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Fermented Foods of the Cold Desert Regions of Western Himalayas and their Potential Health Benefits

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Abstract: Cold desert regions of Indian Himalayas covering Lahaul and Spiti, Ladakh, parts of Kinnaur and Uttarakhand have unique geographical and climatic conditions ranging from sub-tropical heat to sub-freezing temperature, as low as -40°C. The ethnic communities in these regions have unique dietary habits, and depend heavily on fermented foods. The fermented foods are prepared from wide range of substrates such as fruit and vegetable, cereal, legume, dairy, and meat-based in addition to alcoholic beverages. Fermentation is achieved through the use of indigenous, traditional starter cultures locally called as *Phabs* or *Malera*. *Phabs* are barley-based while *Malera* are wheat-based inoculums consisting cereals as carbohydrate substrate, mixture of herbs, spices and prepared using special indigenous process with locally available resources. Fermentation is achieved predominantly through lactic acid bacteria and yeast. Apart from staple cereals and legumes, dairy and meat products constitute major component of the diets of the ethnic communities. Some unique dishes of cold desert regions are hard cheese *Churpe* derived from Yak milk or indigenous cattle breeds, alcoholic beverages like *Lugri, Chhang*, *Angoori*, *Khambir* roti a cereal sourdough based thick flattened bread, steamed dumplings *Siddu* and deep fried *Marchu*. Majority of the fermented foods from cold desert regions have been reported to possess known probiotic strains such as *Lactobacillus* spp., *Streptococcus* spp., *Lactiplantibacillus* spp., *Lactococcus* spp., and emerging probiotics such as *Leuconostoc mesentroides*, *Acetobacter* spp., *Kluveyromyces* spp. These fermented foods consist bioactive molecules such as phenolic acids, flavonoids, gamma-aminobutyric acid (GABA) and polyunsaturated fatty acids such as conjugated linoleic acid (CLA). Several of these fermented foods have been reported to possess array of bioactive properties such as antioxidant, anti-inflammatory, anti-ulcerative, anti-microbial, immunomodulatory and

known to positively influence gut microflora. Characterization of the fermented foods from cold desert regions could provide novel probiotic species, *hitherto* unreported and offer new insights on the nutritional and therapeutic applications of ethnic fermented cuisines of Indian Himalayan Region.

Key words: High altitude, probiotics, lactic acid bacteria, yeast, indigenous starter cultures, polyphenols, polyunsaturated fatty acids, gamma aminobutyric acid, antioxidants.

The Indian Himalayan region (IHR) encompasses the major parts of the Himalayas, spanning 13 Indian States and Union Territories namely Jammu and Kashmir, Ladakh, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, Assam and West Bengal spanning over 3000 km from 15.95° to 39.31°N and 60.85° to 105.04°E (Kumar *et al*., 2021; Yadav *et al*., 2021). The Indian Himalayan region (IHR) has a distinct demography, rich ecological diversity, and cultural richness. Among the varied climatic zones, IHR encompasses a distinct geographic and climatic zone known as the cold desert region. The cold desert regions are primarily arid regions with extremely cold weather (-20 to -30°C), long winters, short summers and low annual precipitation (<10 cm). Ladakh, and Lahaul and Spiti valley in Himachal Pradesh are the primary cold desert regions in the IHR. These regions face sub-tropical heat to sub-freezing temperatures, with permafrost sites above 4900 m a.s.l., experiencing temperatures below 0°C, dropping as low as -23.4°C in the Ladakh region (Wani *et al*., 2020). Further cold desert regions are characterized by intense solar radiation, low oxygen partial pressures and low humidity (Sharma *et al*., 2025).

Animal husbandry and agro-pastoralism are the most common livelihood practice in the cold desert regions due to harsh environmental conditions (Choudhary *et al*., 2024). Although the region is characterized with sparse vegetation, the ecosystem is home to a variety of herbs, vegetables, fruits, and animal resources. Additionally, the region's diverse socio-economic and cultural landscape has led to the evolution of unique innovations in food systems reflecting a rich tradition of ancient culinary knowledge and dietary practices linked to ancient medicinal systems. These ethnic foods are an integral part of the region's cultural heritage, offering distinct flavors and aromas that spark culinary creativity. Food resources in the region range from non-perishable (moisture content <13%) to perishable (moisture content >50%), making preservation essential for off-season availability. Native communities rely strongly on traditional ways to preserve food such as sun drying, brining, smoking and fermentation.

Fermentation, one of the oldest food preservation methods, is crucial for diversifying and preserving food resources (Panda *et al*., 2016). Louis Pasteur famously stated, "Fermentation is life in the absence of oxygen." In the IHR, fermented and non-fermented foods, as well as alcoholic and non-alcoholic beverages, are an integral part of the cultural heritage since ancient times (Tamang, 2020; Rawat *et al*., 2021). The ethnic communities of IHR consume more than 400 different types of fermented foods and alcoholic beverages, which are produced naturally or with the addition of starter cultures like lactic acid bacteria (LAB), resulting in desirable biochemical changes (Voidarou *et al*., 2020). These fermented foods are enjoyed as staple foods, side dishes, curries, soups, savouries, pickles, condiments, and drinks, reflecting the region's diverse geography and climate (Tamang, 2022). Fermentation naturally boosts the nutritional value and taste of food by increasing vitamins, amino acids, proteins, flavours and aroma (Sharma *et al*., 2020).

Geographical and agroclimatic variations in cold desert regions have led to diverse dietary and cultural practices. Each fermented product in the Himalayan region is known by a unique local name, reflecting the diverse languages and dialects of the ethnic communities in the area. These names are often derived from Indo-European and Tibeto-Burman languages (Tamang, 2022). This cultural diversity, specifically domestic cooking and value addition process often results in variation in microbial diversity that in turn offer wide range of product characteristics and functionalities not limiting to just taste, texture and aroma. The indigenous communities ferment cereals, milk, vegetables, fruits and meat to variety of products for enhanced taste, shelf life and cultural beliefs. Lactic acid bacteria and yeast are key players in the fermentation process,

Fig. 1. Photographs of commonly consumed fermented foods of the Himalayan region are adapted from the book "Ethnic cuisines of Himachal Pradesh" (Gupta et al., 2023).

with LAB converting carbohydrates into lactic acid and yeast contributing to the fermentation of various foods and beverages, thereby altering physicochemical properties and increasing the nutritional quality of the food products (Gunawardena *et al*., 2024). Additionally, fermented foods also offer wide array of health benefits ranging from antioxidant, anti-hypertensive, immune modulatory and gastro-intestinal protective functions. Lactic acid bacteria have been reported to possess angiotensin-converting enzyme inhibitory peptides and gamma-aminobutyric acid, which helps to prevent and treat hypertension (Hur *et al*., 2014). Moreover, the hydrolase enzymes produced by these bacteria break down polypeptides into small peptides and amino acids that possess several bioactive properties, primarily the gut-immune axis (Wang *et al*., 2020; Guan *et al*., 2025). Further fermentation generates organic acids and aromatic compounds with a unique flavour profile, which can be explored in food and culinary flavouring applications (Li *et al*., 2024). Despite the availability of significant literature, there are no detailed reports available on the fermented foods of cold desert regions, their composition and health benefits. In this context, the present work attempts to compile the various fermented foods from the cold desert regions of IHR and describe their nutritional and bioactive properties in an attempt to popularise them.

Classification of Fermented Foods

Fermentation is a traditional method of preserving foods such as vegetables, milk, and meat products. It is a common practice in many cultures and is enjoyed worldwide. Fermentation is a process that involves the growth of specific microbes and the enzymatic conversions of food components (Marco *et al*., 2021). The fermented foods consumed in the cold desert regions can be classified based on the substrate used for fermentation. Broadly, fermented foods are (i) vegetable-based, (ii) cereal-based, (iii) legume-based, fruit-based, (iv) dairy and meat-based and finally alcoholic beverages. The fermentation is achieved through the use of indigenous traditional starter cultures locally called as phabs or malera. Phabs are barley-based and predominantly utilised in Ladakh/Lahaul, while malera is a wheat-based slurry. These starters have very high bacterial diversity, primarily lactic acid bacteria (LAB) and yeast species. Common LAB species include *Enterococcus* spp., *Streptococcus* spp., *Leuconostoc* spp., *Lactobacillus* spp., and *Pediococcus* spp. Additionally, yeasts and moulds such as *Debaryomyces* spp., *Kluyveromyces* spp., *Saccharomyces* spp., *Geotrichium* spp., *Mucor* spp., *Penicillium* spp., and *Rhizopus* spp. are also involved in the fermentation process (Sharma *et al*., 2026).

Plant-based Fermented Foods

Vegetable-based fermented food: Dehydration and fermentation are important strategies for the long-term preservation of vegetables in resource-limited conditions and prolonged seasonal unavailability of fresh produce such as that of cold-desert regions. On the nutrition front, fermentation enhances the digestibility and micronutrient bioavailability in vegetables. Communities in the cold desert regions ferment several vegetables such as mustard, turnip, radish, and bamboo shoots (Sharma *et al*., 2026). Evaluation of the fermented vegetable foods revealed the presence of lactic acid bacteria as abundant flora (Dwivedi *et al*., 2024; Tamang, 2022). One of the common fermented vegetable dishes in Ladakh is *Gya-labuk* and *Nyungma,* fermented dishes of radish and turnip, respectively. These vegetables are buried underground, and this technique is called pit fermentation. Such practices are also adopted in other high-altitude regions of Uttarakhand and Western Nepal. Some popular dishes include *Sinki* (fermented radish) (Tamang *et al*., 2016). It has been reported that pit fermentation technique results in very high bacterial diversity and microbial load that contribute to improved gut health among the population that predominantly consumes low-fibre diet. As mentioned earlier, fermentation is usually accompanied with dehydration. During the summer season, the vegetables, particularly green leafy vegetables, radish, turnip and cauliflower, are sun-dried and fermented. Sun-drying is a low-cost technique and enhances the shelf life of perishable agri-horti produce (Sharma *et al*., 2026). The combination of solar drying and fermentation is central to the food systems of cold desert regions, focused towards the reduction of spoilage, seasonal shortages and enhanced nutritional outcomes. In recent years, fermented vegetables are gaining popularity for their health benefits and unique properties among various fermented foods. Vegetables contain antioxidants, primarily polyphenols, which exhibit various beneficial properties, including anti-inflammatory, anticancer, antithrombotic, hepatoprotective, and antiallergic effects (Liu *et al*., 2024). Polyphenols are classified into phenolic acids, flavonoids, stilbenes, and lignans. Flavonoids are the most abundant and are often found in plants in glycosylated form. Fermentation can increase the bioavailability of antioxidants by converting glycosylated forms into aglycone or free forms. For example, fermentation of red pepper has been shown to increase its phenolic content and free radical scavenging activity. This increase is likely due to the higher phenolic content after fermentation (Gunawardena *et al*., 2024). Similarly, fermenting a vegetable mix (carrots, turnips, white cabbage, parsnips, celery, and onions) with *Lactobacillus plantarum*, increases iron absorption (Samtiya *et al*., 2021). Moreover, cabbage is commonly used in vegetable fermentation, with sauerkraut being a popular product. Sauerkraut is typically salted with 0.5%-3.5% NaCl solutions and involves various microorganisms viz., *Lactococcus lactis, Weissella koreensis, Leuconostoc carnosum, Leuconostoc mesenteroides*, and *Leuconostoc citreum* during the initial stages and towards the end of fermentation, *Lactiplantibacillus plantarum* and *Pediococcus parvulus* became dominant (Xu *et al*., 2024). Fermented vegetables like cabbage, carrot, broccoli, and beetroot containing *Lactobacillus sakei, Lacticaseibacillus curvatus, Ciborinia allii,* and *Lacticaseibacillus lactis* bacteria inhibited nitric oxide (NO) production in immune cells and reduced inflammation markers in mice with colitis. They also improved colon health and reduced liver enzyme levels (Liu *et al*., 2024). Choi *et al*. (2013) found that fermented cabbage can lower triglycerides, total cholesterol, and LDL-cholesterol in rats on a high-cholesterol diet. It also reduces cholesterol accumulation in the aortic tissue of rabbits on a high-cholesterol diet. Additionally, fermented vegetables regulate liver enzymes to reduce cholesterol levels in both rabbits and rats. Another popular fermented vegetable from IHR, particularly high-altitude Eastern Himalayas (Sikkim) is Gundruk. Preparation of Gundruk involves fermentation of green leafy vegetables with lactic acid bacteria such as *Lactobacillus fermentum*, *L. casei*, *L. plantarum* and *L. pseudoplantarum*. Gundruk is used as an appetizer and has been reported to possess probiotic properties with other benefits such as acidification, coagulation, antimicrobial activity (Aggarwal *et al*., 2025). In Western Himalayan region, following green leafy crops are primarily used for food applications viz., *Urtica dioica, U. hyperborea* (Bichu Buti), *Chenopodium album* (Bathua), *Taraxacum officinale* (Dandelion) and variety of species from the *Allium* genus (Sharma *et al*., 2024; Sharma *et al*., 2025).

Cereal-based fermented foods: Cereal grains are important sources of carbohydrates, proteins, minerals, dietary fibre, and vitamins. Cereal-based fermented products can be categorised into four types based on their metabolites: alcoholic (dominated by yeast-produced ethanol and carbon dioxide), acetic (producing large amounts of acetic acid by *Acetobacter*), lactic (with lactic acid bacteria as dominant microbes producing lactic acid), and ammonia or alkali (involving *Bacillus* and fungal species releasing ammonia) (Marco *et al*., 2017). Cereal-based fermented products are staple in cold desert regions. Some commonly consumed cereal-based fermented foods in Cold desert and surrounding regions are Khambir, Siddu, Selroti, Bhatooru, and Seera. These are energy dense and consumed throughout the year, specifically during winters (Tamang, 2022). Khambir is a flatbread made from wheat or barley and is a major staple. Khambir is prepared using yeast starter culture or buttermilk and possess lactic acid bacteria, yeast, *Bifidobacterium* sp., as predominant group of microbes. Khambir is reported to possess wide range of phenolics and flavonoids, originally present in the cereal substrate. *p*-coumaric acid was the predominant phenolic acid which has been reported to possess wide range of biological activities. Aqueous extracts derived from Khambir possessed anti-microbial properties against enteropathogens and possessed strong free radical scavenging activity and reducing power properties. Further, the Khambir extracts alleviated arsenic toxicity induced oxidative stress by enhancing the endogenous antioxidant activity and mitochondrial potential, which prevented DNA fragmentation as evaluated in rat intestine model (Hor *et al*., 2019). Another important fermented dish in the cold arid zone of Himachal Pradesh is Siddu, a fermented, steamed dumpling made from wheat. The filling used in the dumplings usually contains walnut paste along with spices. Siddu is known to have excellent digestibility and contributes to thermogenesis, and is consumed predominantly in winters. In high altitude regions of Uttarakhand, the Bhotiya community prepares a cereal-based fermented pudding locally called Nyog-Je. Likewise, dishes such as Pili and Dhuru made from fermented millet, butter offers energy dense diet to local communities in the winters and agriculture off-season (Sharma *et al*., 2026). Cereal-based fermented foods and beverages offer an excellent alternative to dairy products and to people with lactose intolerance, dairy allergies, or those seeking a low-fat diet (Cai *et al*., 2024). The functional potential of fermented cereals is enhanced by probiotics. The original aroma of cereals contributes to the final fermented flavour by producing volatile compounds like aldehydes, ketones, esters, and alcohols, as well as non-volatile compounds such as amino acids and sugar acids through microbial activity (Zhu *et al*., 2024). The microorganism populations in fermented cereal foods range from 1×10^6 to 1×10^9 CFU/g, with a LAB to yeast ratio of approximately 100:1. LAB plays a key role in producing compounds during cereal fermentation (Cai *et al*., 2024). Fermentation of cereal-based matrices like malted barley flour, barley flour and wheat aleurone with *P. freudenreichii* leads to anti-hypertensivity activity (Chamlagain *et al*., 2018).

Legume-based fermented food: Legumes constitute an important component in the staples of ethnic communities in the cold desert regions. Some unique legume foods of Western Himalayan region are black pea-based dishes. Black pea is native to Spiti valley and Ladakh and is grown in small clusters in Lingti and Upper Spiti valley. They have unique polyphenols and are rich source of complex carbohydrates and proteins. The high dietary fibre content offers sustained energy release in the harsh climatic conditions (Sharma and Gupta, 2023). Another important legume from the region is Horsegram (*Macrotyloma uniflorum*), locally known as kulath. Boiled kulath is consumed along with flattened breads and consumed as side dish with Khambir roti in winters. Another staple legume food is native red kidney bean (*Phaseolus vulgaris* L.), locally known as rajmah. It is consumed as lentil soup (dal) and also as fermented dish. Fermented rajmah is rich source of probiotics, dietary fibre and antioxidants along with high innate proteins (Dwivedi *et al*., 2024). Legume proteins offer nutritional, environmental, and economic advantages in the food industry. However, challenges like antinutritional compounds and poor sensory properties limit their use. Fermentation, particularly lactic acid fermentation, is a promising solution to enhance the taste, health benefits, and technological properties of legume-based products.

Researchers and industry are increasingly exploring this method for creating healthier and more appealing legume products (Emkani *et al*., 2022). Legume fermentation is commonly used in preparation of bakery products, Asian cuisine ingredients, dairy substitutes, and animal feed (Cichońska and Ziarno, 2021). Legume-based fermented foods represent traditional bioprocesses where microbial activity transforms pulse-like soybeans and black gram into nutrient-dense products with enhanced digestibility and bioactive profiles. These foods improve protein quality, reduce anti-nutritional factors such as phytates and lectins, and generate probiotics, vitamins, and antioxidants, making them valuable for nutrition security (Manzoor *et al*., 2021). For instance, many soybean fermented products are produced in various regions of the world, such as using *Aspergillus oryzae* to make miso paste and soya sauces (Sakandar *et al*., 2023). Lentil composite flour, made from a blend of lentil, barley, wheat, quinoa, and chickpea grains, undergoes fermentation and germination to increase peptide, free amino acid, and GABA levels while reducing antinutritional factors like tannins, phytic acid, and trypsin inhibitory activity (Sakandar *et al*., 2023). Additionally, fermenting mung and adzuki bean sprouts with *Lactiplantibacillus plantarum* has cytostatic and cytotoxic effects (Świeca *et al*., 2020). In chickpea bread, this bacterium reduces oligosaccharides and increases free amino acids, lysine, and total phenolic content (Galli *et al*., 2019). Hence, legume-based fermented foods are a traditional and nutritious way to turn legumes into probiotic-rich superfoods that have been enjoyed for generations worldwide.

*Fruit-based fermented foods and beverages***:** The Himalayan region is home to a variety of wild fruits and flowers, such as Seabuckthorn (*Hippophae rhamnoides* L.), Kaphal (*Myrica esculenta*), Hisalu (wild raspberry), mango, wild pomegranate, wild fig (*Ficus palmata*), lemon, apple, apricot, grapes, and Rhododendron (*Rhododendron arboreum*). These wild fruits and flowers are used to produce a variety of pickles, juices, jams, and fruit-based drinks in the temperate and sub-tropical altitudes of IHR. Seabuckthorn, kaphal, wild pomegranate, and fig are generally used to prepare non-fermented juices, chutneys, and vegetable curries, or consumed as such when ripe. Fruits like mango, lemon, and apricot are typically used to make pickles, which are naturally fermented and rich in probiotics that promote gut health, produce beneficial acids and aid in detoxification. Fruit wines are made from grape sources, while ciders are fermented beverages made from apple (Awasthi *et al*., 2025). In the IHR, popular alcoholic beverages, including angoori, chulli, apple cider, and hisalu, are the major ones produced in the Himalayan region. The fermentation of fruit wines and ciders is primarily carried out by the yeast-like *S. cerevisiae* (Tomar *et al*., 2023).

Angoori/Kinnauri is consumed during ceremonial functions such as marriage and local festivals in the Kinnaur region of Himachal Pradesh. It is prepared by fermenting wild red and green grapes. Red grapes contain 5% of ethanolic content, while green grapes have 3.5% (Kanwar and Bhushan, 2020). It is a traditional beverage enjoyed during local festivals and weddings by the tribal community. *Angoori* is produced by fermenting crushed grapes using *Phab* as a starter culture. (Thakur and Bhalla, 2019; Tomar *et al*., 2023). *Chulli*, a popular fruit-based alcoholic drink in the region, is made from dried wild apricots. *Chulli* contains 3% ethanol content and is typically consumed in the winter season (Kanwar and Bhushan, 2020).

Animal based Fermented Foods

Animal-based foods, such as meat, fish, and dairy, play a crucial role in ensuring nutritional security in the cold desert region, where vegetation is limited. The region relies on various species of indigenous cattle, buffalo, sheep, goats, and churu/churi (a cow-yak hybrid) for these animal products (Nehal, 2013). Some unique indigenous species of cold desert regions are Yak (*Bos grunniens*) and Pashmina goat (*Capra hircus*) (Hassan *et al*., 2022). Dairy products and meat are staple in every household. However, these products are perishable and susceptible to microbial contamination (Karanth *et al*., 2023). Preservation practices are essential to extend their shelf life. Fermentation sun drying, and smoking are the most common preservation strategies adopted by the indigenous communities. Several fermented animal products including curd, buttermilk, cheese, dried and fermented meat are common and consumed as a source of proteins. The ethnic communities of Lahaul

and Spiti and Ladakh use preserved meats as ceremonial dishes and served during community celebrations. Communities in Ladakh prepare a unique fermented meat dish called Syakpa, consisting fermented meat, boiled herb and stewed vegetables. Syakpa possess thermogenic properties and are consumed in harsh winters. In Changthang region of Eastern Ladakh, the nomadic communities prepare a fermented dish consisting barley, meat and local herbs called Paba (Sharma *et al*., 2026). They are used as source of energy especially when seasons are changing. Another unique practice of the Lahaul and Spiti region is that the meals are accompanied by fermented meat and fermented barly beverage called Lugri (Savitri and Bhalla, 2007). The pairing of ethnic dishes in the cold desert regions provide great insights onto their ecological adaptation and ethnic culture. Singh and Kumar (2025) reported that fermented fish is a valuable source of protein and minerals that complements staple foods like rice. The dietary and cultural practices in the cold desert regions of Western Himalayas mirrors the food habits observed in the high altitude Northeastern Himalayan region, where fermented meat sausage *kargyong, gemma*, is widely consumed (Tamang, 2022).

Apart from meat, naturally fermented dairy products like curd, buttermilk (used to prepare Kadi, Jhol, Nudu, butter, cottage cheese, dried cheese, etc.) are most commonly consumed. These naturally fermented foods are a source of essential nutrients, serve as a source of probiotics, and contribute to the rural economy (Nehal, 2013; Choudhary *et al*., 2024). *Lactobacillus plantarum, L. fermentum,* and *Lactococcus lactis* are the primary microorganisms in naturally fermented foods and help in improving gut microbiota, digestibility, and bioactive peptides with antimicrobial and antioxidant qualities (Tamang, 2022; Singh and Kumar, 2025). Nag *et al*. (2021, 2023) identified a probiotic yeast species *Kluyveromyces marxianus* PCH397 isolated from Yak milk. The strain possessed probiotic and therapeutic properties and was characterised for its ability to produce extracellular β-Galactosidase enzyme, which hydrolyses lactose. The authors reported that the species may have potential applications in the production of prebiotics such as lactulose and galacto-oligosaccharides (GOS). Likewise, Baliyan *et al*. (2023) identified and isolated probiotics and conjugated linoleic acid (CLA)-producing LAB strains with strong antioxidant activity from the bovine milk from the Lahaul valley in the Western Himalayan cod desert region. One of the strains, *Latilactobacillus curvatus* LGM:16, produced *cis*-9 and *trans*-11 conjugated linoleic acid isomers and possessed strong free radical scavenging activity. Dairy microorganisms-derived CLA have been reported to possess myriad bioactivities ranging from anti-obesity, anti-inflammatory, anti-carcinogenic, cardioprotective, osteosynthetic, and immunomodulatory (Badawy *et al*., 2023). Most of these biological activities are attributed to *cis-9,* and *trans-11* isomers (c9, t11) of CLA. The ability of *Latilactobacillus curvatus* strain LGM:16 to accumulate both these isomers indicates their potential nutraceutical/ therapeutic properties of dairy products of cold desert regions of Western Himalayas.

Among the several dairy products, *Churpe/ Churpi* stands out as a unique fermented product of Indian Himalayas. *Churpe* is a naturally fermented dairy product, consumed in most of the high-altitude Himalayan region, particularly in cold desert regions. This fermented cheese product is consumed in other Himalayan regions such as Sikkim, Darjeeling, Arunachal Pradesh, Nepal, and Bhutan (Choudhary *et al*., 2024). *Churpe* is considered as the world's hardest cheese. Traditionally *Churpe* is prepared from different sources of cattle milk including cow, yak, Zomo (cow X yak) and Germo (Zomo X yak). Owing to its hardness, *Churpe* is used as masticator by the nomadic communities and shepherd to avoid freezing of jaws under extreme conditions. This rennet-free fermented cottage cheese is made by curdling buttermilk with natural microbes using the back-slopping method. The cheese is shaped into strips, sun-dried, and hand-rubbed to achieve a floury texture (Choudhary *et al*., 2024). *Churpe* is rich in protein, essential amino acids, and micronutrients such as calcium, iron, and zinc, meeting dietary requirements, and contains nearly 55 to 57 g of protein per 100 g and a good amount of sulfur-containing amino acids, indicating its nutritional importance (Sharma *et al*., 2025). This food contains various probiotic species, particularly strains of *Lactobacillus*, *Leuconostoc*, *Lactococcus*, and *Streptococcus,* followed by acetic acid bacteria, mainly *Acetobacter* (Choudhary *et al*., 2024).

Lactobacillus delbrueckii was the most abundant strain found in *Churpe*, from the Lahaul and Spiti and Zanskar region, making it a potential natural probiotic source. Moreover, local ethnic communities consume it either by making thick soup called thukpa, Femer/Dhuru as a sweet dish or by chewing it to release its health benefits and flavour (Hussain *et al*., 2022).

Alcoholic Beverages

The preparation of alcoholic and non-alcoholic beverages practised by ethnic tribes in the Himalayan region has turned it into a cultural heritage (Savitri and Bhalla, 2007). In the cold desert region, fermented and alcoholic beverages are made using cereals (such as rice, millets, barley, maize, or wheat), fruits (grapes, wild apricot, or apple), jaggery, medicinal herbs, etc. To start the alcoholic fermentation process, a starch-rich substrate with high amylopectin and low amylose content is used to prepare traditional starter cultures that are passed down through generations. *Keem, balam/ balma, Phab, marcha or khesung*, and *dhehli* are primarily used as starter cultures to initiate the fermentation process (Tomar *et al*., 2023; Sen *et al*., 2025). The preparation of these starter cultures varies from region to region. *Phab*, also known as marcha or khesung in the Northeastern region, is prepared using sticky rice high in amylopectin and low amylose. The process for the preparation of phab is presented in Figure 2. Some species and wild herbs like the roots of Chituor guliyojara (*Plumbago zeylanica* L.), the flower of sengreknna (*Vernonia cinerea*), leaves of bheemsenpatte (*Buddleja asiatica* Lour.), ginger, and red dry chili are added (Sen *et al*., 2025), while in the Northern region, it is prepared by fermenting husked barley wrapped in *Artemisia* leaves (Tomar *et al*., 2023). C*hang/Skyems, Sura, Soor/ghenti, Jann, Tongba, Angoori, Jhol,* and *Daru* are popular fermented beverages prepared and served at ceremonial functions in the Himalayan region (Tamang *et al*., 2016; Thakur and Bhalla, 2019; Tomar *et al*., 2023).

Chhang: It is a traditional alcoholic beverage made from barley or rice, has been consumed by tribal populations for centuries. It is commonly known as Jhol and Chakti. Thakur and Bhalla (2019) summarize that *Chhang* is a popular turbid, acidic cereal-based alcoholic beverage prepared by solid-state fermentation using a husk less barley variety known as grim and semi-cooked rice with the traditional inoculum *'phab'*. The fermentation process is carried out for 4-5 days (Rawat *et al*., 2021; Tomar *et al*., 2023). *Chhang* is valued for its energising and refreshing properties and is served at every

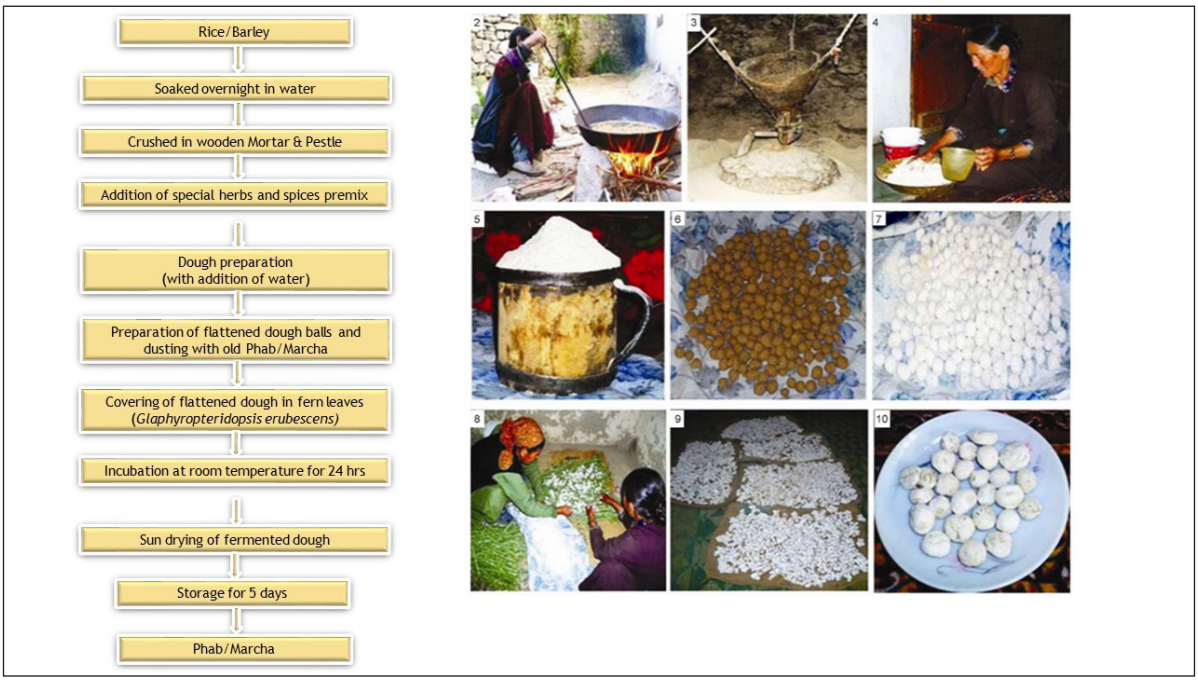

Fig. 2. Process flow for the preparation of Phab/Marcha (2a) and Photographic representation of traditional Phab preparation (Adapted from Angmo and Bhalla, 2014).

social gathering. Moreover, researchers found high levels of riboflavin, pantothenic acid, niacin, calcium, and iron in this beverage. Its probiotic potential and antioxidant properties are due to the presence of *Lactiplantibacillus plantarum* in phabs (Majumder *and* Bhattacharya, 2024). The solid material left after filtration of *Chang* is known as Lum. *Chang* is consumed in the winter season to protect people in cold regions from the winter cold. *Sura/Arak* is a distilled beverage prepared by distilling *Chang*, which has a high alcohol content. It is also known as daru in some regions of the Himalayas. Similarly, *Ark* or *ara* is prepared by fermenting a mixture of barley, apple, wild apricot, and pear, popular in the upper Himachal region, primarily in Kinnaur (Tomar *et al*., 2023).

*Sur/Sura***:** It is a distinctive beverage prepared using finger millet (*Eleucine coracana*) as a substrate. The fermentation process involves two stages: the primary stage includes natural fermentation, while the secondary stage involves the addition of *dhehli*, a traditional inoculum containing various bioactive herbal components (Tomar *et al*., 2023). In some parts of the Himalayan region, especially in the northern and northeastern regions, *Tongba*, an alcoholic beverage, is prepared using finger millet and a traditional starter culture, *phab*. The process is carried out in a special bamboo vessel known as a Dhungro and the beverage is rich in secondary metabolites, primarily ethyl-α-D-glucopyranoside (α-EG) and cyclo (L-Leu-L-Pro) (Sen *et al*., 2025).

Lugri : *Lugri* is another popular fermented alcoholic beverage prepared by the tribal people of Lahaul valley. Cooked cereals such as wheat, barley, rice is used as substrates and indigenous starter culture "*phab*" is used for fermentation of the substrate. Fermentation is induced by lactic acid bacteria, yeast and molds present in phab (Thakur and Bhalla, 2004; Thakur *et al*., 2015). The *lugri* is further purified and distilled to a alcoholic drink called "Arak" containing 5 to 7% alcohol and served during local community functions and ceremonies (Angmo and Bhalla, 2014). It was observed that *lugri* prepared from rice substrate possessed probiotic abundance. Baliyan *et al*. (2021) isolated 43 strains with probiotic properties such as cell surface hydrophobicity, antioxidant activity, anti-microbial activity and cell-auto aggregation, and exopolysaccharide production. The authors observed that strain *Lacticaseibacillus paracasei* exhibited highest free radical scavenging activity among the different strains isolated from undistilled rice *lugri*. Thus, it is evident that, these indigenous products not only serve the purpose as alcoholic beverages but also as probiotics with potential health benefits.

Nutraceutical Potential of Fermented Foods

*Source of polyphenols***:** Fermented foods made through spontaneous or probiotic fermentation often has improved flavour, functionality and bioavailability compared to non-fermented foods. During fermentation, polyphenols are used as substrates and broken down into smaller, more bioactive compounds (quercetin, kaempferol, gallic acid, ellagic acid) by polyphenol-associated enzymes (PAEs), such as tannases, esterases, phenolic acid decarboxylases and glycosidases present in microorganisms, thereby enhancing the bioavailability and biological activities in fermented foods (Yang *et al*., 2023). This biotransformation process in polyphenol-rich fermented food promotes the growth of beneficial bacteria like lactic acid bacteria, *Bifidobacterium* and yeast, improving their functional activity and safety while inhibiting the growth of pathogenic microorganisms. For instance, fermentation of apple juice with six LAB, namely *Lactobacillus plantarum*, *L. helveticus*, *Lactobacillus casei*, *L. paracasei*, *L. acidophilus* and *Bifidobacterium lactis,* increases the antioxidant properties by boosting caffeic acid and phloridzin levels (Wu *et al*., 2020). Recent research shows complex interactions between probiotic bacteria and polyphenols, suggesting the potential of developing novel fermented functional foods. Table 1 and Fig. 3 represent the chemical structures of major bioactive compounds present in fermented foods.

Improved dietary fibre bioavailability and nutrient accessibility: Dietary fibers, particularly complex polysaccharides, are essential for gut microbiota, as they support the growth of beneficial bacteria. The complex structure of these fibers can limit the fermentability and accessibility to gut microbes. Fermentation processes break down these complex structures into simpler forms, thereby increasing their prebiotic potential. For example, fermenting

cabbage enhances the nutritional value by breaking down complex carbohydrates and anti-nutrients, making it easier to digest and promoting the growth of healthy gut bacteria (Park and Maanna, 2025). Moreover, yogurt is a functional food that enhances mineral concentration and bioavailability, such as calcium and potassium, through fermentation (Valentino *et al*., 2024). Another study found that fermenting cereals with LAB can reduce the antinutrient levels and improve iron absorption by removing non-nutritive compounds that inhibit mineral absorption. This process also boosts the activity of enzymes such as amylase, phytase, hemicellulase, and protease, thereby improving shelf life, digestibility, and nutritional content (Şanlier *et al*., 2017).

Source of probiotics: Fermented foods are rich in probiotics, containing live microbes such as *Lactobacillus* and *Bifidobacterium* species, which promote gut health, aid digestion, and boost immunity. These live bacteria produce antimicrobial compounds, increase gut microbiota diversity, improve digestion and help to reduce inflammation (Ibrahim *et al*., 2023; Soemarie *et al*., 2021). Some studies suggest that combining probiotics can enhance their adhesion to surfaces, as β-glucan is fermentable by gut microbiota in the cecum and colon (Ningtyas *et al*., 2019). *Lactobacillus plantarum*, a probiotic commonly used in fermentation processes, has the ability to produce lactic acid, which enhances conversion, flavour, and texture, making it a popular choice in industrial food technology (Anal *et al*., 2019).

Health Benefits of Fermented Foods

In cold arid regions, the digestion process may be hindered by climatic conditions. Locals often consume fermented foods such as *babroo, chilra, bhaturu, chang, sura,* and *soor* (Sharma *et al*., 2013). Fermented foods are made with specific ingredients that produce unique flavours and health benefits. Live microbes in these foods synthesise metabolites like lactic acid, acetic acid, carbon dioxide, ethanol, and antimicrobial peptides during fermentation. These compounds, either individually or in combination, inhibit the growth of pathogenic organisms and prolong the shelf life of perishable products (Voidarou *et al*., 2020; Tomar *et al*., 2023). Exopolysaccharides produced by LAB strains have been studied for their health benefits, such as antioxidant, anti-diabetic, anti-carcinogenic and immunomodulatory properties (Leeuwendaal *et al*., 2022). Fermented foods contribute to gut microbial stability by suppressing the growth of pathogenic microorganisms. Some studies reported that

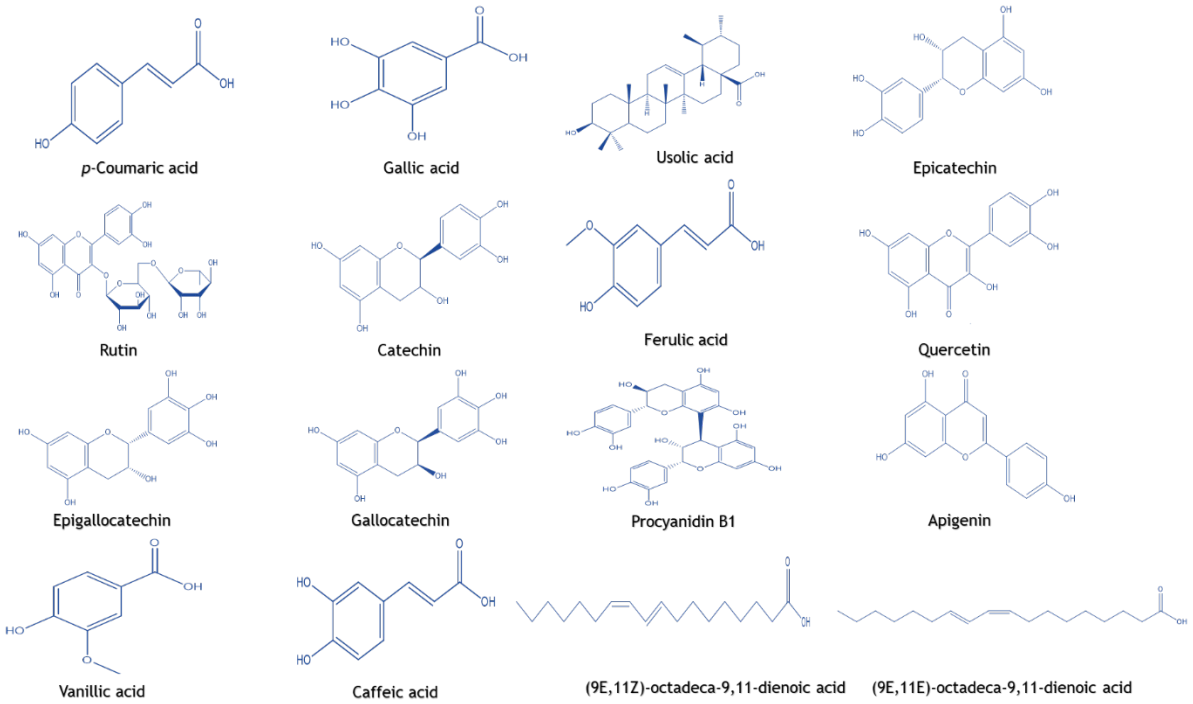

Fig. 3. Chemical structure of major bioactive compounds identified in fermented foods of cold desert regions.

Table 1. Major Microrganisms, potential bioactive compounds and health benefits of fermented foods

S No.	Food Name	Major Ingredient	Origin	Method of Preparation	Microrganisms	Potential Bioactive Metabolites	Health benefits	Reference
Cereal								
1.	Tagi Khambir	Wheat flour	Ladakh, Leh	Khambir is prepared by sourdough fermentation of wheat flour with yeast or butter milk for 6-7 hrs. Fermented dough is rolled into small balls and flattened to form a thick round bread.	*Lactic acid bacteria, Bifidobacterium* sp., *Escherichia coli*, *Salmonella* sp., *Vibrio* sp.,	Gallic acid, Ferulic acid Protocatechuic acid, *p*- hydroxy benzoic acid, *p*- Coumaric acid	Improves antimicrobial activity Improves antioxidant activity	Hor *et al*., 2019
2.	Chyang or Kodo ka janr	Finger millet	Lahaul Spiti, Kinnaur	Rice grains are washed and soaked in water (1: 2). Powdered phab is added on cooked grains. Then it is kept for fermentation for 2-3 days.	*Lactic acid* sp., *Bacillus* sp., *Saccharomyces cerevisiae*, *Pediococcus pentosaceus*, *Saccharomyces fibuligera*	Ferulic acid, Oryzenols, Vanillic acid, Protocheteoic acid	Helps in digestion Enhances gut microbiota	Thapa and Tamang, 2004; Majumder and Bhattacharya., 2024; Thakur *et al*., 2015; Cuvas-Limon *et al*., 2021
3.	Lugdi/ Chakti	Rice/ Barley	Kinnaur, Ladakh	Rice grains are soaked in water for 24 hours, then mixed with powdered phab and fermented for 15-30 days. The liquid part is separated from the solid part using a bamboo basket or cloth, resulting in a product called lugri..	*Lactobacillus* sp., *Saccharomyces cerevisiae, Bacillus subtilis, Acetobacter aceti*	Gallic acid	Improves digestibility Probiotics provides easier digestion	Kanwar *et al*., 2011; Kumar *et al*., 2019
4.	Marchu	Wheat flour/ Buckwheat flour	Lahual Spiti	Wheat or buckwheat flour is fermented with malera or treh, shaped into spirals called Dosha, and deep-fried after 4-5 hours of fermentation.	*Lactobacillus plantarum, L. acidophilus, L. lactis, Leuconostoc, Bacillus* sp., *Sacchromyces cerevisiae*	Gamma amino butyric acid	Production of beneficial bioactive compounds Enhances the B vitamin levels especially thiamine, riboflavin and nicotinic acid.	Dwivedi *et al*., 2024
5.	Siddu	Wheat flour	Kinnaur	Siddu is a fermented wheat bread made by kneading flour with yeast and letting it rise for 3–4 hours. It is stuffed with walnut, poppy seed, or lentil then sealed, and steamed until cooked. Served hot with ghee or dal.	*Lactobacillus plantarum, Leuconostoc mesenteroides*	Daidzein, Epicatechin, Catechin, Epigallocatechin, Gallocatechin, Vitexin,Taxifolin, Myricetin, Tricin, Quercetin, Luteolin Apigenin, Procyanidin B1, Kaempferol, and Procyanidin B2	Improves intestinal balance Improves nutrient absorption	Rawat *et al*., 2018; Dwivedi *et al*., 2024

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S No.	Food Name	Major Ingredient	Origin	Method of Preparation	Microrganisms	Potential Bioactive Metabolites	Health benefits	Reference
Cereal								
6.	Chilra	Buckwheat	Lahaul and Spit	Buckwheat flour and wheat flour are mixed (4:1) into a semi solid paste. Khameer is added. Mixture is fermented at 25-30°C for 8-10 hrs. when it becomes double of its size , it is made into a flattened cake.	*Lactobacillus* sp.	Gallic acid	Reduction of gastrointestinal disorders	Dwivedi *et al.*, 2024; Kanwar *et al.*, 2007
7.	Skyu	Wheat	Ladakh	Vegetables and dough are kneaded into flattened balls. These flattened balls are then put in pot with water and vegetables and steamed on low heat.	*Lactobacillus fermentum, L.* plantarum, Leuconostoc *sp.*	Ferulic acid	Improvement of digestibility LAB produces B-vitamins	Hussain *et al.*, 2022
8.	Chhutagi	barley	Ladakh	The flattened dough is cut into circular shapes. The dough is then cooked in thick soup made with vegetables or meat .	*Lactobacillus* sp.	Ferulic acid	Increases immunity Reduces bloating and constipation	Hussain *et al.*, 2022
9.	Seera	Wheat flour/millet flour	Kinnaur	Wheat grains are soaked in water for 3-4 days to allow fermentation. Grains are then grounded. Steeping is done to allow starch, and proteins to settle. Settled material is dried , and is called Seera.	*Lactobacillus plantarum, Leuconostoc mesenteroides, Saccharomyces cerevisiae*	Gallic acid	Improves gut health and provides probiotics Helps in weight management	Singh *et al.*, 2019
10.	Malera / treh	Wheat	Chamba, Kasol	Cleaning and washing of finger millet. Soaking in water and crushing into a coarse paste. Transfer it to earthen pot and add lukewarm water and starter culture. Cover and ferment for 2-3 days.	*Bifidobacterium* sp.	Ferulic acid	Antioxidant acitivity Anti- inflammatory and skin protective functions.	Thakur *et al.*, 2012; Dwivedi *et al.*, 2024; Sharma *et al.*, 2018; Rawat *et al.*, 2018
Milk			Milk					
11.	Maar	Milk	Zanskar , Ladakh	Maar is the commonly used butter eaten in Ladakh. After the churning of curd , butter is separated from buttermilk by filtering through cotton cloth.	Lactobacillus plantarum, L. fermentum, Lactobacillus brevis	Gallic acid	It is rich in most easily absorbable form of Vitamin A Necessary for thyroid and adrenal health	Raj and Sharma, 2015; Soulti and Roussis, 2007
12.	Labo	Milk	Ladakh	Buttermilk is boiled then cooled for 10-20 min. The causes separation of solids from liquid. The liquid whey is known as chhurkhu and solid cottage cheese as labo.	*Streptococcus thermophiles, Leuconostoc sp, Lactobacillus plantarum*	Gallic acid	Cures gastrointestinal disorders Enhanced immune function and reduction of inflammation	Raj and Sharma 2015; Angmo *et al.*, 2016; Sik *et al.*, 2023

Table 1. Major Microrganisms, potential bioactive compounds and health benefits of fermented foods

S No.	Food Name	Major Ingredient	Origin	Method of Preparation	Microrganisms	Potential Bioactive Metabolites	Health benefits	Reference
Cereal								
13.	Jho	Milk	Leh	Milk is boiled and then cooled. It is then inoculated with buttermilk that was made previously. The starter is then incubated overnight at a warm place.	*Lactobacillus* sp., *L. plantarum*	Gallic acid	Provides anti-fungal properties by inhibiting the growth of *Aspergillus flavus*	Raj and Sharma, 2015; Angmo *et al*., 2016
14.	Chhurpi	Yak milk / Cow milk	Leh, Ladakh	Cow's milk is fermented for 24 hours at 15-25°C to separate cream and obtain butter-milk. The butter-milk is boiled to curdle milk solids, filtered to remove excess liquid, and collected as the soft variety of chhurpi.	*Lactobacillus* sp., *Bifidobacterium* sp.	Gallic acid, Quercetin	Provides anti-bacterial activity against various pathogens. Used as a chewing gum or masticator for obtaining extra energy for the body and movement of jaws during winter	Choudhary *et al*., 2024; Bintsis, 2023
15.	Chhura	Milk	Ladakh	Chhura or dried cheese is made by drying buttermilk. The dried product is known as chhura. The drying of buttermilk is done by drying under the sun.	*Lactobacillus* sp.	Gallic acid	Produces anti-microbial properties. Helps in digestion and acidity	Raj and Sharma, 2015
Meat								
16.	Moqmoq	Goat / sheep	Ladakh	Wheat dumplings stuffed with finely chopped meat, animal fat. The dumplings are generally steam-cooked in a specially designed vessel, called as moqto.	Lactobacillus fermentum, Lactobacillus plantarum	NR	Provides antimicrobial activity against various pathogens. Enhances immune cell activity	Hussain et al., 2022; Ahsin *et al*., 2025; Arief *et al*., 2014
17.	Gemma/ Jamma	Goat/ chevon	Ladakh	Goat / Chevon meat is made from red meat mixed with finger millet, wild pepper, chilli powder and salt.	*Enterococcus* sp. *Leuconosto***c sp.** *Pediococcus* sp.	NR	Suitable for protein deficiency.	Rai *et al*., 2010; Rosma *et al*., 2016; Ahsin *et al*., 2025
18.	Sharjen	Goat	Ladakh	Air dried meat is eaten and cut into strips. Meat is also roated by burying the meat in the dung fuelled. When soaking of dried meat is done. Then the product is known as sharjen .	*Enterococcus* sp. *Leuconostoc* sp., *Pediococcus* and *Weissella* sp.	NR	Enhances protein digestibility. Reduces biogenic amines	Rosma *et al*., 2016; Ahsin *et al*., 2025
19.	Kheuri	Sheep	Ladakh	Chopped meat (lungs, liver) of slaughterd animals are put into cleaned empty sheep stomach. The stomach is stitched and then frozen in cold storage.	Lactobacillus plantarum	NR	Increases Antioxidant activity Development of beneficial organic acid	Rosma *et al*., 2016; Cunha *et al*, 2018; Arief *et al*., 2014

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S No.	Food Name	Major Ingredient	Origin	Method of Preparation	Microrganisms	Potential Bioactive Metabolites	Health benefits	Reference
20.	Faak Kargyong	Yak/ Chevon	Ladakh	The lean meat of yak/ cattle/pigs with fat are chopped finely and combined with crushed garlic and ginger. The mixture is stuffed into gastro intestinal tract of yak or ox.	*Lactobacillus casei, L. brevis, Leuconostoc mesenteroides, Pediococcus pentosaceous, Bacillus subtilis, B. mycoides, B. thuringiensis, Micrococcus* and *Staphylococcus*	NR	Increases protein availability and helps mineral absorption.	Rai *et al.*, 2010; Pohlmann *et al.*, 2011; Ahsin *et al.*, 2025
21.	Nyakir	Yak/Beef/ Lamb	Ladakh	The fish is cooked in water, the skeleton is removed and the boneless part is mixed with spices and salt. The whole mixture is then moulded into a round shape The product is fried in oil and then boiled in curry for softening.	*Lactobacillus* sp.	NR	Provides multivitamins and aids in immunity. Beneficial in winters, prevents cold .	Hussain *et al.*, 2022; Arief *et al.*, 2014; Ahsin *et al.*, 2025
22.	Thakpol	Goat/ sheep / Lamb		Ground roasted barley, animal fat, blood and salt are kneaded into a dough. A bun type bread is made, which is cookd on hot ash for 2-3 hrs. The blood added for thakpol is collected from thoracic cavity of dead animals after removing lungs and heart.	*Lactobacillus, Lactococcus, Pediococcus, Streptococcus, Enterococcus, Carnobacterium, Tetrogenococcus, Leuconostoc,* and *Oenococcus*	NR	Involvement in the regulation of appetite and weight. Development of beneficial organic acid	Rosma *et al.*, 2016; Arief *et al.*, 2014; Ahsin *et al.*, 2025
				Fruit wines				
23.	Angoori/ Kinnauri	Grapes	Kinnaur,	Grapes are crushed with sugar, water, and Phab in wooden casks for 12-15 days. The mixture is stirred daily until fermentation is complete. Juice is then collected through siphoning or distillation.	Bacillus licheniformis	*p*-Coumaric acid, Caffeic, Ferulic and Sinapic acid	Cures joint pain, constipation flatulence and swelling in pregnant women. Improves skin complexion. Relief from severe itching	Lata *et al.*, 2021; Sharma and Sharma, 2017; Garrido and Borges 2013; Li et al., 2017
24.	Chulli wine	Wild apricot	Kinnaur	The fruits are washed, deseeded and crushed into pulp, which is placed in a clean container. Natural wild yeasts initiate fermentation, and sugar may be added if needed. The mixture is loosely covered and left to ferment for 5–10 days.	Saccharomyces cerevisiae	Kaempferol Quercetin, Rutin Chlorogenic acid, Neochlorogenic acid, Protocatechuic acid, Catechin	Probiotics improve gut microbial balance Reduces oxidative stress	Sharma *et al.*, 2014; Rai *et al.*, 2016
25.	Local apple cider	Apple	Kinnaur	Grinding apples followed by warming and covering with muslin cloth for fermentation.	Saccharomyces cerevisiae, S. bayanus	Caffeic, *p*-Coumaric and Ferulic acid	Anti-inflammatory activities Improvement of gastrointestinal health Reduction of potential anti nutritive factors	Kanwar and Keshani, 2016; Cousin *et al.*, 2017

Table 1. Major Microrganisms, potential bioactive compounds and health benefits of fermented foods

S No.	Food Name	Major Ingredient	Origin	Method of Preparation	Microrganisms	Potential Bioactive Metabolites	Health benefits	Reference
Vegetables								
26.	Thukpa	Nappa cabbage	Spiti, Leh and Ladakh	For thukpa preparation add frying ginger and garlic in heated oil. Then add vegetables and chicken along with spices and water for cooking it. Lastly add boiled noodles and sauces with coriander leaves.	*Leuconostoc mesenteroides Lactobacillus plantarum, L. brevis, Pediococcus pentosaceus, and Enterococcus* sp.	GABA	Helps in cold and cough during winters	Shahbazi *et al*., 2021; Wei and Marco, 2025
27.	Shangsho-tsodama	Lepidium latifolium	Ladakh	Lepidium latifolium leaves are steamed and stir fried. When the bitterness is gone leaves are used in soup preparation.	*Bacillus* sp.	Quercetin gallic acid Catechin, Epicatechin	Antioxidant activity Protects against cellular damage. *L. latifolium*, actively kills cancer cells. Plant shows anti-microbial activity against various disease causing microbes.	Saxena *et al*., 2026; Kaur *et al*., 2013
28.	Zatsot/ Zathuk	Urtica hyperboria	Ladakh	Zatsot/Zathuk is prepared from the leaves of Urtica. And it is mixed with different types of Thukpa.	*Bacillus* sp.	Chlorogenic acid, Caffeic acid, and Quercetin	Radical scavenging activities. Act as an antioxidative agent	Saxena *et al*., 2026; Dolma *et al*., 2025; Zomba *et al*., 2023
29.	Skoche	Wild onions	Ladakh	Wild onions are collected and cooked with barley s flour. During winters it is sun dried with garlic and local butter.	*Bacillus* sp.	Quercetin derivatives	Boosts immunity Anti-inflammatory properties	Saxena *et al*., 2026; Benke *et al*., 2025
30.	Kabra tsodma	Capparis spinosa	Ladakh/ Leh	Young leaves and stems of Capparis spinosa are plucked, boiled to reduce bitterness, and cooked as a vegetable to make curry.	*Bacillus* sp.	Apigenin Kaempferol Flazin Guanosine	Improvement of metabolism Boosts immunity and act as anti-inflammatory agent Used for curing hyper acidity	Saxena *et al*., 2026; Zhang and Ma, 2018; Angmo *et al*., 2022; Muthaiah *et al*., 2010

LAB species isolated from traditional fermented fruits and vegetables have antimicrobial activity against *E. coli*, *Salmonella,* and *Bacillus* (Tamang *et al*., 2016). Consuming fermented foods like yoghurt and kefir regularly can improve gut health by increasing beneficial bacteria such as *Lactococcus*, *Bifidobacterium*, *Lactobacillus*, and *Akkermansia*, which enhance gut barrier function by colonising the gut lining and inhibiting harmful microorganisms like *Proteobacteria* and *Enterobacteriaceae* concentrations (Dimidi *et al*., 2019; Leeuwendaal *et al*., 2022). Moreover, modified dietary fibres and polyphenols can improve the substrate bioavailability, thus supporting the proliferation of beneficial gut microbiota. Additionally, probiotics are beneficial for gut health, immunity, metabolic disorder and cardiovascular diseases. Alcoholic beverages contain probiotic strains like *Lactobacillus*, *Pediococcus*, *Leuconostoc*, *Bacillus*, *Staphylococcus*, and *Weissella,* which can improve gut health and have anti-inflammatory, pain-relieving, and strength-restoring properties (Baliyan *et al*., 2024; Sen *et al*., 2025). Similarly, probiotics derived from kefir have been shown to upregulate important metabolic pathways and help in fighting conditions like Non-Alcoholic Fatty Liver Disease (NAFLD). Kefir has anti-cancer properties that are attributed to various compounds such as bioactive peptides, EPS, and sphingolipids, making it a popular subject of research in recent years (Leeuwendaal *et al*., 2022). Some studies found that microorganisms such as *Bacillus breve, B. bifidum, B. pseudolongum*, and *Lactobacillus* can convert linoleic acid (LA) into conjugated linoleic acid, which has been shown to inhibit multistage carcinogenesis at various sites and aid in the prevention or treatment of conditions like hypercholesterolemia and obesity (Voidarou *et al*., 2020). Obesity is caused by dysregulation in adipogenesis, the process of converting pre-adipocytes into fat cells. Baliyan *et al*. (2025) found that using certain microbial strains such as *Lacticaseibacillus paracasei*, *Latilactobacillus curvatus*, *Lactiplantibacillus paraplantarum*, and *Enterococcus faecalis* can help to regulate this process and reduce obesity by controlling lipid accumulation and triglycerides. Fermented soy products have been found to have anti-inflammatory effects on the body. Nattokinase, a fibrinolytic enzyme derived from natto,

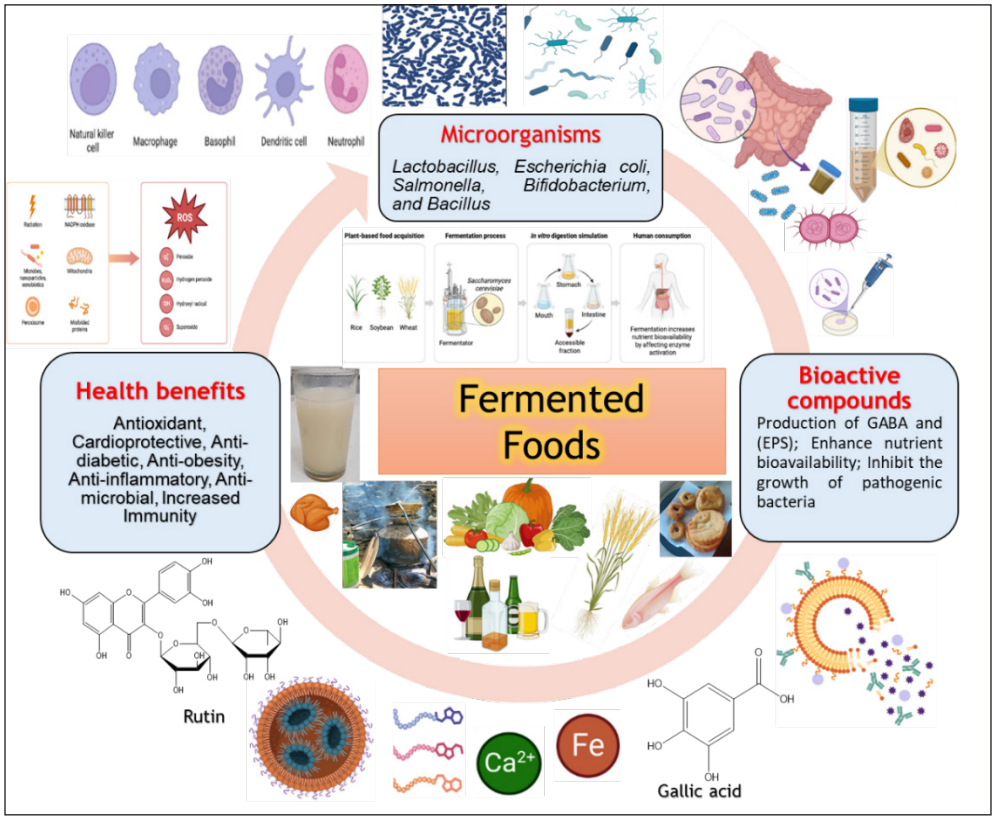

Fig. 4. Health benefits of Fermented foods.

Japanese boiled soybeans fermented with *Bacillus subtilis*, has cardioprotective and haematological benefits due to its anti-inflammatory and antioxidant properties (Shahbazi *et al*., 2021). Fermentation of cereals with LAB enhances nutrient availability by breaking down carbohydrates and non-digestible compounds, increasing amino acids and B vitamins, and lowering levels of polyphenols, phytates, and tannins. This process enhances iron absorption and eliminates anti-nutrient compounds that can hinder digestion and absorption (Şanlier *et al*., 2017). Furthermore, bioactive metabolites such as gamma-aminobutyric acid (GABA) and extracellular polymeric substances (EPS) produced during fermentation have various effects on immune modulation, oxidative stress and inflammatory pathways. Microorganisms in fermented foods release amino acids and bioactive peptides that convert fats into healthier forms during the fermentation process (Leeuwendaal *et al*., 2022). Therefore, consumption of fermented food products promotes human health by providing several health benefits as mentioned in Table 1 and Fig. 4.

Conclusions

Fermented foods can be explored from various angles, including tourism, scientific research, sustainable agricultural practices, and community development. The traditional and authentic production process of fermented food and beverages could attract tourists to the Himalayan regions, providing economic strength to local communities. Empowering local communities, especially women, is crucial for cultural preservation and can help preserve wild and native food plants, which are key ingredients in the sensory attributes of ethnic fermented foods. The presence of bioactive compounds and potential health benefits in traditional fermented foods presents a promising area for scientific investigation. Further research in this field will help validate the data and explore potential applications in development of novel probiotics, therapeutics and functional foods.

Authors contribution

Conceptualization, SG, PB, KS and VS; Methodology, SG, PB, KS and VS; Validation, VS; Resources, VS; Data Curation, SG, PB, KS and VS; Writing – Original Draft Preparation, SG, PB, KS and VS; Writing – Review and Editing, SG, PB, KS and VS; Visualization, SG, PB, KS.; Supervision, VS.; Project Administration, VS.; Funding Acquisition, VS.

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Competing Interests

The authors declare no competing interests.

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