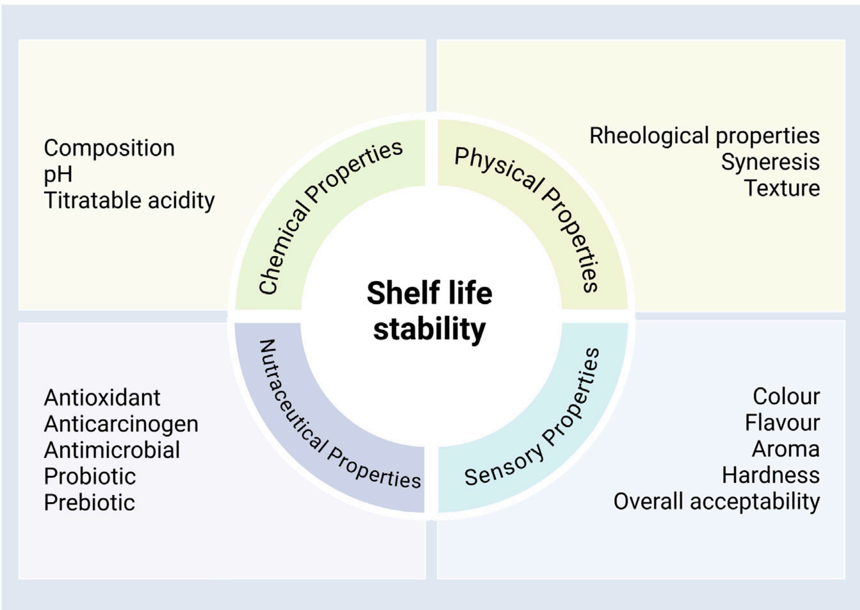


FIGURE 5
Chemical, Physical, Nutraceutical and Sensory Properties effect on the yoghurt shelf-life stability. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/n03s697.

(2.5%–4.6%), iron (6.2%–8%), and zinc (7.5%–10%) (De Toledo et al., 2018). Yoghurt fortified with 8% passion fruit peel and seed flour also had higher fiber levels (insoluble: 4.3 g, soluble: 1.3 g) than the control (insoluble: 0.2 g, soluble: 0.1 g).

The form of fruit incorporation influences yoghurt composition. Dry cantaloupe increased protein, whereas cantaloupe purée had the lowest protein content, with no impact on lipids (Kermiche et al., 2018). Mango peel polysaccharides used as a fat replacer reduced fat and TS while increasing protein (Al-Sheraji et al., 2017). Yoghurt enriched with monk fruit sweetener showed a slight, non-significant increase in TS, fat, and carbohydrates, with a minor protein reduction (Ban et al., 2020). Comparing blended and 'fruit-on-bottom' yoghurts with strawberry, sourberry, or blueberry, no significant differences in protein and fat contents were observed (Ścibisz et al., 2019). However, yoghurt with uvaia pulp had lower protein and lipid levels but higher moisture (Bianchini et al., 2020). Regardless of form, fruit-enriched yoghurt enhances nutritional value, offering a balanced diet for consumers.

### 3.2.2 pH and titratable acidity (TA)

In conventional yoghurt production, pH and TA reach approximately 4.2 and 90–100 mmol/L, respectively, after 2.5 h of incubation at 45°C with a starter culture (Niamsiri and Batt, 2009). Annona fruit pulp reduced the pH compared to control yoghurt, attributed to increased microbial-accessible carbohydrates enhancing starter culture activity and organic acid production (Senadeera et al., 2018). Apple pomace (2%–3% w/w) addition post-fermentation significantly lowered pH and increased TA (Wang et al., 2019). Passion fruit peel and seed flour also reduced pH in drinking yoghurt (De Toledo et al., 2018). Banana, papaya, and watermelon supplementation increased acidity, with watermelon yoghurt showing the lowest pH (4.27) (Roy et al., 2015). Jambolan (*Eugenia jambolana*) pulp and uvaia (*Eugenia pyriformis*) also decreased pH in conventional and lactose-free yoghurt (Bezerra et al., 2015; Bianchini et al., 2020).

Pomegranate seed fortification (5%–20%) reduced pH due to inherent acids like citric and malic acid (Bchir et al., 2020). Red dragon fruit addition showed an inverse relationship with pH, declining as fruit concentration increased (Fitratullah et al., 2019). Variability in pH occurred with strawberry (4.15), blueberry (4.07), and sourberry (4.01) additions, likely due to natural acidity (Ścibisz et al., 2019). Conversely, cantaloupe increased pH and lowered acidity due to its neutral pH (Kermiche et al., 2018), while avocado pulp had no effect (Hertanto and Pramono, 2019). Peach-flavored drinking yoghurt had a higher pH when made with skim milk than whole milk (Gonzalez et al., 2011).

The stability of natural pigments depends on pH, as demonstrated with Hibiscus flower extract for microbial quality assessment in milk (Madushan et al., 2021). Yoghurt with encapsulated cactus pear showed minor pH fluctuations during storage (Carmona et al., 2021). Pomegranate seed-fortified yoghurt maintained a consistent pH over 28 days (Van Nieuwenhove et al., 2019). Inulin and polydextrose as fat replacers with banana purée reduced pH (4.31–4.01) while increasing TA (1 g/100 g–1.14 g/100 g) over 21 days (Srisuvor et al., 2013). Monk fruit sweetener in camel milk yoghurt significantly lowered pH by day 7 but remained stable thereafter, without affecting TA (Buchilina and Aryana, 2021).

Açaí fruit-enriched skim milk yoghurt with five starter cultures showed pH increases in *Bifidobacterium lactis* and *B. longum* strains over 28 days (do Espírito Santo et al., 2010). TA, however, increased in Açaí yoghurt compared to the control, from 0.92 mg lactic acid $g^{-1}$ (day 1) to 1.08 mg lactic acid $g^{-1}$ (day 28). Overall, the incorporation of various fruit pulps, peels, and sweeteners in yoghurt significantly influences pH and acidity, with effects varying based on the fruit's inherent acidity, sugar composition, and interaction with starter cultures. These findings highlight the potential of fruit-based fortification to modify yoghurt properties and improve its nutritional and sensory attributes.

## 3.3 Physical properties of fruit incorporated yoghurt

The incorporation of fruits into dairy yoghurt alters the physicochemical and technological properties due to the modification of physical attributes of conventional yoghurt, which subsequently influences consumer attraction and perception.

### 3.3.1 Syneresis

Syneresis, the accumulation of whey protein on the yoghurt surface, is a significant quality defect affecting consumer acceptability. Senadeera et al. (2018) reported higher syneresis in Annona-enriched yoghurt due to casein network contraction and thermodynamic incompatibility between Annona polysaccharides and milk proteins. Similarly, adding natural colorants from plant extracts (hibiscus, blue pea, turmeric, and spinach) post-fermentation increased syneresis (Wijesekara et al., 2022). Pomegranate seed incorporation at various concentrations (5%–20% wt/vol) also elevated syneresis from 36.16% to 43.44%, likely due to the seeds' low water-holding capacity (Bchir et al., 2020).

Conversely, certain fruit additions reduced syneresis. Apple pomace (3% w/w) improved water retention within the casein gel matrix (Wang et al., 2019). Banana, papaya, and watermelon pulps, particularly at 15% (v/v), significantly lowered syneresis, with banana showing the greatest reduction (Roy et al., 2015). Passion fruit peel and seed flour-enriched drinkable yoghurt exhibited lower syneresis than plain versions (De Toledo et al., 2018), attributed to the fiber's water-holding capacity.

Syneresis is also influenced by pH decline during storage, which weakens electrostatic forces stabilizing casein micelles (De Toledo et al., 2018). Increasing passion fruit peel and seed flour concentration strengthens the gel matrix, minimizing whey separation (De Toledo et al., 2018). Skim milk enhances firmness, consistency, and cohesiveness in passion fruit peel yoghurt (Do Espírito Santo et al., 2012), while mango peel polysaccharides improve non-fat yoghurt texture and reduce syneresis (Al-Sheraji et al., 2017). Monk fruit (*S. grosvenorii*) fortification decreases syneresis *via* electrostatic interactions between mogrolaglycone and casein (Ban et al., 2020). Grape skin flour from grape pomace reduced syneresis by 10% (Marchiani et al., 2016), and date paste improved yoghurt texture while lowering syneresis (Haneen, 2019). Overall, studies suggest that fruit-derived carbohydrates enhance yoghurt texture and rheology while mitigating syneresis. Thus, incorporating fruits not only improves biochemical properties but also addresses technological defects, enhancing consumer appeal.

### 3.3.2 Textural profile–viscosity, cohesiveness, consistency, firmness

Viscosity is a crucial physical property of yoghurt. The interaction between κ-casein and β-lactoglobulin on the casein micelles is essential for this viscosity and gel strength (Karnopp et al., 2017). As evident, the inclusion of persimmon marmalade into yoghurt has enhanced the water holding capacity and viscosity compared to the control samples (Arslan and Bayrakci, 2016). Yoghurt fortified with 0.5% and 1% (w/w) apple pomace increased the viscosity than the rest of the treatment (0.1%) and the control (Wang et al., 2019). Moreover, Wang et al. (2019) stated that the addition of 1% apple pomace (w/w) before fermentation favoured aggregation of casein micelles at an early stage of fermentation causing the onset of gelation, which positively effect on the viscosity.

A study by Pan et al. (2019) used pomegranate juice powder in substitution of sugar, which enhanced the viscosity due to the formation of soluble complexes between hydroxyl (-OH) groups of the phenolic compounds of pomegranate juice powder and casein. Moreover, this incorporation has increased the values of firmness, consistency, cohesiveness and index of viscosity of all the samples, reaching a maximum on the 14th day and slightly decreasing thereafter. The addition of purple grape juice into yoghurts resulted in a higher cohesiveness and viscosity, while the incorporation of grape skin flour enhanced the hardness and the consistency of yoghurt, suggesting the stabilizing effect of the fibre in grape skin in maintaining the hardness and the consistency, preventing the water mobility (Karnopp et al., 2017). Avocado pulp enriched in yoghurt increased the viscosity significantly due to the high concentration of total solids in avocado pulp (Hertanto and Pramono, 2019).

Mango peel polysaccharides are found to contribute to high viscosity in yoghurt due to the formation of interactions with dairy proteins (Al-Sheraji et al., 2017). Similarly, pectin in orange peel (*Citrus sinensis*) leads to an increase in the viscosity in yoghurt, when elevated the pectin concentrations from 0.2% to 0.5% (Arioui et al., 2017). Pectin comprises galacturonic acid residues linked by α (1–4) bonds and partially acetylated or esterified with methyl groups, which possess gelling, thickening and stabilizing properties (Arioui et al., 2017). Monk fruit sweetener in camel drinkable yoghurt increased the viscosity during storage due to the post-acidification that led to whey separation and increase in protein cross-links as explained by Buchilina and Aryana (2021). They observed whey separation in the second week slightly, which continued up until 42 days, which was significant at 21, 28, 35 and 42 days. Pineapple peel powder supplemented yoghurt reported great whey separation throughout the storage, which may be due to the thermodynamic incompatibility of polysaccharides (a phenomenon where polysaccharides and proteins spontaneously separate into two liquid phases in a water system) in pineapple and milk proteins and depletion of the flocculation of casein micelles in the presence of non-adsorbing polymers such as dietary fibre, which unbalanced the osmotic potential (Sah et al., 2016).

## 3.4 Sensory properties of fruit incorporated yoghurt

The sensory properties of fruit-incorporated yoghurt are governed by complex biochemical and physicochemical interactions that significantly influence consumer perception and product acceptability. The integration of fruit or fruit pulps into yoghurt modifies key attributes, including appearance, texture, flavor, and aroma, necessitating an in-depth understanding of these changes to optimize formulation strategies and maintain sensory stability throughout storage. Color is a key determinant of consumer acceptance (Ścibisz et al., 2019; Dimitrellou et al., 2020) and thus influencing consumer appeal, largely determined by the natural pigments in fruits, such as anthocyanins (berries), carotenoids (mango, papaya), and betalains (beetroot). These bioactive compounds are highly susceptible to oxidative degradation, pH fluctuations, enzymatic activity, and thermal processing, leading to undesirable discoloration and pigment instability. Studies have demonstrated that anthocyanins, for example, degrade rapidly in acidic environments and under light exposure, resulting in reduced visual appeal over storage (Rodríguez-Mena et al., 2023). Encapsulation techniques and the addition of natural stabilizers such as ascorbic acid and polyphenols have been investigated as potential strategies to enhance pigment retention and prevent oxidative deterioration (Shishir et al., 2024).

Due to health concerns, plant extracts from fruits and vegetables are increasingly replacing synthetic food colorants (Carmona et al., 2021). Chouchouli et al. (2013) demonstrated enhanced color in yoghurt enriched with grape seed extracts from Moschofilero (yellow) and Agiorgitiko (red) varieties. Similar trends were observed in yoghurts supplemented with blueberry, grape, and aronia, where redness ($a^*$) increased (Dimitrellou et al., 2020). Passion fruit juice fortification enhanced yellowness ($b^*$) while reducing redness and lightness, improving consumer appeal (Ning et al., 2021). Blanched date water used for milk reconstitution increased $a^*$ (less greenness) and $b^*$ (more yellowness) but did not significantly impact $L^*$ (lightness) (Trigueros et al., 2012). Date paste fiber also influenced yoghurt color (Hashim et al., 2009). Cupuassu pulp (*Theobroma grandiflorum*) enhanced lightness and yellowness due to carotenoid migration (Costa et al., 2015). Avocado pulp altered conventional yoghurt color, requiring careful fruit selection to maintain consumer appeal (Hertanto and Pramono, 2019).

The incorporation of fruit-derived polysaccharides and fibers influences yoghurt's rheological behavior, impacting viscosity, gel structure, and syneresis. High-pectin fruits such as citrus, apple, and mango contribute to increased viscosity by interacting with casein micelles, leading to enhanced gel strength and reduced whey separation (Gofur et al., 2024). However, excessive fruit addition can weaken protein–protein interactions, resulting in undesirable textural changes such as phase separation and excessive water migration. The incorporation of strawberry preparations in yoghurt reduces total antioxidant activity by 23% and phenolic content by 14%, with anthocyanin levels declining by 24% over shelf-life (Oliveira et al., 2015). The interaction between hydrocolloids, proteins, and polyphenols affects yoghurt's functional and textural properties, necessitating optimized formulations for stability. Additionally, fruit acidity can influence casein coagulation, altering the microstructure of yoghurt gels (Nongonierma et al., 2007). Controlled pH adjustments and homogenization strategies have been proposed to mitigate these adverse effects and ensure consistent texture.

The incorporation of fruits modifies the flavor profile of yoghurt through the introduction of volatile organic compounds, organic acids, and phenolic compounds. Volatile organic compounds such as esters, aldehydes, and terpenes contribute to fruit aroma, whereas organic acids influence tartness and balance sweetness perception. However, interactions between fruit polyphenols and dairy proteins can lead to flavor masking, astringency, and bitterness due to protein-polyphenol complex formation (Quan et al., 2019; Lakshmikanthan et al., 2024). Furthermore, post-fermentation biochemical changes, including the production of acetaldehyde, diacetyl, and ethanol, further alter the flavor dynamics of fruit-incorporated yoghurt. Thus, sensory studies need to focus on stragies that optimizing fermentation conditions, selecting fruit varieties with complementary flavor profiles, and applying controlled enzymatic treatments that can mitigate undesirable flavor alterations while enhancing the overall sensory complexity of the compounded product.

Sensory evaluation highlights the impact of fruit on yoghurt acceptability. Pomegranate juice powder improved taste, texture, and appearance (Pan et al., 2019), while grape pomace reduced acceptability due to bioactive compounds causing sourness and unpleasant texture (Marchiani et al., 2016). Passion fruit peel and seed flour (2% w/w) improved sensory attributes, delivering a sweet flavor and thick texture (De Toledo et al., 2018). A similar study found that 13% (w/w) passion fruit pulp and 2% (w/w) peel enhanced flavor and overall acceptability (Shabong et al., 2021).

The natural sugar content and acidity of fruit significantly affect yoghurt's sensory perception. Fruits with high fructose content, such as bananas and mangoes, contribute to inherent sweetness, reducing the need for added sugars. Conversely, fruits with high citric or malic acid concentrations, such as berries and passion fruit, introduce tartness, which can influence consumer acceptance (Morais et al., 2023). Formulation adjustments, including controlled fermentation and selective enzymatic hydrolysis of fruit sugars, can be proposed to standardize the sweetness-acidity equilibrium across different fruit variants. Pectin from orange peel improved sensory attributes by stabilizing aroma compounds (Arioui et al., 2017). Frozen pomegranate seeds (20% w/v) enhanced color and taste (Bchir et al., 2020). Uvaia pulp increased flavor and acceptability in lactose-free and regular yoghurts (Bianchini et al., 2020). Papaya pulp (10%) intensified sensory properties due to its aroma compounds (Mpopo et al., 2020). Strawberry incorporation showed a positive correlation with sensory attributes (Kowaleski et al., 2020), whereas elderberry juice (25% w/w) led to an astringent aroma and excessive purple color (Cais-Sokolińska and Walkowiak-Tomczak, 2021). Walnut-enriched yoghurt outperformed flaxseed-fortified versions in sensory acceptance due to its higher fat content and creamier texture (Baba et al., 2018). Guava pulp contributed to firmer yoghurt texture due to its pectin content, while soursop pulp required adjustments to balance acidity (Buriti et al., 2014). Overall, fruit additions enhance yoghurt's sensory appeal by improving color, aroma, and texture. However, careful formulation is essential to balance flavor, maintain visual appeal, and optimize consumer acceptance.

Despite the promising potential of fruit-incorporated yoghurt in functional food development, several challenges remain in maintaining consistent sensory attributes, particularly during extended storage. Oxidative degradation of volatiles, microbial activity, and enzymatic modifications can lead to off-flavors, textural deterioration, and pigment instability. Advanced analytical techniques such as gas chromatography-mass spectrometry for volatile profiling, differential scanning calorimetry for texture evaluation, and electronic nose technology for aroma stability assessment can provide deeper insights into sensory transformations and improve formulation precision. Moreover, future studies should focus on refining ingredient selection, optimizing processing conditions, and leveraging novel stabilization techniques to enhance consumer acceptance while ensuring functional and nutritional integrity.

## 3.5 Probiotics, prebiotic and Synbiotics properties of fruit incorporated yoghurt

The demand for food products enriched with probiotics is increasing, as manifested in the global market for probiotics reached a value of about 58 billion U.S. dollars in 2022 (Global probiotics market value 2022–2027: M. Shahbandeh, 2023). These probiotic products are required to contain a sufficient amount of live microorganisms, at least 9 $\log_{10}$ colony-forming units to deliver health benefits to the consumer (Tufarelli and Laudadio, 2016). The interest in foods enriched with probiotics stems from their various physiological and psychological health benefits as well as their nutritional value (Figure 2) (Voidarou et al., 2020; Tanihiro ET AL, 2024).

Strengthening the immune system, regulating microflora by reducing the population of pathogen bacteria, especially in the gastrointestinal system, reducing blood cholesterol levels and anti-carcinogenic effects are some of the important benefits provided by probiotics (Wollowski et al., 2001; Jackson et al., 2002; Rafter, 2003; Kobyliak et al., 2016; Lau and Chye, 2018). Lactic acid bacteria (LAB) are the most commonly utilized functional bacterial group in probiotic food manufacturing (Meybodi et al., 2020), where the families *Lactobacillaceae* and *Bifidobacteriaceae* consist the majority of LAB, while some strains of *Enterococcus*, *Propionibacterium*, *Saccharomyces*, *Bacillus* and *Escherichia* are also characterized for their probiotics potential (Mollakhalili et al., 2017).

Yoghurt is one of the main dairy products which is rich in probiotic properties due to the buffering capacity of milk, and the proper fermentation process followed by refrigerated storage conditions which enable enhanced survival of probiotic bacteria (Meybodi et al., 2020). However, the use of fruit and fruit purées may cause an increase in the amount of some antimicrobial components in yoghurt and this may negatively affect the viability of probiotics (do Espírito Santo et al., 2012b; Rodríguez et al., 2021). Furthermore, the use of fruits with high acidity causes a decrease in the pH of yoghurt, and the probiotic population due to the increase in acidity (Donkor et al., 2007). Kailasapathy et al. (2008) observed that the viability of the *Bifidobacterium animalis* subsp. *lactis* LAFTI® B94 decreased more rapidly during storage compared to the *Lactobacillus acidophilus* LAFTI® L10 in stirred-type yoghurts, added with a mix of mango, mixed berry, passion fruit and strawberry. As stated, the reason behind the result was the higher sensitivity of *B. animalis* subsp. *lactis* LAFTI® B94 to the level of oxygen over the storage.

The optimum growth pH for *B. animalis* subsp. *lactis* was higher as revealed by its higher abundance in the range of pH 4.4–4.5 compared to the final pH of the yoghurt (4.1–4.5). In contrast, when açaí pulp was used (3, 5, 7% w/v) the final pH of yoghurts significantly decreased compared to plain yoghurt, while the abundance of probiotic bacteria (*L. acidophilus* and *Bifidobacterium bifidum*) was not affected during the 21-day storage period (de Almeida et al., 2008). Also, do Espirito Santo et al. (2010) found that the abundance of *L. acidophilus* L10, *B. animalis* subsp. *lactis* Bl04 and *Bifidobacterium longum* Bl0 were increased in yoghurt with 7% (w/v) açaí pulp after 4 weeks of storage. The contrasting results for viability of *Bifidobacterium* spp. across the studies reported by different authors can be attributed to the differences in the strains used, as the probiotic potential of *Bifidobacterium* spp. is highly strain-dependent (de Almeida et al., 2008; Vitheejongjaroen et al., 2021). The substrate specificity and the versatility of probiotic microorganisms may also play a key role in their abundance in fruit-enriched yoghurts (Fernandez and Marette, 2017).

In particular, some probiotic microorganisms can easily utilize sucrose and fructose. In the study (Lourens-Hattingh and Viljoen, 2001), *Saccharomyces boulardii*, which is a probiotic yeast that cannot utilize lactose but can utilize sucrose and fructose, has been used in yoghurt production and the amount of this yeast in fruit yoghurts was found to be higher than in plain yoghurt. Therefore, it supports the point that, in the presence of various fruit and fruit pulps, yoghurt is enriched in sucrose and fructose, which are not found in plain yoghurt, causing a high survival rate. Further, the type of fruit and/or the fruit pulp used posed a significant effect on the abundance of the probiotics in fruit-enriched yoghurts. In a study by Kailasapathy et al. (2008), plain yoghurt was found to contain a higher abundance of *L. acidophilus* than yoghurts containing either mixed berry or passion fruit, while there was no difference in the same bacteria in yoghurts containing mango and strawberry, in comparison to the plain yoghurt. In another study by Sendra et al. (2008), it was found that orange fibre increased the viability of *L. acidophilus* CECT 903, *Lactobacillus casei* CECT 475 and *B. bifidum* CECT 870, while lemon fibre increased the viability of only the two former microorganisms and had an inhibitory effect on *B. bifidum*. However, the use of fruit and fruit pulps in yoghurt production has diverse effects on probiotic bacteria as summarized in Table 1, attributed to the type of fruit and/or fruit pulp used, the rate of incorporation and the type of species and/or strain of probiotic microorganism utilized.

## 3.6 Nutraceutical properties of fruit-incorporated yoghurt

Food and beverages that deliver therapeutic, preventative and health-promoting benefits rather than providing conventional nutrients are defined as functional foods which have recently gained huge popularity (Senadeera et al., 2018; Abdel-Hamid et al., 2020; Dimitrellou et al., 2020). Yoghurt, as a healthy food product, has earned a higher acceptance among consumers on its own due to its additional health-promoting benefits (Figure 1). For instance, strengthening the immune system, improving gut health, enhancing the metabolism and being a therapeutic agent for health burdens of non-communicable nature, such as cancer, osteoporosis, cardiovascular disorders and obesity mainly due to the probiotic properties of fermented milk and milk products (Vanegas-Azuero and Gutiérrez, 2018; Abdel-Hamid et al., 2020). Simultaneously, natural fruits are also acclaimed as an important and excellent source of antioxidants, polyphenols and prebiotic fibre that boost the health of animals and humans (Fernandez and Marette, 2017). For instance, anthocyanins, which are plant-based natural pigments, are known to ameliorate oxidative stress by suppressing the formation of reactive oxygen species by scavenging free radicals (Sah et al., 2016). Several recent studies confirmed the capabilities of antioxidants to prevent the development of chronic diseases, which exhibited a vast range of biological activities such as antioxidative, antimicrobial, anti-mutagenic, anti-carcinogenic/anti-tumorigenic and anti-inflammation (Ścibisz et al., 2019). Thus, a blend of yoghurt and fruits together is an excellent functional food that has the potential to act as a therapeutic agent, health promoter and a provisioner of additional nutrients for consumers (Fernandez and Marette, 2017; De Azevedo et al., 2018).

### 3.6.1 antioxidant properties

Several recent studies have reported the use of fruits in dairy yoghurts to enhance their antioxidant properties (Figure 3).

The review logically discusses the impact of several possible fruit/fruit pulp incorporations on antioxidant properties that have been used in prior research (Figure 4).

It is noted that the higher antioxidant levels of yoghurt with fruits could be due to its polyphenol components. Those components enhance the degree of hydrolysis and produce small peptide bonds, which contribute to the antioxidant activities in yoghurt (Abdel-Hamid et al., 2020). The stage of fruit addition in yoghurt also has been reported to be an important factor in terms of total phenolic content (TPC) and antioxidant activity (Durmus et al., 2021). Reviewing a few evidential references, the addition of pomegranate seeds to dairy yoghurts exhibited strong antioxidant activity, compared to the conventional yoghurt which is likely due to the destruction of fruit cells and migration of phenolic compounds from the fruit pulp to yoghurt by osmotic pressure (Bchir et al., 2020) during processing. Further, pomegranate peel and honey concomitantly incorporated and fortified freeze-dried yoghurt reported a higher level of phenolic content, thus, enhancing the antioxidant activities (Kennas et al., 2020). Black mulberry in yoghurt possesses different bioactive compounds, especially anthocyanins, such as cyanidin-3-glucoside and cyanidin-3-rutinoside, which protect against oxidative damage of the product (Durmus et al., 2021). The combination of purple grape juice and grape skin flour, and the incorporation of grape seeds evident a significant radical scavenging capacity and ferric iron-reducing power due to the antiradical and reducing power of polyphenol (Karnopp et al., 2017; Chouchouli et al., 2013). Moreover, the addition of grape pomace in skim milk yoghurt accelerated the growth of LAB during fermentation due to polyphenols (De Azevedo et al., 2018).

The addition of pineapple peel and pineapple pomace powder enhanced the antioxidant activity of yoghurt, as estimated by 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay and OH radicals (hydroxyl radical scavenging assay) (Sah et al., 2016). In addition, among the different forms of pineapple powders, the freeze-dried peel and pomace powder showed strong radical scavenging activities compared to the oven-dried samples. The total phenolic compounds and antioxidative properties were higher in yoghurt supplemented with papaya pulp, thus confirming the suitability of papaya as a functional food ingredient in yoghurt production (Amal et al., 2016). The available literature has inferred the promising results of guava fruit pulp, persimmon (*Diospyros kaki* L.) and mango (*Mangifera indica* L.) in functional yoghurt production since they enhance the free radical scavenging activity attributed to their higher total phenolic and total flavonoid compounds (Blassy et al., 2020). Similarly, the inclusion of date (*Phoenix dactylifera* L.) paste was reported to contribute to antioxidant activity (Haneen, 2019). Probiotic yoghurt fortified with monk fruit (*Siraitia grosvenorii*) extract demonstrated significantly higher antioxidant activity compared to control probiotic yoghurt. Additionally, increasing the amount of monk fruit extract resulted in a consistent rise in antioxidant activity showing a proportional relationship of antioxidant power to the extract concentration. (Abdel-Hamid et al., 2020).

Related to the fact of fermentation, El-Said et al. (2014) explained the addition of fruit after yoghurt fermentation enhanced the antioxidant activity since degradation of anthocyanin during the incubation and interaction of phenolic compounds with protein or peptides are minimal when the gel is enriched with fruit after fermentation. The addition of pomegranate peel extract into stirred yoghurt before the inoculation resulted in higher antioxidant activities than the pomegranate peel extract added after inoculation (El-Said et al., 2014). This is supported by the result gained by Durmus et al. (2021) in black mulberry-incorporated yoghurt which yielded higher TPC due to the release of phenolic substances by acids or microbial enzymes from fruit tissues or glycoside during fermentation.

### 3.6.2 Lowering the risk of cardiovascular diseases

The addition of walnut oil enhanced the amount of monounsaturated and polyunsaturated fatty acids, which reduces the risk of cardiovascular diseases (Baba et al., 2018). White grape varieties also play a major role in lowering the risks of chronic diseases, and cardiovascular diseases. Furthermore, most of the meta-analysis and epidemiological studies confirmed the positive influence of the combination of fruit and yoghurt on cardiovascular diseases, driven by the probiotic properties of yoghurt and prebiotic properties of phytonutrients in fruits (Fernandez and Marette, 2017). Strawberry and chia seed incorporation in yoghurt has proven and opened the potential to create new market avenues for functional fermented products containing higher dietary fibre, minerals, and omega-3 fatty acids, delivering cardio-protective functions (Kowaleski et al., 2020).

### 3.6.3 Anti-carcinogenic properties

Karaaslan et al. (2011) suggest the potential of incorporating fruits as a valuable chemo-protective complementary supplement alternative for the bio-manufacturing of chemo-preventive and nutraceutical food with added value. This is supported by Sah et al. (2016) reporting, that the yoghurt supplemented with pineapple peel, demonstrated the potential of using it as a stronger antimutagenic compound and additionally as a prebiotic ingredient. Polyphenol-enriched citrus pomace has also exhibited efficient cytotoxicity against human tumor cell lines representing human breast carcinoma (Alamoudi et al., 2022). Further, pomegranate-pomace extract in drinking yoghurt indicated that the extract displayed potent anticancer activity and cytotoxic effects against A-549 lung carcinoma (Alsubhi et al., 2022). Goat's stirred yoghurt fortified with carob molasses (a fruit juice concentrate produced from various sugar-rich fruits) also has given positive results in reducing cancer showing that a higher incorporated concentration results in higher effectiveness (Shalabi, 2022).

### 3.6.4 Anti-diabetic properties

Reformulation of yoghurts matrix with Salal berry (*Gaultheria shallon*) and Blackcurrant (*Ribes nigrum*) aqueous extract as an anti-diabetic beverage resulted in enzyme inhibition, such as of blood glucose level regulating enzymes, α-amylase, α-glucosidase and dipeptidyl peptidase IV (Ni et al., 2018). The same authors delineated that blackcurrant pomace-incorporated yoghurt displayed the highest potential for α-glucosidase inhibition due to the peptides released from caseins during the fermentation process. Similarly, yoghurt with restricted elderberry (*Sambucus* spp.) juice suggested the potential of α-amylase and α-glucosidase inhibition as an effective strategy for controlling type-2 diabetes mellitus (Cais-Sokolińska and Walkowiak-Tomczak, 2021). Drinking yoghurt with passion fruit peel and seed flour showcased a higher amount of insoluble fibres and mineral elements, which extend more health benefits such as lowering the risk of diabetes (De Toledo et al., 2018). *Synsepalum dulcificum* also known as miracle fruit or miracle berry pulp extracts has resulted in significant anti-diabetic activities when included in functional yoghurt (Fazilah et al., 2018)

### 3.6.5 Anti-hypertensive properties

The synergistic effect of yoghurt supplemented with blueberry was well demonstrated in Shi et al. (2019) using a diet-induced obese mouse model. Based on the study, both systolic and diastolic blood pressure significantly declined in the mice supplemented with blueberries, however, the active compound of blueberry (Cyanidin-3-O-β-glucoside) did not reduce the blood pressure in high-fat and high-carbohydrate fed animals. This suggested the anti-hypertensive effect of blueberry fruit may not only associated with Cyanidin-3-O-β-glucoside (Shi et al., 2019).

### 3.6.6 Anti-bacterial properties

Natural phenols account for an effective antimicrobial activity in the food industry. Probiotic yoghurt supplemented with *S. grosvenorii* fruit extract acquired antibacterial activities against *Escherichia coli*, *Salmonella typhimurium* and *Listeria monocytogenes* (Abdel-Hamid et al., 2020). According to Yapa et al. (2023), probiotic yoghurts made with buffalos' milk and fortified with 10% of bael fruit pulp had viable counts of $>10^8$ CFU/g between 1 and 14 days of storage, but after 21 days, they sharply decreased. This could be because the phenolic components in bael extract have antibacterial properties. A study (Zaki and Naeem, 2021) which was done to evaluate the effect of citrus peel on the shelf life of drinking yoghurt stated that the ethanol-extracted orange peel demonstrated the strongest antibacterial efficacy against *Pseduomone aeruginosa* and *Bacillus cereus*. Further, it says the ethanol extracts that exhibited the highest antimicrobial characteristics are orange peels followed by mandarin peels and lemon peels. This is supported by Viuda-Martos et al. (2008) and Pavithra et al. (2009) who highlighted that flavonoids and phenols are linked to the antibacterial properties of citrus, while monoterpenes such as D-limonene and linalool are the active ingredients responsible for the antibacterial properties of citrus peel oils. Overall, it is evident that fruit-enriched yoghurt enhances the functional properties of yoghurt due to its potent bioactive components. The inclusion of fruits such as pomegranate and açaí pulp elevates the nutraceutical profile of yoghurts, providing antioxidative, anti-inflammatory, and cardioprotective benefits. These products meet consumer demand for health-oriented foods while positioning fruit-incorporated yoghurts as a cornerstone of the functional food market.

## 3.7 Shelf-life stability of fruit-incorporated yoghurt

The overall organoleptic and physicochemical quality of fermented dairy products deteriorate during chilled storage, transportation and therefore, the degree of stability of physicochemical, sensory and functional properties influences the shelf-life and consumer acceptability of the products (Deshwal et al., 2021). Figure 5 shows the possible factors that affect the shelf-life stability of yoghurt.

The shelf life of yoghurt (about 6–8 weeks under refrigerated conditions) mainly depends on the production method and the packaging materials (Ścibisz et al., 2019). Even though, the incorporation of fruits into yoghurt may lead to contamination by the yeasts and moulds, sterilization before addition into yoghurt may enhance the shelf life of fruit yoghurts. However, different characteristics of yoghurt can be affected and altered during cold storage due to varying chemical, physical, biological and biochemical factors during the transportation, storage and on-shelf.

### 3.7.1 Colour and antioxidant stability

The colour in the fruit-incorporated yoghurt is mainly due to the phenolic compounds; the anthocyanins. Degradation of pigments is mainly influenced by enzymes, the presence of oxygen, metallic ions, sulfur dioxide and ascorbic acid (Ścibisz et al., 2019). Anthocyanin stability of yoghurt depends on several environmental factors, such as temperature, pH, water activity, light and microbial activity. In addition, the stability of anthocyanin depends on the intermolecular co-pigmentation between anthocyanins and phenolic compounds, self-association among anthocyanins, fat content in yoghurt and the degree of pectin methoxylation used in yoghurt production.

Instrumental colour parameters exhibited an increase in $L^*$ value in fruit on the bottom-type or blended-type yoghurt during the storage. A rapid increase in $L^*$ was observed in blended-type yoghurts compared to the fruit on the bottom type, due to the degradation of anthocyanin. Yoghurt supplementation with strawberry and sour cherry displayed the loss of red colour during the cold storage due to the formation of yellow and brown polymerization pigments through anthocyanin degradation, which ultimately led to a change of colour from red to orange (Ścibisz et al., 2019). The same authors reported that the half-life of anthocyanin in strawberry, sour cherry and blueberry on bottom-type yoghurt was enhanced with time compared to the blended-type. Encapsulated microparticles of yellow-orange cactus pear (*Opuntia ficus-indica*) pulp with maltodextrin and cactus mucilage exhibited higher stability of indicaxanthin, which is the main betaxanthin pigment in cactus pears (>80% retention). Yellow-orange cactus pear pulp encapsulated with maltodextrin and cactus mucilage as a natural yellow colourant for yoghurt demonstrated pigment protection due to electrostatic interaction or hydrogen bond formation between indicaxanthin and polymers (maltodextrin or mucilage) (Carmona et al., 2021). In contrast, the total colour change of yoghurt enriched with cactus microparticles during the 28 days of shelf life was negligible (Carmona et al., 2021). Replacement of pomegranate juice powder as a sugar substitute slightly declined the white index of the yoghurt during storage, which is a crucial criterion for the white colour foods (Pan et al., 2019). On day one, the control had the highest white index (59.81) followed by 1% pomegranate juice powder (58.46), 3% pomegranate juice powder (57.78) and 5% pomegranate juice powder (56.62) whereas, a similar white index was resulted at day 21 in pomegranate juice powder enriched yoghurts due to the formation of the soluble complexes by compaction of the solid matrix and reduced gel opacity.

Anthocyanin stability of pomegranate juice fortified yoghurt was higher in the yoghurt added with pomegranate juice before fermentation than after fermentation because 90% of anthocyanin degradation occurred by 13 days of storage when pomegranate juice added after fermentation (Cano-Lamadrid et al., 2017). Even though most of the anthocyanin degrades during the fermentation process in fermented milk products, anthocyanin is stabilized during cold storage. Thus, the addition of bioactive compounds before fermentation showcases strong stability during cold storage. Yoghurt fortified with hazelnut skins reported an increase of antioxidative levels during the storage without any modification in phenolic compounds, thus it confirmed the stability of the functional ability of yoghurt fortified with hazelnut skins (Bertolino et al., 2015). The potential modifications that might occur during the storage of natural fruit products incorporated yoghurts aiming to maintain the colour and functionality should be given more focus in future studies.

### 3.7.2 Microbial stability

According to the codex standards (2023), the sum of microorganisms constituting the starter culture (symbiotic cultures of *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*) in fermented milk and yoghurt should be min. $10^7$ (CFU/g, in total) while the labelled microorganisms (cultures of *S. thermophilus* and any *Lactobacilli and* species) should be a minimum of $10^6$ (CFU/g, in total).

Fruit products act as a nutritional source not only for the beneficial but also for the detrimental microorganisms during the production and storage of yoghurt. The microbial count was not significantly affected in yoghurt supplemented with pomegranate juice during the 30 days of cold storage, which mean value ended up at $6.16 \times 10^8$ CFU/g irrespective of the step (before or after

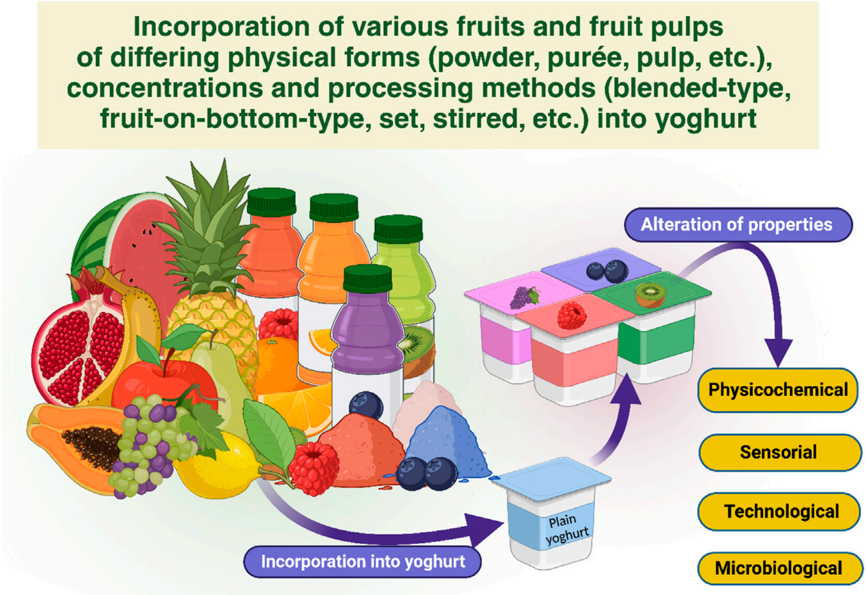


FIGURE 6
Impact of fruit incorporation in various forms, concentrations, and processing methods on the physical, chemical, microbiological, sensory, and nutraceutical properties of yoghurt. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/a17c174.

fermentation), of adding pomegranate juice, making the yoghurt a carrier of probiotics (Cano-Lamadrid et al., 2017). Probiotic yoghurt enriched with banana purée acts as a nutrient supplement for probiotic bacteria and starter culture. The bacterial number significantly enhanced during the first 7 days and remained constant over the storage of 21 days (Srisuvor et al., 2013). Monk fruit sweetener in drinking yoghurt did not significantly affect the growth of *S. thermophilus*, *L. bulgaricus* and *L. acidophilus*. Further, the growth of coliforms, yeast and mould was not observed during the storage, ascribed to the adequate heat treatment and proper storage conditions, that prevented post-pasteurization contamination (Buchilina and Aryana, 2021).

The addition of mango and guava fruit pulps in soy yoghurt did not influence the viability of probiotics and starter culture bacteria during the storage of 28 days. Moreover, the same study (Bedani et al., 2014) mentions that the addition of tropical fruit pulps like mango pulp, might lead to a reduction in the probiotic strains' functionality. A slight significant decrease was observed throughout the storage period. Albeit, preservatives were not used in the previous study, some fruits might contain natural microbial growth inhibitors, which may have affected the viability of starters and probiotics. Further, they confirmed the microbiological safety of fruit yoghurt for human consumption, since no coliform, *Escherichia coli* and yeast were detected. do Espırito Santo et al. (2010) studied the effects of açaí pulp addition and different probiotic bacteria in yoghurt which resulted in higher probiotic counts in all fruit-incorporated yoghurts compared to their control without fruit pulp on day 14.

Interestingly, dragon fruit-incorporated yoghurt was found to be able to store for 15 days under refrigerated conditions (4°C) without their quality parameters being altered (Jayasinghe et al., 2015). Counting the data the shelf life of the fruit yoghurt varied significantly based on the type of fruit pulp incorporated. However, the fruit that enriches yoghurt shows a shelf life of 28–42 days which is less than that of conventional yoghurt production. Despite bacteria, yeast and mould growth exhibit a direct influence on the shelf life of fruit yoghurt. Therefore, it is necessary to conduct further research to investigate the enhancement of the shelf life of fruit yoghurt while stabilizing the physiochemical, technological, sensorial and microbiological attributes. The shelf life of fruit-incorporated yoghurts is influenced by factors like microbial activity, anthocyanin degradation, and physical changes during storage. Techniques such as encapsulation and the use of natural stabilizers are pivotal in maintaining product integrity, extending shelf-life, and ensuring market viability. Thus, the incorporation of various fruits and fruit pulps in different physical forms (powder, purée, pulp, *etc.*), concentrations, and processing methods (blended-type, fruit-on-bottom-type, set, stirred, *etc.*) into yoghurt significantly influences its physical, chemical, microbiological, sensory, and nutraceutical properties as illustrated in Figure 6. As comprehensively discussed in this article, these modifications impact yoghurt's overall quality, consumer acceptance, and potential health benefits, highlighting the importance of selecting appropriate fruit types and processing techniques to achieve the desired product characteristics.

## 3.8 Conclusion

The incorporation of fruits and fruit pulps into dairy yoghurts offers synergistic benefits, combining the health-promoting properties of fruits with the nutritional and probiotic advantages of fermented dairy. This blend not only enhances the functional and nutraceutical value of yoghurt but also introduces novel sensory and textural attributes that cater to diverse consumer preferences. Despite the transformative potential of fruit-incorporated yoghurts, challenges such as altered physicochemical properties, microbial instability, and reduced probiotic viability during storage persist, necessitating targeted solutions. This review has highlighted the advances, challenges, and opportunities in the field, providing a comprehensive understanding of the interactions between fruit components and yoghurt matrices. By addressing issues such as syneresis, pH fluctuations, and microbial stability, the dairy industry can develop strategies to optimize product quality and shelf-life. Looking ahead, future research should focus on exploring underutilized fruits and their by-products (e.g., peels, seeds) to maximize resource efficiency and nutritional benefits. Advanced preservation methods, such as encapsulation technologies, natural stabilizers and processing technologies, can extend the shelf life while maintaining the integrity of bioactive compounds. Additionally, consumer acceptability studies through sensory trials will provide valuable insights into market preferences, enabling the development of innovative products that balance functionality, sustainability, and consumer satisfaction. The findings of this review serve as a roadmap for researchers and industry professionals, fostering innovation and ensuring that fruit-incorporated yoghurts continue to meet evolving market demands while supporting health and sustainability objectives.

## Author contributions

HP: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. RM: Writing – review and editing. SP: Writing – review and editing. AW: Writing – review and editing. SJ: Writing – review and editing.

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