Indian J Anim Health (2025), 64(2)- Special Issue: 273 - 291
DOI: https://doi.org/10.36062/ijah.2025.spl.04325

Review Article

Plant-based flavour components for fermented dairy products: A comprehensive review

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Abstract

The fermented dairy sector is experiencing a major shift, driven by growing consumer demand for naturally flavoured, clean-label, and functionally enhanced products. This review examines the role of plant-based flavour components in this evolving landscape. The flavour formation in dairy systems, including yoghurt, cheese and kefir is described, and the incorporation of exogenous plant-sourced volatiles and non-volatiles is highlighted. The plant sources, from conventional herbs and fruits, their key flavour compounds, bioactive properties (e.g., antioxidant, antimicrobial), and mechanisms of incorporation into dairy matrices are discussed. Further, the contribution of lactic acid bacteria (LAB) in the bio-transformation of plant precursors and shaping sensory attributes is highlighted. Advances in analytical techniques for characterizing flavour interactions and sensory evaluation are also reviewed. Furthermore, the influence of plant-based flavours on product stability, consumer acceptance, and marketability is assessed. Current technological barriers, including encapsulation of volatile components, alongside regulatory considerations related to natural labelling, are mentioned. The review concludes with future directions such as precision fermentation, microbiome-based approaches, and the utilization of sustainable, and underexplored plant-based flavour components that holds promise for the development of functional, nutritious, and consumer-preferred fermented dairy products.

Keywords: Clean-label, Encapsulation, Fermented dairy, Food innovation, Plant-based flavours, Sensory attributes

Highlights

- Plant-based flavours enhance sensory profiles of fermented dairy products (FDPs) and provide antioxidant, antimicrobial benefits.
- LAB biotransform plant precursors into aroma compounds, enhancing flavour of FDPs.
- Flavour integration needs balance to avoid inhibiting starters and undesirable bitterness/masking in FDPs.
- Future innovation lies in precision fermentation and nanoencapsulation based advance flavour delivery in FDPs.

INTRODUCTION

The consumption of fermented dairy products (FDPs) by human dates back to 3000 B.C., when early Turkish sheep milk yogurt was first prepared. Likewise, kefir was prepared in the Caucasus mountains in 2000 B.C. The benefits of yogurt are known since 1275, when Marco Polo described its use to boost the health of soldiers of Genghis Khan (Zhang et al., 2023a). The FDPs are prepared from raw milk by the action of lactic acid bacteria (LAB) or by co-fermentation of LAB, bifidobacteria and lactose-fermenting yeasts (Zhang et al., 2023b). The current global market of FDPs is worth 5.9 billion \$ in 2025 and is expected to reach 11.1 billion \$ by 2035 with a compounded annual growth rate (CAGR) of 6.5% (Future Market Insights [FMI], 2025). As far as India is concerned, around 10% of milk produced is converted to fermented dairy products like *dahi* or curd, *lassi*, *shrikhand* etc (Mudgal & Prajapati, 2017). The export and import quantities (Million Tonnes or MT) of fermented and acidified milk products for India in 2023-24 were 2501.17 MT and 1000.47 MT, respectively (Department of Animal Husbandry and Dairying [DAHD], 2025). The FDPs are gaining popularity mainly due to growing consumer awareness about their gut health benefits and diverse, complex appealing flavours, besides a variety of other perceived therapeutic effects (Das et al., 2021a; Gao et al., 2025).

Flavour is not just a quality attribute; rather it is the defining factor in approvability, liking for purchase and acceptance of FDPs. The flavour profile in these products is a harmonious blend of biochemical reactions between the familiar tang of yoghurt to the

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more complex umami of old cheese (Zhang et al., 2024). During fermentation, this symphony is mainly orchestrated by starter and adjunct cultures of microbes, which results in the synthesis of an extremely large range of significant compounds such as aldehydes, ketones, acids, and esters (Vinicius et al., 2020). With increased awareness and health consciousness, there is a shift in focus of the consumers who are now seeking products with natural and plant-based ingredients, as opposed to their synthetic equivalents. The combination of clean-label products based on recognizable ingredients and their perceived health benefits is fuelling the surge in market demand of such products, including FDPs (Asioli et al., 2017).

The integration of plant-based flavours into FDPs is, in many ways, a return to tradition. Culinary heritage across the globe offers testaments to this long-standing practice, from Indian *masala dahi* (yoghurt infused with spices like cumin and coriander), *aamrakhand* (a mango-flavoured *shrikhand*, relished as a popular fermented dessert in Maharashtra and Gujarat) and *kesar dahi* (curd incorporated with saffron) to Middle-Eastern *labneh* (strained yoghurt) garnished with *za'atar* (thyme) (Nagaraja Roopashri et al., 2023; Sirajuddin et al., 2024; Dimassi et al., 2025). However, modern food science is now moving beyond tradition to systematically explore these combinations. The goal is to optimize flavour delivery, enhance functionality through bioactive compounds, and precisely meet contemporary market demands for health and wellness. The central challenge lies in successfully incorporating highly volatile and often potent plant compounds into a biologically active, complex matrix like fermented dairy without compromising beneficial microbial activity, product stability, safety, or the delicate sensory balance.

With this background, the present review critically summarizes the recent scientific advancements on the use of plant-based flavour components in FDPs (Fig. 1). Its scope is extensive, encompassing the fundamental chemistry and microbiology of flavour formation, the diverse sources and multifaceted properties of plant ingredients, their intricate mechanisms of interaction with the dairy matrix, and their ultimate impact on sensory and functional properties of the FDPs. Further, this review also discusses the analytical methods and future research opportunities. The purpose is to provide a comprehensive and insightful resource for the benefit of the product developers, food scientists, microbiologists, in general and the dairy industry in particular.

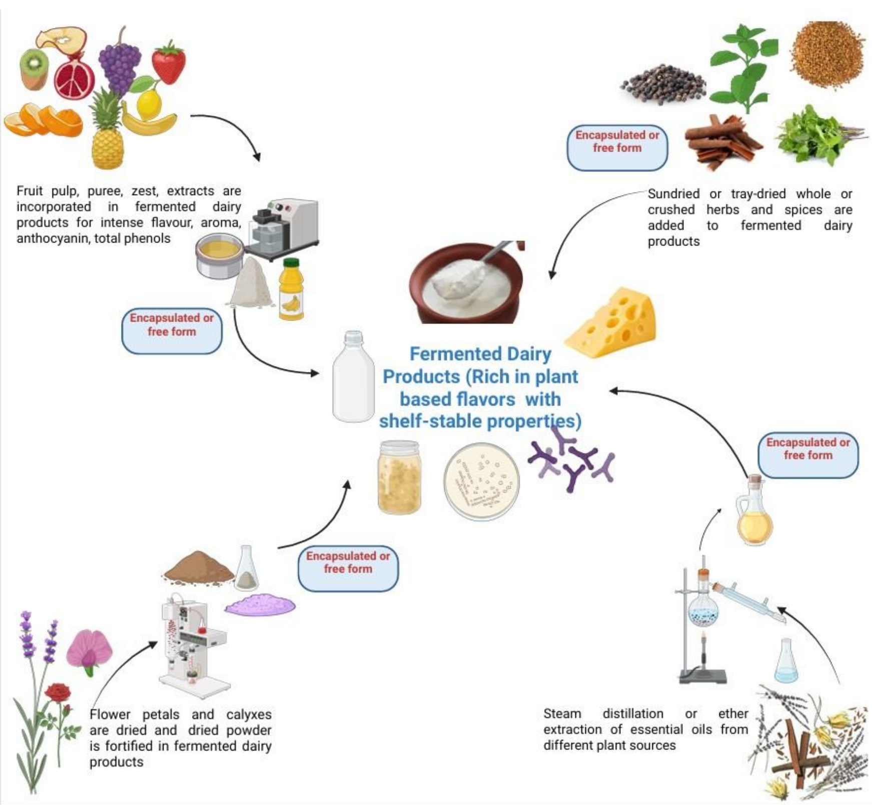

Fig. 1. Use of different plant-based flavour components in fermented dairy products (FDPs)

Fundamentals of flavour formation in fermented dairy products

To check the impact of adding plant-based flavours, it is essential to understand the native flavour landscape of FDPs. This foundation of unique, complex, tangy, and appealing flavour development in FDPs is built upon basic chemistry and the biological transformation by the beneficial microorganisms.

Flavour chemistry and perception: The flavour of FDPs is a multimodal sensory experience arising from the complex interplay of volatile organic compounds (VOCs) and non-volatile compounds (Zhang et al., 2024). This is not a simple list of ingredients, but a dynamic and evolving system. In fact, VOCs are the primary drivers of aroma and are detected by the olfactory system. For example, carbonyls like diacetyl and acetoin are quintessential for buttery, creamy notes, crucial in products like cultured butter and certain cheeses. Aldehydes like acetaldehyde is a key contributor to the characteristic "green" and fresh yoghurt aroma. Acids, including short-chain fatty acids like acetic (vinegar) and propionic (sharp) contribute to sharpness and tang, while lactic acid provides the foundational sourness. Esters like ethyl acetate and ethyl hexanoate impart fruity notes, which can be desirable in many fermented products (Spence, 2021; Zhang et al., 2024). Sulfur compounds, including methanethiol, dimethyl sulfide, and others are critical for the pungent, savory notes in many surface-ripened and hard cheeses (Martínez-Cuesta et al., 2013).

Non-volatile compounds primarily influence the basic tastes on the tongue. Organic acids like lactic, acetic, and citric acids directly contribute to sourness (Spence, 2021; Zhang et al., 2024). Specific peptides and amino acids generated from protein breakdown can impart brothy, umami, or, if unbalanced, tastes bitter. Minerals or salts naturally present in milk also contribute to a subtle saltiness (Zhang et al., 2024).

Flavour perception is governed not only by the absolute concentration of these compounds but also by their individual sensory thresholds-the minimum concentration at which a compound can be detected (Niimi, 2021). Perhaps more importantly, synergistic and antagonistic interactions between compounds are common. This means the overall flavour is not merely the sum of its parts. For instance, sub-threshold levels of certain compounds can enhance the perception of others, a phenomenon known as perceptual synergy (Giri et al., 2010). The matrix itself plays a crucial role; For example, the fat content in dairy products solubilizes lipophilic (fat-loving) flavour compounds, modulating their release during consumption and thereby affecting the temporal flavour profile and perceived intensity.

Biological pathways in dairy fermentation: The primary architects of flavour formation in FDPs are lactic acid bacteria (LAB), including genera such as *Lactococcus*, *Lactobacillus*, *Streptococcus*, and *Leuconostoc* (Bhattacharya et al., 2022; Hu et al., 2022). While the primary function is the fermentation of lactose to lactic acid, providing the characteristic tangy sourness (Chen et al., 2017), flavour contribution is far more sophisticated and occurs through three key biochemical pathways.

Proteolysis- This is the enzymatic breakdown of milk caseins by proteinases and peptidases from LAB into a complex mixture of peptides and free amino acids (FAAs). These FAAs are not only taste-active themselves, but also serve as crucial precursors for further flavour-generating reactions (Hu et al., 2022).

Lipolysis- This involves the limited breakdown of milk fats (triglycerides) into free fatty acids (FFAs) by microbial lipases. These FFAs can have distinct soapy or goaty notes at high concentrations but, more importantly, are precursors for a range of potent aroma compounds. They can be enzymatically transformed into methyl ketones (blue cheese), lactones (peachy, creamy notes), and esters (fruity notes) (Verma et al., 2025).

Citrate metabolism- Certain LAB, notably *Leuconostoc* species and *Lactococcus lactis* ssp. *lactis* biovar *diacetylactis*, can metabolize citrate present in milk. This pathway is the primary source of the crucial butter-like aroma compounds, diacetyl and acetoin (Hu et al., 2022). It is critical to distinguish between flavour development in animal-derived dairy and plant-based dairy alternatives. Plant-based substrates (e.g., from soy, oats, or almonds) inherently lack lactose and casein. This necessitates the use of different, often less well-understood starter cultures, which typically result in distinct, and sometimes undesirable flavour profiles (e.g., beany, grassy, or cereal notes) that require significant masking or modulation with added flavour compounds (Hu et al., 2022). This review focuses specifically on the use of plant flavours within a traditional dairy matrix.

Plant-based flavour components - sources and properties

The botanical kingdom offers a vast and diverse palette of flavours for the innovative food scientists. These components are derived from various parts of plants and are used in multiple physical forms, each with its own advantages and challenges.

Classification of plant-based flavourings: Plant-based flavourings for FDPs can be systematically categorized based on their source and processing:

Herbs and spices- Used in whole, fresh, dried, or powdered forms in FDPs. Examples include mint for freshness, cinnamon for warmth, and vanilla for its rich, sweet aroma (Modupalli et al., 2022). They provide a "whole-food" appeal that is highly valued in clean-label products.

Fruits- Incorporated in FDPs as purees, juices, concentrates, or zests (Priyashantha et al., 2025). Berry purees in yoghurt are a classic example, while citrus zest is prized in fresh cheeses for its intense, top-note aroma without the added acidity of juice. Carrot, apple, pineapple, guava, and mango pulp incorporated *shrikhand* in the western parts of India are also very popular (Sirajuddin et al., 2024).

Flowers- Used as delicate extracts or infusions in FDPs. Lavender and rose are popular for their floral, premium connotations, often used in speciality products (Mebakerlin & Chakravorty, 2015).

Extracts and Oleoresins- Plant extracts are concentrated preparations obtained using food-grade solvents (Das et al., 2024a). Oleoresins are particularly valuable, as they capture both the volatile aroma compounds and the non-volatile components, such as pigments, pungent principles (e.g., piperine in black pepper), and fat-soluble antioxidants (e.g., curcumin in turmeric (Fan et al., 2020).

Essential oils (EOs)- Essential oils (EOs) are the volatile, aromatic essences of plants, typically extracted via steam or hydro-distillation (Das et al., 2023; Moirangthem et al., 2024). They are highly concentrated complexes, predominantly composed of terpenes, terpenoids, phenylpropanoids, and other volatile molecules. Although potent, they are challenging to work with due to their volatility and susceptibility to oxidation.

Major plant families and their key flavour compounds: Understanding the phytochemicals present in various plant families helps predict flavour profiles and functional properties. Some of the plant families and their principal phytochemical compounds responsible for flavour in FDPs are given below:

Lamiaceae (Mint Family)- This family is a treasure trove for savoury and herbaceous flavours. It includes rosemary, sage, thyme, oregano, mint, and basil (Inanoglu et al., 2023). Their EOs are often rich in phenolic monoterpenes like thymol (in thyme-antiseptic and pungent), carvacrol (in oregano- spicy and warm), and eucalyptol (in rosemary- camphorous) (Grigore-Gurgu et al., 2025). These compounds are not only potent flavourants, but also possess significant antimicrobial and antioxidant activities (Fan et al., 2020).

Apiaceae (Carrot Family)- This family provides a range of warm, citrusy, and anise-like flavours and includes coriander, caraway, dill, fennel, and cumin. They are characterized by high contents of monoterpene hydrocarbons like limonene (citrusy) and pinene (piney), and oxygenated monoterpenes like linalool (floral, in coriander) and carvone (spearmint/caraway, in dill and caraway) (El-Ahmady et al., 2021).

Citrus (Rutaceae Family) - The peel (zest) of citrus fruits like lemon, lime, and orange is exceptionally rich in volatile oils. Limonene is the predominant compound, often constituting over 90% of the oil (da Cruz et al., 2023). Other key contributors include citral (a mix of geranial and neral, providing a strong lemon aroma), ã-terpinene, and myrcene, which together deliver the characteristic fresh and bright citrus aroma (Saleem et al., 2024).

Bioactive roles of phytochemical compounds beyond flavour: The incorporation of plant components is generally for dual-purpose, serving as both a flavour enhancer and a functional fortification. This aligns perfectly with the consumer demand for foods that support health and wellness.

Antioxidant activity- Many plant compounds, particularly phenolics, are powerful antioxidants (Das et al., 2020; Biswas et al., 2023;). They can scavenge free radicals, delaying the onset of lipid oxidation in FDPs (Wu et al., 2024). Lipid oxidation leads to rancid off-flavours, so the addition of ingredients like rosemary extract (rich in rosmarinic acid and carnostic acid) or turmeric (curcumin) can significantly extend the product's shelf-life and maintain sensory quality (Amadou et al., 2018).

Antimicrobial activity- Phenolic compounds like thymol and carvacrol, and certain aldehydes like cinnamaldehyde, exhibit broad-spectrum antimicrobial activity. They can inhibit the growth of pathogenic bacteria (e.g., *Listeria monocytogenes, Salmonella* spp., *Escherichia coli, Staphylococcus aureus* etc.) and spoilage microorganisms like bacteria, yeasts and molds (Das et al., 2023; Das et al., 2024a; Moirangthem et al., 2024), thereby enhancing product safety and stability. However, this needs a critical balancing act: the concentration must be high enough to control spoilage, but low enough to avoid inhibiting the vital starter cultures during the crucial fermentation process.

Health-promoting effects- Beyond basic food preservation, many phytochemicals are linked to various health-promoting effects, including anti-inflammatory, anti-carcinogenic, and cardio-protective properties (Biswas et al., 2023). Incorporating these into widely consumed foods like yoghurt represents a significant opportunity in the functional food sector (Bader Ul Ain et al., 2022).

Mechanisms of flavour incorporation and transformation

Simply adding a plant ingredient to a dairy product is not a guarantee of success. The method of incorporation and the subsequent interactions within the matrix are critical determinants of the flavour of the final FDP. The mechanism behind integration of plant-based ingredients as flavour compounds is discussed as follows:

Integration in fermented dairy matrices: The choice of incorporation strategy profoundly influences flavour stability, distribution, and release. Different methods of integrating plant-ingredients in different FDPs are given below:

Direct addition- This is the simplest method, involving the mixing of plant powder, puree, or essential oil directly into the milk before or after fermentation (El-Sayed & Youssef, 2019). While straightforward, it can lead to rapid loss of volatile compounds during processing, may result in uneven distribution, or negative interactions.

Encapsulation- This advanced technology addresses the limitations of direct addition by trapping flavour compounds within a protective carrier matrix (Das et al., 2024b). Common wall materials include maltodextrin, gum arabic, modified starches, and whey or soy proteins. Techniques like spray-drying, complex coacervation, or liposome formation are employed. Encapsulation protects the volatile compounds from heat, light, and oxygen during processing and storage, and can be engineered to provide controlled release during consumption, enhancing the flavour experience (Salehi et al., 2018).

Infusion- This traditional method involves steeping whole or crushed plant material (e.g., vanilla beans, lavender flowers) in the milk base, often with gentle heating, prior to fermentation (Al-Khusaibi, 2019). This allows for a more subtle and integrated flavour extraction. However, it requires careful optimization of time and temperature to avoid extracting undesirable bitter, or astringent compounds, or damaging heat-sensitive milk components (Hasan et al., 2024). Key physico-chemical factors within the FDP itself significantly affect the fate of added plant volatiles. These include the product's pH (which can catalyze hydrolysis of certain compounds), fat content (a reservoir for lipophilic flavours), protein content (a potential binding agent), and the physical structure of the gel (which can hinder diffusion).

Microbial transformation of plant flavour precursors: One of the most fascinating aspects of adding plants to FDP is the dynamic interaction between the plant compounds and the microbial cultures. LAB and other dairy cultures are not passive bystanders; they can actively bio-transform plant compounds, creating novel flavour molecules that were not present in the original ingredient (Hoff et al., 2021). A prime example is the hydrolysis of glycosidically bound volatiles. Many plants store their aroma compounds in a non-volatile, sugar-bound form, known as glycosides (Caffrey & Ebeler, 2021). These precursors are odourless, but can be a hidden reservoir of aroma. Microbial enzymes, particularly β-glucosidases produced by certain strains of LAB and yeasts, can cleave the sugar moiety releasing the active, volatile aglycone (e.g., linalool from its glycoside, geraniol from its glycoside). This enzymatic "activation" can significantly enhance the final aroma profile of the product during fermentation and storage. Furthermore, LAB can metabolize other plant-derived compounds. For instance, certain lactobacilli can decarboxylate or reduce phenolic acids (Porras-Guardado et al., 2025). *Lactobacillus plantarum* can metabolize ferulic acid (common in cereals and some fruits) to 4-vinylguaiacol, which has a distinctive spicy, clove-like aroma (Knockaert et al., 2012). This opens up possibilities for using selected microbial strains as "microbial cell factories" to generate desired flavours *in situ* from inexpensive plant precursors (Romero-Suarez et al., 2022).

Specific plant-based flavour components used in FDPs

Some specific plant ingredients (such as herbs and spices; citrus and other fruit components; flower extracts and infusions; novel and unconventional plant compounds, etc.), their applications in FDPs, and relevant research findings are presented in Table 1 as well as discussed below:

Herbs and spices: Herbs and spices are the workhorses of savoury and warm flavouring, offering both robust flavours and significant functional benefits. Some popular herbs and spices used in FDPs are:

Mint (*Mentha* spp.)- The key compound is menthol, which activates transient receptor potential melastatin 8 (TRPM8) receptors in the mouth, providing a characteristic cooling sensation (Kazemi et al., 2025). It is widely used in yoghurts, labneh, and drinking yoghurts. Research demonstrated that spray-dried encapsulated peppermint oil showed significantly better retention and a more controlled release profile in yoghurt compared to free oil, preventing the typical "first-impact" overwhelming mintiness (Salehi et al., 2018).

Cinnamon (*Cinnamomum* spp.)- Cinnamaldehyde is the dominant compound responsible for the warm, sweet, and woody notes (Farag et al., 2022). Studies have shown that adding cinnamon powder or extract to yoghurt not only enhances its flavour, but also boosts its antioxidant capacity (Mbaeyi-Nwaoha et al., 2024). Interestingly, cinnamaldehyde, at specific sub-inhibitory concentrations, can moderate the post-acidification activity of LAB during refrigerated storage, potentially improving the shelf-life without halting fermentation (Pannerchelvan et al., 2024).

Vanilla (*Vanilla planifolia*)- Vanillin is the primary flavour compound, but high-quality vanilla extract contains hundreds of other compounds that contribute to its complexity. Despite its high cost, it remains a global favourite. The form used (whole bean, extract, or oleoresin) greatly influences the authenticity and depth of the flavour (Manyatsi et al., 2024).

Fenugreek- Shori (2016) investigated the incorporation of fenugreek seed powder into *dahi* (Indian yoghurt). The study found that fenugreek not only imparted a characteristic sweet, maple-like aroma (primarily from the compound sotolon) but also improved the antioxidant activity of the *dahi*. Notably, it enhanced the survival of probiotic bacteria (*Lactobacillus acidophilus*) during refrigerated storage, suggesting a prebiotic-like protective effect.

Table 1. Plant-based flavour sources, their key characteristics, and functional benefits through application in fermented dairy products (FDPs)

Category	Plant Source	Key Flavour Compounds	Form Used	Application in Fermented Dairy	Key Findings and Functional Benefits	References
Herbs & Spices	Mint (*Mentha* spp.)	Menthol, Menthone	Fresh leaves, powder, encapsulated oil	Yoghurt, Labneh, Lassi	Provides a cooling sensation. Encapsulation improves volatile retention, Provides controlled release in yoghurt.	(Salehi et al., 2018)
	Ocimum basilicum (basil)	Linalool Cardinol	Essential oil	Yoghurt	Essential oil did not affect the textural properties of the yogurt; Showed good antiradical activity and sensory acceptability.	(Azizkhani & Parsaeimehr, 2018)
	Cinnamon (*Cinnamomum verum*)	Cinnamaldehyde, Eugenol	Powder, Bark, Extract	Yoghurt, Fermented milk drinks	Imparts warm, sweet notes; Enhances antioxidant capacity; Can moderate post-	(Jiménez-Redondo et al., 2022)

Cont. Table 1.

Table 1., Cont. ...

Category	Plant Source	Key Flavour Compounds	Form Used	Application in Fermented Dairy	Key Findings and Functional Benefits	References
					acidification by LAB, extending shelf-life.	
	Vanilla (*Vanilla planifolia*)	Vanillin, p-Hydroxy-benzaldehyde	Extract, Oleoresin, Powder	Yoghurt, Ice cream, Cream, Cheese	Provides a rich, sweet, and creamy aroma. Preferred over synthetic vanillin for premium products.	(Manyatsi et al., 2024)
	Fenugreek (*Trigonella foenum-graecum*)	Sotolon, 3-Hydroxy-4,5-dimethyl-2 (5H)-furanone	Seed powder, Extract	Dahi, Lassi	Imparts a characteristic maple-like, sweet aroma. Improves antioxidant activity and enhances the survival of probiotics during storage.	(Shori, 2016)
Fruits	Citrus (Lemon, Orange, Lime)	Limonene, Citral, ã-Terpinene	Zest, Essential oil, Juice	Cheese (Ricotta, Goat cheese), Yoghurt	Provides intense aroma without excess acidity. Limonene is the dominant volatile. Protects against oxidation and adds a fresh, top-note.	(Busetta et al., 2022)
	Berries (Strawberry, blueberry)	Esters, Aldehydes, Alcohols, Anthocyanins	Puree, Concentrate, Freeze-dried powder	Yoghurt, Kefir, Quark	Contribute sugars, acids, colour, and complex volatiles. Anthocyanins interact with milk proteins, altering colour and potentially enhancing antioxidant activity.	(Œcibisz & Ziarno, 2023)
	Kiwi, mango, red berry, and strawberry	Terpene compounds (Mostly linalool, ß-phellandrene, geraniol, and a-terpineol)	Puree	Sheep Yogurt	Reduces unpleasant odor and off-flavor, and increased overall acceptance of yogurts Increases the total terpene volatile organic compound profiles of yogurts.	(Garofalo et al., 2024)
Flowers	Lavender (*Lavandula angustifolia*)	Linalool, Linalyl Acetate	Extract, Infusion, Essential oil	Specialty cheeses, Yoghurt	Provides floral, herbaceous notes. Dosage is critical; high levels can impart a soapy flavour. Used	(Semeniuc et al., 2023)

Cont. Table 1.

Table 1., Cont. ...

Category	Plant Source	Key Flavour Compounds	Form Used	Application in Fermented Dairy	Key Findings and Functional Benefits	References
					in premium, artisanal products.	
	Hibiscus (*Hibiscus rosa-sinensis*)	Organic Acids, Anthocyanins	Extract, Powder	Yoghurt, Fermented milk	Provides a vibrant red colour and tart, cranberry-like flavour. Fortification increases antioxidant activity and results in sensorily acceptable products.	(Ali et al., 2023)
Novel/ Exotic Sources	Moringa (*Moringa oleifera*)	Flavonoids, Glucosinolates	Leaf Powder, Extract	Yoghurt, Functional drinks	Rich in nutrients and polyphenols. Enhances nutritional value and antioxidant capacity, but its distinct grassy flavour requires masking or encapsulation.	(Leone et al., 2016)
	Matcha (Green Tea)	Catechins, Theanine	Powder	Yoghurt, Cream Cheese, Frozen yoghurt	Provides a distinct, slightly bitter, umami-rich flavour. Highly valued for its high antioxidant content and association with health.	(Vu et al., 2017)
	Spent hops (*Humulus lupulus*)	β-Acids (Humulone), â-Acids, Myrcene	Extract	Specialty cheeses	Known for creating novel, bitter-cheese profiles. Contributes to a circular economy by upcycling waste.	(Alfeo et al., 2023) (Roy, 2020)
	Gentiana lutea	3-methyl butanoic acid and phenethyl acetate 2,3-butanediol, diacetyl, methyl acetate, 2-phenylethyl	Rhizome powder	Goat cheese	Exhibited reduced unpleasant notes compared to unflavored goat cheeses. Promising flavoring agent in	(Coelho et al., 2023)

Cont. Table 1.

Table 1., Cont. ...

Category	Plant Source	Key Flavour Compounds	Form Used	Application in Fermented Dairy	Key Findings and Functional Benefits	References
		acetate			enhancing the sensory experience and reducing goaty perceptions.	
	Diospyros kaki Thunb.	Acetaldehyde, acetoin, and diacetyl	Leaf extract	Herbal yogurt	Improved antioxidant activity and water holding capacity.	(Joung et al., 2016)
	Nelumbo nucifera	Acetic acid	Leaf extract	*Herbal yogurt*	Improved yogurt organoleptic and acceptability property, in terms of favored flavor, viscosity, and texture.	

Citrus and other fruit components: Fruits provide sweetness, acidity, colour, and a complex bouquet of volatile compounds that are highly appealing in dairy products.

Lemon/Lime/Orange zest- The coloured outer part of the citrus peel, or zest is rich in flavour-packed oil glands (Saleem et al., 2024). In cheese applications (e.g., ricotta, mascarpone, goat cheese), zest is often preferred over juice because it delivers intense aroma without introducing significant additional water, acidity, or sugars that could affect the cheese's texture, pH, and whey separation (Fox et al., 2017). Limonene is the dominant volatile, but the minor constituents define the specific citrus character (da Cruz et al., 2023).

Fruit purees- Berry (strawberry, blueberry, raspberry) and other fruit purees are ubiquitous in yoghurt. They contribute a complex mix of sugars (for sweetness and fermentation), acids (for tartness), pigments (anthocyanins), and a wide range of volatiles (esters, aldehydes, terpenes) (Œcibisz & Ziarno, 2023). These components interact dynamically with the dairy matrix. A study by Şengül et al. (2022) on blueberry yoghurt found that anthocyanins from the fruit bound to milk proteins, which slightly altered the colour hue from blue to more purple-red and potentially formed complexes that could enhance the stability and bioavailability of the antioxidants. In another study by Sirajuddin et al. (2024), *shrikhand* incorporated with carrot pulp showed improved flavour scores as compared to the control sample.

Flower extracts and infusions: Floral flavours are associated with premium, artisanal, and novel product categories. Some commonly used flowers in FDPs are given below:

Lavender (*Lavandula angustifolia*)- The key aroma compounds are linalool and linalyl acetate, which provide floral, fresh, and slightly herbaceous notes (Crişan et al., 2023). It is used in specialty cheeses and yoghurts. The dosage is absolutely critical, as sensory studies have shown that levels perceived as pleasant and floral at low concentrations can quickly become soapy and medicinal at slightly higher concentrations (Öztürk et al., 2017).

Hibiscus [*Hibiscus sabdariffa* (roselle) and *Hibiscus rosa-sinensis*]- The dried calyces are used, providing a vibrant red-purple colour, a tart cranberry-like flavour (from organic acids like hibiscus acid), and a rich profile of anthocyanins and other polyphenols (Shukla et al., 2019). Ali et al. (2023) fortified yoghurt with *Hibiscus* extract and found a dose-dependent increase in antioxidant activity and overall acceptable sensory scores, positioning it as a promising ingredient for functional and colourful dairy products.

Novel and unconventional plant compounds: Innovation often involves looking beyond the conventional to create unique value propositions and tap into emerging health trends.

Moringa (*Moringa oleifera*) plant parts - The different plant parts, like leaf, flower, pods, etc. of moringa plant are celebrated as a "superfood" due to their high content of proteins, vitamins, minerals, and polyphenols, along with proven therapeutic potential

(Madane et al., 2019; Das et al., 2024c). Addition of moringa leaves to yoghurt enhances nutritional density and antioxidant activity (Gomes et al., 2023). However, as Leone et al. (2016) noted, its distinct, potent grassy and vegetal flavour requires careful balancing with other flavours (e.g., citrus, vanilla), or the use of encapsulation to mask it for broader consumer acceptance.

Unconventional edible flowers (e.g., rose, violets, elderflower) - These are gaining traction for their novelty, aesthetic appeal, and premium image. They are typically used as infusions or extracts (Duggirala et al., 2024).

Spent hop extracts- A by-product of the brewing industry, spent hops are rich in bitter acids (alpha-acids, humulones) and terpenes (myrcene, humulene) (Alfeo et al., 2023). Researchers are exploring the use of spent hop in creating novel, bitter-cheese profiles, akin to traditional bitter cheeses, while also upcycling an industrial waste stream (Roy, 2020).

Analytical approaches for characterization of flavour compounds

Deconstructing the complex flavour of a plant-infused FDPs requires a sophisticated system of analytical techniques to bridge the gap between actual chemical composition and human perception. The first and most critical step in extraction and sample preparation techniques is to isolate the flavour compounds from the complex, often fatty, dairy matrix without creating artefacts or losing key volatiles. A number of extraction techniques are nowadays available. Solid-Phase Microextraction (SPME) is a widely used, solvent-free technique. In this method, a fused silica fiber coated with a stationary phase is exposed to the sample's headspace (the air above the sample), absorbing volatile compounds (Jeleñ & Wieczorek, 2023). It is ideal for profiling VOCs in cheese and yoghurt due to its sensitivity, simplicity, and ability to provide a snapshot of the aroma compounds available for perception (Giri et al., 2010). The Solvent-Assisted Flavour Evaporation (SAFE), although is more labor-intensive, but highly effective distillation technique performed under high vacuum. It is particularly suited for fat-rich matrices like dairy, as it allows for the gentle and near-complete isolation of volatiles from the matrix with minimal thermal degradation or artefact formation, yielding a very representative aroma extract for detailed analysis (Sullivan et al., 2021).

The Supercritical Fluid Extraction (SFE) technique uses supercritical CO_2, (at high pressure and temperature) as a solvent. It is considered a "green" technology and is excellent for extracting thermolabile compounds from plant materials to create high-quality, solvent-free "natural" extracts for use in dairy (Kessler et al., 2022).

Chromatographic and spectrometric methods: Once extracted, the complex mixture of compounds must be separated and identified by the following methods:

Gas Chromatography-Mass Spectrometry (GC-MS)- This is the undisputed gold standard for the separation and identification of volatile compounds (Deda et al., 2019). The sample is vaporized and carried by a gas through a long, narrow column, separating compounds based on their affinity for the column's coating. As they exit the column, they are ionized and identified by a mass spectrometer (Regmi & Agah, 2018). When coupled with Gas Chromatography-Olfactometry (GC-O), a human sniffer at the outlet port describes the aroma of each eluting compound, allowing analysts to determine which of the hundreds of detected compounds are actually responsible for the aroma (the "aroma-active compounds") (Giri et al., 2010).

High-Performance Liquid Chromatography (HPLC)- This technique is used for separating and quantifying non-volatile and semi-volatile compounds that are not amenable to GC (Sica et al., 2020). It is indispensable for analyzing compounds like organic acids, specific polyphenols, pigments (e.g., anthocyanins, curcumin), and bitter peptides (Donno et al., 2020).

LC-MS (Liquid Chromatography-Mass Spectrometry)- This combines the separation power of HPLC with the identification capability of MS (López-Fernández et al., 2020). It is particularly useful for identifying non-volatile flavour precursors, such as glycosidically bound volatiles, and for tracking the products of microbial biotransformation of phenolic acids and other polar compounds (Diez-Simon et al., 2019).

Sensory and consumer evaluation: Instrumental data, while precise, is meaningless without correlation to human perception. Sensory evaluation provides this crucial link. Some common sensory or consumer evaluation methods are discussed below:

Descriptive analysis- This is a sophisticated tool where a panel of 8-12 trained assessors quantitatively evaluates a product against a defined lexicon of sensory attributes (e.g., "intensity of rosemary aroma," "cooling sensation from menthol," "bitterness from polyphenols," "creaminess") (Kemp et al., 2018). This generates a sensory "fingerprint" of the product (Puri et al., 2016).

Hedonic testing- This type of testing uses large panels of untrained consumers from the target market to measure the degree of liking (Bareen et al., 2025). The 9-point hedonic scale (from 1="dislike extremely" to 9="like extremely") is a classic method for determining overall acceptability and purchase intent (Addo-Preko et al., 2023).

Threshold determination- This research establishes the minimum concentration of a specific plant extract or compound that can be detected (detection threshold) or recognized (recognition threshold) in a specific dairy matrix (Sipos et al., 2021). This is fundamental for dosage optimization, ensuring that the flavour is perceptible without being overpowering or causing off-flavours (Niimi, 2021).

Impact on sensory quality and shelf life

Effects on sensory quality: The successful incorporation of plant flavours is judged by their ultimate impact on the product's sensory profile and its stability over time. The impact of incorporating plant-based flavour compounds in FDPs is multifaceted and can be both positive and negative, requiring careful formulation. As far as positive contributions is concerned**,** at optimal doses, plant flavours can create highly appealing and innovative products that stand out in the market (Sharma et al., 2024). Examples include rosemary-infused fresh cheese (Himed-Idir et al., 2021), lavender flower powder in Gouda-type cheese (Semeniuc et al., 2023), spiced yoghurt (El-Sayed & Youssef, 2019), and goat milk kefir with ginger and cinnamon (Setiyoningrum et al., 2019). They can also effectively mask undesirable off-flavours, such as the "beany" notes in protein-fortified yoghurts or the slight bitterness of some functional ingredients (Pua et al., 2022).

However, if not properly managed, plant components can introduce undesirable sensory attributes (Pua et al., 2022). These include excessive bitterness or astringency from polyphenols (e.g., from green tea or high concentrations of some herbs), overwhelming herbaceous or "green" notes, or soapy perceptions from certain floral compounds at high doses (Dwivedi, 2022). The dairy matrix itself can modulate these effects; for example, higher fat content can mask bitterness by coating the tongue, while proteins can bind to certain flavour compounds, reducing their perceived intensity (Tian et al., 2025).

Effects on shelf-life: The inherent bioactivity of plant compounds directly translates into tangible benefits for product quality and shelf-life, by virtue of their antioxidant and antimicrobial effects.

Antioxidant effects- Lipid oxidation is a major cause of quality deterioration in dairy products, leading to rancid off-flavours. The polyphenols in plant extracts act as free radical scavengers and metal chelators, interrupting the oxidation cascade (Das et al., 2020; Biswas et al., 2023). For instance, Amadou et al. (2018) demonstrated that ginger extract was highly effective in controlling the formation of primary (peroxides) and secondary (malondialdehyde) lipid oxidation products in fortified yoghurt during storage, thereby preserving its fresh flavour.

Antimicrobial effects- Compounds like thymol (thyme), carvacrol (oregano), and cinnamaldehyde (cinnamon), and other phytochemicals possess strong antimicrobial properties. They can disrupt microbial cell membranes, effectively suppressing the growth of spoilage organisms like yeasts and molds, as well as pathogens like *L. monocytogenes, Salmonella* spp.*, E. coli, S. aureus,* etc. This extends the microbiological shelf-life of the product (Das et al., 2023; Das et al., 2024a). The critical consideration here, is selective inhibition. The concentration of the antimicrobial plant compounds must be carefully calibrated to be high enough to control spoilage, but low enough not to inhibit the vital starter and probiotic cultures during fermentation and throughout storage.

Overcoming technological challenges with flavour compounds

Navigating the practical challenges of formulation is essential for successful product commercialization. However, overcoming the inherent challenges of volatility, instability, and potent flavours requires advanced food engineering approaches like encapsulation. As previously discussed, encapsulation is a key technology. Spray-drying is the most common industrial-scale method for converting liquid EOs and extracts into stable, free-flowing powders. This greatly enhances handling, reduces volatility, and protects the core material (Garavand et al., 2022). More advanced techniques like nanoemulsions (oil-in-water droplets with a diameter of <100 nm) are being researched and implemented (Das et al., 2021b; McClements et al., 2021). Nanoemulsions can improve the dispersion of EOs in the water-based dairy matrix, increase their bioavailability, and allow for lower usage levels of the potent (and often expensive) oil by dramatically increasing its surface area and perceived intensity (Das et al., 2024b). The ultimate goal of many delivery systems is not just protection but controlled release-ensuring the flavour is released at the desired moment, typically during mastication in the mouth, rather than being lost during processing or storage (Weisany et al., 2022).

Legal and Regulatory requirements

The term "natural flavour" is not a marketing buzzword, but a legally defined term with strict requirements that vary by region. Therefore, strict legal and regulatory compliance is very much important before product development and commercialization. Although some plant components have gained the Generally Recognized As Safe (GRAS) status by the US- Food and Drug Administration (FDA) due to their long history of use (Das et al., 2024a), some of the available regulations and/or standards are presented below:

USA (U.S. - FDA): According to the Code of Federal Regulations (CFR Title 21, §101.22), a natural flavour is "the essential oil, oleoresin, essence or extractive, protein hydrolysate, distillate, or any product of roasting, heating or enzymolysis, which contains the flavoring constituents derived from a spice, fruit or fruit juice, vegetable or vegetable juice, edible yeast, herb, bark, bud, root, leaf or similar plant material, meat, seafood, poultry, eggs, dairy products, or fermentation products thereof, whose significant function in food is flavoring rather than nutritional" (Fan & Bin, 2024).

European Union (European Food Safety Authority - EFSA): Regulation (EC) No 1334/2008 is the key legislation governing flavourings. It defines a "natural flavouring substance" as one that is obtained by appropriate physical, enzymatic, or microbiological processes from material of vegetable or animal origin. All flavourings, including natural ones, must undergo a safety assessment before they can be marketed in the EU (Taylor & Linforth, 2010; Younes et al., 2020).

Labelling and Compliance: Claims like "contains natural mint flavour" require that the mint flavour is derived from the mint plant itself (Goodman, 2017). Using encapsulated EOs or extracts still qualifies as "natural flavouring", provided the carriers and processes used are approved for food use (Tsitlakidou et al., 2023). Additionally, compliance with allergen labelling is critical (Chang et al., 2023); for example, if a tree nut extract is used as a flavour, it must be declared on the label.

Indian standards: In order to meet the relevant Food Safety Standard Authority of India (FSSAI) compositional standards, fermented milk products (e.g., yogurt and lassi) must s, have fat content (≥3%), solids-not-fat (SNF≥8.5%). Further, the nature of added cultures as well as limits on non-dairy ingredients like herbs, spices, including natural flavourings should in no case be more than 50 %. The product gets certification, only when free from off-flavours, harmful microbes, and complies with general safety and hygiene standards as per FSSAI and the Bureau of Indian Standards (BIS) (Rasane et al., 2017).

Market trends and Consumer response

The market for flavoured FDPs is vast and continuously evolving. The "clean-label" and "natural" claims are among the most powerful drivers (Fan & Bin, 2024). Consumers are increasingly scrutinizing ingredient lists, preferring products with recognizable ingredients like "real strawberry puree" or "vanilla bean extract" over generic "natural flavour." There is also a growing interest in ethnic and exotic flavours that offer novel experiences (Yang & Lee, 2019), such as turmeric latte yoghurt, matcha green tea cheese, or yoghurts with Middle Eastern spices like cardamom and sumac. The main challenge for manufacturers is managing the often-high cost of authentic, high-quality natural ingredients (like real vanilla) against consumer price expectations, while ensuring consistent flavour delivery, colour, and stability throughout the product's shelf life (Kumari et al., 2025).

Commercial applications: Examining the commercially available FDPs incorporated with plant ingredients provides understanding into successful strategies and regional preferences of plant ingredients in FDPs. Some global and regional examples are given below:

Indian sub-continent- The tradition of adding spices and herbs to *dahi* (yoghurt) and *lassi* (a yoghurt-based drink) is deeply entrenched. Products like *jeera* (cumin), buttermilk and cardamom-flavoured yoghurt are staples. Modern Indian dairy brands are innovating combinations of FDPs like *dahi, lassi, shrikhand,* fortified with saffron, cardamom, black pepper, mint, cucumber, mango, ginger, carrot, apple, *amla* (Indian gooseberry), etc. (Nagaraja Roopashri et al. 2023; Sirajuddin et al. 2024).

Mediterranean region- Herbs have a significant role in Mediterranean cuisine. Greek yoghurt is famously used in *tzatziki*, flavoured with dill, mint, and garlic (Killeit, 2022). In cheeses, herbs like oregano, thyme, and rosemary are common additions (Himed-Idir et al., 2021). A specific example is Hiiumaa Island cheese from Estonia, which is traditionally flavoured with caraway seeds (Sõukand & Kalle, 2016).

Western markets- Innovation here is often focused on premium, organic, and functional FDPs (Mukherjee et al., 2022). This includes yoghurts with superfruit purees (açai, pomegranate, goji berry) (Chang et al., 2019), probiotic drinks and shots with ginger and turmeric for their anti-inflammatory properties (Azeez & Lunghar, 2021), and speciality artisan cheeses infused with herbal ingredients like lavender (Crişan et al., 2023), fennel, or even green tea (Tzima et al., 2020).

East Asia- Matcha (finely powdered green tea) is a hugely popular flavour for a wide range of dairy products, including frozen yoghurt, ice cream, cream cheese, and milk beverages (Vu et al., 2017). It is valued not only for its distinct, slightly bitter, umami-rich flavour but also for its high concentration of catechins, which are potent antioxidants (Kochman et al., 2020).

Innovations in product development: A significant innovation in the dairy industry is the development of symbiotic yoghurts. These products contain probiotic bacteria (e.g., *Bifidobacterium* spp., *L. acidophilus*) and are fortified with prebiotic fibers (e.g., inulin, fructooligosaccharides) (Abdul Manan, 2025). The addition of fruit extracts or purees serves many purposes: it provides desirable flavour and natural colour, and the fruit-derived polyphenols may act as co-pre-biotics, synergistically enhancing the survival and activity of the probiotic cultures through the gastrointestinal tract (Shori, 2016). Another significant area of innovation is in reduced-sugar and low-fat products (Sirajuddin et al., 2024). Here, potent plant flavours like cinnamon, vanilla, and cocoa are strategically used to help compensate for the loss of sweetness and mouthfeel, thereby providing a more satisfying and complex flavour profile that appeals to health-conscious consumers (Modupalli et al., 2022). Several plant-based flavour sources, their key characteristics, applications in different FDPs are summarized in Table 1.

Future perspectives

The incorporation of plant-based flavours in FDPs is an evolving area for future research and innovation. Several exciting and emerging future perspectives in this aspect are:

Precision fermentation and microbial tailoring: Beyond random microbial transformation, this process involves the deliberate selection or genetic engineering of microbial strains specifically for their ability to bio-transform specific plant precursors into highly desirable flavour molecules under controlled fermentation conditions (Hoff et al., 2021). For example, screening for and using LAB strains with exceptionally high β-glucosidase activity to efficiently release floral terpenes from fruit or herb glycosides (Paventi et al., 2025). As understanding of the gut microbiome increases, researchers are focusing on the interaction of specific plant polyphenols from fortified FDPs with the human gut microbiota (Wróblewska et al., 2023). This could lead to the development of FDPs that deliver targeted, synergistic health benefits, such as modulating specific bacterial populations for improved metabolic health (Beltrán-Velasco & Clemente-Suárez, 2025). The recent developments, like Next Generation Sequencing (NGS), functional genomics, metabolomics, proteomics, transcriptomics, etc., will further facilitate understanding of microbial dynamics as well as biochemical processing occurring in FDPs (Fernández et al., 2015). More research on use of plant ingredients as "pre-biotics", exploration of novel "synbiotics", and emergence of "para-prebiotics (ghost probiotics)" and "postbiotics" will provide more possibilities in understanding the functionality of FDPs (Zhang et al., 2023b).

Sustainability: Nowadays, more thrust is given to source flavours from upcycled plant-based food industry by-products in FDPs (Dhiman et al., 2025). Fruit peels (citrus, apple), pomace from juicing, spent grains from brewing, and coffee grounds are all rich sources of flavour precursors. From these, bioactive compounds can be valorized and utilized in the dairy processing industry, thereby reducing waste but at the same time creating sustainable, and cost-effective ingredients (Hashimoto et al., 2024). This is possible by exploring unexplored plant sources through (i) systematic bioprospecting of underutilized, regional, or wild botanicals can uncover unique flavour profiles and novel functional compounds for FDPs, offering a point of differentiation in a crowded market (Singh & Kumar, 2025), (ii) conducting research on advanced next delivery systems for volatile flavour compounds. This includes the refinement of nanoemulsions (Das et al., 2021b; McClements et al., 2021), the development of solid lipid nanoparticles (Paul et al., 2025), and niosomes (Dehnad et al., 2024) for even more targeted flavour delivery, enhanced stability, and improved bioavailability of plant-based flavours in FDPs.

Conclusion

The integration of plant-based flavour components into FDPs represents a dynamic and emerging area perfectly suiting to the rising consumer demands, besides fitting into the sustainable development goals (SDGs). This review has highlighted that beyond mere flavouring, these plant ingredients offer significant functional benefits, with notably enhanced antioxidant and antimicrobial activities that improve product shelf-life and safety. The successful development of such products requires a thorough understanding of flavour chemistry, microbial interactions, and matrix effects within the dairy system. While challenges related to flavour stability, cultural inhibition, and regulatory compliance exist, advanced technologies like encapsulation and nanoemulsions offer promising solutions. The strong consumer desire for clean-label, natural, and healthy products ensure continued growth and innovation in this aspect. Future research should focus on harnessing microbial potential for flavour biotransformation through precision fermentation and microbiome tailoring, exploring sustainable plant sources, and developing next-generation delivery systems to develop more nutritious, delicious, and healthier fermented dairy products.

Conflict of interest: The authors declare that there was no conflict of interest between them.

Author's contribution: AKD: Conceived the idea; AD, DB: Searched the literature, drafted the manuscript and prepared the figure; PKN, AKD, PD: Reviewed and edited the manuscript

Data availability statement: All data are available within this manuscript.

Use of artificial intelligence tools: The Author used ChatGPT-5.0 for minor language correction of the manuscript after the authors wrote the initial draft. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Received – 11.10.2025, Accepted - 19.11.2025, Published - 28.11.2025 (Online), 01.12.2025 (Print)

Section Editor: Dr. Subrota Hati, Editorial Board Member