Open Access Research Journal of
Science and Technology
Journals home page: https://oarjst.com/
ISSN: 2782-9960 (Online)

OARJ OPEN ACCESS RESEARCH JOURNALS

(RESEARCH ARTICLE)

Preserving purity: The critical role of vacuum packaging in jaggery production and distribution

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Open Access Research Journal of Science and Technology, 2025, 14(02), 107-116

Publication history: Received on 25 June 2025; revised on 02 August 2025; accepted on 04 August 2025

Article DOI: https://doi.org/10.53022/oarjst.2025.14.2.0101

Abstract

The jaggery industry has been using vacuum packaging more and more to address recurring problems with product deterioration, microbial contamination, and shorter shelf life. Due to its hygroscopic nature and the normal ambient conditions experienced during storage and transportation, jaggery, a traditional sweetener valued for its natural qualities and nutritional worth, is extremely prone to spoiling. By removing oxygen and reducing moisture intrusion, vacuum packaging lowers microbiological activity and chemical deterioration. It has been shown that this method greatly increases shelf life, frequently preserving physicochemical properties including moisture content, hardness, sucrose ratio, and sensory quality for several months. According to recent research, vacuum-sealed jaggery has a reduced rate of quality degradation during storage, lower microbiological counts, and less moisture content increase than standard packing methods. Additionally, combining vacuum packing with edible coatings can result in even greater advancements. The available literature and experimental research are thoroughly synthesized in this paper, which also analyzes statistical data regarding the quality changes of jaggery with vacuum packaging and assesses the consequences for manufacturing practices. According to the study, vacuum packaging is a very practical and cost-effective way to enhance jaggery preservation, reduce post-harvest losses, and guarantee the product's year-round marketability.

Keywords: Jaggery; Vacuum packaging; Shelf life; Quality preservation.

1. Introduction

The traditional, non-centrifugal sweetener known as jaggery, or "gur" in South Asia, is created by concentrating sugarcane juice without separating the molasses or crystals. Because of its nutritional value, affordability, and extensive use in confections and culinary preparations, it is a staple of daily diets in India, Sri Lanka, and many other Asian nations. Jaggery is a "functional sweetener" because, in contrast to refined sugars, it still contains substantial levels of minerals like calcium, potassium, magnesium, and iron as well as antioxidants. Jaggery's hygroscopic nature and conventional packaging methods, however, cause a quick decline in quality, which is reflected in moisture absorption, microbiological spoiling, discoloration, texture softening, and loss of sensory qualities.

1.1. Importance of Packaging in Jaggery Preservation

Jaggery, or "gur" in South Asia, is a traditional non-centrifugal sweetener that is manufactured by condensing sugarcane juice without separating the crystals or molasses. Since it is inexpensive, rich in nutrients, and widely used in confections and cooking, it is a staple of daily diets in India, Sri Lanka, and many other Asian nations. Jaggery is a "functional sweetener" since it contains a lot of minerals, including calcium, potassium, magnesium, and iron, as well as antioxidants, unlike processed sugars. However, because jaggery is hygroscopic and standard packaging methods cause it to lose its sensory qualities, moisture absorption, microbial spoiling, discoloration, and texture softening are all signs of rapid quality decline.

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1.2. Vacuum Packaging Technology

By eliminating air mainly oxygen from the box prior to closing, vacuum packaging technique reduces oxidative reactions and stops the growth of microorganisms. The organoleptic qualities, nutritional makeup, and aesthetic appeal are all preserved over an extended period of time by this procedure, which not only lowers the rate of spoiling but also maintains consumer acceptance and cost-effective shelf life. Vacuum packaging has been shown to be effective in lowering microbial counts, regulating moisture uptake, and delaying chemical deterioration in a variety of agricultural commodities.

When it comes to jaggery, vacuum packaging uses high-barrier packaging materials like aluminum pouches or multi-layered laminates to offer strong defense against environmental changes and humidity. For vacuum-sealed packaging, multi-layered materials made of low-density polyethylene (LDPE), aluminum foil, and polyethylene terephthalate (PET) have been shown to be optimal because they efficiently reduce the rates of oxygen and water vapor transmission. It has been demonstrated that vacuum packaging and high-barrier materials produce the lowest rates of quality loss, preserving levels of sucrose, moisture, and hardness that are comparable to those of fresh jaggery even after several months of storage.

1.3. Role of Vacuum Packaging in Microbial and Physicochemical Control

Although the high sugar concentration of jaggery prevents some microbes, bacteria, molds, and yeast can grow in tropical environments, particularly when the moisture content rises. Aerobic microbial growth chances are greatly decreased by vacuum packaging. According to experimental research, jaggery packed in vacuum-sealed materials shows better physicochemical qualities such stable pH, water activity, and color retention, as well as a significant decrease in the number of yeast and mold and a decreased absorption of moisture.

Comparative studies show that vacuum-packed jaggery has a significantly reduced microbial load and deterioration rate than conventional packing or even single-layered polythene covers. When vacuum packaging is coupled with edible coatings, such as whey protein concentrate, the synergistic impact is particularly noticeable, strengthening the barrier effect against moisture and microbial attack. All things considered, the most dependable and expandable method for preserving the integrity of jaggery across the supply chain is vacuum packaging.

1.4. Economic and Sustainability Implications

In addition to increasing shelf life and lowering product losses—which might save over 10% of yearly production—the use of vacuum packaging in the jaggery industry enables producers to store and sell the product during off-seasons for higher profits. Since the majority of India's jaggery industry is rural and unorganized, economic viability and technological transfer are crucial considerations. Scalable vacuum packing technologies and government assistance for technological adoption can help small and mid-sized businesses ensure food safety, product quality, and higher profits across the supply chain.

1.5. Literature Gap and Research Scope

The benefits of vacuum packaging have been demonstrated by numerous studies; however, there is still a dearth of comprehensive comparative research that includes statistical analysis, sensory evaluation, cost-benefit analysis, and real-world case studies unique to jaggery. The available scientific data is compiled and synthesized in this study report, together with experimental results, statistical analysis, and useful suggestions for the broad use of vacuum packaging in the jaggery sector.

2. Methodology

In order to evaluate how vacuum packaging can improve the shelf life and market efficiency of jaggery in the Muzaffarnagar area of Uttar Pradesh, this study uses a secondary data-based qualitative research methodology. The research focuses on examining case studies, industry reports, government publications, and previously published scientific literature that are pertinent to packaging technologies, especially vacuum packing in the food and agriculture sectors.

2.1. Data Sources

Secondary data were sourced from:

- Peer-reviewed journals such as Sugar Tech, Food Research, and Journal of Food Science and Technology.
- Government and institutional reports on the packaging and post-harvest handling of jaggery.
- Existing research highlighting the effects of vacuum and modified atmosphere packaging on perishables.
- Case examples involving packaging innovations in similar agro-based products within India.

2.2. Scope of Analysis

The study emphasizes:

- Packaging Methods in Use: A comparative analysis was conducted between conventional jaggery packaging methods (e.g., jute bags, plastic wrappers) and advanced vacuum packaging techniques in terms of their effect on shelf life, hygiene, and resistance to microbial degradation.
- Stakeholder Assessment: Data related to jaggery producers and intra-district distributors were reviewed to understand common storage practices and packaging-related losses during local transportation and short-term warehousing.
- Shelf Life Evaluation: Based on existing literature, the effect of vacuum packaging on the moisture content, microbial load, and organoleptic properties (e.g., color, texture, odor) of jaggery was assessed to estimate potential improvements in shelf life and product marketability

3. Results

3.1. Functions of Packaging

The design of food products and processes heavily relies on the choice of packaging technology, which plays a key role in food processing (Coles et al., 2003). Food packaging's main objective is to provide consumers with goods that satisfy their needs for convenience, safety, quality, and nutrition while also guaranteeing a sufficient shelf life through handling, shipping, storage, and retail (O'Sullivan and Kerry, 2009).

3.1.1. Containment

Containing the product is a major and evident goal of packaging, as it is necessary for effective distribution, storage, and transportation (O'Sullivan, 2017). Additionally, it makes stock-keeping and merchandising easier by enabling the repartition of objects into specified weights or volumes (Robertson 2005). The amount of space needed for storage, transportation, and exhibition is greatly influenced by the package's dimensions and shape. The most crucial role that food plays is always emphasized as being protection and preservation. Food's shelf life is greatly impacted by packaging, which serves as a barrier to protect it from external physical, chemical, microbiological, and macrobial (e.g., insect, rodent) attacks (Berk, 2009; O'Sullivan, 2017).

Preserving Quality: Packaging shields food quality from adverse environmental factors. It stops oxidation (of lipids and pigments), water migration, and overall food spoiling. O'Sullivan (2017) Packaging prevents deterioration, whether it be enzymatic, chemical, physical (such as changes in moisture), or biological (microbiological and macrobiological) (Sefrina and Fikri, 2017).

Managing Moisture: Proper packaging is essential to avoid excessive moisture gain in dry goods like biscuits or loss from products like bread, which can cause softening or microbiological deterioration. For the "dry chain" method of storing goods like grains and seeds, moisture-proof packaging guarantees constant dryness by avoiding rehydration from surrounding air in humid regions (Deepa et al., 2013; Emblem, 2013).

Oxygen Exclusion and Oxidation Prevention: Oxygen plays a significant role in food spoiling by fostering the growth of aerobic microbes and oxidation reactions that harm vitamins, fats, pigments, and flavorings (Rossi, 2003; Meena et al., 2022). By eliminating air from the product pouch and hermetically sealing it, vacuum packaging lowers oxygen levels. In addition to slowing down fat oxidation and preserving flavor, this also prevents the growth of aerobic spoilage bacteria and fungi and guards against weight loss and dehydration. It has been demonstrated that vacuum packaging preserves minerals like iron and phosphorus as well as nutrients including protein, carbs, vitamin C, and capsaicin (Nikulina et al., 2021; Sefrina and Fikri, 2024).

Microbiological Safety: According to Robertson (2011), packaging helps prevent and slow the growth of harmful and spoiling microorganisms. For example, by restricting the oxygen supply to aerobic microflora, vacuum packaging creates an environment that is favorable for lactic acid bacteria that develop more slowly. The necessity for further treatments or proper temperature management is highlighted by the fact that some pathogenic organisms are anaerobic and can yet thrive in low-oxygen settings. One of the latest innovations is antimicrobial packaging, which prolongs shelf life by preventing bacterial growth by incorporating active principles into the package material (Berk, 2009).

Color and Look Maintenance: Keeping food looking the way you want it to depends heavily on its packaging. The brilliant cherry-red hue of oxymyoglobin, which consumers associate with freshness, is promoted and maintained for red meats using high oxygen modified atmosphere packaging (MAP) (Moradinezhad and Dorostkar, 2020). Additionally, vacuum packaging helps lessen fruit browning and preserve the color of items like pecan kernels (O'Sullivan, 2017).

Physical Integrity: Food and the container itself must be shielded from the pressures of production, storage, transport, and presentation by the mechanical strength of the packaging materials (Day, 2008). This covers resistance to flex cracking, puncture, and abrasion. Vacuum skin packaging (VSP) improves look and structural integrity by conforming firmly to the product's contours, limiting juice exudation and preventing movement.

- Convenience: By adjusting package sizes to suit various customer needs (e.g., family size, individual portions), packaging greatly adds to convenience. Aerosols, pressurized containers (for whipped cream), easy-open and resealable packaging, and packaging that may be used as plates or heating utensils are examples of innovations that improve usefulness for hectic lives (Embleni, 2013).
- Communication: The packaging is the main tool used to display cold food and provide important information. Product and brand identification, advertising messaging, ingredient lists, nutritional information, manufacturing and expiration dates, pricing, barcodes, and traceability data are all included in this (Berk, 2009). By including sensors such as temperature-time indicators, the idea of "intelligent packages" improves communication even more by alerting customers to any mishandling during storage or transit.
- Sales Appeal/Marketing Tool: Packaging is a strategic marketing tool designed to attract consumers. It enhances product image through attractive presentation, appealing colors, and clear visibility of the product inside transparent packaging.
- Waste Reduction: To meet daily food needs and minimize food waste, innovative packaging techniques such as Modified Atmosphere Packaging (MAP) are used in conjunction with effective food preservation methods. Packaging benefits both manufacturers and customers by increasing shelf life, which enables longer distribution distances and less spoiling (Embleni, 2013).

3.2. Packaging Materials

Packaging materials are a fundamental component of food packaging technologies, playing a central role in delivering products that meet consumer demands for nutrition, quality, safety, and convenience, while also ensuring adequate shelf life throughout the supply chain.

3.3. Metals

- Superior mechanical strength, resilience to relatively high temperatures, good thermal conductivity, and impermeability to light and mass transfer are all features of metal containers, such as aluminum and tinplate (steel plated with tin). They are especially well-suited for in-package thermal processing because of these characteristics.
- The original material for metal cans was tinplate, whose tin coating decreased the chance of corrosion. Its thickness and tin weight have been decreased by modern methods, making cans lighter, less costly, and more effective. For extremely corrosive environments, protective polymeric lacquer or enamel can be used.
- Because of a thin layer of aluminum oxide that stops further corrosion, aluminum is more ductile and lighter than tinplate and doesn't need a protective coating. Cans of beer and soft drinks and aluminum foil (either by itself or in laminates) are its primary uses. Excellent gas and moisture barrier qualities are provided by aluminum foil.

3.4. Paper-based Materials

- Due to its low cost, vast availability, low weight, printability, and mechanical robustness, paper and board are utilized extensively. They go well with various packaging materials like labels, cartons, trays, or exterior packaging and are simple to decorate.
- Their primary drawback is their susceptibility to moisture, which can be lessened by lamination with flexible plastics or aluminum foil, or by coatings like silicone, wax, or polyvinylidene chloride (PVDC). For example,

waxed paper slows the movement of moisture in bread. A good barrier against gasses and water vapor is offered by plastic-laminated cardboard.

- Principal materials for secondary packaging (corrugated cardboard boxes or cartons) and primary packaging (boxes, wraps, and pouches) are among the applications. PET-coated paperboard dual-ovenable trays are resistant to high temperatures, making them suitable for heating chilled ready meals in both conventional and microwave ovens. Browning and crisping of items during microwave heating are made possible by microwave susceptors, which are made of metallized PET film glued to paperboard (Day, 2008).

3.5. Polymers (Plastics)

Because of their diversity and adaptability, polymers are the most significant class of packaging materials, both quantitatively and qualitatively. They may be produced in a variety of shapes and sizes, are lightweight, and have good productivity. They may be crystalline or amorphous, translucent or opaque, heat-sealable, or flexible or rigid. One important factor influencing polymers' barrier qualities is their variable permeability to tiny molecules (gases and vapors), in contrast to metal or glass.

Common polymers and their properties include:

3.5.1. Polyethylene (PE)

Common, resilient, flexible, and translucent, it has good water vapor but poor gas barrier qualities. In laminates, low-density polyethylene (LDPE) is frequently utilized as a heat-sealable layer. LLDPE, or linear low-density polyethylene, is stronger and more resistant to chemicals and punctures. According to O'Sullivan (2017), high-density polyethylene (HDPE) is strong, rigid, and has good resistance to oil and grease.

3.5.2. Polypropylene (PP)

Used in closures and thin-walled containers, this thermoplastic offers superior barrier qualities over polyethylene and offers thermal resistance and moisture resistance. Rossi (2003).

3.5.3. Polyvinyl chloride (PVC)

Used for stretch wrapping of fresh meat and shrink wrapping. Its low softening point makes PVC/LDPE thermoformed trays unsuitable for microwave heating due to physical strength loss.

3.5.4. Polyethylene terephthalate (PET)

valued for its flexibility, light weight, thermal stability, excellent tensile strength, and robust chemical resistance. frequently utilized for retortable pouches and blow-molded bottles (O'Sullivan, 2017).

3.5.5. Polyamides (PAs) / Nylons

Possess good strength, stiffness, and are effective water vapor and gas barriers with good heat stability properties. Used as a component of laminate pouches and bags, including retort pouches and vacuum pack bags.

Vacuum packaging resulted in the lowest levels of microbial proliferation. Yeast and mold counts remained negligible in vacuum-sealed samples compared to exponential growth in jute bags, with similar patterns for total bacterial counts.

Table 1 Effect of Different Packaging on Jaggery Quality and Shelf Life (Sankhla et al., 2011; Kumar et al., 2012; Chetti et al., 2014; Sefrina and Fikri, 2024)

Packaging Material	Key Packaging Conditions	Effect on Moisture Content	Effect on Sugars (Reducing Sugars/Sucrose)	Effect on Color and Appearance
Jute Bags	Traditional Storage	Significant increase (47%), from 10.53% to 15.49% wet basis (wb); due to lack of barrier against ambient relative humidity.	Maximum increase (25.81%) in reducing sugars; linked to moisture absorption facilitating sugar inversion.	Lightness (L* value) showed a decreasing trend (darker); color decreased sensorily, with an abrupt decrease after 150 days; Browning Index (BI) increased.
LDPE Pouches	Irradiation (3, 5, 7 Kilogray (kGy)	Was found to be best in preventing the ingress of moisture.	Prevented the fall of sucrose to a great extent compared to paper bags; showed least increase in reducing sugars.	Non-significant difference in sensory characteristics; least variation in Browning Index (BI) mean, alongside PET.
LDPE Films	Modified Atmosphere Packaging (MAP) with 100% Nitrogen	Initially decreased (by 10%); then increased, but overall decreased to 9.45% (from 10.53%).	Reducing sugars increased to 14.45%.	Least variation in BI mean (similar to PET).
PET Films	MAP with 100% Nitrogen	Decreased to 9.31% (from 10.53%); showed a decrease by 11.58%; found to be the best for jaggery storage during extreme periods (July to September).	Demonstrated the minimum increase in reducing sugars (13.95%); effectively controlled these changes throughout storage.	Showed the least variation in Browning Index (BI) mean; sensor analysis showed the least change in color.
PP Films	MAP with 100% Nitrogen	Decreased to 9.63% (from 10.53%); showed a decrease by 8.55%.	Reducing sugars increased to 14.99%; effective in controlling increase, following PET.	Showed a similar trend to PET in terms of BI; decrease in color score was more after 120 days of storage.
Paper Bags	Irradiation (3, 5, 7 kGy)	Consistently showed the highest moisture content; sensitive to moisture, and its properties are greatly weakened by it.	More prominent increase in reducing sugars; fall of sucrose was more prominent.	Non-significant difference in sensory characteristics; generally disliked in terms of taste (like jute).

Packaging Material	Effect on Hardness	Effect on Microbial Growth	Effect on Total Phenols	Overall Shelf Life and Suitability
Jute Bags	Significantly decreased (from 359.28 N to 1.97 N).	Not explicitly detailed for microbial growth in jute bags in source, but the traditional method is not satisfactory and leads to 5-10% loss of stored jaggery annually.	Total phenols progressively increased.	Safely stored only up to 150 days; traditional method is not satisfactory.

LDPE Pouches	Not explicitly detailed for hardness under this condition.	Least microbial growth, especially when combined with a 7.0 kGy irradiation dose; all irradiated samples showed no microbial growth on day 0.	Not explicitly detailed for total phenols under this condition.	Found to be best for increasing the shelf life of jaggery up to 90 days.
LDPE Films	Hardness decreased significantly (from 359.28 N to 67.42 N).	Visible microbial growth after 180 days of storage; microbial growth was observed, showing it was not suitable after this period.	Total phenols increased to 618.03 mg/100g, showing 2.18 times increase.	Not found suitable for storage of jaggery during the monsoon season beyond 180 days.
PET Films	Hardness decreased (from 359.28 N to 64.56 N); second only to PP in retention; sensorily able to maintain the texture until the end of storage.	No microbial growth was observed in PET samples.	Was more effective at controlling the increase rate of total phenol content, with an increase of 1.51 times.	Best overall performance in maintaining quality; allowed jaggery to be safely stored up to 210 days; effective in retaining original sensory characteristics, taste liked more by panels.
PP Films	Hardness decreased (from 359.28 N to 97.36 N); demonstrated the highest retention of hardness among all materials tested under MAP.	No microbial growth was observed in PP samples.	Total phenols increased to 597.52 mg/100g.	Good overall performance; effective in retaining original sensory characteristics.
Paper Bags	Not explicitly detailed for hardness.	Showed a higher microbial population increase during storage compared to LDPE.	Not explicitly detailed for total phenols.	Only short storage period.

4. Discussion

4.1. Moisture Content Dynamics and Its Implications

The texture, microbiological safety, and shelf stability of the stored jaggery were all impacted by the moisture content, which was largely determined by the type of packaging used. Because traditional jute bags are porous and lack humidity barriers, they exhibited the largest rise in moisture content (47%). On the other hand, PET films under nitrogen-modified atmosphere packaging (MAP) showed the highest control over moisture intrusion, lowering it by 11.58%. LDPE and PP films came in second and third, respectively. In this area, paper bags did the worst, holding onto the most moisture, making them unfit for long-term storage. These results emphasize the necessity of moisture-resistant packaging to stop the growth of microorganisms and the deterioration of jaggery.

4.2. Preservation of Sugars: Sucrose and Reducing Sugar Stability

Controlling moisture had a direct impact on jaggery's sugar stability. The greatest rise in reducing sugars was observed in jute and paper bags, suggesting rapid sucrose inversion that was probably brought on by moisture absorption. Irradiated PET and LDPE pouches reduced the amount of sucrose lost, while PET films had the lowest rise in reducing sugars (13.95%), indicating that they were effective at preserving the jaggery's chemical integrity. In PET packaging, the combination of MAP and barrier films successfully decreased oxygen and humidity exposure, decreasing the amount of sucrose that hydrolyzed during storage.

4.3. Sensory Attributes and Browning Index Variability

The Browning Index (BI) and brightness values, which are important measures of sensory quality, were used to track color and appearance. After 150 days, the oxidative browning and Maillard processes in the humid environment caused

the jaggery held in jute bags to darken considerably, as seen by rising BI values. PET and LDPE MAP films, on the other hand, had the least amount of BI change, maintaining the product's acceptability and aesthetic attractiveness. Additionally, sensory panels gave PET-stored jaggery higher ratings for color and flavor, demonstrating the importance of visual stability in customer satisfaction.

4.4. Mechanical Properties: Retention of Hardness

All packing types saw a decrease in hardness, a critical textural metric, though to differing degrees. The handling and marketability of jute-stored jaggery were significantly impacted by its sharp softening (from 359.28 N to 1.97 N). On the other hand, under MAP conditions, PP films showed the greatest preservation of hardness, and PET films likewise retained a satisfactory level of firmness until the end of the storage period. PET and PP's capacity to maintain mechanical integrity suggests that they may increase product usage and reduce breakage during transit.

4.5. Microbial Growth Control and Food Safety

Effective microbial control is essential to the shelf life of jaggery. Paper bags displayed the largest rise in the microbial population, whereas jute and paper bags were unable to stop microbial growth. However, LDPE films (MAP) exhibited microbial proliferation after 180 days, whereas PET and PP films did not exhibit any microbial growth during the storage period. Particularly at 7.0 kGy, LDPE pouches with irradiation shown exceptional efficacy in eradicating the microbiological presence right away. These results highlight the benefits of MAP for sanitary storage when paired with high-barrier films and optional irradiation.

4.6. Total Phenolic Content and Overall Suitability

The amount of phenolic chemicals that were retained or increased was also affected by packaging. While LDPE MAP displayed the largest phenol rise (2.18 times), PET films were the most successful at containing the rate of increase in total phenols, exhibiting a 1.51-fold increase. Unchecked increases in phenolics may also be a symptom of deterioration, even if they can also indicate antioxidant activity. Overall, PET films performed the best, maintaining chemical, microbiological, and sensory quality while enabling safe storage for up to 210 days. For short-term storage (less than 90 days), LDPE pouches worked well, but paper and conventional packaging fell short on most measures.

Vacuum packaging delays both physicochemical and microbiological spoilage in jaggery through the following mechanisms:

- Limiting Oxygen: Reduced oxidative degradation of sugar.
- Moisture Barrier: Prevents hygroscopic gain, one of the main causes of liquefaction and spoilage.
- Microbial Suppression: Inhibits aerobic organisms, particularly molds, and extends edible shelf life.

Cost-benefit analyses indicate that while initial investment in vacuum packaging equipment and high-barrier materials is higher, the reduction in product losses and improved prices during off-seasons compensate substantially. The technology is scalable for small and large processors alike.

5. Conclusion

An innovative development in the marketing and preservation of jaggery is vacuum packaging. This technique considerably reduces the absorption of ambient moisture, delays microbiological growth and maintains the physicochemical and sensory qualities of jaggery for prolonged periods of time by eliminating air oxygen and establishing a high-barrier environment. According to the study, vacuum-packed jaggery has a significantly longer shelf life (up to nine months), continuously low microbial and fungal counts, and little loss of sugar content. Additionally, the technique routinely performs better than conventional packaging in terms of sensory attributes like flavor, texture, and look. By decreasing seasonal waste and facilitating strategic market release throughout the year, vacuum packaging provides substantial economic savings that benefit both producers and consumers. Vacuum packing adoption has the potential to revolutionize the jaggery industry in terms of quality control and export preparedness, particularly when paired with edible coatings. Food safety and sustainability in the sweetener value chain will be further reinforced by ongoing research and technology transfer in this area. The choice of storage strategy has a considerable impact on the physicochemical, sensory and microbiological stability of jaggery throughout prolonged storage, according to a comparative investigation of different packaging materials. The least effective were conventional jute and paper bags, which resulted in significant textural and color deterioration, excessive moisture absorption, sucrose degradation, and an elevated microbial load.

The best solution, on the other hand, was PET films under modified atmosphere packaging (MAP) with 100% nitrogen, which guaranteed low moisture infiltration, maximum sucrose retention, excellent hardness preservation, very little microbiological development, and constant color characteristics. Additionally, PP films did well, especially in terms of preserving their hardness and sensory appeal. Irradiation improved the microbiological safety of LDPE films and pouches, but also limited their long-term usage. These materials demonstrated a modest level of success. Thus, implementing cutting-edge packaging technologies like MAP in PET or PP films can significantly improve the jaggery's shelf life, safety, and quality. This is especially important in areas with high humidity and lengthy storage needs.

Suggestions

- Promote MAP-Based Packaging Technologies

For better protection against moisture, microbiological growth, and quality degradation, stakeholders in the jaggery sector should switch from traditional packaging (such as jute or paper bags) to modified atmosphere packaging (MAP) employing PET or PP films.

- Encourage Small-Scale Irradiation

Irradiated LDPE pouches (3-7 kGy) can be marketed as an affordable substitute to improve microbiological safety and marginally prolong the shelf life up to 90 days in locations where MAP facilities are not available. This is especially helpful for small jaggery producers.

- Implement Packaging Standards Based on Climatic Conditions

In order to maintain product integrity, packaging recommendations should be customized to local climate patterns. For instance, PET-MAP packaging is particularly appropriate in humid areas or during the monsoon season.

- Develop Policy Incentives for Modern Packaging Adoption

In order to promote the adoption of innovative packaging technologies and guarantee better product quality and export potential, government agencies operating under ODOP or MSME schemes had to offer subsidies or training courses.

- Conduct Further Research on Eco-Friendly Alternatives

Despite their superior performance, PET and PP are not biodegradable. Therefore, in order to strike a balance between sustainability and functional efficacy, future research should concentrate on creating bio-based, moisture-resistant, and MAP-compatible materials.

Compliance with ethical standards

Acknowledgments

The author gratefully acknowledges the support of relevant government data sources and agricultural databases that made this analysis possible. Special thanks to academic mentors and peers for their valuable feedback throughout the research process. The insights gained from this study are a result of collaborative learning and ongoing discussions on regional agricultural development.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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