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Review Article

Bioprospecting of Traditional Fermented Beer of Northeast India: With Special Reference to the Galo Tribe of Arunachal Pradesh

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Abstract: Northeast India is well known for its unique practices of preparing alcoholic beverages and other fermented foods. Traditionally prepared rice beer is thought to possess various medicinal and therapeutic properties due to the utilization of numerous indigenous plant species during its preparation. It exhibits rich microbial diversity, whose synergistic action converts the starchy components of rice into beneficial metabolites such as sugar, alcohol and organic acids. It is locally believed that traditional rice beer is effective in treating worm expulsion, insomnia, body aches, inflammation and urinary issues. The bioprospecting result re-establishes our belief in using traditional rice beer as a medicinal probiotic while retaining all of its other sensory properties as a beer. The present review provides a comprehensive overview of traditional rice beer from Northeast India, with special reference to the Galo tribe, an ethnic community of Arunachal Pradesh. It discusses the ingredients, methods of preparation and associated traditional knowledge, along with the ethnobotanical aspects of starter cake preparation. In addition, the review examines microbial diversity, fermentation dynamics and metabolite profiles across different regions. Strategies for enhancing the shelf life of the rice beer are also discussed. Thus, with appropriate scientific interventions, traditionally prepared rice beer can be effectively commercialized, supporting traditional knowledge systems and boosting the economy of tribal communities.

Keywords: Ethnobotany; Fermentation; Metabolites; Microbial diversity; Probiotics; Starter cake.

Introduction

The World Health Organization (WHO) has classified the traditional beverage as "unrecorded alcohol," taking into consideration its diverse social, economic and cultural significance in the whole world (WHO, 2014). The Northeast region of India is well known for its traditional practice of preparing and consumption of alcoholic beverages and other fermented foods. Rice beer preparation and its consumption have been a common practices since time immemorial among all indigenous communities of Northeast India and are known by different local names (Figure 1) (Ghosh and Das, 2004; Jeyaram *et al.*, 2008). The traditional rice beer is widely appreciated for its unique soothing taste, aroma, color and

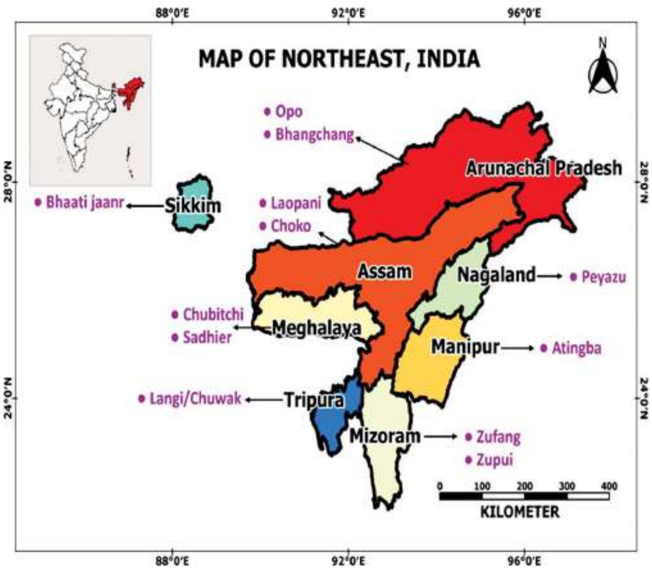

Fig. 1. Map of Northeast India indicating ethnic communities involved in fermented beverages (magneta) across the eight states (black).

nutritional as well as therapeutic values. These attributes are largely associated with its diverse microbial consortia involved in fermentation as well as the utilization of numerous medicinal herbs in the starter cake (Tamang *et al.*, 2007; Jeyaram et al., 2008). This round-to-flattened starter culture harbors a complex community of alcohol yielding and amylolytic yeasts, lactic acid bacteria (LAB) and starch degrading moulds which are collectively involved in the fermentation process (Dung *et al.*, 2006). During fermentation, microbial enzymes deconjugate the phenolics from the fibers (Sokrab *et al.*, 2012; 2014). Consequently, the presence of free polyphenols derived from either rice or medicinal herbs contributes to the antioxidant potential of various rice beer varieties (Deka *et al.*, 2018). Previous studies have reported several microorganisms in starter cultures, including *Saccharomycopsis fibuligera*, *Pichia burtonii*, *Mucor circinelloides*, *Saccharomycopsis capsularis* and lactic acid bacteria such as *Lactobacillus plantarum*, *Pediococcus pentosaceus* and *Lactobacillus brevis* (Tamang *et al.*, 2007). Tribal people have their own set of long-standing customs and beliefs, which they adhere to when producing starter cultures. Among the numerous indigenous communities practicing traditional rice beer fermentation in Northeast India, the Galo tribe, which is one of the prominent tribes of Arunachal Pradesh, was selected for the present study due to their distinctive fermentation process, particularly the use of rice husk ash and the traditional starter culture "Opop," and relatively underexplored microbial diversity.

Rice beer brewed following traditional methods generally has a short shelf life, which necessitates scientific intervention for long term storage and commercialization. In the current food and beverage landscape, there is an increased focus on convenience-oriented products due to rapid transformation in consumers lifestyles; however, the inability to preserve this beverage for extended periods restricts its transportation to wider markets, thereby limiting it primarily to local or rural consumption. Additionally, lack of proper standardized hygiene practices can sometimes lead to spoilage, which can bring about product loss. Therefore, the present study aims to bioprospect the traditional fermented rice beer of Northeast India with special reference to the Galo tribe of Arunachal Pradesh in order to gain insights into the fermentation processes that may contribute to improving its quality and shelf life, while also exploring potential strategies to enhance its stability and broader applicability as a culturally significant traditional beverage.

Literature search and documentation of Galo fermentation practices

Literature search strategy

Google Scholar, PubMed and Web of Science were systematically searched from journal inception until March 2026 to identify relevant reviews and peer-reviewed research articles. The search focused on studies related to fermented rice beverages, including their preparation methods, starter cultures, microbial diversity, metabolite profiles, shelf-life enhancement strategies and associated ethnobotanical aspects. The search items included combinations of keywords such as "fermented rice beverages of Northeast India," "fermented beverage," "microbial diversity," "Major metabolites," "ethnobotany of rice beer," "cultural significance of rice beer," "lactic acid bacteria," "probiotics" and "shelf life." Titles and abstracts were initially screened to identify relevant studies.

Full-text articles of the selected studies were further evaluated, and relevant data were extracted using a structured data extraction template based on the objective of the review.

Documentation of traditional fermentation practices of the Galo tribe

Field-based documentation of traditional rice beer preparation was conducted in Higi Bagra village (28°04’48.20"N 94°45’32.35"E), located in West Siang district of Arunachal Pradesh, India. It has an average elevation of approximately 489 meters above sea level and is characterized by high humidity, heavy rainfall and moderate climatic conditions. Traditional knowledge related to the rice beer preparation was documented through direct interactions and participatory observation with local village informant who demonstrated and explained the preparation process. Prior Informed Consent (PIC) was taken during the investigation. Ethnobotanical information was recorded using standard survey methods, and plant specimens were collected, preserved and identified through morphological comparison with regional floras and taxonomic references at the Botanical Survey of India, Arunachal Pradesh Regional Centre, Itanagar.

Traditional rice beer practices among the Galo tribe of Arunachal Pradesh

The Galo community, one of the major indigenous groups belonging to the Abotani lineage (Abo-Tani, meaning the great ancestor of humankind), follows a distinctive method for rice beer preparation. In this process, boiled rice is mixed with rice husk ash (locally known as *ampe*) and subsequently inoculated with a traditional starter culture called “Opop” (Figure 2). The incorporation of burnt rice husk and rice straw ash represents a unique traditional practice, which has also been reported among other communities such as the Mising tribe (Kardong *et al.*, 2012b). Previous studies have demonstrated that rice husk ash (RHA) exhibits high porosity and efficient filtration characteristics, sometimes outperforming conventional commercial filter aids such as diatomite and perlite in terms of filtration flow rates and clarity of the filtrate (Van Kruining, 1988; Villar *et al.*, 1997; Villar *et al.*, 2004). These practices reflect the indigenous knowledge systems of tribal communities, which have evolved through generations of empirical observation and refinement, highlighting the functional importance of locally available materials in traditional fermentation processes.

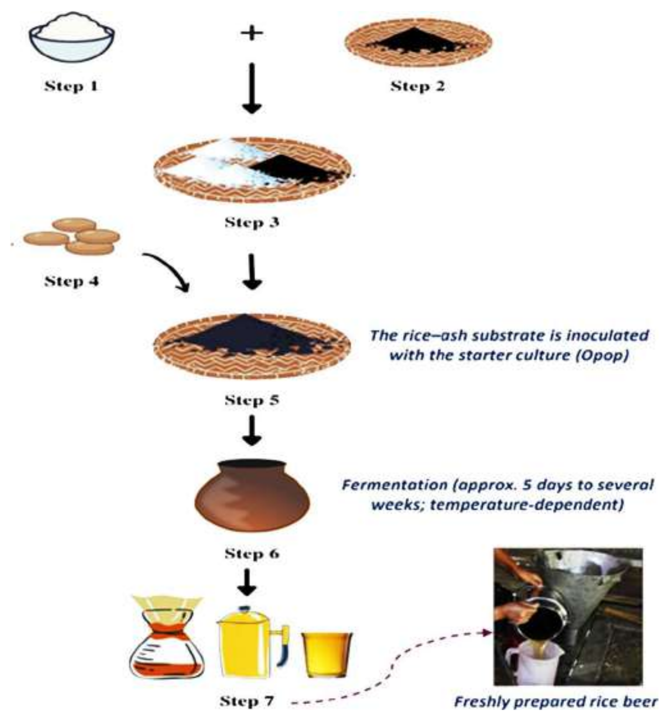

Fig. 2. Schematic representation of traditional rice beer preparation. **Step 1 & 2**. Local rice variety is boiled and rice husk is burnt into ashes called as ampe. **Step 3.** The boiled rice and ashes (ampe) are then cooled on traditional Bamboo mat. **Step 4.** The boiled rice and husk are mixed proportionately and rubbed on the mat for proper mixing and inoculated with Starter cake (about 30-50 grams/kg). **Step 5.** The mixture of rice, ash and starter cake is packed in a traditional way. Fermentation takes place for 5-10 days during summer season and for a month in winters. **Step 6.** Finally, after maturity the late fermented stage is filtered in a conical bamboo basket (Das and Deka, 2012; Das *et al.*, 2012; Kardong *et al.*, 2012a; Bhatt *et al.*, 2018; Mishra *et al.*, 2019). Created with BioRender.com.

Preparation of opop (starter culture) and opo (rice beer) by the Galo tribe

For the preparation of the starter cake (opop), the rice is soaked in water for around two to three hours and then pounded into a fine powder. Simultaneously, freshly collected leaves and stems of medicinal plants are pounded into a fine

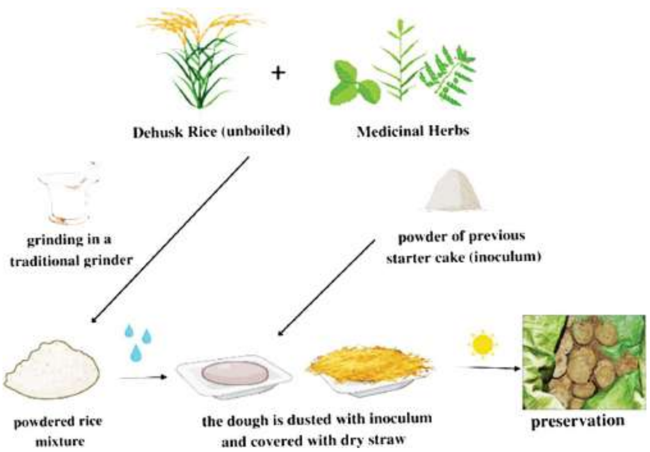

Fig. 3. Work flow of the traditional method of starter cake preparation.

paste using a wooden mortar. The plant material is then mixed with rice flour to make a dough, from which small cakes are prepared. These cakes are subsequently dusted with the previous starter cake, which serves as a source of microbial inoculum (figure 3). The dusting process is typically done in a sterile and undisturbed place, often on a clean elevated surface such as the roof of a local house. While this practice is traditionally believed to protect the starters from negative influences, the scientific purpose lies in maintaining the sterility of the starter cakes. The starter cakes are rough in texture, dull white in appearance and are stored in a sterile place. According to local knowledge, high-quality starters are comparably more fragile and prone to contamination by undesirable microorganisms. Hence, as a precautionary measure, on the seventh day, the starter cakes are dusted with roasted leaves of *Diospyros lanceifolia Roxb.,* which are believed to provide protection against detrimental microorganisms.

For the preparation of *"opo"* (rice beer), cooked rice is mixed with burnt rice husk. The mixture is then spread on a traditional bamboo mat called "Peche" to cool it down. Further, the mixture is rubbed thoroughly on the mat for proper mixing, and an appropriate quantity of opop powder is added. The quantity of starter (opop) used here differs according to each individual's needs and preferences. Additionally, a direct correlation has been seen between higher amounts of opop used and faster fermentation rates. However, this increase in the quantity of opop, which speeds up the fermentation process, can also lead to spoilage of the rice beer. This can also be determined by the sour smell coming out of the fermented mass. The mixture of boiled rice, burnt husk and opop is then packed in locally available *"ekkam"* leaves (*Phrynium pubinerve*). During the winter season, this bundle is kept on *"matum"* (a shelf above the fireplace), as the warmth from the fire helps speed up the fermentation process. Whereas in the summer, it is placed in another sterile part of the house. During the summer season, the fermentation process takes place over 5 days. Whereas in the winter, it takes around two weeks to a month.

An ethnobotanical aspect of starter cake preparation

In the Galo community of Arunachal Pradesh, starter cakes are prepared using the leaves, fruits and stems of a variety of plant species. Some of the plant species include *Saccharum officinarum (sugarcane), Thelypteris clarkei C.F., Diospyros lanceifolia Roxb., Capsicum annuum, Solanum indicum L.,* and the leaves of *Artocarpus heterophyllus Lam* (jackfruit). These plant products not only contribute to characteristic properties of starter culture but also provide essential nutrients for the microbiota's endurance and healthy growth in the starter cakes. Several studies have documented the use of medicinal plant species in fermented rice beverages across different tribes (Table 1). In the Galo community, plants with antioxidant, antidiabetic and antimalarial properties are commonly used. The medicinal herbs used in the starter cake are also reported to be effective against cough and dysentery (Gogoi *et al*., 2013; Shrivastava, 2015). Furthermore, the fruits of the *Solanum indicum*, which they use to impart a characteristic bitter taste, are known for their antineoplastic properties and are also used for liver diseases and pruritus. Similarly, *Capsicum annum* (chilies), apart from its cultural use in warding off the evil eye, has certain medicinal values, including treatment of alcoholic gastritis, abdominal pain, anorexia, diarrhea and respiratory ailments including common cold and cough. It is also reported to possess antifungal and antioxidant properties (Mohanraj *et al*., 2018; Vivek-Ananth *et al.*, 2023). Thus, the utilization of these plant species highlights the interplay between microbial functionality and traditional knowledge and offer valuable insights into the nutritional significance of fermented rice beverages.

Microbial diversity

The starter cake harbors a diverse microbial community, including starch-degrading molds, lactic acid bacteria (LAB), acetic acid bacteria (AAB) and alcohol-producing yeasts (Kanwar *et al.*, 2011; Tamang *et al.*, 2015; Jani and Sharma, 2021). The microbial diversity of rice beer fermentation is highly dynamic and characterized by a succession of functionally distinct microbial groups. The progression from starter cake-inoculated rice to final beer formation shows a strong correlation between microbial diversity and its succession. Amylolytic fungi, like those of genus *Rhizopus,* present in the starter cakes initiate the process by hydrolyzing rice starch into simple sugars, which are subsequently used by the yeast *Saccharomyces cerevisiae* for ethanol production (Li *et al.*, 2021).

The schematic chemical equation for the production of ethanol from glucose is as follows:

$$\text{Glucose} \xrightarrow{\text{Yeast}} \text{Ethanol} + \text{Carbon dioxide}$$

$$C_6H_{12}O_6 \xrightarrow{\text{Yeast}} 2\,C_2H_5OH + 2\,CO_2$$

Recent advances in genomics and proteomics, particularly high-throughput sequencing (HTS), have significantly improved our understanding of microbial diversity in traditional rice beer. Although some studies have reported the microbial composition of the starter cultures (Bhuyan *et al.*, 2014; Das *et al.*, 2014; Ghosh et al., 2015; Sha *et al.*, 2017; Das et al., 2019; Yumnam *et al.*, 2024), comprehensive characterization of microbial communities and their functional role in alcoholic beverage fermentation remains limited (Dung *et al.*, 2005). HTS-based studies have revealed a diverse array of fermenting microorganisms. For instance, Sha *et al.* (2017) reported the presence of 15 bacterial phyla and 2 fungal phyla in thiat and marcha, traditional starters from Sikkim and Meghalaya. Subsequently, another study using HTS reported a total of 594 fungal species in the dry starters of Northeast India, including Chowan, dawdim, hamei, humao, khekhrii and phut (Sha *et al.*, 2019). Das *et al.* (2019) reported that LAB emerged as the dominant group among diverse bacterial communities in rice beer varieties of Assam, including Apong (Nogin and poro), Xaaj and Joubishi, represented by *Lactobacillus*, *Weissella* and *Pediococcus*. Other genera such as *Acetobacter, Dickeya, Enterobacter, Gluconobacter, Pseudomonas* and *Staphylococcus* were also identified as part of the core microbiota.

Across fermented beverages of different tribes in Assam, Sikkim and Meghalaya, Firmicutes and Proteobacteria consistently emerge as the dominant phyla, while Bacteroidetes and Actinobacteria occur in relatively lower proportions (Sha *et al.*, 2017; Yumnam *et al.*, 2024). A similar trend has also been observed in rice wine Koji from China, where Firmicutes and Proteobacteria are significantly higher (Zhao *et al.*, 2022), indicating a common microbial pattern across traditional rice beverages and starter cultures.

Further Lactic acid bacteria (LAB) were identified as the key microorganisms contributing to the production of flavor (Jiang *et al.*, 2002). LAB species such as *Lactobacillus bifermentans, L. pentosus, L. casei*, *L. plantarum*, *Limosilactobacillus fermentum*, *Lactiplantibacillus plantarum* and *Pediococcus pentosaceus* have been reported in the rice beer from Northeast India (Handique and Deka, 2016; Das *et al.*, 2019; Yumnam *et al.*, 2025). These LAB exhibit probiotic properties; for instance, *P. pentosaceus* has been reported to inhibit harmful gastrointestinal pathogens, elicit immunological responses and produce bacteriocins against Gram-positive pathogens such as *Staphylococcus aureus* and *Listeria monocytogenes* (Mora *et al.*, 1997; Nghe and Nguyen, 2014). Giri *et al.* (2018) isolated *Lactobacillus plantarum* from Bhaati jaanr, rice beer from Sikkim, and reported satisfactory in vitro probiotic properties, including acid and bile tolerance, auto-aggregation, antimicrobial activity and antibiotic susceptibility. The strain also enhanced the mineral bioavailability via heightened phytase activity, rapid acidification and organic acid production, thereby improving the safety and nutritional quality of the fermented beverage. Similarly, Das *et al.* (2019)

identified LAB strains such as *P. pentosaceus, L. pentosus, L. casei* and *L. plantarum* from rice beers in Assam, which exhibited antioxidant activity, tolerance capacity and adherence properties, highlighting their potential as probiotics and thus their use as therapeutics.

Beyond their role in fermentation, LAB are associated with a wide range of health benefits. These include immune responses such as reducing the severity of eczema (Weston *et al.*, 2005) and potential antitumor effects observed in *in vitro* studies (Hirayama and Rafter, 1999). In addition, LAB also help inhibit pathogenic bacteria in the gut by increasing the production of intestinal mucins, which act as a physicochemical barrier and support phagocytosis (Yolken *et al.*, 1994). Additionally, LAB produces beneficial products such as bacteriocins, vitamins and organic acids (Yadav and Shukla, 2017). Another interesting function of LAB is cholesterol reduction bile salt deconjugation, which has been associated with reduced blood cholesterol levels in probiotic-treated individuals (Ashar and Prajapathi, 1998; 2000) (Figure 4).

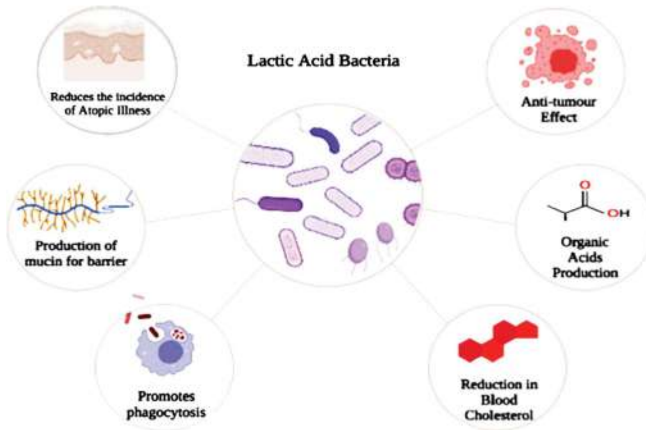

Fig. 4. Probiotic potential of Lactic acid bacteria (Yolken et al., 1994; Ashar and Prajapathi, 1998; Hirayama and Rafter, 1999; Ashar and Prajapathi, 2000; Rautava et al., 2002; Weston et al., 2005; Yadav and Tangpu, 2009; Yadav and Shukla, 2017). Created with BioRender.com.

Major metabolites in rice beer

Traditional rice beer has gained increasing scientific interest due to its rich composition of micronutrients, macronutrients and bioactive compounds, which offers potential health benefits. It serves as a rich source of diverse metabolites, including a wide range of organic acids, carbohydrates, amino acids, alkaloids, volatile aromatic compounds and other metabolic intermediates, the majority of which arise as natural products of microorganisms or as intermediates in their primary metabolic pathways (Sauer *et al.*, 2008). Key examples include organic acids such as acetic, butyric, lactic and propanoic acids, which are known to exhibit significant antibacterial and gut-health-promoting properties (Tanaka *et al.*, 2016). In addition, these organic acids enhance the shelf life of rice beer by inhibiting the growth of spoilage microorganisms such as *Escherichia coli* and *Salmonella* spp. (Salmond *et al.*, 1984; Blocher and Busta, 1985).

A comprehensive study by Das *et al.* (2019) on major rice beer varieties of Assam revealed a diverse array of metabolites, including 18 organic acids, 18 saccharides, 8 amino acids, 11 sugar alcohols, 1 vitamin and several nutraceutical compounds such as oxazolidine-2-one, thiocoumarine, carotene and acetyl tyrosine. Metabolic profiling of rice beers from Northeast India has demonstrated significant regional variations in composition and quality (Das *et al.*, 2014). The type of rice used in fermentation is one of the critical factors influencing both the flavor and nutritional profile of the resulting beer. For instance, white rice is generally known for its clean and neutral taste but contains relatively lower levels of antioxidants and fiber. In contrast, brown rice provides rich amounts of essential minerals, dietary fiber and vitamins that support digestive and metabolic health. Further pigmented rice varieties, such as black and red rice, are particularly rich in bioactive compounds such as anthocyanins and polyphenols, respectively (Charoenphun *et al.*, 2025). In the context of traditional practices, the Galo community predominantly utilizes white rice for fermentation, which imparts a relatively neutral taste and may influence the nutritional and antioxidant profile of the beverage. Supporting this, recent LC–MS-based metabolomic analysis of a traditional red rice beer (*Zufâng*) revealed a wide range of bioactive metabolites such as phenolics, polyunsaturated fatty acid derivatives, sphingolipids and terpenoids, which are associated with antioxidant, anti-inflammatory, cardioprotective and potential anticancer activities (Lalnunfeli *et al.*, 2026). From a nutritional perspective, rice beer contains both simple and complex carbohydrates. In Galo rice beer, glucose predominates, while raffinose (a complex trisaccharide) and galactose are also present (Das *et al.*, 2014). The presence of complex sugars such as raffinose has been associated with several health benefits, such as prevention of diabetes, obesity, heart disease and certain gastrointestinal diseases (Anderson *et al.*, 2009). In addition to nutritional composition, rice beer contains a wide range of volatile aromatic compounds that contribute to its distinct sensory profile by imparting alcohol-like, sweet, fruity and pungent notes. Among these, phenylethyl alcohol has been consistently reported as one of the most abundant aromatic compounds in rice beers of Northeast India (Das *et al.*, 2014; Myrphet *et al.*, 2023). It is an important constituent of many essential oils, flavors, and perfumery, and moreover, it exhibits antimicrobial properties (TGSC, 2014). It has also been suggested that bitterness in rice-based fermentation may come from the presence of bitter amino acids due to the presence of hydrophobic groups (Slaughter *et al.*, 1987). In Galo rice beer, several amino acids, including leucine, valine, isoleucine, phenylalanine and histidine, contribute to bitterness, thereby influencing both the nutritional value and sensory characteristics of the beverage. Additionally, organic acids such as lactic, succinic and oxalic acids play important roles in fermentation and overall flavor development (Das *et al.*, 2014).

Short shelf life of rice beer: a major challenge

Beer shelf life is determined by microbiological, colloidal, foam, color and flavor stability. According to Hough (2010), changes in sensory properties limit the shelf life of most food products. Generally during the fermentation, yeast multiply and increase in the beginning of fermentation (Lyumugabe *et al.*, 2012), which later on either die or undergo autolysis, in which their cell components are released into the beer. At this point, mesophilic LAB as well as other contaminating microorganisms proliferate rapidly, and the flavor of the beer changes as a result of the metabolites produced by these microbes. Such microorganisms produce acetic acids, aromas, pellicles, fruity odors and off-flavors, rendering unpleasant taste, odor and texture (Lyumugabe *et al.*, 2012; Konfo *et al.*, 2021). Hence, one of the major concerns is to resolve the low shelf life of traditional rice beer of Northeast India.

Pasteurization is commonly employed to extend the shelf life through mild heat treatment (approximately 60°C), which inactivates fermenting yeast and potential spoilage microorganisms (Milani and Silva, 2022). However, this approach is not well suited for traditional rice beer due to its higher viscosity and associated elimination of amylolytic enzymes and active yeasts, resulting in reduced turbidity (Novellie and Schaepdrijver, 1986). Moreover, heat treatment negatively affects the original beer's freshness, flavor and probiotic effect.

Various strategies have been explored to enhance the shelf life. For instance, Mangang and his team, using established starters and an ethanolic extract of *Albizia myriophylla* bark, attempted to extend the shelf life of traditional rice beer "Atingba" of Manipur. The shelf life stability of Atingba was significantly extended (Mangang *et al.*, 2017). Hence, this extract might have some bioactive compounds that may have impaired the activities of undesirable microbes and extended the shelf life of beer (Lyumugabe *et al.*, 2012; Mangang *et al.*, 2017). Low-temperature treatment is another conventional approach, as it reduces yeast metabolism activity, thereby decreasing amino acid and sugar metabolism as well as limiting alcohol synthesis (Etschmann *et al.*, 2002), and thereby inhibiting the growth of spoilage microbes. However, when new shanlan rice wine was subjected to a CO_2 top pressure that steadily rose from 0 to 1.3 MPa at 25°C and 5°C, it was seen that yeast growth was hindered by pressure and stress, causing a rise in intracellular trehalose throughout the first four months, which helps the yeast to grow under stress. Except for lactic acid, CO_2 top pressure considerably reduced the synthesis of higher alcohols, esters, total amino acids, and ethanol. As CO_2 is generally acknowledged as an inert byproduct of cellular metabolism, the inhibition of CO_2

might become a potential parameter in the retardation of yeast growth and improvising the quality of the fermentation process (Yang, 2019).

Lee *et al.* (2012) and Lyumugabe *et al.* (2012) found that static cultures had higher tartaric, acetic and malic acid concentrations than agitated cultures. Static culture provides an extension of the shelf life of the products (Salmond *et al.*, 1984; Blocher and Busta, 1985). This method represses the growth of spoilage bacteria such as *Salmonella spp.* and *Escherichia coli*, including the inhibition of important metabolic pathways (Krebs *et al.*, 1983), stress on intracellular pH homeostasis (Cole and Keenan, 1987), membrane disruption (Freese *et al.*, 1973), and the accumulation of toxic anions (Booth *et al.*, 1989). Another approach to improving the shelf life of rice beer involves the use of artificial CRISPR arrays to selectively suppress acetic acid bacteria (AAB) by targeting essential genes involved in metabolic and stress response genes, such as those involved in ethanol oxidation (alcohol and aldehyde dehydrogenases), as well as NADPH- and ATP-consuming enzyme-encoding genes (Ran et al., 2013; Matsutani and Yakushi, 2018; Shen *et al.*, 2021). This targeted strategy can inhibit AAB while allowing beneficial microbes such as LAB to proliferate. However, such approaches are technically complex, extensive and may not be feasible or culturally acceptable in tribal settings.

There are various other approaches in which the shelf life of rice beer or rice wine has been enhanced and previous research has primarily focused on the effects of physicochemical parameters such as pH, osmotic pressure, SO_2 addition, temperature, or nutrient availability (Ciani *et al.*, 2006; Robinson *et al.*, 2012; García-Ríos *et al.*, 2014). However, the concern is if it's possible to increase the shelf life of rice beer while maintaining its probiotic impact, as is the case with traditional Northeast rice beer. The recent findings also suggest that besides all of these, the ecological interaction has a crucial role in determining the individual species contribution in the result of alcoholic fermentation (Wang *et al.*, 2015; Bagheri *et al.*, 2020). Hence, reformulating the microbial consortium using different strategies would increase the microbial complexity of the final wine and its shelf life. Thus, an appropriate starter would be established with good fermentation kinetics, efficiency to utilize nitrogen sources, and good ethanolic and osmotic stress (Varela *et al.*, 2004). For example, the introduction of *non-Saccharomyces* starters such as *Hanseniaspora vineae* (usually combined with *Saccharomyces*). *H vineae,* an active fermenting yeast, also creates a juicy ecology and prevents contamination from aerobic bacteria and yeasts. Furthermore, it has a complementary secondary metabolism with *Saccharomyces*, increasing the flavor complexity of the wine via benzenoid and phenylpropanoid synthetic pathways, which are almost non-existent in the conventional yeast starters. Unlike *Saccharomyces*, *H. vineae* creates a friendly surrounding for the other strains because of the favorable conditions it generates, such as optimum low temperatures, reduced synthesis of medium-chain fatty acids, low nitrogen demand during fermentation, and a high acetylation capability of aromatic higher alcohols, which are known inhibitors of yeast (Carrau and Henschke, 2021). Thus, co-inoculation of both Saccharomyces and non-Saccharomyces can also be an effective strategy for improving the shelf life, which can be used to unravel the challenges (Figure 5). Further ways to monitor and control the desired metabolites at different stages of fermentation need to be explored. Moreover, a synthetic approach needs to be applied to control the types of microbes and the consortia's microbial succession to make beneficial changes to the beer, such as improving shelf life, taste, aroma and nutritional value, etc.

Conclusion and Future Perspectives

Under the spectrum of craft beers, traditional rice beer has a fair chance of being embraced by communities across the country and beyond. Bioprospecting studies highlight its potential as a functional probiotic beverage that retains desirable sensory properties. The incorporation of medicinal herbs in the starter cake, along with dynamic microbial succession during fermentation, enhances its therapeutic properties, including antioxidant and anthelmintic activities. Furthermore, LAB present in rice beer already has a history of health-promoting interactions with the human gut, making

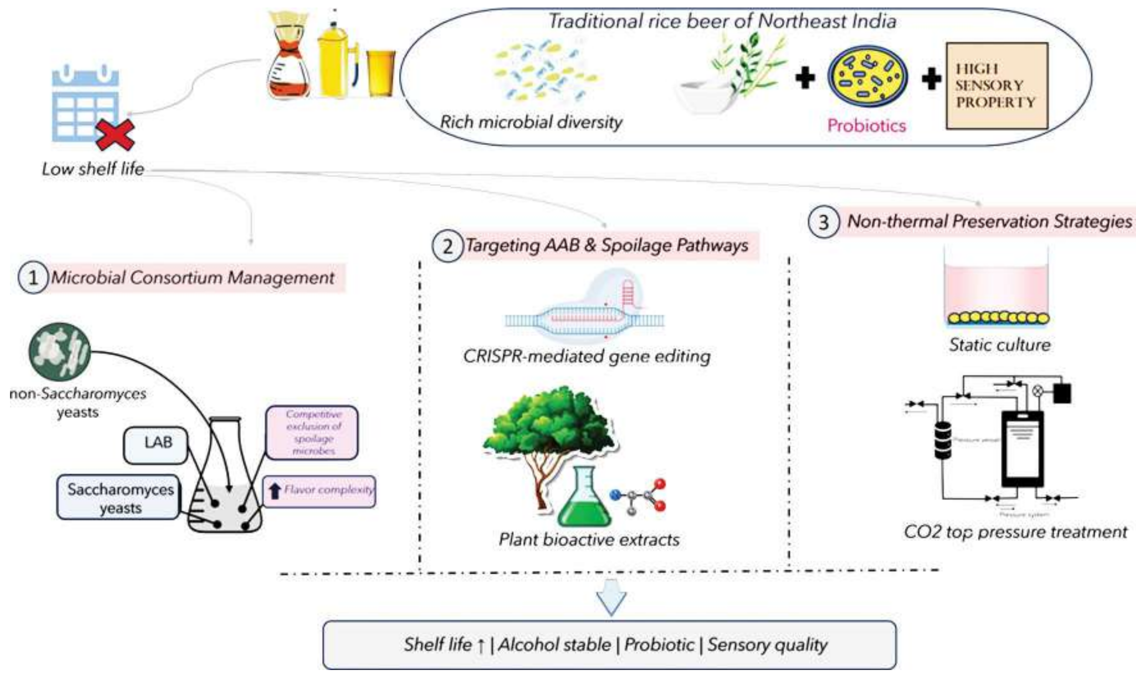

Fig. 5. Schematic overview of potential strategies, derived from previous studies, to improve the shelf life of traditional rice beer while maintaining alcohol content, sensory content and probiotic potential (Lee *et al.*, 2012; Lyumugabe *et al.*, 2012; Ran *et al.*, 2013; Mangang *et al.*, 2017; Matsutani and Yakushi, 2018; Yang, 2019; Carrau and Henschke, 2021; Shen *et al.*, 2021).

them promising candidates for functional enhancement and development into improved probiotic formulations.

However, the lack of standardization in preparation methods, including variation in starter cake ingredients, selection of microbial strains and environmental conditions, leads to significant variability in microbial composition and bioactive compounds. As a result, traditional rice beer remains non-standardized, limiting its scalability and commercialization. Additionally, key aspects of the fermentation process, such as process parameters, microbial succession and metabolite dynamics, remain insufficiently understood.

Therefore, modern scientific and technical approaches, such as the selection of appropriate microbial strains, standardization of the fermentation process, and improving process control, should be undertaken. Such strategies will help enhance product consistency, shelf life and functional quality while preserving its traditional essence. Overall, integrating scientific advancements with indigenous knowledge can facilitate the development of an improved product, commercialization and socio-economic upliftment of tribal communities associated with traditional rice beer production.

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