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"ULTRASOUND-ASSISTED EXTRACTION OF NATURAL PRESERVATIVES FROM CURRY LEAF (*MURRAYA KOENIGII*) WASTE AND THEIR APPLICATION IN ENHANCING THE SHELF LIFE OF DAIRY PRODUCTS: PANEER, CURD, AND MILK

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Abstract: Natural preservatives are becoming more popular due to customer demand for clean -label foods. Processing curry leaves produces a significant amount of waste, including wasted leaves, stalks, and trimmings, which are rich in bioactive substances such flavonoids, phenolic acids, carbazole alkaloids, and essential oils with potent antibacterial and antioxidant qualities. An effective, environmentally benign way to recover these chemicals is using ultrasound -assisted extraction (UAE). Plant cell walls are disrupted by acoustic cavitation, which increases extraction yield while lowering energy, time, and solv ent consumption. Additionally, UAE protects heat-labile chemicals more effectively than traditional methods. The obtained extracts exhibit potential as useful dairy product additives. Curry leaf extracts prolong the refrigerated shelf life of paneer withou t sacrificing taste quality by inhibiting spoilage microbes and slowing lipid oxidation. Optimal extract concentrations in curd prevent unwanted microbial growth while maintaining advantageous starter cultures. The extracts limit oxidative degradation and pathogenic and spoilage bacteria in cheese. These results demonstrate curry leaf waste valorization through UAE as a sustainable approach that supports the circular bioeconomy's tenets while providing natural, environmentally friendly dairy preservation — directly satisfying customer demand for minimally processed, safe foods.

Key words: bioactive compounds, natural preservatives, curry leaf waste, ultrasound -assisted extraction (UAE), and shelf-life extension

I. INTRO DUC TIO N

Due to the increasing need for safe, wholesome, clean-label food products with longer shelf lives worldwide, food preservation has grown in importance as a field of study (FAO, 2024). Large amounts of agricultural and food processing waste have been produced concurrently with the sharp rise in food production and consumption, posing se rious global environmental, economic, and sustainability challenges (United Nations Environment Program [UNEP], 2024).

The United Nations Environment Program claims that millions of tons of food waste are produced every year (UNEP, 2024). As a result, the idea of waste valorization has become a successful tactic for turning agricultural byproducts into valuable ingredients while also lowering pollution levels and advancing a circular bioeconomy (Kumar et al., 2025).

The United Nations Environment Program reports that millions of tons of food waste are produced each year, much of which contains important phytochemicals that are underutilized despite their potential uses in functional food development an d food preservation (UNEP, 2024). As a result, the idea of waste valorization has become a successful tactic for turning agricultural byproducts into valuable ingredients while also lowering pollution levels and advancing a circular bioeconomy (Kumar et al., 2025).

Curry leaf (Murraya koenigii) waste is one of the several plant-based agricultural leftovers that has garnered scientific interest due to its remarkable phytochemical composition and abundance (Sharma et al., 2024). Curry leaf, or Murraya koenigii, is a member of the Rosacea family and is grown extensiv ely in India, Sri Lanka, Bangladesh, Nepal, Malaysia, and other tropical nations due to its culinary, nutritional, and therapeutic value (Sharma et al., 2024).

Carbazole alkaloids including mahanimbine, girinimbine, koenimbine, murrayazoline, flavonoids, p henolic acids, tannins, terpenoids, tocopherols, carotenoids, chlorophylls, vitamins, and volatile essential oils are among these substances (Sharma et al., 2024). Curry leaves' high content of phenolic compounds, which can scavenge reactive oxygen species and stop oxidative food deterioration, is the main reason for their antioxidant action (Sharma et al., 2024).

The simplicity, effectiveness, and sustainability of Ultrasound-Assisted Extraction (UAE) make it one of the most promising green extraction methods (Chemat et al., 2023). High-frequency ultrasonic waves (20–100 kHz) are transmitted into a solution containing plant material in order to perform ultrasound-assisted extraction (Chemat et al., 2023).

Because they supply high-quality proteins, calcium, phosphorus, vitamins, and other vital nutrients n eeded for growth and health, dairy products play a crucial role in the human diet (Aneja et al., 2023). Because of their nutritional content a nd consumer acceptance, paneer, curd, and milk are among the most popular dairy products in India (Aneja et al., 2023).

Antimicrobial Activity

Curry leaf (*Murraya koenigii*) contains the carbazole alkaloids, flavonoids, phenolic compounds, terpenoids, and essential oils that contribute to its antimicrobial activity. These compounds have demonstrated inhibitory effects against several foodborne pathogens and spoilage microorganisms. Carbazole alkaloids isolated from curry leaf have shown antimicrobial potential against different bacterial strains (Ramsewak et al., 1999). Extracts of *M. koenigii* have also demonstrated antibacterial activity against organisms such as *Staphylococcus aureus, Bacillus subtilis, Escherichia coli,* and *Pseudomonas aeruginosa* (Vats et al., 2011).

Antioxidant Activity

Curry leaf is rich in phenolic compounds, flavonoids, and carbazole alkaloids, which contribute to its antioxidant properties. Different extracts of *M. koenigii* have demonstrated free-radical-scavenging activity and significant antioxidant potential (Ningappa et al., 2008). The antioxidant activity of the curry leaf has also been associated with its polyphenol content and extraction conditions (Sasidharan & Menon, 2011). These properties are particularly important in dairy preservation because antioxidants can help reduce lipid oxidation and rancidity.

Anti-inflammatory Activity

Curry leaf contains bioactive carbazole alkaloids that have demonstrated anti-inflammatory potential. Compounds isolated from *M. koenigii* were reported to possess anti-inflammatory activity (Ramsewak et al., 1999). Methanolic extracts of curry leaf also showed anti-inflammatory and analgesic effects in experimental models (Gupta et al., 2010). Further studies on curry leaf alkaloids reported significant reduction in the experimentally induced inflammatory responses (Mani et al., 2013).

Antidiabetic Activity

Murraya koenigii has traditionally been investigated for its potential role in diabetes management. Curry leaf extracts demonstrated hypoglycemic and anti-hyper glycemic effects in the experimental diabetic models (Yadav et al., 2002). Aqueous leaf extracts were also reported to reduce blood glucose levels in the normal and experimentally induced diabetic animals (Kesari et al., 2005). These findings suggest that phytochemicals present in curry leaves may influence glucose metabolism and oxidative stress associated with diabetes.

Anticancer Activity

Carbazole alkaloids are important bioactive compounds in curry leaves and have been extensively investigated for anticancer properties. Curry leaf carbazole alkaloids were reported to induce apoptosis and affect cellular pathways in human oral cancer cells (Utaipan et al., 2017). Studies on mahanine-rich fractions have also demonstrated cytotoxic effects against cancer cells

(Satyavarapu et al., 2020). The phytochemical composition and biological activities of curry leaf extracts have further supported their potential as a source of anti-cancer compounds (Ghasemzadeh et al., 2014).

Hepatoprotective Activity

The antioxidant-rich fraction of curry leaf has demonstrated potential hepatoprotective effects. A polyphenol-rich extract of *M. koenigii* was reported to protect the liver tissue against experimentally induced oxidative and chemical damage (Desai et al., 2012). The protective effects were associated with the antioxidant properties of the plant's phenolic constituents. The presence o f phenolics and other phytochemicals may therefore contribute to protection against hepatic oxidative stress (Abeysinghe et al., 2021).

Cardioprotective Activity

The antioxidant and phytochemical constituents of curry leaf may contribute to cardiovascular protection. *M. koenigii* leaf extract demonstrated protective effects against experimentally induced cardiotoxicity in rats (Sandamali et al., 2020). These effects were associated with the ability of the extract to reduce oxidative and tissue damage. The antioxidant potential of c urry leaf has also been suggested as one of the mechanisms underlying its possible cardiovascular benefits (Abeysinghe et al., 2021).

Immunomodulatory / Anti-inflammatory Activity

Curry leaf extracts have demonstrated potential immunomodulatory effects in experimental studies. Aqueous and methanolic extracts were reported to influence inflammatory and oxidative -stress-related markers in diabetic experimental models (Paul et al., 2011). Changes in the inflammatory cytokines suggested that curry leaf phytochemicals may influence immune responses. Anti-inflammatory activity of total alkaloid extracts from curry leaves has also been reported (Mani et al., 2013).

Antifungal Activity

Curry leaf extracts have shown inhibitory activity against selected fungal microorganisms. Ethanol extracts of *M. koenigii* demonstrated antifungal activity against organisms including *Candida albicans*, *Aspergillus niger*, and species of *Penicillium* (Disegha & Izionworu, 2014). Antimicrobial investigation of the curry leaf extracts have also reported activity against fungal organisms (Vats et al., 2011). This activity indicates the potential application of curry leaf extracts in controlling fungal spoilage in food products.

Antiviral Activity

The antiviral activity of *M. koenigii* is comparatively less studied than its antioxidant and antimicrobial activities. Recent research has identified curry leaf-derived alkaloids and chlorophyll-related compounds with potential activity against viral entry mechanisms in experimental systems (Paul et al., 2026). Earlier phytochemical investigations have also suggested that certain compounds present in *M. koenigii* may possess antiviral potential (Ghasemzadeh et al., 2014). However, further in-vitro, animal, and clinical studies are required to establish the antiviral efficacy of curry leaf extracts.

Antiulcer Activity

Curry leaf has been traditionally associated with gastrointestinal protective properties. Total alkaloidal extracts from *M. koenigii* leaves demonstrated protective effects against experimentally induced gastric ulcers (Mani et al., 2013). The observed activity was reported to be dose dependent, suggesting that curry leaf alkaloids may contribute to gastric protection. The gastroprotective potential of curry leaf has also been discussed in phytochemical and pharmacological reviews (Abeysinghe et al., 2021).

Neuroprotective Activity

The neuroprotective potential of curry leaf is associated mainly with its carbazole alkaloids and antioxida nt compounds. Total alkaloidal extracts from M. koenigii demonstrated protective effects in experimental models related to dementia and cognitive impairment (Mani et al., 2012). Carbazole-type compounds isolated from curry leaf have also been investigated for their effects on neurite development and memory-related functions (Yano et al., 2020).

Conclusion

This review of literature establishes a strong scientific foundation for valorizing curry leaf (*Murraya koenigii*) processing waste as a natural preservative for dairy products through ultrasound-assisted extraction (UAE). Curry leaf itself is well documented as a rich source of antioxidant and antimicrobial phytochemicals (Ghasemzadeh, Jaafar, Rahmat, & Devarajan, 2014; Osuala et al., 2025), and emerging evidence confirms that its processing residues —particularly stalks—retain comparable bioactive value, with antioxidant activity rivaling synthetic additives like TBHQ (Pyla, Jahnavi, Sagubandi, & Padmaja, 2024).

This repositions curry leaf waste from a disposal burden into a genuine resource for the circular bioeconomy.

UAE has been shown to be an efficient, optimizable extraction technique, with response surface methodology confirming that

ultrasonic power, temperature, and solvent concentration significant ly influence both yield and bioactivity while minimizing degradation of heat-sensitive compounds (Ghasemzadeh, Jaafar, Karimi, & Rahmat, 2014). However, industrial translation of such green extraction methods remains a bottleneck, requiring further work on scalable, cost-effective processes and delivery systems such as active packaging (Borah et al., 2024).

The applicability of such extracts to dairy preservation is strongly supported across product categories. Paneer's short shelf life has been extended through plant-derived coatings incorporating cinnamon oil (Raju & Sasikala, 2016) and pomelo peel extract (Joshi et al., 2025); curd's microbial vulnerability has been mitigated using fermented plant materials combined with lactic acid bacteria (Mozuriene et al., 2016); and cheese preservation has benefited from natural antimicrobials delivered via active nanocoatings (Lima, de Carvalho, Vieira, Moreira, & Conte-Junior, 2021) and biopreservation strategies (Silva, Teixeira, Cadavez, & Gonzales -Barron, 2023). Successful product development additionally requires the validating bio-availability and sensory acceptability, not just phyto-chemical content, as demonstrated in fortified dairy formulations (Kandyliari et al., 2023).

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