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Fortified Jaggery: A Pathway to Functional and Nutraceutical Foods

Arvind Kumar Pandey[a], Garima[b], Seema Paroha[c], Vishnu Prabhakar Srivastava[d]*

[a]Department of Chemistry, Model Degree College, Rajmahal, Sahibganj , Jharkhand, India
[b]Department of Chemistry, D. D. U. Government P. G. College, Saidabad, Prayagraj-221508, UP, India
[c]Natinal Sugar Institute, Kalyanpur, Kanpur-208017, UP, India
[d]Department of Chemistry, University of Allahabad, Prayagraj-211002, India

***Corresponding Author:**
Vishnu Prabhakar Srivastava
Email ID: vbsrivastava@allduniv.ac.in

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ABSTRACT
Jaggery, a traditional non-centrifugal sugar, is emerging as a promising carrier for fortifying functional and nutraceutical foods. This review examines how jaggery's nutritional value can be enhanced by incorporating essential micronutrients, herbal extracts, and bioactive compounds. It also discusses processing techniques such as vacuum impregnation and osmotic dehydration, focusing on their effects on nutrient retention and sensory properties. Additionally, the health benefits of fortified jaggery are explored, including its role in managing anemia, boosting the immune system, and promoting gut health. The review highlights the challenges of large-scale production, regulatory considerations, and future prospects for fortified jaggery as a functional food product.

Keywords: *Fortified Jaggery, Nutraceutical Foods, Functional Foods, Nutrient Retention, Anemia Management*

1. INTRODUCTION
Jaggery, commonly referred to as non-centrifugal sugar, is a traditional sweetener obtained from the evaporation of sugarcane juice or palm sap without undergoing the centrifugal process. Unlike refined sugar, jaggery is unrefined and preserves essential minerals and nutrients, such as iron, calcium, magnesium, and phenolic compounds [1]. Historically, jaggery has been a staple sweetener in South Asia, Africa, and Latin America, where it is often consumed as a natural source of energy and nutrients [2]. Its deep, caramel-like flavor and rich nutrient profile have garnered attention in modern diets as a healthier alternative to refined sugar [3]. In recent years, the market for jaggery has expanded beyond traditional consumption to include functional food products, such as fortified snacks, beverages, and dietary supplements [4]. The growing consumer preference for natural and nutrient-dense sweeteners has further driven the demand for jaggery, positioning it as a promising base for the development of functional and nutraceutical foods [5].

Functional foods are defined as foods that provide health benefits beyond their basic nutritional content, often containing bioactive compounds such as antioxidants, probiotics, and essential vitamins [6]. Nutraceuticals, derived from food sources, are concentrated bioactive substances that may provide therapeutic effects, including disease prevention and health promotion [7]. Incorporating bioactive compounds, such as polyphenols, flavonoids, and essential minerals, into foods like jaggery can transform them into functional foods with specific health benefits [8]. For instance, fortified jaggery enriched with iron can address anemia, while the addition of herbal extracts such as moringa or spirulina can provide antioxidant and anti-inflammatory effects [9]. This approach aligns with the increasing consumer focus on foods that contribute to overall health and wellness [10]. Techniques such as vacuum impregnation and osmotic dehydration have been employed to infuse jaggery with iron, zinc, calcium, and plant extracts, thus creating a functional product with specific health benefits [11-14].

This approach not only addresses micronutrient deficiencies but also positions fortified jaggery as a viable functional food in the nutraceutical market [15]. Additionally, fortification offers an opportunity to innovate within the traditional jaggery market, expanding its applications to health-conscious consumers seeking natural and nutrient-rich sweeteners [16].

2. NUTRITIONAL PROFILE OF JAGGERY

Jaggery, also known as non-centrifugal sugar, is a traditional sweetener widely consumed in South Asia, Africa, and Latin America [17]. It is made by boiling raw sugarcane juice or palm sap until it solidifies, without undergoing any refining or bleaching processes [18]. As a result, jaggery retains its natural nutrients, making it a more nutritious alternative to refined sugar. This section explores the nutrient composition, comparative analysis with other sweeteners, and nutritional gaps in conventional jaggery.

1. Composition and Nutrient Content

Jaggery is primarily composed of carbohydrates, essential minerals, vitamins, and phenolic compounds that contribute to its health benefits. A detailed analysis of its nutrient composition is provided below:

i. **Carbohydrates:** Jaggery is predominantly composed of sucrose, accounting for approximately 65-85% of its total composition [19]. Additionally, it contains small quantities of glucose and fructose, which provide immediate energy [20]. These sugars are present in their unrefined form, aiding in the retention of natural antioxidants and micronutrients. Complex carbohydrates in jaggery help prevent sudden spikes in blood glucose levels, offering a slower and sustained energy release [21].

ii. **Minerals:** Jaggery is a rich source of essential minerals, including iron, calcium, magnesium, potassium, phosphorus, and zinc [22]. Iron content in jaggery is particularly noteworthy, ranging from 10 to 13 mg per 100 g, making it beneficial for individuals with anemia or iron deficiency [23]. Calcium and magnesium are vital for bone health, while potassium assists in maintaining electrolyte balance and regulating blood pressure [24].

iii. **Vitamins:** Though not a primary source of vitamins, jaggery contains traces of vitamin B-complex, particularly riboflavin and niacin, both of which play a role in energy metabolism [25]. Some studies suggest the presence of small quantities of vitamin A and vitamin C, though the concentrations vary based on the source and processing method [26].

iv. **Phenolic Compounds and Antioxidants:** Jaggery contains polyphenolic compounds that exhibit antioxidant properties, reducing oxidative stress and inflammation [27]. Phenolic acids, such as ferulic acid and gallic acid, contribute to these antioxidant effects, making jaggery beneficial in combating free radical damage [28].

2. Comparative Analysis with Other Sweeteners

When comparing jaggery with other common sweeteners such as refined sugar, honey, and maple syrup, several nutritional advantages are evident.

i. Refined Sugar:

Composed almost entirely of sucrose, refined sugar lacks essential nutrients and minerals (29). It undergoes extensive processing, leading to the loss of natural nutrients. In contrast, jaggery retains key minerals like iron, calcium, and magnesium, making it a more nutrient-dense alternative (30).

ii. Honey:

Composed almost entirely of sucrose, refined sugar lacks essential nutrients and minerals (29). It undergoes extensive processing, leading to the loss of natural nutrients. In contrast, jaggery retains key minerals like iron, calcium, and magnesium, making it a more nutrient-dense alternative (30).

iii. Maple Syrup:

Maple syrup is known for its manganese and zinc content, which support immune health (34). However, it is lower in iron and calcium compared to jaggery (35). The antioxidant profile of jaggery, enriched by its phenolic content, further enhances its nutritional benefits (36).

3. Nutritional Gaps in Conventional Jaggery

Despite its nutrient-rich profile, conventional jaggery has several nutritional gaps that can be addressed through fortification and enhanced processing techniques.

i. Protein Deficiency:

Jaggery primarily consists of carbohydrates and contains negligible protein (37). Incorporating plant-based proteins, such as soy or pea protein, during the processing stage can address this gap (38).

ii. Vitamin Deficiency:

Conventional jaggery is low in essential vitamins such as vitamin C, D, and B12 (39). Enrichment with these vitamins can transform jaggery into a functional food with broader health applications (40).

iii. Low Fiber Content:

Jaggery lacks dietary fiber, which is essential for gut health and regulating blood sugar levels (41). Integrating dietary fibers, such as psyllium husk or oat bran, can enhance its nutritional value (42).

4. Functional and Nutraceutical Fortification of Jaggery

Jaggery, traditionally regarded as a natural sweetener, offers a unique opportunity for functional and nutraceutical fortification. By incorporating essential nutrients, bioactive compounds, and plant extracts, jaggery can be transformed into a health-promoting functional food that addresses micronutrient deficiencies while retaining its cultural significance. This section explores the potential of fortified jaggery as a functional and nutraceutical food, highlighting key techniques, benefits, and market opportunities.

A. Nutrient-Enrichment: Bridging Nutritional Gaps

Conventional jaggery is rich in carbohydrates and minerals such as iron, calcium, and magnesium, but lacks specific nutrients essential for addressing prevalent micronutrient deficiencies. Fortification techniques, such as vacuum impregnation and osmotic dehydration, enable the incorporation of vital nutrients like zinc, vitamins B and C, and omega-3 fatty acids (43). These fortificants not only enhance the nutritional profile but also expand the application of jaggery in health-focused food products. For instance, iron-fortified jaggery has been successfully developed to combat anemia, especially in regions where iron deficiency is a public health concern (44). Similarly, jaggery infused with vitamin C improves immune function and provides antioxidant support, positioning it as a natural remedy for immune-boosting foods (45).

Figure 1.https://rightshift.in/blogs/right-health/jaggery-nutritional-value.html

i. Iron Fortification:

Iron-fortified jaggery has been successfully developed to combat anemia, particularly in regions with high iron deficiency prevalence demonstrated a 30% increase in iron content using vacuum impregnation techniques without compromising the sensory attributes of the final product [46-47].

ii. Vitamin C Enrichment:

Jaggery infused with vitamin C has been shown to improve immune function and provide antioxidant support. A study found that vitamin C-enriched jaggery retained 85% of its ascorbic acid content after 8 weeks of storage, highlighting its potential as an immune-boosting functional food [49-50].

iii. Zinc and Omega-3 Fatty Acids:

Fortification with zinc and omega-3 fatty acids not only addresses nutritional deficiencies but also expands the application of jaggery in health-focused food products. A study on omega-3 fortified jaggery revealed a significant increase in DHA levels, making it a potential dietary supplement for cardiovascular health [51-52].

B. Bioactive Compounds: Unlocking Therapeutic Potential

Bioactive compounds such as polyphenols, flavonoids, and plant extracts can be incorporated into jaggery to enhance its therapeutic properties. Turmeric, ginger, and ashwagandha are potent bioactive that can be infused to provide anti-inflammatory, antioxidant, and adaptogenic benefits [53]

i. Turmeric-Fortified Jaggery:

Contains curcumin, known for its anti-inflammatory and anticancer properties, making it a functional food for inflammatory conditions. Sharma and researcher demonstrated that turmeric-fortified jaggery exhibited a 40% increase in curcumin content, contributing to its antioxidant capacity [54-55].

ii. Ginger-Enriched Jaggery:

Provides gingerol, a potent antioxidant that aids in digestion and reduces oxidative stress A study found that ginger-enriched jaggery significantly reduced oxidative stress markers in rats after a 4-week supplementation [56].

iii. Ashwagandha-Infused Jaggery:

Acts as a natural adaptogen, reducing stress and enhancing overall well-being ashwagandha-infused jaggery demonstrated a 25% increase in cortisol reduction compared to non-fortified samples, supporting its potential as a functional food. These bioactive-infused jaggery products not only cater to health-conscious consumers but also tap into the growing market for functional foods and nutraceuticals [57].

5. Technological Innovations: Enhancing Nutrient Retention

The fortification of jaggery requires advanced processing techniques to retain nutrient stability while maintaining sensory attributes. Techniques such as microencapsulation, nano emulsion, and spray drying are employed to ensure the effective delivery of micronutrients without compromising the taste or texture of jaggery [54-55].

i. Microencapsulation:

Protects sensitive nutrients like omega-3 fatty acids and probiotics, enabling controlled release and enhanced bioavailability. The microencapsulation using maltodextrin and gum arabic increased the stability of omega-3 fatty acids in fortified jaggery by fifty percent [58].

ii. Nanoemulsion:

Improves the solubility of fat-soluble vitamins, facilitating their uniform distribution in jaggery. In a study on vitamin D-enriched jaggery, nano-emulsion technology effectively increased vitamin retention during storage by 30%. These technological advancements not only extend the shelf life of fortified jaggery but also open avenues for product diversification, such as jaggery-based health bars, confectioneries, and nutraceutical supplements [59].

6. Fortification Methods: Expanding Nutritional Horizons

Fortifying jaggery involves incorporating essential nutrients, herbal extracts, and bioactive compounds to create a nutritionally enhanced product that addresses micronutrient deficiencies and provides functional health benefits. This section discusses three major fortification methods: micronutrients, herbal extracts, and bioactive compounds. Micronutrient fortification is a targeted approach to mitigate nutrient deficiencies, particularly in regions where dietary intake of essential minerals is inadequate. Jaggery, already rich in iron, can be further fortified with additional micronutrients such as zinc and calcium to amplify its health benefits.

i. Iron Fortification: Iron-deficiency anemia remains a major public health concern in many developing

countries. Fortifying jaggery with iron significantly improves hemoglobin levels, especially in vulnerable populations like children and pregnant women. Studies have shown that iron-fortified jaggery can effectively reduce anemia and enhance cognitive function by 20% over a 12-week intervention period [60].

ii. **Zinc Fortification:** Zinc is essential for immune function and cellular metabolism. Zinc-enriched jaggery, achieved through techniques like vacuum impregnation, has shown promising results in combating zinc deficiency and promoting growth in children. Zinc-fortified jaggery improved immune response markers in school-aged children by 25 percents [61].

iii. **Calcium Fortification:** Calcium Fortification: Calcium-fortified jaggery serves as a natural supplement to prevent bone-related disorders. Calcium fortification ensures optimal bone health without altering the taste profile of jaggery. A study demonstrated that calcium-fortified jaggery reduced the risk of osteoporosis by 15 percents in postmenopausal women [62].

7. Bioactive Compounds: Polyphenols and Antioxidants

Bioactive compounds such as polyphenols and antioxidants play a significant role in preventing chronic diseases and promoting overall health. Fortifying jaggery with these compounds enhances its therapeutic potential and positions it as a functional food product [63].

i. **Polyphenol-Rich Jaggery:** Polyphenols, such as catechins and flavonoids, are powerful antioxidants that reduce inflammation and protect against cardiovascular diseases. Fortifying jaggery with extracts like Triphala significantly increases its polyphenol content A study reported that Triphala-fortified jaggery exhibited a 35% increase in total polyphenol content [64].

ii. **Antioxidant-Enhanced Jaggery:** Antioxidants such as vitamin C, vitamin E, and beta-carotene can be incorporated to improve immune function and reduce oxidative stress. Techniques like microencapsulation help in retaining the stability of these compounds during storage and processing. The microencapsulation of vitamin C in jaggery retained 90% of its initial antioxidant capacity after 8 weeks of storage [65].

8. Techniques Employed in Fortification

Fortifying jaggery effectively requires the application of advanced processing techniques to ensure the uniform distribution of nutrients and bioactive compounds while maintaining its sensory characteristics. Two prominent techniques employed in the fortification of jaggery are Vacuum Impregnation and Osmotic Dehydration, each offering distinct advantages in nutrient uptake and retention [66].

i. **Vacuum Impregnation: Enhancing Nutrient Uptake:** Vacuum impregnation (VI) is a technique that applies a vacuum to facilitate the penetration of nutrient solutions into the porous structure of food products, including jaggery This process is particularly effective for incorporating micronutrients such as iron, zinc, and calcium without compromising the structural integrity of the jaggery matrix [67].

Process:

a. The jaggery blocks or granules are submerged in a nutrient-enriched solution.

b. A vacuum is applied to evacuate the air from the porous matrix.

c. Upon releasing the vacuum, atmospheric pressure forces the nutrient solution into the voids, ensuring uniform distribution of the fortified compounds.

ii. **Osmotic Dehydration: Enhancing Nutrient Retention:** Osmotic dehydration (OD) leverages osmotic pressure to introduce nutrients and bioactive compounds into jaggery while simultaneously reducing its moisture content. This technique is particularly effective in retaining thermolabile nutrients and maintaining the structural integrity of the jaggery matrix [68]

Process:

a. The jaggery blocks or granules are immersed in a hypertonic solution containing dissolved nutrients such as iron, zinc, calcium, and herbal extracts.

b. Osmotic pressure drives water out of the jaggery matrix while infusing the nutrient solution into the matrix.

9. Conventional Processing Methods:

Conventional processing techniques in jaggery production primarily include vacuum evaporation, open-pan boiling, and sun drying. These methods have been widely used due to their simplicity and cost-effectiveness; however, they come with certain limitations in terms of nutrient loss and degradation [69].

i. **Vacuum Evaporation: Minimizing Nutrient Loss:** Vacuum evaporation involves concentrating sugarcane

juice at reduced pressure and temperature. This method effectively reduces the water content, thereby extending the shelf life of jaggery [70].

ii. **Open-Pan Boiling: Economical but Nutrient-Depleting:** Open-pan boiling is a traditional method involving boiling sugarcane juice in open pans until it solidifies into jaggery. While this method is economical, prolonged exposure to high temperatures can lead to significant nutrient loss, especially in vitamins and phenolic compounds [71].

iii. **Sun Drying: Traditional but Nutrient-Depleting:** Sun drying is a low-cost, traditional method for moisture reduction. However, it exposes jaggery to environmental contaminants and oxidative damage, resulting in nutrient losses

This section provides a comparative analysis of conventional processing methods, highlighting the trade-offs between cost-effectiveness and nutrient retention, setting the stage for exploring advanced processing techniques in subsequent sections.

10. Health Benefits of Fortified Jaggery

Fortified jaggery is more than just a natural sweetener; it is an emerging functional food with significant health benefits. By incorporating essential nutrients, bioactive compounds, and herbal extracts, fortified jaggery addresses various health concerns, including anemia management, immune boosting, and gut health. This section explores these health benefits, supported by clinical studies and comparative analysis with other fortified products [72].

i. Potential Health Benefits

a. Anemia Management: Iron deficiency anemia (IDA) remains one of the most prevalent nutritional disorders worldwide, especially affecting women and children in developing countries. To address this issue, iron-fortified jaggery has emerged as a potential dietary intervention. Incorporating iron sulfate or ferrous fumarate into jaggery has shown promising results in elevating hemoglobin levels and alleviating anemia symptoms in affected populations [73]. Clinical studies have provided evidence supporting this claim.

For instance, Sakthibalan et al. demonstrated that adolescent girls with anemia experienced a significant improvement in hemoglobin levels after an 8-week supplementation with iron-fortified jaggery [74]. Furthermore, iron-fortified jaggery offers a natural, affordable, and culturally acceptable alternative to conventional iron tablets. It is generally better tolerated, causing fewer gastrointestinal side effects and avoiding the metallic aftertaste commonly associated with synthetic iron supplements [75].

b. Immune Boosting: Zinc plays a vital role in supporting immune function, wound healing, and cellular repair, making it an essential micronutrient for maintaining overall health. Zinc-enriched jaggery, fortified with compounds such as zinc sulfate or zinc gluconate, has been identified as a promising functional food to enhance immune responses, especially in vulnerable groups like children and the elderly [76]. Clinical studies further support its efficacy.

For instance, research. demonstrated that children aged 6-12 years who consumed zinc-fortified jaggery experienced a notable reduction in respiratory infections, which was attributed to enhanced immune function [77]. When compared to conventional zinc tablets or syrups, zinc-fortified jaggery is more readily accepted due to its natural sweetness and ease of consumption. This makes it a more practical and palatable approach for regular zinc supplementation [78].

c. Gut Health: Herbal and prebiotic fortification of jaggery represents an emerging functional food strategy aimed at improving digestive health. Incorporating natural bioactives such as Moringa, Spirulina, and Ashwagandha along with prebiotic fibers into jaggery can significantly promote gut health.

These compounds stimulate the growth of beneficial gut microbiota, thereby enhancing digestion and nutrient absorption [79]. Preliminary clinical evidence suggests that Ashwagandha-enriched jaggery may help alleviate symptoms associated with irritable bowel syndrome (IBS), including bloating and irregular stool consistency [80]. When compared to conventional prebiotics and probiotic supplements, fortified jaggery offers a dual advantage: it delivers dietary prebiotic fibers along with a range of natural antioxidants, resulting in a multifunctional food that is both therapeutic and nutritionally dense [81].

11. Challenges and Future Prospects of Fortified Jaggery

Fortified jaggery has the potential to emerge as a functional food product with significant health benefits. However, several challenges persist in its large-scale production, market acceptance, and regulatory compliance. This section discusses these challenges and explores future prospects in the context of fortified jaggery.

i. **Uniform Nutrient Distribution:** Uniform nutrient distribution during jaggery fortification is a key technological challenge. Due to its dense matrix, integrating micronutrients uniformly requires precise techniques such as vacuum impregnation and osmotic dehydration, which demand strict control of

processing parameters to ensure consistency [82-83]. Variability in nutrient dispersion can compromise nutritional quality and product reliability. To overcome this, researchers suggest adopting advanced mixing and blending technologies tailored for jaggery systems, enabling better nutrient integration and reducing processing losses [84].

ii. **Nutrient Stability During Processing:** Heat-sensitive nutrients such as vitamin C, polyphenols, and various bioactive compounds are highly prone to degradation during conventional high-temperature processing methods like open-pan boiling and spray drying. These techniques, commonly used in jaggery production, often lead to substantial nutrient loss, thereby diminishing the intended functional value of the fortified product [85-86]. To address this, researchers recommend adopting advanced drying technologies such as microwave-assisted drying and freeze drying. These methods operate at lower temperatures and allow better control over thermal exposure, significantly reducing nutrient degradation while preserving the bioactive profile of the final product [87].

iii. **Scalability and Cost-Efficiency:** Transitioning fortified jaggery production from small-scale operations to industrial-scale manufacturing involves numerous challenges, including high costs of advanced equipment, strict quality control requirements, and expensive raw materials [88]. In addition, maintaining the product's shelf life presents further obstacles, as fortified jaggery is susceptible to moisture absorption, microbial growth, and nutrient degradation during storage [89]. These factors can compromise both economic feasibility and product integrity. To address these challenges, researchers propose integrating automated and continuous processing systems to enhance scalability, lower production costs, and ensure consistent quality [90]. Furthermore, employing innovative packaging technologies—such as moisture barriers, oxygen scavengers, and antioxidant-coated materials—can effectively preserve the product's stability and extend its shelf life [91].

12. Future Prospects of Fortified Jaggery:

The future of fortified jaggery lies in leveraging technological innovation, product diversification, and strategic consumer outreach. Advanced processing methods such as spray drying, microencapsulation, and vacuum impregnation are being developed to improve nutrient stability and shelf life while minimizing undesirable sensory alterations [92]. In parallel, expanding the product portfolio to include fortified jaggery powders, snack bars, and confectioneries offers the opportunity to cater to varied consumer preferences and increase market penetration [93]. Continued research and development, especially through collaborations with academic institutions and government agencies, is essential to establish cost-effective fortification techniques and standardized protocols for large-scale production [94]. Additionally, consumer education initiatives highlighting the health benefits of fortified jaggery are crucial for building awareness, fostering trust, and sustaining long-term market demand [95].

3. CONCLUSION

Fortified jaggery effectively merges traditional dietary practices with modern nutritional requirements by incorporating essential micronutrients such as iron, zinc, and calcium, thus addressing prevalent nutritional deficiencies while preserving cultural relevance. Enriched with bioactive compounds and herbal extracts like ashwagandha and spirulina, it not only serves as a nutrient-dense sweetener but also offers therapeutic benefits, including anemia management, immune support, and bone health enhancement. Advanced processing techniques like vacuum impregnation and spray drying have improved nutrient retention and stability, yet challenges in mass production, such as ensuring uniform nutrient distribution and regulatory compliance, persist. Consumer education and market acceptance are pivotal for establishing fortified jaggery as a mainstream functional food, with future research needed to optimize fortification processes, integrate novel bioactive compounds, and diversify product formats, ultimately positioning it as a sustainable and health-promoting dietary option.

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