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A Comprehensive Review on Herbal Fortification of Traditional Indian Cheeses: Focus on Cheese Enriched with *Bergenia ciliata* Rhizome Extract

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Abstract

The physiological benefits of phytochemicals from medicinal plants are well documented, and their incorporation into foods is gaining popularity. Fresh acid-coagulated cheeses, traditional Indian dairy products, represent a novel delivery matrix for plant-derived bioactives. This literature review critically evaluates the feasibility of using *Bergenia ciliata* rhizome extract as a natural antioxidant source in such cheeses. We systematically examine the phytochemical composition of *Bergenia ciliata*, focusing on its major polyphenols (bergenin, gallic acid, catechin, ellagic acid, and afzelechin) and their radical-scavenging mechanisms. The review also synthesises current knowledge on the effects of herbal fortification on the physicochemical, textural, colour, and sensory properties of fresh acid-coagulated cheeses. Key technological challenges, including bitterness, colour darkening, and moisture migration, are identified. Important research gaps are highlighted: the lack of standardised extraction protocols, scarce data on the bioaccessibility of *Bergenia ciliata* polyphenols in cheese matrices, and the absence of Indian consumer acceptability studies. Finally, we propose future directions such as microencapsulation, hurdle technologies for shelf-life extension, and clinical efficacy trials for *Bergenia ciliata*-fortified cheeses. This review provides a foundational framework for developing commercial functional cheeses that combine traditional knowledge with modern food science.

Keywords

• Functional Dairy • Herbal Fortification • Bergenia Ciliata • Antioxidants • Polyphenol-protein Interactions • Fresh Acid-coagulated Cheese • Nutraceuticals

Review Methodology

This work is structured as a critical narrative review rather than a systematic review. The literature was identified through searches of PubMed, Scopus, Web of Science, and Google Scholar using combinations of the following keywords: *Bergenia ciliata*, bergenin, herbal fortification, paneer, chhana, acid-coagulated cheese, polyphenol–protein interactions, functional dairy, microencapsulation, and shelf-life. Searches were conducted between January 2024 and December 2025 without language restrictions. Inclusion criteria were: (i) peer-reviewed studies on the phytochemistry, antioxidant activity, or safety of *Bergenia ciliata*; (ii) studies on the physicochemical, textural, sensory, or microbiological properties of fresh acid-coagulated cheeses; (iii) studies on the incorporation of plant extracts or polyphenols into dairy matrices; and (iv) authoritative regulatory or commercial sources relevant to functional dairy products.

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Exclusion criteria were: (i) studies on non-dairy matrices without relevance to cheese; (ii) studies on *Bergenia* species other than *Bergenia ciliata* unless directly comparative; and (iii) non-peer-reviewed sources except for regulatory documents. No formal quality assessment or risk-of-bias assessment was performed because this is a narrative review. Evidence was synthesised thematically and is presented with explicit labelling of whether findings were directly demonstrated in *Bergenia ciliata*, demonstrated in another plant extract, demonstrated in another dairy matrix, or are proposed expectations. A total of 87 articles were identified, of which 62 met the inclusion criteria and were included in this review.

1. Introduction

For centuries, medicinal plants have been used to treat diseases and maintain health. Their therapeutic effects are attributed to diverse secondary metabolites [1]. Among these, *Bergenia ciliata* (commonly known as patharchur) is particularly noteworthy [2]. Traditional medicine systems have long utilised this plant, and modern research has confirmed its abundance of polyphenols, which exhibit potent antioxidant and anti-inflammatory activities [3].

India boasts a wide variety of traditional cheeses, mostly handmade and consumed fresh [4]. These cheeses are characterised by high moisture content, a mildly acidic pH, and a spongy texture, making them excellent vehicles for incorporating herbal extracts. However, adding plant extracts to such matrices poses challenges, including moisture imbalance, texture hardening, colour changes, and off-flavours [5]. This review aims to evaluate the potential of *Bergenia ciliata* rhizome extract as a functional ingredient in fresh Indian cheeses.

The specific objectives of this review are: (i) to elucidate the phytochemistry and antioxidant mechanisms of *Bergenia ciliata*; (ii) to describe the processing and quality attributes of traditional acid-coagulated cheeses; (iii) to synthesise information on the impact of herbal fortification on cheese quality; and (iv) to propose strategies for mitigating sensory and stability issues in cheeses fortified with *Bergenia ciliata* rhizome extract.

The anticipated outcome is a blueprint for producing a commercially viable, antioxidant-rich cheese that honours indigenous knowledge while meeting modern quality standards [6]. It is important to clarify at the outset that the specific application of *Bergenia ciliata* rhizome extract in fresh acid-coagulated Indian cheeses remains unexplored. Consequently, many statements in this review regarding the transfer, retention, and commercial viability of bioactives in the cheese matrix are hypotheses, extrapolations, or expectations based on analogous dairy systems, rather than established facts. These are explicitly identified as such throughout the text.

1.1 Indian Traditional Cheeses – Contextual and Characteristic Features

India's dairy heritage includes numerous traditional products, though many remain poorly characterised scientifically. Among fresh acid-coagulated cheeses, paneer and chhana are relatively well described, but they are not interchangeable matrices [7]. Both are typically made by heating milk to 80–85 °C and adding a coagulant (citric acid or sour whey), yet their handling after coagulation differs. Paneer is pressed into a compact, sliceable matrix with a relatively firm and cohesive body. Chhana is usually drained and kneaded with less pressing, so it remains softer, higher in moisture, and more pasty or granular. These differences affect extract distribution, polyphenol–protein interactions, moisture retention, and the sensory and textural response to herbal fortification [8].

Consequently, paneer and chhana should be considered separately when selecting extract addition

levels and incorporation points. Paneer's compact structure may limit diffusion of added extract and intensify local colour or flavour if mixing is incomplete, whereas chhana's higher moisture and softer matrix may favour dispersion but also increase the risk of moisture migration and textural softening. Such cheeses generally have a moisture content of 60–68%, fat 12–20%, and protein 14–18% (dry basis), depending on milk composition and processing, although paneer tends toward the lower moisture end and chhana toward the higher end. Their high water activity and mildly acidic pH (5.8–6.0 for the final product, distinct from milk pH and curd pH) limit shelf-life under refrigeration due to microbial spoilage [9]. The bland flavour and open structure favour the absorption of liquid extracts, making them suitable for fortification. Studies on paneer and chhana have shown that extracts of ginger, turmeric, mint, and amla can be added at 0.5–1.0% without compromising quality, providing a precedent for other applications [10].

Kneading is a critical step that develops the characteristic elastic texture and must be performed while the curd is still warm. Subsequent pressing and moulding are followed by cooling. The entire process takes only a few hours, which restricts contamination but also limits shelf life. The addition of herbal extracts may alter the microbial ecology of both spoilage organisms and indigenous lactic acid bacteria; low polyphenol levels may be tolerated by, or even stimulate, some lactic acid bacteria, whereas higher levels can inhibit spoilage organisms and potentially lactic acid bacteria [11]. The net effect on each group therefore warrants separate investigation. Specifically, the concern relates primarily to spoilage organisms such as *Pseudomonas* spp., *Enterobacteriaceae*, and moulds, which are sensitive to polyphenols, while indigenous lactic acid bacteria (e.g., *Lactococcus*, *Leuconostoc*) may exhibit varying tolerance depending on strain and polyphenol concentration. Differential effects on these groups should be characterised to optimise fortification levels for shelf-life extension without compromising starter cultures.

2. Related Work

Several comprehensive reviews have addressed functional foods and nutraceuticals. The fortification of dairy products with plant bioactives has been explored [12]. The phytochemistry and pharmacological activities of *Bergenia ciliata* have been documented [1]. Extraction techniques for plant bioactives have also been reviewed [13]. However, the specific application of *Bergenia ciliata* rhizome extract in fresh acid-coagulated Indian cheeses remains unexplored, which is the focus of this review.

3. *Bergenia ciliata*: Phytochemistry and Antioxidant Potential

The rhizome of *Bergenia ciliata* is rich in secondary metabolites. Major bioactive constituents include bergenin (a C-glycoside of gallic acid), gallic acid, catechin, ellagic acid, (+)-afzelechin, and p-hydroxybenzoyl glucoside [2]. Table 1 summarises these compounds and their established antioxidant mechanisms [14].

Bergenia ciliata extracts display strong radical-scavenging activity in various in vitro assays [3]. DPPH assays yield IC_{50} values of 15–30 µg/mL, comparable to ascorbic acid, while ABTS decolourisation assays give EC_{50} values of 20–40 µg/mL. These values are directly demonstrated in *Bergenia ciliata* rhizome extracts [3]. These activities correlate strongly with total phenolic and flavonoid content. Ethanol is a more effective solvent than water or hexane for extracting these bioactives [13].

The antioxidant mechanisms include direct free-radical quenching, metal chelation (preventing Fenton-type reactions), and upregulation of endogenous antioxidant enzymes; these mechanisms are demonstrated for specific compounds in *Bergenia ciliata* or analogous polyphenols, and should not be

Table 1: Major antioxidants in *Bergenia ciliata* rhizome extract

Compound	Class	Mechanism of action
Bergenin	C-glycoside	Direct radical scavenging; metal chelation
Gallic acid	Phenolic acid	Hydrogen atom transfer; upregulates SOD/CAT
Catechin	Flavanol	Inhibits lipid peroxidation; Fe^{2+} chelation
Ellagic acid	Tannin derivative	Nrf2 activation; ROS quenching
(+)-Afzelechin	Flavanol	Peroxyl radical trapping (ORAC)

inferred as general polyphenol biology without compound-specific evidence [15]. The extract also shows moderate lipophilic antioxidant activity in β-carotene bleaching assays, indicating protection of lipid matrices from oxidative damage [16].

4. Extraction Techniques and Standardisation of Bioactive Compounds

The efficiency of herbal fortification depends fundamentally on the extraction method used to recover bioactives from plant material. The choice of technique influences not only yield and phytochemical profile but also the stability and bioactivity of the extract in food systems. This section critically examines extraction approaches for *Bergenia ciliata* rhizome, their advantages and limitations, and the need for standardisation [13].

Conventional techniques such as maceration, Soxhlet extraction, and decoction are widely used [17]. Maceration is simple and inexpensive but time-consuming and yields lower recoveries. Soxhlet extraction is more efficient but uses elevated temperatures that can degrade thermolabile compounds like gallic acid and catechins. Decoction uses boiling water, which is suitable for water-soluble constituents but inefficient for hydrophobic polyphenols.

Advanced techniques ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and pressurised liquid extraction (PLE) offer higher yields, shorter times, and better preservation of bioactive integrity [18]. UAE uses high-frequency sound waves to disrupt cell walls; MAE uses electromagnetic radiation to accelerate mass transfer; PLE operates at elevated temperature and pressure to enhance solubility and diffusion.

Table 2 summarises the trade-offs among conventional and advanced extraction methods for *Bergenia ciliata* rhizome, with emphasis on parameters relevant to commercial dairy processing.

Details of solvent selection, thermal degradation risks, and recovery of specific bioactives are discussed in the text. Briefly, ethanol–water mixtures are superior for polyphenols and flavonoids, while non-polar solvents are suited for lipophilic compounds. Thermal degradation risk is highest for Soxhlet and decoction due to elevated temperatures. Industrial scalability is highest for maceration and decoction due to simplicity and low cost.

Solvent selection is critical. Hydrophilic solvents (ethanol, methanol) are superior for polyphenols and flavonoids, while non-polar solvents (hexane) are suited for lipophilic compounds [3]. Ethanolic extracts of *Bergenia ciliata* consistently show higher total phenolic content and antioxidant activity than aqueous or hexane extracts. The ethanol concentration (typically 50–90%) affects selectivity: higher concentrations favour less polar compounds like bergenin.

Despite these options, the lack of standardised protocols is a major barrier to commercialisation [19]. Variability in parameters solvent type, temperature, duration, solid-to-solvent ratio leads to extracts with

Table 2: Comparison of extraction methods for *Bergenia ciliata* rhizome bioactives

Method	Solvent	Temp.	Time	Yield	Thermal risk	Scalability
Maceration	Ethanol–water, methanol–water, or water	Ambient	Long	Low–moderate	Low	High
Soxhlet	Ethanol, methanol, or hexane	Elevated	Moderate–long	Moderate–high	High	Moderate
Decoction	Water	Near boiling	Moderate	Low–moderate	High	High
UAE	Ethanol–water or water	Ambient–moderate	Short	High	Low–moderate	Moderate–high
MAE	Ethanol–water or water	Moderate–elevated	Very short	High	Moderate–high	Moderate
PLE	Ethanol–water or water	Elevated	Short	High	Moderate–high	Moderate–high

disparate phytochemical profiles and bioactivities, complicating reproducible fortification. A validated, harmonised protocol is essential for batch-to-batch consistency and regulatory approval.

Identification and quantification of marker compounds are cornerstone to standardisation [1]. For *Bergenia ciliata*, bergenin and gallic acid are proposed as suitable markers due to their abundance, stability, and well-known bioactivities. High-performance liquid chromatography (HPLC) with diode-array detection or mass spectrometry enables precise quantification, facilitating quality control. Establishing reference standards and acceptance criteria for marker content would enhance product reliability.

Equally important is characterising the stability of bioactives under processing and storage conditions [14]. Heat, light, oxygen, and pH variations can degrade polyphenols. Preliminary studies indicate that bergenin and gallic acid are moderately stable below 60 °C but susceptible to photo-oxidation. This has implications for cheese processing, where milk is heated to 80–85 °C; protective measures may be needed.

Encapsulation and nanoemulsification are emerging technologies to enhance stability and bioavailability [19]. Microencapsulation with biopolymers can shield bioactives from environmental stressors, control release, and mask undesirable sensory attributes. Encapsulated extracts have been successfully incorporated into dairy products, suggesting applicability to cheese. Integrating encapsulation with standardised extraction protocols could provide a robust commercial pathway.

Economic viability must also be considered [20, 21]. Advanced techniques, while superior, involve higher capital and operational costs. A cost–benefit analysis should evaluate whether premium pricing for functional cheeses offsets these expenses. Sustainable sourcing of *Bergenia ciliata* rhizomes further influences feasibility.

5. Impact of Herbal Fortification on Cheese Quality

The addition of plant extracts to cheese induces a cascade of physicochemical and sensory modifications, summarised below from studies on paneer, chhana, quark, and similar fresh cheeses [5].

A consistent trend is a reduction in moisture content with increasing extract concentration, attributed to the water-binding capacity of extract polysaccharides and proteins, as well as phenolic-casein interactions that cause matrix contraction and whey expulsion [10]. For instance, paneer with 1% *Inula britannica* extract showed a moisture drop from 68% to 62%; this quantitative result is demonstrated in another plant extract and another dairy matrix, not in *Bergenia ciliata*-fortified cheese [10]. Similar behaviour is hypothesised for other fresh cheeses, including *Bergenia ciliata*-fortified cheese, but this remains to be experimentally demonstrated. While fat and protein percentages may rise relatively, absolute fat recovery

can be modulated by extract-induced changes in curd structure.

The pH may be influenced if the extract is acidic (typically pH 4.5–5.5) [8]. However, at fortification levels of 0.1–1.0%, pH shifts are usually less than 0.2 units, remaining within the acceptable range for fresh cheeses. Lactic acid bacteria viability is generally unaffected at < 1% extract; indeed, low polyphenol levels may promote growth, whereas > 2% can exhibit antimicrobial effects. Thus, careful concentration selection is needed to preserve characteristic acidity [22].

Water-holding capacity is also affected, as polyphenols can cross-link proteins, reducing pore size and free water [5]. This can yield a firmer texture but may also impart a drier mouthfeel. Optimisation is required to balance firmness and moisture retention.

Textural parameters such as hardness, gumminess, and chewiness tend to increase with extract addition, while cohesiveness and springiness are often maintained [5]. These changes stem from reduced moisture, protein cross-linking via tannin–protein interactions, and reinforcement of the casein network. In quark cheese with ginseng extract, hardness increased by 50–60% at 1% addition; this quantitative result is demonstrated in another plant extract and another dairy matrix, not in *Bergenia ciliata*-fortified cheese [5]. For softer cheeses, the effect may be less pronounced. By extrapolation, a comparable hardness increase is expected in *Bergenia ciliata*-fortified cheese, but this is a hypothesis requiring direct experimental validation. Excessive hardening can produce a gritty, mealy texture, necessitating careful concentration control. Adhesiveness may decrease due to surface moisture loss, while fracturability may increase, resulting in a more brittle structure. These alterations are not inherently detrimental but require sensory validation [23].

Colour changes are inevitable with most plant extracts [10]. The dark brown hue of *Bergenia ciliata* extract, from oxidised polyphenols, reduces lightness (L*) and increases redness (a*) and yellowness (b*). Consumer acceptance depends on product positioning; a "natural herbal" cheese may be tolerated if colour is uniform and appealing. Microencapsulation or whitening agents could mitigate colour shifts, albeit at added cost. Co-fortification with natural colorants (annatto, turmeric) could offset darkening, though this may interfere with antioxidant activity.

Colour stability during storage is another concern, as polyphenols can undergo further oxidation, leading to progressive darkening. Vacuum or modified-atmosphere packaging (high CO_2, low O_2) can slow this. Additionally, tannins may react with iron from equipment, causing black spots; hence, stainless steel or food-grade plastics are recommended [24].

The primary goal of enhancing antioxidant capacity is generally achieved [15]. Studies report a strong linear correlation ($r > 0.9$) between extract concentration and ABTS/DPPH scavenging activity in cheese. However, the actual activity in cheese is typically 30–60% of that of the free extract, due to binding with milk proteins and fat; this quantitative result is demonstrated in other plant extracts and other dairy matrices, not in *Bergenia ciliata*-fortified cheese [8]. This reduction arises from polyphenol–casein interactions. Hydrophobic interactions occur between the aromatic rings of phenolic compounds and nonpolar side chains of caseins, while hydrogen bonding involves phenolic hydroxyl groups and amide or carbonyl groups of the protein backbone. Proline-rich regions of caseins can further stabilize these interactions by providing open, flexible binding sites. Tannin-like constituents may also cross-link caseins, reducing the pool of free polyphenols available for radical scavenging. For example, quark with 1% ginseng extract (80% ABTS inhibition) showed 56% inhibition [5]. The interaction between phenolic compounds and caseins can be further understood by considering the specific binding mechanisms. Gallic acid, a small phenolic acid, primarily interacts through hydrogen bonding with the carbonyl groups of the protein backbone and through hydrophobic interactions with aromatic residues. Catechin, a flavanol, can form both hydrogen bonds and hydrophobic interactions, and its galloyl moiety may enhance binding affinity.

Tannin-like constituents, such as ellagic acid derivatives, can cross-link caseins through multiple hydrogen bonds and hydrophobic interactions, leading to protein aggregation and reduced polyphenol bioavailability. These mechanisms are demonstrated for specific polyphenol–casein systems and are proposed here as likely mechanisms for *Bergenia ciliata* polyphenols, pending direct experimental confirmation. These interactions are pH-dependent, with binding generally stronger near the isoelectric point of caseins (pH 4.6) due to reduced electrostatic repulsion. The presence of proline-rich regions in caseins, particularly in β-casein and κ-casein, provides flexible binding sites that can accommodate phenolic compounds through hydrophobic stacking and hydrogen bonding. This mechanistic understanding explains why measured antioxidant capacity in the finished product does not necessarily correspond to the activity of the extract before incorporation, and it highlights the importance of optimising extract addition levels and incorporation methods to maximise bioactive retention. The bioaccessibility of polyphenols from cheese is an active research area; preliminary findings suggest that the protein matrix may protect polyphenols through the upper gastrointestinal tract, enhancing colonic delivery [19]. Monitoring antioxidant activity over shelf life is crucial, as degradation can occur due to oxygen and enzymatic activity. Encapsulation can protect polyphenols and prolong their active half-life.

5.1 Evidence Hierarchy

To clarify the strength of evidence supporting statements in this review, Table 3 categorises the evidence base according to direct relevance to *Bergenia ciliata*-fortified fresh acid-coagulated cheeses.

Table 3: Evidence hierarchy for claims regarding *Bergenia ciliata*-fortified fresh acid-coagulated cheeses

Evidence category	**Example**	**Direct relevance**
Bergenia ciliata rhizome studies	Phytochemistry/antioxidant activity	High for extract
Bergenia + dairy	Direct cheese experiments	Currently limited/absent
Other herbal extracts + paneer/chhana	Texture/sensory studies	Moderate
Other polyphenols + cheese	Protein interactions	Moderate
General functional-food literature	Encapsulation/stability	Indirect

Statements in this review are labelled according to this hierarchy to distinguish directly demonstrated findings from extrapolations and hypotheses.

6. Sensory Challenges and Consumer Acceptance

Herbal cheeses often exhibit bitter, astringent, or off-odour notes during sensory assessment [10]. *Bergenia ciliata* contains gallotannins and ellagitannins, which interact with salivary proteins and bitter taste receptors, imparting astringency and bitterness [2]. In similar products, extract levels below 0.5% are generally acceptable, while ≥1% often leads to rejection.

The Indian palate, however, is accustomed to bitter and astringent notes (e.g., fenugreek, bitter gourd), which may permit moderately higher inclusion levels [25]. Nevertheless, masking strategies such as encapsulation with liposomes or cyclodextrins, co-fortification with sweet spices (cardamom, cinnamon), or fermentation with tannin-metabolising strains should be explored [19]. Their point of application within the manufacturing sequence is not equivalent. Incorporating encapsulated or free extract into a pre-coagulation slurry in milk can improve dispersion and may allow interactions with caseins during coagulation, but a portion may be lost in whey during draining [8]. By contrast, blending the extract or encapsulated preparation into the curd after drainage and during kneading reduces exposure to whey losses and permits tighter dose control, although distribution may be less uniform unless mixing is

vigorous. Surface application after moulding is simplest but creates a concentration gradient and uneven colour and taste. For *Bergenia ciliata*, pre-coagulation addition with a filtered, well-dispersed slurry is hypothesised to favour uniformity, whereas post-drainage addition may better preserve bioactives and mask bitterness if the encapsulated form is used. These expectations are based on analogous dairy systems and require direct experimental verification. The earthy, root-like aroma of *Bergenia ciliata* may not appeal to all consumers; blending with essential oils (clove, nutmeg) could improve flavour [1]. Extract concentrations above 0.5% often cause sharp declines in overall acceptability, even though antioxidant activity continues to rise; this threshold is demonstrated in other plant extracts and other dairy matrices, not in *Bergenia ciliata*-fortified cheese. There exists a delicate balance between bioactivity and sensory quality. The functional threshold the maximum extract concentration that does not significantly reduce hedonic scores (by ANOVA/RM-ANOVA) compared to the control typically lies between 0.5% and 1.0% for most fresh cheeses; this range is demonstrated in other plant extracts and other dairy matrices, not in *Bergenia ciliata*-fortified cheese, and has not yet been established for *Bergenia ciliata* [10]. Urgent sensory studies with Indian panellists ($n > 100$) are needed; the proposed sample size is a recommendation, not a demonstrated requirement.

Furthermore, if the cheese is used in cooked dishes (e.g., frying), heat may degrade some tannins, altering bitterness perception, while flavour compounds may evolve differently.

7. Processing Technology for Herbal Fortification

The method of incorporating herbal extracts significantly influences final product quality [12]. Extracts (liquid or powder) can be added to milk before coagulation, to curd during kneading, or applied to the surface or by dipping the final product. Each approach has merits and drawbacks.

Adding polyphenols directly to milk ensures uniform distribution and better retention, as they interact with caseins during coagulation [8]. However, the buffering capacity of extracts may hinder acid coagulation. Addition during kneading allows better concentration control and batch-to-batch consistency but may lead to inhomogeneous distribution. Surface application is simple and dose-flexible but creates a concentration gradient, causing uneven colour and taste.

Previous work on other fresh cheeses indicates that dispersing the extract in water (10–20% w/v) and adding it to milk before heating and coagulation yields the most consistent results [10]. Filtration of the extract is necessary to remove insoluble particles and avoid a sandy mouthfeel. A homogenisation step may further improve dispersion.

Microencapsulation in food-grade wall materials (maltodextrin, gum arabic, alginate) is a proposed strategy to mask bitterness and improve stability [19]. Encapsulation is hypothesised to protect bioactives from heat, oxygen, and protein interactions, and may enable controlled release during digestion. Encapsulated green tea extract has been successfully used in cheese to mask flavour while retaining antioxidant activity; similar strategies are proposed for *Bergenia ciliata*, though direct experimental validation is required. The added value must be weighed against the cost, but for a premium functional product, encapsulation is a justifiable hypothesis pending cost–benefit analysis [26].

8. Shelf-life and Packaging

Fresh acid-coagulated cheese is inherently perishable. Herbal extracts with antimicrobial properties can extend shelf life [11]. Gallic acid and catechin, for example, exhibit activity against Gram-positive bacteria and some moulds [2]. Thus, fortified cheese may have a longer shelf life than plain cheese, but

this depends on concentration and requires experimental verification.

Packaging is crucial for product stability [24]. Vacuum packaging or modified atmosphere (30–60% CO_2) inhibits aerobic microbes and oxidative rancidity. Light-protective packaging (e.g., aluminium foil laminate) prevents photo-oxidation of polyphenols. Accelerated shelf-life studies (e.g., at 15 and 25 °C) with regular monitoring of microbial counts, lipid oxidation (TBARS), and antioxidant activity are proposed as necessary future work to define optimal conditions [5].

9. Regulatory and Safety Considerations

The regulatory status of *Bergenia ciliata* rhizome extract for dairy use must be evaluated separately from its traditional medicinal use, toxicological evidence, food-use history, and regulatory authorization. *Bergenia ciliata* is not currently on the FDA's GRAS list nor evaluated by FSSAI (India) for dairy use [2]. However, FDA GRAS status is not the only relevant regulatory criterion; other jurisdictions and frameworks may apply. The following distinctions must be made:

1. **Traditional medicinal use**: *Bergenia ciliata* has a long history of use in Ayurvedic and traditional medicine [1].
2. **Toxicological evidence**: Acute oral toxicity, subchronic toxicity, genotoxicity, and reproductive toxicity data are required to establish safety at the proposed extract concentration, extraction solvent, formulation, and exposure level [12].
3. **Food-use history**: Traditional use does not automatically establish food safety at a particular extract concentration, extraction solvent, formulation, or exposure level.
4. **Regulatory authorization**: The extract must be authorised for food use in the target jurisdiction. In India, FSSAI regulations govern novel foods, food ingredients, and additives.
5. **Permissible ingredient/extract status**: The specific extract preparation (solvent, concentration, marker compound profile) must be evaluated as a permissible ingredient.
6. **Contaminant requirements**: Extracts must be tested for heavy metals, pesticides, aflatoxins, and microbiological contaminants following Good Manufacturing Practices [12].
7. **Dose/exposure assessment**: A quantitative dose–exposure assessment is required to establish safe levels of intake for the target population.

Given the long history of human use, the risk is likely low, but this is not sufficient scientific justification for food-safety approval. Standardisation based on marker compounds (e.g., bergenin content) is essential for batch-to-batch consistency [18]. Authoritative regulatory sources should be consulted for jurisdiction-specific requirements.

10. Future Perspectives and Research Gaps

Despite the promising outlook, several critical gaps must be addressed before commercialisation.

Extraction protocols are highly inconsistent, with varied methods (maceration, Soxhlet, UAE) and solvents. No standardised extract profile exists. A validated HPLC method for quantifying marker compounds in both extract and cheese matrix is proposed as a priority for future research [13].

Shelf-life studies: the refrigerated shelf life of fresh cheese is reported as 5–7 days in some studies, during which polyphenols may degrade and oxidative rancidity develop; this value is demonstrated in other dairy matrices and should not be generalised to *Bergenia ciliata*-fortified cheese without direct measurement. Accelerated shelf-life studies (e.g., 25 °C/60% RH) and packaging trials are required [11]. Microencapsulation could be a solution.

In vivo efficacy: to claim "functional food" status, antioxidant effects must be demonstrated in vivo, not just in vitro. Animal studies (e.g., rats on a high-fat diet) are proposed as the necessary first step.

Economic feasibility: commercial production requires cost–benefit analysis covering extract cost, incorporation method, and yield impact; this is proposed as a necessary future step [27].

Consumer preferences: India's gourmet cheese market is diverse. Extensive sensory studies across socio-economic strata, age groups, and regions are proposed as necessary future work [10]. Willingness-to-pay studies would also be insightful [28].

Traditional knowledge integration: involving ethnic and traditional cheese makers in product development is proposed as essential. Their expertise in delicate processing steps, combined with food technology, can yield novel products. The Ayurvedic heritage of *Bergenia ciliata* may attract health-conscious consumers [1].

11. Conclusion

This integrated review critically evaluates the feasibility of developing a functional cheese fortified with *Bergenia ciliata* rhizome extract. The plant is rich in polyphenols notably bergenin and gallic acid which confer strong antioxidant capacity [17]. Available evidence from *Bergenia ciliata* extracts and analogous fortified dairy systems suggests that these bioactives may be incorporated and retained in the cheese matrix, although direct experimental validation is required. If confirmed, this would make such cheeses a suitable vehicle for functional food development.

The physicochemical changes induced by rhizome extract addition moisture loss, texture hardening, and colour darkening must be managed [5]. Polyphenol protein interactions can cause bitterness and astringency. Therefore, standardisation of extract concentration through sensory screening is imperative. Encapsulation and hurdle technologies are proposed as promising avenues to overcome these challenges, pending experimental validation [19].

While the potential is substantial, critical research gaps remain: standardised extraction protocols, stability data, in vivo efficacy, consumer acceptance, and economic viability [21]. Addressing these gaps is proposed as the pathway to a commercially viable, antioxidant-rich cheese that leverages indigenous knowledge and meets modern quality standards [14].

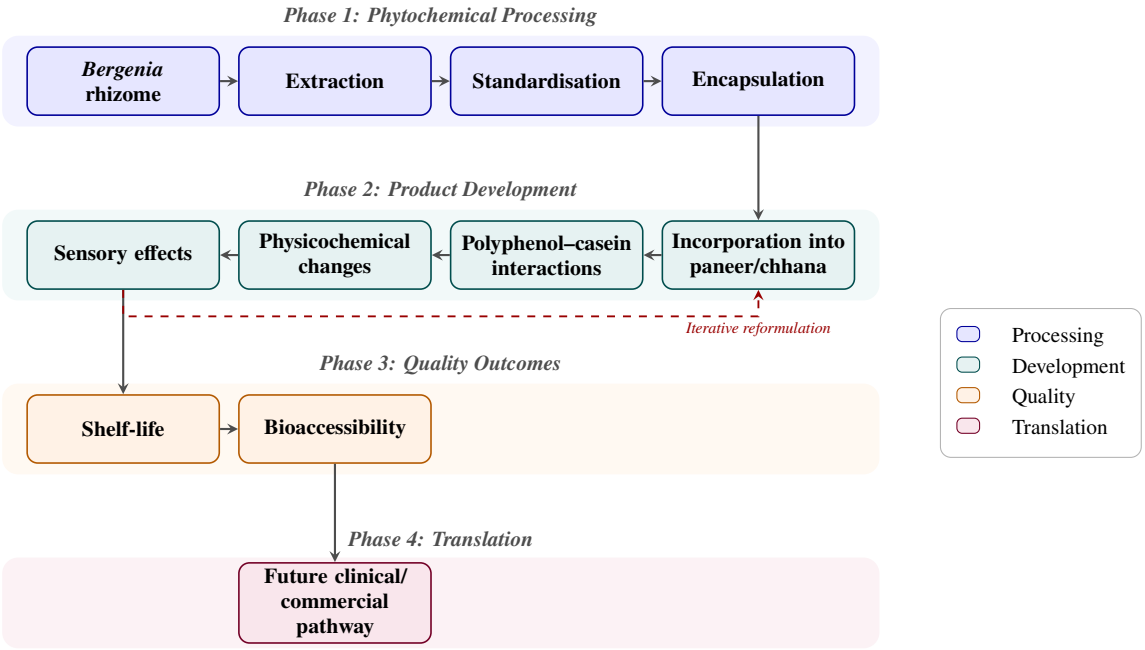


Figure 1: Conceptual framework for the development of *Bergenia ciliata*-fortified fresh acid-coagulated Indian cheeses. The framework is organised into four phases: (1) phytochemical processing (rhizome extraction, standardisation, encapsulation); (2) product development (incorporation into paneer/chhana, polyphenol–casein interactions, physicochemical and sensory changes); (3) quality outcomes (shelf-life and bioaccessibility); and (4) translation (future clinical and commercial pathway). A dashed feedback loop indicates iterative reformulation based on sensory and quality outcomes.

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