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Development and Characterization of Fibre-enriched Almonds and Oat Milk-derived Plant-based Cottage Cheese Alternative

Gourab Chatterjee[1], Shamama Khurshid[1], Sahil Ansari[1],
Sumita Das[1], Aritra Bhaduri[2], Anjan Mishra[3]

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ABSTRACT

Background: This research presents a method for developing and characterizing a plant-based cottage cheese alternative derived from almond and oat milk, with high dietary fiber content, to meet the increasing demand for plant-based or non-dairy alternatives post-COVID-19.

Methods: The cottage cheese alternative was prepared by extracting milk from raw almonds and oats, followed by controlled preheating, homogenization, pasteurization, coagulation, whey drainage and application of pressure to the mold to achieve the desired consistency and firmness. Proximate composition and microbiological analysis were performed according to the defined method. The developed product underwent compression testing for texture profile analysis and scanning electron microscopy (SEM) for morphological evaluation and its properties were compared with control conventional market-available cottage cheese (paneer). Sensory analysis was conducted using a 9-point hedonic scale.

Result: The yield of the final cottage cheese alternative obtained was 52±1%. Proximate analysis of the product showed 25.72% dietary fiber, 9.96% protein, 14.55% fat, 9.70% total carbohydrates and 64.84% moisture. The product exhibited a similar microstructural matrix and very good textural properties and hardness when compared with the control. Sensory scores indicated excellent overall acceptability of the developed product, making it a plant-based non-dairy alternative to traditional paneer.

Key words: Almond and oat, Cottage cheese alternative, Fibre-enriched, Microstructural matrix, Non-dairy, Texture.

INTRODUCTION

Post-COVID-19, a significant transformation has reshaped global food systems as consumers are increasingly opting for plant-based or non-dairy alternative products. Traditional dairy products, though largely consumed, are now being reconsidered due to health concerns, animal welfare considerations and increasing awareness about lactose and casein intolerance. As per the UN's Food and Agriculture Organization (FAO), livestock supply chains are responsible for a total of 14.5% of greenhouse gas GHG emissions (Hur *et al.,* 2024). Globally, the market size of dairy alternatives was valued at USD 32.38 billion in 2024 and is predicted to grow from USD 36.76 billion in 2025 to USD 91.15 billion by 2032 with a compound annual growth rate (CAGR) of 13.85%. A variety of plant sources for the development of non-dairy alternative products includes-nuts (almond, walnut, cashew, hazelnut, pistachio), legumes (pea, soy, chickpea, peanut), pseudocereals (teff, quinoa, buckwheat), grains and cereals (barley, wheat, oats, rice), seeds (flax, chia, sesame, hemp) and fruits (Aydar *et al.,* 2020; Shori and Al Zahrani, 2022; Tachie *et al.,* 2023; Tangyu *et al.,* 2019). Consumers are abandoning soy with newer options like almonds and oats. In China, soy milk, being a mass-produced product, is now limited due to the introduction of new and premium plant-based milk options. Almonds and oats are rarely sourced from genetically modified organisms (GMOs), are allergen-free and have a lower carbon balance with a better nutritional profile, favorable taste and expanded market presence (Warren *et al.,* 2024).

[1]Department of Food Technology, Haldia Institute of Technology, Haldia-721 657, West Bengal, India.
[2]Anukul Chandra Foods Pvt. Ltd., Pune-411 048, Maharastra, India.
[3]Department of Agricultural Engineering, Haldia Institute of Technology, Haldia-721 657, West Bengal, India.

Corresponding Author: Gourab Chatterjee, Department of Food Technology, Haldia Institute of Technology, Haldia-721 657, West Bengal, India. Email: gourabchatterjee.ft@gmail.com

ORCIDs: https://orcid.org/0000-0001-8894-6551; https://orcid.org/0009-0000-3517-1254; https://orcid.org/0009-0003-8364-621X; https://orcid.org/0009-0001-1347-3099; https://orcid.org/0009-0002-2994-0058; https://orcid.org/0000-0003-0309-3997

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Almonds (*Prunus dulcis*), also classified as "functional food," are a nutrient-dense food that provides daily nutritional needs, provides energy and helps manage appetite (Mabel *et al.,* 2023). It has a low glycemic index (GI), which reduces the risk of developing type 2 diabetes. Mori *et al.* (2011), in their research, stated that a significant reduction in blood glucose concentration was observed after including almonds in the breakfast meal of adults with impaired glucose tolerance (IGT). It also improves satiety, lowers the risk of cardiovascular diseases and limits oxidative damage (Mori *et al.,* 2011). Around 50% of the almond's weight comprises healthy fat (mainly mono and polyunsaturated fatty acids (MUFA and PUFA) (Barreca *et al.,* 2020; Sharma *et al.,* 2024). Antunes *et al.* (2024) reported that 100 g of almond milk contains 11.5% of saturated fatty acids (SFAs), 67% of MUFAs and 22.8% of PUFAs. Ceylan and Ozer (2020), in their study, observed an average of 7.4% SFA (Palmitic acid), 65.53% MUFA (Oleic acid) and 24.45% PUFA (Linoleic acid). USDA's (United States Department of Agriculture) Food Data Central (FDC) (2022) published that almonds consist of proximates-21.4% protein, around 20% carbohydrates and 10-13% total dietary fiber. Pectic polysaccharides and cellulose are the insoluble fibers present in almonds (USDA, 2022). Many clinical trials have proved that almond consumption increases the population of beneficial gut bacteria genera such as *Bifidobacterium, Roseburia, Dialister and Lachnospira,* thereby improving gut health. Its prebiotic effect improves glycemic control and reduces inflammation (Tahiri and Gilbert, 2025). Potassium (K), phosphorus (P), magnesium (Mg) and calcium (Ca) are the rich minerals that are present in *Prunus dulcis* (K>P>Mg>Ca) (USDA, 2022). (Stuetz *et al.,* 2017) in their study observed that almonds contain about 1400 μg/100 g of riboflavin (vitamin B2), which is 3 times more than compared with other nuts like cashew, walnut, pistachio, *etc.* and α-tocopherol (vitamin E) of approximately 35 mg/100g, reaching the recommended daily intake (RDI). Secondary metabolites present in almonds, mainly amygdalin and prunasin, provide anti-tumor, antioxidant, antibacterial and anti-inflammatory properties. Phytosterols alleviate oxidative stress (Altamirano Rojas *et al.,* 2025). Hydrolysable tannins (gallotannins, ellagic acid), lignans (+)-sesamin, (-)-matairesinol), proanthocyanidins (procyanidin B1, B2, B3, B5, B7), flavonoids (cyanidin, genistein, catechin, morin), stilbene (resveratrol-3-O-glucoside) and phenolic acids (chlorogenic acid) are some of the polyphenols present in almonds (Barreca *et al.,* 2020). Almonds have long been used in the food industry in confectionery, bakery, snacks, bars and cereal products in the form of oil, milk, syrup, flour, *etc.* (Javaid *et al.,* 2019).

Oat (*Avena sativa* L.), belonging to the Poaceae grass family, ranks sixth as per the global production data (Le, Hermansen and Vuong, 2025). This cereal yields valuable and distinctive macro-, micro- and phytonutrients (Varma *et al.,* 2016; Yadav *et al.,* 2021). It is an important source of high dietary soluble fibers (10.4%) (mostly β-glucan, 7.52%), carbohydrates (68.7%), protein (13.5%), lipids (5.89%), vitamins and minerals (Cui *et al.,* 2023; Ferranti and Velotto, 2023; Hughes *et al.,* 2021; Yu *et al.,* 2023). β-glucan is the major active component that has various nutritional and functional properties that lower LDL cholesterol and antidiabetic effects and its health claim has been approved by the USFDA, Joint Health Claims Initiative (JHCI) and the French Food Safety Agency (AFFSA) (Martínez-Villaluenga and Peñas, 2017; Paudel *et al.,* 2021; Rasane *et al.,* 2015). Liu *et al.* stated that oats β-glucan has significantly improved symptoms of ulcerative colitis and suppressed mRNA and protein expression of many pro-inflammatory agents in mice (Yu *et al.,* 2022). Avenanthramides, a class of phenolic alkaloids, possess bioactivities such as anti-inflammatory, antioxidant properties, antiproliferative, vasodilation and anti-itch effects that provide additional protection against pancreatic β-cells from damage, colon cancer and skin irritation (Meydani, 2009). Therefore, in this context, the preparation and development of almond and oat milk-derived plant-based cottage cheese alternatives provide a new approach to address consumer demands while integrating health-enhancing features such as fibre enrichment.

Paneer is a traditional Indian *cottage cheese* prepared by heat treatment of milk (normally from cow or buffalo), followed by coagulation with coagulants such as citric acid/lactic acid/vinegar/malic acid/lactic cultures/cultured whey/Ca-lactate/alum, drainage of whey by collecting the coagulum in a muslin cloth, to finally pressing the coagulum by steeping in chilled water (Chaudhari *et al.,* 2022; Dwarakanath *et al.,* 2020; Ibrahim *et al.,* 2024; Khan and Pal, 2011; Sivaranjani *et al.,* 2022) It is used in culinary dishes/snacks. It contains nutrients like vitamins B, K and D, phosphorus, dietary fibre and polyunsaturated fatty acids like ω-3 and ω-6 fatty acids (Feeney *et al.,* 2021). As per the reports of the IMARC group, globally, the market size of paneer reached USD 10.8 Bn in 2024 and is forecasted to reach USD 18.5 Bn by the year 2033 with a 6.2% CAGR (2025-2033). Only in India, its market hit INR 648.05 Bn in 2024 with an expectation of INR 2030.73 Bn by 2033 with 12.85% CAGR during the year 2025-2033.

With these facts, the objective of this research is to provide an almond and oat milk-derived cottage cheese alternative with an enrichment of fibre. Even though there are multiple benefits of almonds and oats and the milk derived from them, they cannot provide the same replica of traditional paneer or cottage cheese until the incorporation of suitable coagulants. Calcium lactate is a well-known coagulating agent that promotes the curdling of milk and has been used by various researchers (Amila *et al.,* 2022; Kumar *et al.,* 2015; Sahu, 2010). The addition of inulin improved the proximate composition as well as the texture of our developed product. Inulin is a prebiotic fibre with good water-holding capacity that promotes gut health, influences glucose homeostasis, enhances mineral absorption, regulates lipid metabolism, lowers blood sugar, relieves depression and lowers the risk of colon cancer (Hughes *et al.,* 2022; Qin *et al.,* 2023; Teferra, 2021).

MATERIALS AND METHODS

The experiment was conducted during the session 2024-2025 in the laboratory of the Department of Food Technology, Haldia Institute of Technology, Haldia, West Bengal, India.

Procurement of raw ingredients and chemicals

Rolled oats and almonds were procured from Nature's Basket store in Kolkata, West Bengal, India; Inulin Powder from NOW Foods, USA; Calcium Lactate from Istore Direct Trading Pvt. Ltd., Maharashtra, India and potable water was sourced from Haldia Municipality, Purba Medinipur, West Bengal, India, specifying IS 10500: 2012 standards.

Preparation of almond milk

Almonds were washed and soaked in potable water at a ratio of 1:3 (w/v) for 10 to 12 hours. After soaking, the weight of the almonds increases by up to 50% of the initial weight. This soaking step facilitates the easier removal of the outer layer (peel) of the almonds. The removal of the peel is a critical step to eliminate any residual impurities, bitterness, or tannins present in the peel to ensure a cleaner and more palatable almond milk. The depeeled almonds were then washed and blended with water in a mixer grinder at a ratio of 1:2 (w/v) to achieve a homogeneous almond-water mixture. The almond-water mixture obtained was strained to remove any solid particles, yielding smooth and liquid almond milk.

Preparation of oat milk

Rolled oats were blended with chilled water temperature of 8-10°C (1:3 w/v) in a grinder at a high speed for 20-30 sec. Chilled water was used to prevent sliminess caused by heat generation during blending. The resulting suspension was strained using a double-layered muslin cloth to remove any oat residue and yield pure oat milk.

Preparation of almond and oat milk-derived cottage cheese alternative

94.8% (w/w) almond milk and 5% (w/w) oat milk was pre-heated at 40-42°C for 2-3 minutes and 45-48°C for 2-3 minutes separately, followed by homogenization at 3000 rpm for 60 seconds and during homogenization, 0.1% inulin powder was added to improve the texture of the final product. After homogenization, pasteurization of almond and oat milk was done at 92°C for 15-20 seconds and successively cooled to 80°C-85°C for coagulation. The pasteurized almond and oat milk is added with 0.1% calcium lactate as a coagulant to obtain a coagulated mixture. The mixture is slowly stirred for 50-60 seconds and filled into a muslin cloth for the drainage of whey. The drained coagulum was steeped in chilled water at 4-8°C and first-stage manual pressure of 0.8 kPa was applied for 5-6 minutes to give the coagulum a definite shape and promote excess whey expulsion. A second-stage mechanical pressure of 5.02 kPa was applied to the mold for 30-35 minutes to produce a well-structured cottage cheese alternative of desired consistency and firmness. The shaped almond and oat milk-derived plant-based cottage cheese alternative is placed in the refrigerator for 30 minutes to achieve its final structure. The moisture of the final product was 64.84%. Fig 1 illustrates the process flow diagram for the preparation and development of fiber-enriched almond and oat milk-derived cottage cheese alternative.

Proximate analysis of almond and oat milk-derived cottage cheese alternative

Gerber Method, as described in IS 10484: 1983, was used to measure the milk fat. Moisture content was measured by the gravimetric method according to IS 10484: 1983 by taking the weight loss of the sample when dried in an oven at a specified temperature. The total carbohydrate content was calculated by subtracting the sum of protein, fat, moisture and ash from the total weight of the sample as per the AOAC standard method 986.25. The remaining portion after all the components are accounted for is considered carbohydrate. The enzymatic-gravimetric method, as per AOAC 21st Edition 2019, 985.29, was used to measure the total dietary fibre content in a sample. This process involves the use of enzymes to break down non-fibre components, leaving behind the dietary fibre, which is further weighed to determine its quantity. The Kjeldahl method, as described in IS: 1479 (Part II): 1961, was used to determine the amount of nitrogen (N) and then protein content was calculated by multiplying N by a conversion factor of 6.38 (N×6.38). At water factor (4 kcal/g for protein and carbohydrate, 9 kcal/g for fat) as described in Analytical Chemistry of Food by CS James, 1999, was used to determine the energy value in kcal of the sample.

Microbiological analysis of almond and oat milk-derived cottage cheese alternative

The total plate count (TPC)/aerobic microbial count of the sample was determined by following the IS: 5402:2012 standard. The sample was plated on a suitable agar medium and aerobically incubated at 30°C ± 1°C for 72 h ± 3 h, after which the number of microorganisms per gram was calculated from the number of colonies obtained. Yeast and Mould (Y and M) Count was measured by following IS: 5403:1999 (Reaff 2005) standard, where the sample was plated on yeast extract-dextrose-chloramphenicol-agar medium and incubated at 25±1°C for 3-5 days.

Sensory analysis

Almond and oat milk-derived plant-based cottage cheese alternative was judged by a semi-trained sensory panelist. Five sensory attributes of the product *i.e.*, color and appearance, flavor, body and texture, taste and overall acceptability, were evaluated using a nine-point hedonic scale where 9 denotes like very much and 1 denotes dislike very much. 5 grams of each sample under chilled conditions (4°C) and after frying were presented along with the control Paneer (Conventional market available cottage cheese-Amul Fresh Malai Paneer), to respective panelists in identical plates labeled with random numbers and in random order. The panels recognized the cottage cheese alternative samples only by code. Sensory panelists were instructed to rinse their mouths by drinking plain water after the assessment of each sample. All assessments were done in individual booths of a sensory laboratory under white light illumination.

Texture profile analysis

Compression testing of the almond and oat milk-derived plant-based cottage cheese alternative with respect to the conventional market available cottage cheese (Amul Fresh

Malai Paneer) was performed by UTM Machine (Tinius Olsen (UK)-Make with Model No: H50KT/130). Samples were cut into cubes (20 mm × 20 mm × 20 mm) and the textural assessment was conducted in a laboratory maintained at 22±1°C. The load range of the machine was 15 kgf with a displacement range of 1000 mm and the test speed was maintained at 12.54 mm/min.

Scanning electron microscopy

The surface morphological features of the developed almond and oat milk-derived plant-based cottage cheese alternative sample with respect to the conventional market available cottage cheese (Amul Fresh Malai Paneer) were observed using Carl Zeiss GeminiSEM 360-Germany. The sample was prepared and fixed to metal stubs with double adhesive carbon tape, followed by gold coating in a vacuum. An accelerating voltage of 5 kV was applied to scan the sample.

RESULTS AND DISCUSSION

Yield of almond and oat milk-derived cottage cheese alternative

The yield of the final almond and oat milk-derived plant-based cottage cheese alternative obtained was 52±1.

Proximate composition of almond and oat milk-derived cottage cheese alternative

The proximate composition of the developed almond and oat milk-derived plant-based cottage cheese alternative is shown in Table 1. Its nutritional content primarily depends on the composition of almond milk and oat milk and the method of manufacture.

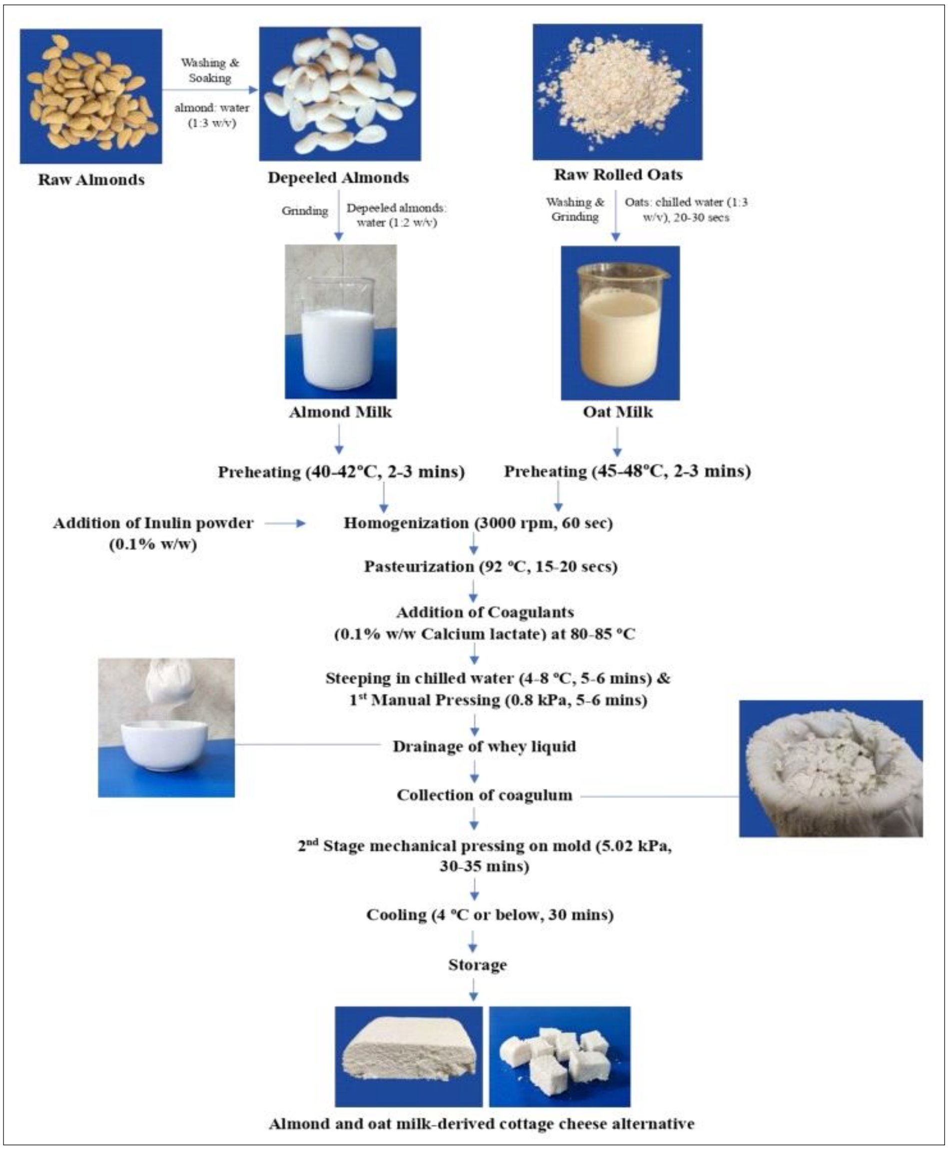

Fig 1: Process flow diagram for the preparation and development of fibre-enriched almond and oat milk-derived plant-based cottage cheese alternative.

Microbiological evaluation of almond and oat milk-derived cottage cheese alternative

Microbiological evaluation of the almond and oat milk-derived cottage cheese alternative resulted in the total plate count/aerobic microbial count of 75 cfu/g and Yeast and Mould Count was found to be <10 cfu/g, which is within the acceptable limit (Table 2).

Sensory analysis of cottage cheese alternative

Table 3 (Radar chart) show the average sensory scores for the sample (almond and oat milk-derived plant-based cottage cheese alternative) and control (Conventional market available cottage cheese - Amul Fresh Malai Paneer). Both samples give a comparable sensory score across all evaluated parameters which include taste, color and appearance, body and texture, flavor and overall acceptability. The color and appearance of almond and oat milk-derived plant-based cottage cheese alternatives were a bit superior to that of control paneer due to the greater whiteness imparted from almond milk. A slightly higher score of almond and oat milk-derived plant-based cottage cheese alternative in flavor is likely to be due to the nuttiness flavor of almond milk and slightly sweet flavor of oat milk. Whereas, almost similar scores were obtained for the taste and body and texture. Hence, overall acceptability indicates that the developed product is a viable plant-based substitute for traditional paneer.

Texture analysis by compression test

Texture profile analysis of the almond and oat milk-derived plant-based cottage cheese alternative was investigated with respect to the control. Representative graphs (Fig 2) illustrate the textural properties of almond and oat milk-derived plant-based cottage cheese alternative sample-A and control paneer-B (conventional market available cottage cheese-Amul Fresh Malai Paneer). From the compression test, this is evident that the final cottage cheese alternative marked as A shows very good textural properties and hardness (Max Force taken 11.14 kgf) with respect to the control marked as B-Control (conventional

Table 1: Nutritional composition of almond and oat milk-derived plant-based cottage cheese alternative.

Parameters	Result	Unit
Energy value	209.59	kcal/100 g
Moisture	64.84	g/100 gram
Dietary fiber	25.72	g/100 gram
Milk fat	14.55	g/100 gram
Protein (N×6.38)	9.96	g/100 gram
Total carbohydrates	9.70	g/100 gram

Table 2: Microbiological evaluation of almond and oat milk-derived plant-based cottage cheese alternative.

Parameters	Result	Unit
Total plate count (Aerobic microbial count)	75	cfu/g
Yeast and mould	<10	cfu/g

Table 3: Sensory Analysis of almond and oat milk-derived plant-based cottage cheese alternative and control (conventional market available cottage cheese-Amul Fresh Malai Paneer).

Sample	Taste	Color and appearance	Body and texture	Flavor	Overall acceptability
Almond and oat milk-derived plant-based cottage cheese alternative	8.2±0.12	8.3±0.18	8.2±0.11	8.4±0.17	8.2±0.12
Control	8.3±0.17	8.2±0.15	8.4±0.16	8.3±0.23	8.2±0.15

Average of 3 trials judged by 7 panelists.

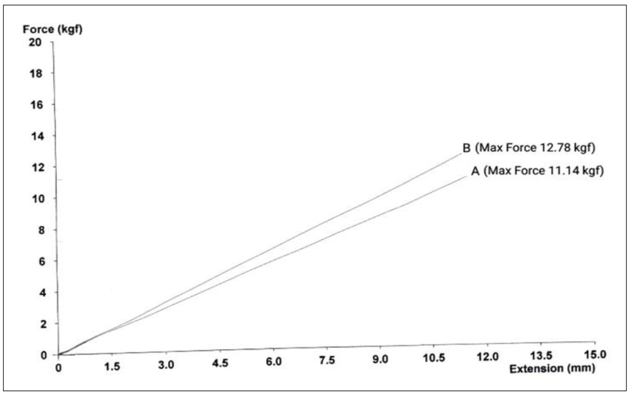

Fig 2: Compression test graph illustrating the textural properties of almond and oat milk-derived plant-based cottage cheese alternative sample- A (under optimal conditions) and B-Control (Conventional market available cottage cheese-Amul Fresh Malai Paneer).

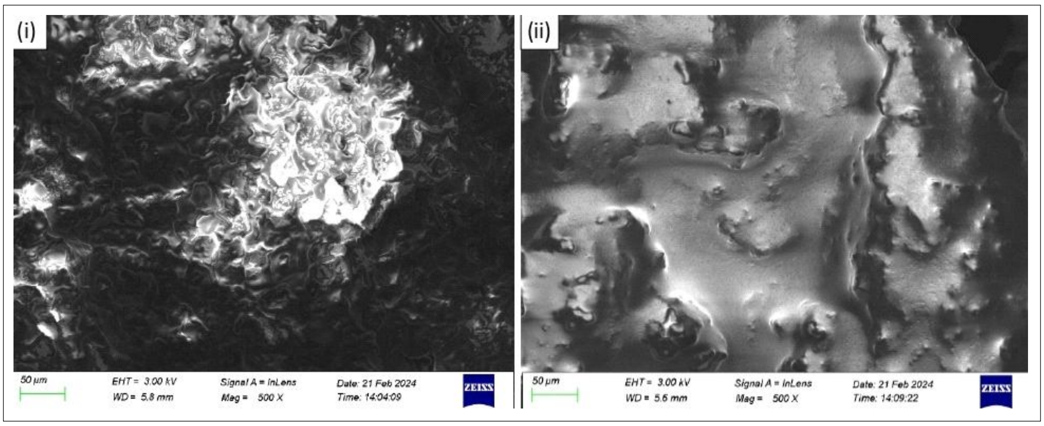

Fig 3: Microstructural study using scanning electron microscopy (SEM) at 500X magnification comparing (i) Almond milk-derived plant-based cottage cheese alternative with (ii) Control (Conventional market available cottage cheese-Amul Fresh Malai Paneer).

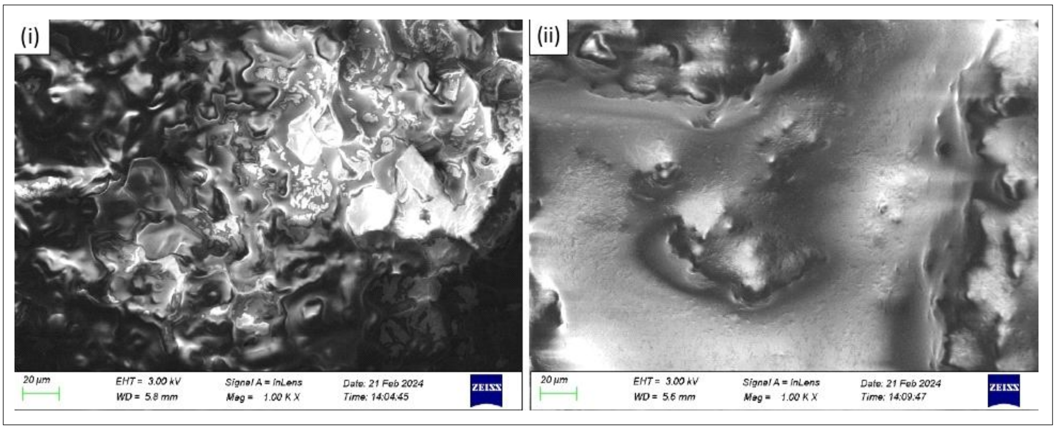

Fig 4: Microstructural study using scanning electron microscopy (SEM) at 1KX magnification comparing (i) Almond milk-derived plant-based cottage cheese alternative with (ii) Control (Conventional market available cottage cheese-Amul Fresh Malai Paneer).

market available cottage cheese -Amul Fresh Malai Paneer-Max Force taken 12.78 kgf) with almost similar maximum displacement range.

Microstructural characterization by scanning electron microscopy (SEM) analysis

The microstructural stability of the almond and oat milk-derived plant-based cottage cheese alternative was evaluated with Scanning Electron Microscopy (SEM) analysis, keeping a conventional market-available cottage cheese as a control. The result shows almond and oat milk-derived plant-based cottage cheese alternative has excellent stability compared to the control and shows similar microstructural matrix stability. Fig 3-4 shows the micrographs of cottage cheese alternative using Scanning Electron Microscopy (SEM) at 500X and 1KX magnification, respectively, comparing (i) Almond and oat milk-derived plant-based cottage cheese alternative with (ii) Control (Conventional market available cottage cheese-Amul Fresh Malai Paneer).

CONCLUSION

Post-COVID-19, a significant transformation has reshaped the global food system as consumers are increasingly opting for plant-based or non-dairy alternative products with protein and fibre enrichment at reasonable pricing. With this growing trend, the present study condenses the method for developing a non-dairy-based fiber-enriched cottage cheese alternative utilizing almond and oats to provide a substitute for conventional market-available cottage cheese (paneer). The present development comes under the category of "designer food" that eliminates nutritional deficiencies and promotes human health. The product revealed satisfactory results in terms of proximate composition, microbiological determination, texture profile analysis and microstructural matrix stability. As a non-dairy, sustainable alternative, this product holds enormous commercial potential for penetration in the global market.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish or preparation of the manuscript.

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