AAU/DR/26/BU/948/2025-26

Technical Bulletin

Post harvest processing and value addition of Assam Lemon

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ALL INDIA CO-ORDINATED RESEARCH PROJECT
ON
POST-HARVEST ENGINEERING & TECHNOLOGY

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Nutritional and Phytochemical Profiling of Assam Lemon

Juice 37.68% – 41.23%

Limonene

38.08-55.40%
(Peel Oil)

Low caloric value

20–29 kcal/100 g

Moderate carbohydrate

(9–10.7 g/100 g)

Dietary fibre

(2.8–4.7 g/100 g)

Vitamin C (53–77 mg/100 g)

Potassium(137–144 mg/100 g)

Calcium (26–62 mg/100 g)
Phosphorus (15–16 mg/100 g)

Titratable

Acidity
4.18-4.35%

Pectin %(dried peel)

12.84% to 19.82%

Total Phenolics

6.07-16.37
mg GAE/L

DPPH Activity

70.57-81.37%
Antioxidant

Key Health Benefits

Anti-diabetic | Antimicrobial | Anti-inflammatory | Antioxidant

Skin Whitening| food additive

Technical Bulletin

Citation

Hussain, T., Bepary, R.H., Hazarika, K., Borah, A., and Baishya, S. (2026) Technical Bulletin on Post harvest processing and value addition of Assam Lemon, ICAR-AICRP on PHET, Assam Agricultural University, Jorhat 785013, Assam

Published by

Directorate of Research (Agri)
Assam Agricultural University, Jorhat-785013

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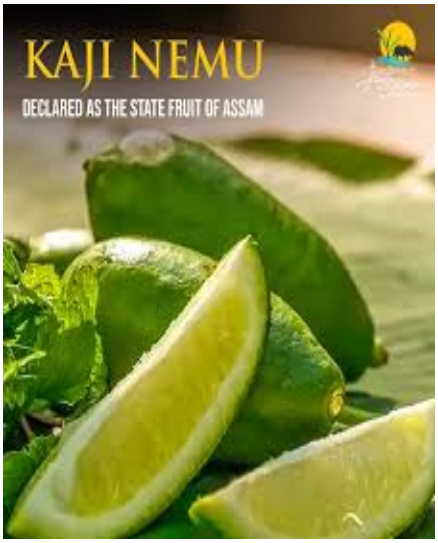
Preface



Credit:awesomeassam@instagram

Assam lemon (Citrus *limon* L. Burm. f.), locally known as "*Kaji Nemu*," represents a distinctive citrus cultivar indigenous to Northeast India, particularly Assam. The fruit was recently declared as “State fruit of Assam” and secured GI tag recognizing its unique aroma, high juice content, and thin rind.

This comprehensive technical bulletin presents recent scientific literature to provide an authoritative overview of Assam lemon's botanical characteristics, cultivation practices, biochemical composition, health benefits, post-harvest management and processing innovations.

The fruit is characterized by its unique seedless trait, distinctive aroma, high citral content (19.38%), and significant limonene concentration (38.08-55.40%) in peel essential oils. Recent advances in post-harvest technologies, including shrink wrapping, perforated polypropylene packaging, and edible coatings, have extended shelf life. Innovative processing methods such as enzyme-mediated debittering, ultrasonic treatment, and microwave-assisted extraction have opened new avenues for value addition. The development of diverse products including essential oils, squash, syrup, ready to serve beverages and candied products demonstrates substantial commercialization potential.

This technical bulletin emphasizes the Assam lemon value processing innovations in transforming this regional fruit into a globally competitive commodity while addressing challenges in storage, quality preservation, and postharvest management.

Authors

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1. Introduction

Figure 1: Assam lemon fruits

Assam lemon (*Citrus limon* L. Burm. f.), regionally known as "*Kaji Nemu*," represents one of the most significant horticultural crops of Northeast India, particularly in the state of Assam. This distinctive citrus cultivar has gained recognition for its unique organoleptic properties, seedless characteristic, and substantial nutritional and medicinal value. In the year 2019, the fruit secured state GI tag for its unique characteristics and in 2024, Government declared it as “State Fruit of Assam”. The Northeast region of India, considered the origin of many citrus species, provides ideal agro-climatic conditions for Assam lemon cultivation, making it an integral component of the region's agricultural economy and cultural heritage.

The fruit is characterized by its distinctive aroma, flavor profile, and predominantly seedless nature, distinguishing it from other lemon varieties cultivated globally. Recent scientific investigations have revealed that Assam lemon possesses exceptional biochemical properties, including high essential oil content rich in limonene (38.08-55.40%), elevated citral concentrations (19.38%), and substantial levels of bioactive compounds with demonstrated therapeutic potential. These attributes position Assam lemon as a valuable resource for pharmaceutical, cosmetic, food, and fragrance industries.

Despite its considerable potential, Assam lemon faces significant challenges related to post-harvest losses, limited shelf life under ambient conditions (approximately 21 days), and inadequate processing infrastructure. The highly perishable nature of the fruit necessitates

immediate processing or preservation interventions to prevent economic losses during peak harvest seasons. Recent research efforts have focused on developing innovative post-harvest management strategies advanced processing technologies, and value-added product formulations to enhance the commercial viability of this indigenous fruit.

This comprehensive technical bulletin was prepared with recent scientific literature providing an authoritative overview of Assam lemon's cultivation practices, biochemical composition, health benefits, and particularly emphasizing on post-harvest management, processing innovations, and commercialization potential. The bulletin aims to serve as a reference document for researchers, processors, entrepreneurs, and policymakers interested in developing the Assam lemon value chain.

2. Cultivation and Agro-climatic Requirements

Assam lemon belongs to the family Rutaceae and is botanically classified as Citrus limon (L.) Burm. f., though some regional variations are also referred to as Citrus limon (L.) Osbeck in scientific literature . The fruit is indigenous to Northeast India, with Assam being recognized as a primary center of cultivation and genetic diversity. The Northeast region is considered the origin of numerous citrus species, and Assam lemon represents one of the most economically important cultivars in this biodiversity hotspot.

The regional significance of Assam lemon extends beyond its agricultural value. It is deeply integrated into the cultural practices, traditional medicine systems, and culinary traditions of Northeast India. Local communities have utilized various parts of the fruit, juice, peel and even seeds for diverse purposes ranging from food preparation to medicinal applications.

2.2 Cultivation Areas in Northeast India

Assam lemon is predominantly cultivated across various districts of Assam, with Tinsukia district emerging as a major commercial production hub. The cultivation has expanded to other northeastern states including Meghalaya, Arunachal Pradesh, Nagaland, and Manipur, where favorable agro-climatic conditions support productive orchards. Recent studies have documented significant morphological and biochemical diversity across different cultivation districts of Assam. A comprehensive survey of 133 populations across 22 districts (Akhtar *et al*. 2024)

revealed that populations from Tinsukia, Dhemaji, Lakhimpur, Dibrugarh, and Jorhat districts exhibited the most desirable seedless characteristics and biochemical profiles closely resembling the original stock. Golaghat district was identified as a linking region displaying both seeded and seedless traits, connecting Upper, Central, Lower, and North Assam regions.

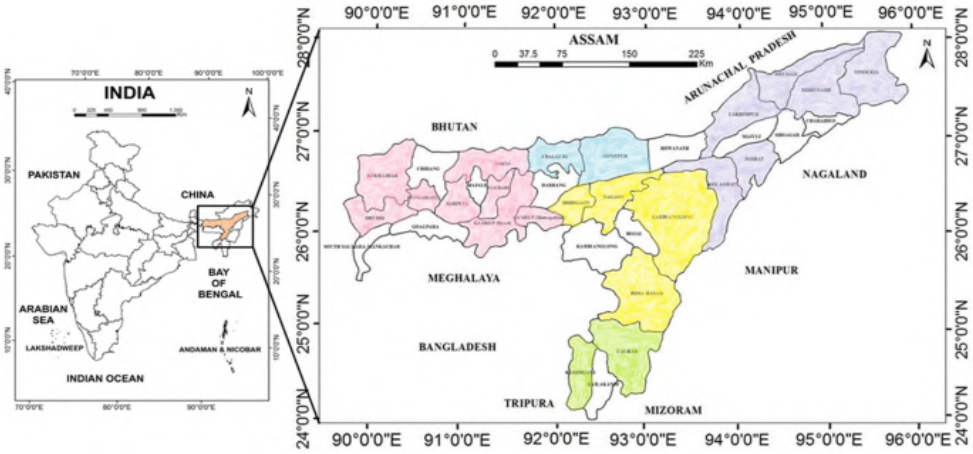

Figure 2: Cultivation area under Assam lemon, Source: Akhtar *et al*., 2024

2.3 Agro-climatic Requirements

Assam lemon thrives in the subtropical to tropical climate of Northeast India, characterized by high rainfall, moderate temperatures, and high relative humidity. The foothills of Arunachal Pradesh and the mid-hills of Meghalaya provide particularly favorable conditions for cultivation. Pruning intensity also affects fruit quality. High pruning intensity (50%) combined with biofertilizer application has been shown to significantly improve fruit morphological and biochemical characteristics, resulting in longer fruits (90.72 mm), heavier fruits (103.67 g), and enhanced biochemical parameters .

3. Biochemical Composition and Phytochemicals Profile

Optimal fruit development occurs when fruits are harvested 120 to 130 days after fruit set, at which stage they develop acceptable physico-chemical qualities including optimal fruit weight (109.28 to 112.95 g), juice content (37.68 to 41.23%), total soluble solids (≥6.3 °Brix), titratable acidity (4.18 to 4.35%), and ascorbic acid content (≥32.41 mg/100g). These parameters serve as reliable maturity indices for harvest decisions.

3.2 Essential Oil Composition

The peel of Assam lemon is particularly rich in essential oils, which constitute a valuable by-product with significant commercial potential. Hydro-distillation of fresh lemon peels yields essential oil with a distinctive chemical profile dominated by monoterpenes and sesquiterpenes.

Limonene emerges as the predominant compound in Assam lemon peel essential oil (LPEO), with concentrations ranging from 38.08% to 55.40% depending on the extraction method and geographical origin. This high limonene content is characteristic of citrus essential oils and contributes significantly to the distinctive aroma and therapeutic properties of the oil. Citral, comprising both α-citral (geranial) and neral (β-citral), represents another major component. Recent studies have reported total citral content of 19.38%, which is comparatively higher than previously documented values. Specifically, α-citral concentrations of 12.02% and neral concentrations of 7.36-10.39% have been identified. The elevated citral content is particularly significant as this compound possesses antimicrobial, anti-inflammatory, and flavor-enhancing properties. Other significant volatile compounds identified in LPEO include decanal (8.14%), which contributes to the characteristic citrus aroma. The essential oil also contains various minor compounds including terpenes, aldehydes, and esters that collectively contribute to the complex aromatic profile.

The chemical composition of essential oils can vary based on several factors including geographical origin, cultivation practices, fruit maturity, extraction method, and post-harvest handling. Studies comparing essential oils from different regions of Northeast India have documented these variations, emphasizing the importance of standardization for commercial applications.

3.3 Vitamins and Organic Acids: Assam lemon is an excellent source of ascorbic acid (Vitamin C), a critical nutrient with antioxidant properties. Fresh fruit juice contains ascorbic acid concentrations ranging from 32.41 to 45.09 mg/100 mL.

3.3 Phenolic Compounds and Flavonoids: Assam lemon contains a diverse array of phenolic compounds and flavonoids that contribute significantly to its antioxidant capacity and health-promoting properties. Total phenolic content in juice ranges from 6.07 to 16.37 mg gallic acid

equivalents (GAE) per liter, with some studies reporting concentrations of 425.33 to 576.33 µg GAE/mL. Flavonoids represent a major class of bioactive compounds in Assam lemon.

Limonin, a bitter limonoid compound, is present in concentrations ranging from 9.21 to 13.92 ppm, with Citrus assamensis (a variety of Assam lemon) exhibiting 13.41 ppm. While limonin contributes to bitterness, it also possesses anticancer and cholesterol-lowering properties.

3.4 Minerals and Proximate Composition: Assam lemon provides essential minerals that contribute to its nutritional value. Dried powder analysis has revealed the presence of sodium, potassium, calcium, magnesium, iron, copper, and zinc. Sugar composition includes both reducing and non-reducing sugars. Fresh juice contains reducing sugars ranging from 1.40% to 2.20% and non-reducing sugars from 3.41% to 7.75%, with total sugar content ranging from 77.32 to 114.82 mg/mL. Juice content is a critical quality parameter for processing applications. Mature fruits yield juice content ranging from 37.68% to 41.23%, with optimal agronomic practices enhancing juice recovery to 40.00 mL per fruit.

4. Health benefits and Therapeutic Properties

4.1 Antioxidant Activity: The essential oil extracted from Assam lemon peel demonstrates strong antioxidant properties in both DPPH and ABTS assays. The high limonene and citral content contributes significantly to these antioxidant effects, which have implications for preventing oxidative stress related diseases and extending the shelf life of food products.

4.2 Anti-diabetic Properties: Recent research has revealed significant anti-diabetic potential of Assam lemon, particularly its peel essential oil. The lemon peel essential oil (LPEO) exhibits good alpha-amylase inhibition activity. Alpha-amylase is a key enzyme involved in carbohydrate digestion, and its inhibition can help regulate postprandial blood glucose levels, making LPEO a potential natural agent for diabetes management.

4.3 Antimicrobial and Anti-inflammatory Effects: Assam lemon peel essential oil demonstrates significant antimicrobial activity against various pathogenic microorganisms. Studies on essential oils from Citrus limon (Kaji Nemu) and related species indigenous to Northeast India have documented broad-spectrum antimicrobial effects.

4.4 Skin whitening and anti-tyrosinase activity: Assam lemon peel essential oil exhibits very strong tyrosinase inhibition activity. Tyrosinase is a key enzyme in melanin biosynthesis, and its inhibition can reduce hyperpigmentation and promote skin lightening. This property positions LPEO as a potential natural ingredient for cosmetic formulations targeting skin whitening and treatment of hyper pigmentation disorders. The diverse therapeutic properties of Assam lemon, supported by recent scientific evidence, validate its traditional medicinal uses and open avenues for developing evidence-based natural health products targeting multiple health conditions.

5. Post-harvest Management and Quality Preservation

5.1 Physiological Changes during Storage

Understanding the physiological and biochemical changes that occur during post-harvest storage is critical for developing effective preservation strategies. Assam lemon, like other citrus fruits, undergoes continuous metabolic processes after harvest that affect quality, shelf life, and marketability.

Respiration and transpiration are the primary physiological processes affecting post-harvest quality. Under ambient storage conditions (30-32°C and 80-85% relative humidity), untreated Assam lemon fruits exhibit a shelf life of only 21 ±1.00 days. During this period, fruits experience physiological loss in weight (PLW) due to moisture loss through transpiration and substrate loss through respiration. Changes in total soluble solids (TSS) occur during storage, with values generally remaining relatively constant initially but showing gradual changes over extended storage periods. The TSS content is influenced by the balance between sugar synthesis and degradation processes. Titratable acidity typically declines during storage as organic acids are metabolized through respiratory pathways. This reduction in acidity affects the TSS: acid ratio, which is a critical quality parameter influencing taste perception.

Ascorbic acid degradation is a significant concern during post-harvest storage. Vitamin C content declines progressively due to oxidation reactions, with the rate of degradation influenced by temperature, oxygen availability, and light exposure. Preservation strategies must minimize ascorbic acid loss to maintain nutritional value. Microbial spoilage represents a major cause of post-harvest fruit losses. Fungal infections, particularly by Penicillium and Aspergillus species, can rapidly deteriorate fruit quality under favorable conditions.

5.2 Packaging Technologies for Shelf life Extension

Advanced packaging technologies have emerged as effective strategies for extending the shelf life of Assam lemon while maintaining quality attributes. Recent research has evaluated various packaging materials and methods, yielding significant improvements in storability.

Individual shrink wrapping has proven to be the most effective packaging method for Assam lemon preservation.



The selection of packaging technology depends on multiple factors including cost, target market, distribution channels, and desired shelf life. For premium markets and long-distance transportation, individual shrink wrapping or perforated PP packaging is recommended. For local markets with shorter distribution chains, simpler packaging methods may suffice.

5.3 Edible Coatings and Surface Treatments

Edible coatings represent an innovative and environmentally sustainable approach to post-harvest preservation. These coatings create a semi-permeable barrier on the fruit surface that regulates gas exchange, reduces moisture loss, and can incorporate antimicrobial or antioxidant agents. The development of edible coatings for Assam lemon represents an active area of research with significant potential for commercial application. Future developments may include coatings incorporating natural antimicrobials, antioxidants, or texture-enhancing agents to further improve preservation efficacy.

5.4 Storage Conditions and Quality Retention

Optimal storage conditions are critical for maximizing shelf life and maintaining quality attributes of Assam lemon. Temperature, relative humidity, and atmospheric composition are the primary environmental factors influencing post-harvest behavior. Ambient storage conditions in

Northeast India typically range from 29-32°C temperature and 55-85% relative humidity. Under these conditions, untreated fruits deteriorate rapidly, with shelf life limited to approximately 21 days. The high temperature accelerates metabolic processes, while fluctuating humidity can cause moisture stress.

Modified atmosphere storage created through packaging technologies significantly extends shelf life by altering the gas composition around the fruit. Cold storage facilities, while not extensively documented in the reviewed literature, would theoretically provide superior preservation by reducing metabolic rates. However, the lack of adequate cold storage infrastructure has been identified as a major challenge for Assam lemon commercialization in Northeast India. Development of cold chain infrastructure represents a critical need for expanding market reach and reducing post-harvest losses. Maturity at harvest significantly influences storage potential. Fruits harvested at optimal maturity (120-130 days after fruit set) with appropriate physico-chemical characteristics exhibit better storage stability compared to immature or over-mature fruits.

The integration of optimal harvest timing, appropriate surface treatments, advanced packaging technologies, and controlled storage conditions represents the most effective strategy for maximizing Assam lemon shelf life and quality retention. Implementation of these integrated post-harvest management systems is essential for commercial success and market expansion.

6. Processed Products and Value Addition

Figure 3: Assam lemons processed and value added product

6.1 Essential Oil Extraction and Applications

Essential oil extraction from Assam lemon peel represents a high-value processing opportunity that transforms a by-product into a premium commodity. The peel, which constitutes a significant portion of fruit waste after juice extraction, is rich in essential oils with diverse applications in pharmaceutical, cosmetic, food, and fragrance industries.

Hydrodistillation is the traditional method for essential oil extraction from Assam lemon peel. This process involves steam distillation of fresh or dried peels, yielding essential oil with characteristic limonene-rich composition (38.08-55.40%) and elevated citral content (19.38%). The hydro-distillation process is relatively simple and can be implemented at small to medium scales, making it suitable for rural processing units.

Microwave assisted extraction (MAE) represents an innovative and efficient alternative to conventional extraction methods. MAE offers several advantages including reduced extraction time, lower solvent consumption, higher yields, and better retention of thermally sensitive compounds. The optimization of extraction parameters (microwave power, time, and solvent ratio) is critical for maximizing oil yield and quality.

Fig 4: discarded fruits after juice extraction

Applications of Assam lemon peel essential oil are diverse and expanding:

1. Pharmaceutical applications: The demonstrated anti-diabetic, anti-tyrosinase, antimicrobial, and anti-inflammatory properties position LPEO as a valuable ingredient for pharmaceutical formulations. The strong alpha-amylase inhibition suggests potential for developing natural anti-diabetic products, while the very strong tyrosinase inhibition indicates applications in dermatological formulations for hyperpigmentation treatment.

2. Cosmetic applications: The skin whitening properties and antioxidant activity make LPEO suitable for cosmetic formulations including skin lightening creams, anti-aging products, and aromatherapy preparations. The pleasant citrus aroma adds sensory appeal to cosmetic products.

3. Food industry applications: LPEO can serve as a natural flavoring agent, antimicrobial preservative, and antioxidant in food products. The high limonene content contributes to characteristic citrus flavor, while antimicrobial properties can extend shelf life of food products.

4. Fragrance industry applications: The distinctive aroma profile dominated by limonene and citral makes LPEO valuable for perfumery and household fragrance products.

5. Functional coatings: The incorporation of LPEO into chitosan based coatings for fruit preservation demonstrates innovative applications in post-harvest technology. Such coatings combine the barrier properties of biopolymers with the antimicrobial and antioxidant properties of essential oils.

The development of essential oil extraction and processing infrastructure represents a significant opportunity for value addition in Assam lemon production. Small-scale distillation units can be established in production areas, providing additional income to farmers and processors while reducing waste.

6.2 Beverage Products

Beverage products represent the most common and commercially viable value-addition pathway for Assam lemon. The distinctive sour taste, high acidity, and refreshing flavor make it ideal for various beverage formulations.

Squash is a concentrated beverage product that requires dilution before consumption. Laboratory experiments have successfully developed lemon squash from seedless lemon fruits with acceptable organoleptic properties.

Syrup represents another concentrated beverage product with high sugar content that acts as a preservative. Lemon syrup prepared from seedless lemon fruits recorded the highest average organoleptic score (7.61) among tested products, indicating superior consumer acceptance. The high sugar concentration in syrup formulations provides excellent preservation, extending shelf life while maintaining flavor and nutritional attributes.

Ready to Serve (RTS) beverages are diluted products ready for immediate consumption. RTS beverages prepared from seedless lemon fruits recorded an organoleptic score of 7.02, which, while lower than squash and syrup, remained acceptable to consumers. RTS products offer convenience but require more stringent preservation measures due to lower sugar and acid concentrations compared to squash and syrup. Bitterness of the processed juice of Assam lemon during storage is a major constraint in processing and marketing which need attention.

The development of beverage products from Assam lemon addresses the challenge of seasonal glut and post-harvest losses while creating year-round availability of lemon based products. The diversity of beverage formulations allows processors to target different market segments and price points.

6.3 Preserved and Candied Products

Preserved and candied products represent traditional value addition methods that transform fresh fruit into shelf-stable products with extended marketability. While specific research on Assam lemon preserved products is limited in the reviewed literature, studies on related citrus species provide valuable insights.

Salt pickle is a traditional preservation method widely practiced in Northeast India. Kachai lemon (Citrus jambhiri), a related species, has been successfully processed into salt pickle, demonstrating the feasibility of this approach for Assam lemon.

Sweet pickle (with and without oil) represents another traditional product. Sweet pickles combine sugar, salt, and spices to create preserved products with balanced sweet-sour taste.

Candied peel products utilize the lemon peel, which is rich in essential oils and pectin. Candied peel (plain and with chocolate coating) has been successfully prepared from related citrus species.

Candied fruit slices (plain and with chocolate) offer similar preservation benefits while maintaining fruit structure. These products appeal to consumers seeking natural, fruit-based confectionery alternatives.

Jellies prepared from citrus fruits capitalize on the natural pectin content in lemon peel. Plain jellies and jellies combined with other fruits (such as Prunus species) have been successfully developed. The natural pectin in Assam lemon peel is particularly valuable, as it eliminates the need for added pectin in jelly formulations.

6.4 Dried Powder and Functional Ingredients

Dried lemon powder represents a versatile value-added product with multiple applications. Recent research has characterized the biochemical contents and nutritional quality of dried

powder from Assam lemon fruits. The drying and powdering process concentrates nutrients including Vitamin C, sodium, potassium, calcium, and other biochemical components.

Dried lemon powder offers several advantages:

1. Extended shelf life without refrigeration

2. Reduced transportation and storage costs due to lower weight and volume

3. Versatile applications in food formulations, beverages, seasonings, and nutraceuticals

4. Retention of key bioactive compounds when properly processed

5. Year-round availability independent of seasonal production

The powder can be incorporated into various food products including baked goods, confectionery, seasoning blends, instant beverage mixes, and dietary supplements. The concentrated flavor and nutritional profile make it suitable for functional food applications.

Natural pectin extraction from Assam lemon peel represents another high-value processing opportunity. The peel contains natural pectin, a valuable gelling agent used in food processing. Pectin extraction can be integrated with essential oil production, maximizing value recovery from peel byproducts. The extracted pectin can be used in jelly production, as a stabilizer in beverages, or sold as a commercial ingredient.

Functional ingredients derived from Assam lemon include:

1. Concentrated phenolic extracts with antioxidant properties

2. Flavonoid rich fractions for nutraceutical applications

3. Essential oil concentrates for pharmaceutical and cosmetic use

4. Fiber rich peel powder for dietary fiber supplementation

The development of dried powder and functional ingredient products positions Assam lemon as a source of value-added ingredients for the food, pharmaceutical, and nutraceutical industries. These products command premium prices and open opportunities for export markets.

7. Innovations in Assam Lemon Processing and future

7.1 Enzyme-mediated Debittering Technology

Bitterness development during storage represents a major quality issue for citrus juices, primarily caused by the limonoid compound limonin. Innovative enzyme-mediated debittering technology

has been developed specifically for Assam lemon juice, addressing this challenge while enhancing beneficial properties.

7.2 Ultrasonic Treatment and β-Cyclodextrin Application

The combination of probe ultrasonication and β-cyclodextrin represents a cutting-edge processing innovation for bitterness reduction and quality enhancement of Assam lemon juice. The ultrasonication technology is designed to be cost-effective and implementable at room temperature, eliminating the need for heating or cooling equipment. This makes it suitable for small and medium-scale processors in rural areas. Recently Assam Agricultural University developed a technology on preservative free Assam lemon juice preservation for longer shelf life.

7.3 Microwave-assisted Extraction

Microwave-assisted extraction (MAE) represents a modern, efficient technology for extracting essential oils and bioactive compounds from Assam lemon peel. This innovation addresses the limitations of conventional extraction methods, offering improved efficiency, reduced processing time, and better quality of extracted compounds. The MAE technology is particularly suitable for commercial implementation in Northeast India, where access to fresh Assam lemon peel is abundant.

7.4 Futures Low cost Processing Equipment Development

The development of low cost processing equipment specifically designed for Assam lemon will address practical challenges faced by small scale processors in Northeast India.

Challenges in Processing of Assam lemon fruits:

1. Unique fruit shape: The distinctive shape of Assam lemon makes conventional citrus processing equipment inefficient

2. Contamination risk: Traditional manual processing methods have high probability of juice contamination, fruit injury and reducing shelf life

3. Seed crushing: Cutting or crushing lemon seeds during processing makes the juice bitter

4. Labor intensity: Traditional processing methods are highly labor-intensive and inefficient

Significance for regional development: The development of appropriate processing technology is crucial for the growth of Assam lemon-based industries in Northeast India. Small processing units operating with minimal capital in small spaces can process seasonal harvest, reduce post-harvest losses, and create value-added products.

Natural pectin utilization: The equipment design should consider the valuable natural pectin present in lemon peel, enabling its recovery for use in various preparations. This integrated approach will maximizes value recovery from all fruit components.

Future directions: The information indicates ongoing testing and refinement of the solution, suggesting continuous improvement based on field experience. Future developments may include mechanization of additional processing steps, integration with packaging systems, and adaptation for processing of other regional fruits.

The low cost equipment innovation requirement represents a practical, implementable solution that addresses real-world challenges faced by Assam lemon processors. This type of appropriate technology development is essential for transforming traditional processing practices and enabling commercial growth of the Assam lemon industry.

8. Future Prospects and Conclusion

Assam lemon (Citrus limon L. Burm. f.) represents a valuable indigenous citrus cultivar of Northeast India with substantial potential for commercial development and global market positioning with value added products of health benefits. Extensive research work on post harvest technology and processing of Assam lemon will definitely help the regional farmers to increase their income from the fruit crop.

Future research scopes:

1. Mechanization: Further development of low cost, appropriate processing equipment tailored to Assam lemon's unique characteristics.

2. Bioactive compound isolation: Detailed characterization and isolation of specific bioactive compounds for pharmaceutical and nutraceutical applications.

3. Integrated processing systems: Development of zero waste processing systems that maximize value recovery from juice, peel, seeds, and other components.

4. Shelf life and storage: Research study on shelf life enhancement and storage conditions specific for Assam lemon

5. Product diversification: Development of novel products including functional beverages, cosmeceuticals, and pharmaceutical formulations.

Commercialization potential: Assam lemon possesses significant potential for commercial development at multiple levels:

1. Local level: Small-scale processing units producing traditional products (pickles, squash, syrup) for regional markets
2. National level: Branded products targeting health-conscious consumers seeking natural, functional foods
3. International level: Essential oils, dried powder, and functional ingredients for pharmaceutical, cosmetic, and food industries.

The unique seedless characteristic, distinctive flavor profile, and validated health benefits position Assam lemon as a premium product capable of commanding higher prices in domestic and international markets.

Conclusion: Assam lemon represents a valuable bioresource with demonstrated nutritional, medicinal and commercial value. Recent scientific advances in post-harvest management, processing technologies, and product development have created a strong foundation for commercial exploitation. The transformation of Assam lemon from a regional fruit to a globally competitive commodity requires integrated efforts in research, technology development, infrastructure creation, and market development. With appropriate investments and policy support, GI tagged Assam lemon can contribute significantly to the economic development of Northeast India while providing health-promoting products to consumers worldwide. The convergence of traditional knowledge, modern science, and innovative technology positions Assam lemon at the threshold of commercial breakthrough, awaiting systematic development and strategic market positioning.

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