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Value-Added Products of Wood Apple (*Limonia acidissima* L.)

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Introduction:

Underutilized fruit crops are increasingly recognized for their potential role in nutritional security and climate-resilient agriculture. Among these, *Limonia acidissima* L., commonly known as wood apple, is a hardy fruit tree belonging to the Rutaceae family. It thrives in arid and semi-arid regions of India, Sri Lanka and neighboring countries. Traditionally consumed as fresh pulp or beverage, wood apple has also been used in Ayurvedic and folk systems of medicine for digestive disorders, inflammation and metabolic disturbances.

Despite its adaptability and therapeutic relevance, the fruit remains largely confined to local markets. Growing demand for natural antioxidants, plant-based functional foods and indigenous ingredients has stimulated renewed scientific interest in wood apple processing and product development. However, comprehensive reviews integrating nutritional composition, processing technologies and commercialization prospects remain limited. This paper consolidates current knowledge to support future research and industrial utilization.

Wood apple is a medium-sized deciduous tree reaching 9–15 m in height. The fruit is spherical with a rigid woody shell that protects the internal aromatic pulp. The hard rind contributes to natural resistance against post-harvest damage, enhancing storage potential relative to softer tropical fruits.

The species tolerates poor soils, high temperatures and limited rainfall, making it suitable for marginal lands and climate-resilient horticulture systems. However, the absence of standardized cultivars and organized orcharding limits consistent raw material supply for industrial processing.

Fresh wood apple pulp typically contains 60–70% moisture, 20–28% carbohydrates, 1–2% protein and less than 1% fat. Dietary fiber ranges between 4–8%, which is higher than many commonly consumed fruits. The calorific value averages 90–120 kcal per 100 g fresh pulp.

The fruit contains calcium, potassium, phosphorus and iron in appreciable amounts. Moderate levels of vitamin C and trace B-

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complex vitamins.

Phytochemical analyses reveal the presence of:

- Phenolic acids and flavonoids
- Coumarins such as umbelliferone
- Triterpenoids including limonin
- Tannins and alkaloids

Antioxidant capacity measured through DPPH, FRAP and ABTS assays confirms strong radical-scavenging activity. Processing methods significantly influence phenolic retention.

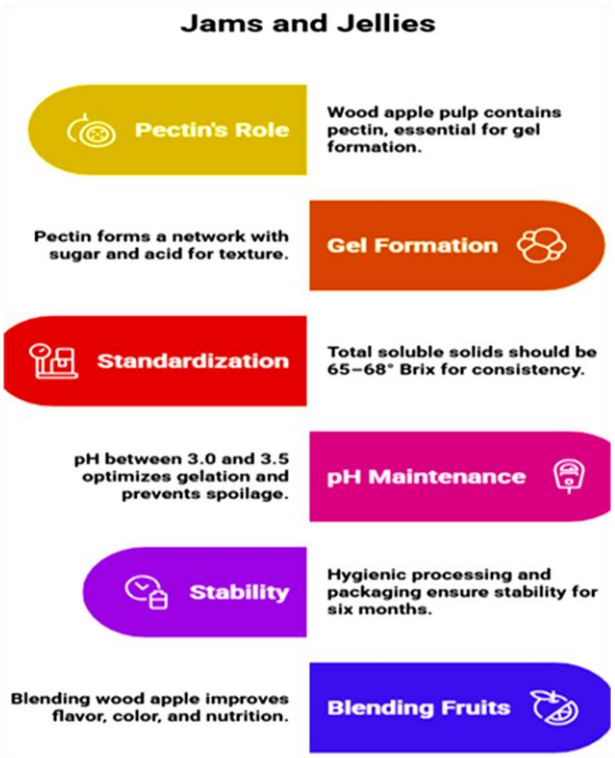
A. Value-Added Product Development

1. Ready-to-Serve Beverages

RTS beverages are formulated by blending fruit pulp or juice with potable water to achieve a balanced consistency and palatability. The total soluble solids are standardized to about 10–14° Brix using sugar syrup, ensuring uniform sweetness and mouthfeel. The mixture is homogenized to maintain stable dispersion of pulp particles and then pasteurized to destroy spoilage microorganisms and enzymes. After thermal processing, the beverage is hot-filled or aseptically bottled under hygienic conditions. Research indicates that properly processed RTS drinks maintain desirable sensory attributes and microbial safety for 60–90 days at ambient temperature, especially when permitted preservatives are incorporated. Fortification with whey protein, vitamins, or herbal extracts enhances nutritional value while retaining physicochemical stability and consumer acceptability.

2. Jams and Jellies

Wood apple pulp naturally contains adequate pectin, which plays a crucial role in gel formation during jam and jelly preparation. In the presence of sugar and acid, pectin forms a stable three-dimensional network responsible for desirable texture and spreadability. Standardization of total soluble solids to 65–68° Brix ensures proper gel consistency, microbial safety, and extended shelf life. Maintaining pH between 3.0 and 3.5 optimizes pectin gelation and prevents spoilage. Under hygienic processing and proper packaging, these products remain stable for up to six months at ambient conditions. Blending wood apple with fruits like mango or guava improves flavor, color, and overall sensory acceptability while enhancing nutritional value.



3. Confectionery and Fruit Bars

Wood apple pulp obtained from Wood apple has been successfully incorporated into fruit bars, candies, and toffees due to its natural pectin, fiber, and characteristic sweet–tangy flavor. The pulp improves texture, binding capacity, and nutritional value of confectionery products. During storage, these products retain moderate levels of antioxidants, particularly phenolic compounds, contributing to added functional benefits. Controlled dehydration and low moisture content enhance shelf stability without major nutrient loss. Such value-added products require simple processing equipment, making them suitable for cottage industries and rural entrepreneurs. They offer good market potential in health-oriented snack segments and local agro-processing enterprises.

4. Dehydrated Powder and Flour

Dehydration of fruit pulp into powder or flour is a widely adopted value-addition strategy that enhances shelf life, reduces bulk, and facilitates easy transportation and storage under ambient conditions without significant microbial spoilage. Common drying technologies include conventional tray drying and advanced freeze drying. Tray drying is economical and suitable for small-scale operations, whereas freeze drying retains better color, aroma, nutrients, and bioactive compounds. Freeze drying operates under low temperature and vacuum conditions, minimizing thermal degradation and preserving higher phenolic content and antioxidant activity compared to hot air drying methods. Despite its superior quality retention, freeze drying involves high capital investment, energy consumption, and longer processing time, which limits its commercial scalability in cost-sensitive markets. The resulting powdered pulp can be standardized for moisture content, particle size, and functional properties to ensure stability, solubility, and compatibility with different food formulations. Dehydrated fruit powder can be incorporated into bakery products such as biscuits, cakes, muffins, and functional breads to enhance flavor, fiber, and micronutrient content naturally. It is also suitable for nutraceutical blends, health supplements, beverage premixes, and instant food formulations due to its concentrated bioactive profile and extended storage stability.

5. Fermented and Specialty Products

Preliminary fermentation studies indicate that the fruit possesses a balanced sugar–acid ratio, which supports its suitability for developing wine-type beverages and other specialty fermented products. The natural fermentable sugars provide an adequate substrate for yeast metabolism, while the inherent acidity helps maintain microbial stability and desirable sensory properties. During controlled fermentation, parameters such as temperature, yeast strain selection, pH, and fermentation duration can be optimized to improve alcohol yield and product consistency. Additionally, fermentation may enhance the extraction and bioavailability of bioactive compounds, including phenolics and antioxidants. This process can also contribute to greater flavor complexity by generating esters, higher alcohols, and other aroma-active compounds.

B. Processing Technologies

1. Pulp Extraction

Pulp extraction is a critical step in fruit processing that determines product quality and yield. The process begins with thorough washing to remove soil, debris, and surface contaminants. After cleaning, the hard shell or outer covering is cracked mechanically or manually to access the edible portion. The pulp is then carefully separated from seeds and fibrous materials using pulpers or sieves. Modern processing units often adopt enzyme-assisted extraction, where specific enzymes such as pectinases break down complex polysaccharides. This treatment enhances pulp recovery, reduces viscosity, improves flow properties, and facilitates easier filtration, resulting in higher efficiency and better-quality processed products.

2. Thermal Processing

- **Pasteurization (85–90°C):**

Pasteurization at 85–90°C is widely applied in fruit- and vegetable-based products to inactivate spoilage microorganisms and reduce pathogenic microbial load without severely affecting nutritional and sensory quality. At this temperature range, most vegetative bacterial cells, yeasts, and molds are effectively destroyed, extending shelf life while retaining heat-sensitive nutrients such as vitamin C to a reasonable extent. The process also helps stabilize color, flavor, and texture. Careful control of time–temperature combinations is essential to avoid overprocessing, which can lead to undesirable changes such as browning, cooked flavors, and loss of bioactive compounds.

- **Hot-Filling Method:**

Hot-filling is commonly used for products such as jams, jellies, and fruit spreads. In this method, the product is heated

to the required temperature and filled into pre-sterilized containers while still hot, typically above 85°C. The heat of the product sterilizes the container's inner surfaces and headspace, reducing the risk of post-processing contamination. After sealing, containers are inverted briefly to ensure complete sterilization of the lid area. This technique improves product safety, enhances shelf stability at ambient conditions, and reduces the need for chemical preservatives while maintaining desirable consistency and spreadability.

3. Dehydration and Packaging

Dehydration is a fundamental processing technology used to enhance the shelf life and stability of powdered food products. By reducing moisture content to safe levels, microbial growth, enzymatic activity, and chemical deterioration are minimized. Effective moisture control is essential because excess humidity can cause caking, lump formation, nutrient degradation, and loss of functional properties. Advanced drying methods such as spray drying, tray drying, or freeze drying help achieve uniform and stable powders. After dehydration, proper packaging becomes equally important. Laminated moisture-barrier packaging materials, often multilayered with aluminum foil or polyethylene films, prevent moisture ingress, oxygen exposure, and light penetration. Such packaging significantly extends product shelf life to approximately 6–12 months under recommended storage conditions.

C. Shelf-Life Characteristics

- **Stability of RTS Beverages (2–3 Months at Ambient Conditions):**

Ready-to-serve (RTS) beverages are formulated with appropriate levels of total soluble solids, acidity, and permitted preservatives to ensure microbiological safety and physicochemical stability. Under normal room temperature storage, typically 25 to 30°C, these beverages remain stable for about two to three months. Stability depends on hygienic processing, proper pasteurization, and airtight packaging. Changes during storage may include slight color variation, sedimentation, or gradual flavor loss. However, if processed and sealed correctly, microbial spoilage is minimal, and the beverage retains acceptable taste, aroma, and nutritional quality throughout the expected shelf life.

- **Shelf Life of Jam and Jelly (Up to Six Months):**

Jam and jelly products have a comparatively longer shelf life, generally up to six months under ambient storage. Their high sugar concentration, usually around 65 percent total soluble solids, creates low water activity, which inhibits microbial growth. Proper pectin gel formation and adequate acidity further enhance stability. When packed in sterilized, moisture-proof containers, these products resist spoilage effectively. Over extended storage, minor issues such as sugar crystallization, color darkening, or slight flavor changes may occur, but overall product safety and acceptability are maintained within the recommended storage duration.

➪ **Phenolic Degradation During Storage:**

Phenolic compounds contribute to antioxidant capacity, color stability, and nutritional value of fruit-based products. During storage, degradation of phenolics may occur due to oxidation, enzymatic reactions, and exposure to environmental factors. Higher temperatures accelerate chemical reactions, leading to faster loss of phenolic content. Oxygen permeability of packaging materials also plays a critical role, as oxygen promotes oxidative degradation. Light exposure may further intensify these changes. Therefore, selecting suitable packaging materials with low oxygen transmission rates and storing products under controlled temperature conditions significantly reduces phenolic loss and preserves product quality.

D. Functional and Health-Promoting Properties of Wood Apple

➪ **Antioxidant activity, reducing oxidative stress markers**

Wood apple contains phenolic compounds, flavonoids, and vitamin C that scavenge free radicals, lower lipid peroxidation, and reduce oxidative stress biomarkers, thereby supporting cellular protection and overall metabolic health.

➪ **Anti-diabetic potential, observed in preliminary animal studies**

Preliminary animal experiments indicate that wood apple extracts may help regulate blood glucose levels, improve insulin sensitivity, and reduce hyperglycemia, suggesting promising anti-diabetic potential requiring further clinical validation.

➪ **Digestive support due to high dietary fiber**

The high dietary fiber content in wood apple promotes bowel regularity, improves gut motility, supports beneficial intestinal microbiota, and aids in preventing constipation and digestive discomfort.

- **Antimicrobial properties attributed to phenolics and coumarins**

Bioactive compounds such as phenolics and coumarins present in wood apple exhibit antimicrobial effects against selected bacterial and fungal strains, contributing to its potential role in natural food preservation and health protection.

- **Support for development as a functional food ingredient**

These combined bioactive, nutritional, and therapeutic attributes justify the incorporation of wood apple into value-added products, supporting its development as a scientifically validated functional food ingredient for health-oriented consumers.

E. Market Potential and Commercial Perspectives

Demand for indigenous functional foods is expanding globally. Value addition increases profitability by extending shelf life and diversifying product forms. However, commercialization is constrained by irregular supply chains, lack of standardized cultivars and limited mechanization.

Government support for rural processing units and increasing consumer awareness of traditional fruits may enhance market penetration.

F. Research Gaps and Future Directions

Future work should focus on:

- Cultivar standardization and yield improvement
- Mechanized shell-cracking technologies
- Microencapsulation of bioactive compounds
- Probiotic and low-sugar functional formulations
- Life-cycle and economic feasibility assessments

Wood apple (*Limonia acidissima* L.) represents a nutritionally valuable and climate-resilient fruit with substantial potential for value-added processing. Advances in product development and preservation technologies have improved commercial feasibility, yet systematic supply chain development and industrial scaling remain essential. Strategic research integration across horticulture, food science and market economics will be critical to transforming this underutilized species into a viable functional food commodity.