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REVIEW ARTICLE

Revitalizing minor fruit production: Strategies for crop improvement and value addition

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Abstract

Minor fruits hold great potential for value addition and processing into market lead products with high commercial value. Despite being underutilized in agriculture due to limited crop improvement efforts, lack of awareness and vulnerability to biotic and abiotic stresses, they offer significant opportunities for economic empowerment and environmental sustainability. Minor fruits like bael, bilimbi, jamun, aonla, phalsa, ber, kiwi, rambutan, longan, fig, tamarind, passion fruit, persimmon, karonda, khejri, carambola, chironji, pilu, wood apple, loquat, West Indian cherry, mahua, monkey jack, rose apple, red pear, sea buckthorn and durian have numerous health benefits both directly and indirectly. Through value-addition processes such as drying, canning and processing into value-added products, these fruits can be transformed into marketable commodities with an extended shelf life. Value addition enhances the income-generating capacity of small-scale farmers, thereby contributing to poverty alleviation and rural development. Promoting nutrition can be enhanced by proper water and nutrient management, genetic strategies and postharvest handling. Secondly, it explores the role of value addition in creating employment opportunities and fostering entrepreneurship particularly among marginalized communities. By encouraging sustainable agricultural practices such as organic farming and agroforestry, crop development and value-addition initiatives can mitigate environmental degradation and promote sustainable agriculture. This dual focus on economic empowerment and environmental sustainability underscores the potential of crop improvement in minor fruits as a catalyst for holistic rural development.

Keywords: crop improvement; employment opportunities; sustainable agriculture; underutilized fruits; value addition

Introduction

Minor fruits are generally defined as underutilized fruits with high potential value but limited cultivation. Perhaps, defining minor fruit crops precisely is challenging. Roughly 30000 plants are estimated to be important, among which 15000 are known to be used as medicines on a worldwide basis (1). Generally, these fruits can be consumed in smaller quantities than other fruits; this is because they are considered less appetizing or more difficult to find. A group of fruits presently growing in a scattered and unattended way on roadsides, homestead land, wasteland, etc. is considered as minor fruits. These fruits, though consumable by human beings are relatively less palatable than major fruits, have lesser demand in the market and are grown to a limited extent (2).

The main issue is that the significance of these fruits has not been effectively communicated to potential buyers. Minor fruits especially grown in Assam, Bihar, Jharkhand, Tripura, West Bengal and also other North eastern states are well known for cultivation without any intense care (3). In recent times, underutilized fruit species have gained increasing acknowledgment from various stakeholders, such as researchers, development practitioners, private companies, policy makers, funding agencies, rural communities and consumers. It is now envisioned that indigenous biodiversity can significantly contribute to food and nutritional security and poverty alleviation (4). Fresh fruits are in high demand due to their rich content of vitamins and minerals, which is why they are often referred to as 'protective food'. To alleviate malnutrition in arid, hilly and tribal areas, the production of minor fruits should be significantly increased. This can be achieved by expanding the cultivation area and enhancing the yield of these crops, thereby increasing their availability and contributing to improved nutritional standards (5).

Generally minor fruits are a good source of carbohydrate, vitamins, minerals and antioxidants which aid in preventing malnutrition in the tribal sector. For example, kendu (*Diospyros melanoxylon* Roxb) comes under the underexploited species, endemically native tree of India and extensively distributed over the peninsular plains and lower hills, particularly within the dry deciduous forests of central,

western and northern India (2). Kendu fruit has immense potential in providing various nutritional and pharmaceutical properties which holds carbohydrates, calcium, phosphorus and carotene (equivalent of vitamin A) (2).

The utilization of minor fruits across various sectors offers significant benefits. Therefore, researchers should focus on the dissemination and promotion of these underutilized fruits. This to certain extent, can be attained by proper processing and value addition. The fruit's value can be raised by converting it into products like jam, jelly, squash, puree, fruit bar, fresh juice, murabba, pickle etc. to expand their lifespan (6). Apart from value addition, it is a source of livelihood because it has more medicinal and therapeutic properties which is used in ayurvedic and unani medicines which indirectly benefits the users. The plant parts have been used as local medicine in eastern states which will give quick healing from injuries (7). Undoubtedly, minor fruit crops promote sustainable development, biodiversity conservation and regional economic growth. Policy makers and agricultural practitioners should focus on the cultivation and preservation of local minor crops for regional biodiversity conservation and sustainable economic growth (8).

Hence, the importance of minor fruits has been thoroughly explored and discussed in this review paper, highlighting their nutritional, medicinal and economic value. The paper emphasizes their potential in addressing malnutrition, promoting sustainable agricultural practices and contributing to rural development through value addition and diversification of income sources.

Crop improvement strategies

Producing minor fruit crops are key initiatives in diversified agriculture, local economy support, dietary diversity and niche markets. An underutilized fruit offer several benefits-being ease of cultivation, hardiness, climate resilience, abundance of phytochemicals and medicinal properties that are of much importance to meet the nutritional needs of rural areas, especially in arid and semi-arid regions (9). Strategic use of biotechnological tools also enhances crop improvement, leading to increased yields, improved quality and more sustainable agricultural practices (10). Thus, emphasis must be placed on the conservation and nutritional characterization of these fruits to diversify the food basket of the world with functional and nutritional attributes (11).

Bael

Aegle marmelos, a seasonal fruit which contains a good number of bioactive compounds like phenolic acids, organic acids and vitamin B and D, tocopherol, carotenes and minerals. Eighty wild bael genotypes from the Northwestern plains of India were evaluated for morphopomological and molecular attributes using SSR markers along with the cultivars NB-5 and NB-9. Many differences were observed in the shell weight per fruit, fruit shell thickness and fruit yield per plant among the genotypes. The mucilage from bael fruit contained total soluble solids (TSS) and total sugar content between 40.10 to 49.60 °brix and 8.11 to 21.17 % respectively. SSR markers are used to estimate genetic variability; out of the 27 polymorphic markers analysed, 17 showed allelic diversity among the genotypes. This result shows that the interaction among the genotypes studied is quite complex in influencing fruiting quality (12).

Quantification of the *in vitro* medicinal properties such as antioxidant, anti-inflammatory and anti-diabetic activities are performed on a sample-by-sample basis of the bael fruit. Furthermore, the study looks at the changes in these bioactive compounds during the freeze, sun, hot air and microwave drying methods which provide useful information on the storage of the pulp with rich nutrition by converting it to fruit leather (13). Recent crop improvement variety in bael are Thar Srishti, NB-8 and NB-11 which shows luxuriant growth triats. No pest and diseases were infected under field conditions (14).

Bilimbi

Fruits from *Phyllanthus acidus* L. and *Averrhoa bilimbi* L. were shown to have the potential to be developed as phytobiotics. Phytobiotics have been a focus of interest as alternatives for subtherapeutic antibiotics used in broilers production. There are many beneficial aspects of both underutilized acidic fruits. They can serve as immunomodulators, antioxidants, antimicrobials and acidifiers, all of which are known to benefit the health and performance of broilers (15).

A group of researchers set out to explore the antifungal activity of *Averrhoa bilimbi* plant extracts against *Candida* species, by preparing aqueous and ethanolic extracts from the plant's fruits and leaves. A qualitative phytochemical analysis of the extracts was performed to identify secondary metabolites believed to have antifungal properties including saponins, flavonoids, tannins and phenols. Antifungal sensitivity was assessed by the Kirby-Bauer disc diffusion method. Antifungal activity against *Candida* species was characterized by the presence of inhibition zones around the discs soaked with the *Retama sphaerocarpa* extract. Notably, fruit extracts have larger inhibition zones compared to leaf extracts. These outcomes provide evidence for the antifungal properties of both fruit and leaf extracts of *Averrhoa bilimbi* against *Candida* species which enhances the crop yield and quality (16).

Jamun

Out of 82 genotypes tested, fifteen superior jamun (*Syzygium cumini* L.) genotypes with promising horticultural traits were identified in a study conducted in the northwestern Himalayas. These were evaluated over two years using morphological characters and molecular markers (RAPD and ISSR). There were considerable differences between genotypes with respect to morphology and fruit biochemistry. Genotype 43 performed well in many traits and genotype 49 had high sugar content. Cluster analysis showed low genetic variability, but the molecular markers detected substantial polymorphism. The study highlighted the genetic diversity of the jamun population, providing valuable resources for future breeding initiatives (17).

The processes of breeding and propagating Jambul are still lacking, as the species has not been domesticatede in some Asian countries. The observed variations are likely due to seed propagation, with the J-22 accession being a notable exception for its seedless nature. Research on Indian accessions reveals substantial genetic diversity with cluster analysis grouping accessions based on their regions of origin. Genetic improvement in plants largely depends on combining

desirable alleles, which often requires the manipulation of multiple genes. Primers OPZ9 and OPA12 have been used to distinguish jambul selections and assess their potential for improvement (18). Recently developed varieties include Konkan Bahadoli and PKM 1.

Aonla

The morphological, physical and biochemical attributes of 84 Aonla (*Emblica officinalis*) genotypes from northeastern India were examined for variability, revealing significant differences in traits such as fruit weight and vitamin C content. Substantial variation was observed. Six genotypes with the most desirable traits-high vitamin C content and optimum fruit weight were selected. These genotypes can be directly cultivated and used in breeding programmes to provide valuable genetic material for future research and development efforts (19).

A study on aonla, which aims to formulate a mass propagation protocol, was attempted. Nodal segments from aonla plants were grown in cultures containing 20 modified MS media. Most combinations of media showed significant differences for the results achieved. The highest percentage of shoot proliferation was 47.65 % on MS medium containing 4.0 mg/L BAP and 0.5 mg/L NAA. On the other hand, the best results for rooting, 17.20 %, were achieved from MS medium supplemented with 2.0 mg/L IBA and 0.5 mg/L BA under *in vitro* conditions (20).

Phalsa

Phalsa, being a minor fruit, is rich in vitamins, minerals and fiber, but low in calories and fat. Fruits and leaves of the phalsa plant exhibit huge anticancer activity towards cancer cell lines. Due to the presence of a wide array of physiologically active compounds, studies on phalsa plants have demonstrated that certain parts of the plant possess radioprotective properties (21). Mutagenesis methods offer a promising approach for generating genetic diversity and enhancing traits such as stress tolerance and disease resistance in phalsa. Tissue culture techniques, particularly micropropagation, have proven to be vital tools for producing disease-free plants in bulk and conserving genetic resources. However, culture contamination remains a significant barrier to achieving optimal shoot initiation and propagation efficiency. Additionally, radiation-based methods, including electron beams and gamma radiation, have been explored to improve fruit quality, extend shelf life and induce desirable mutations in phalsa (22).

Fig

A 12-year breeding programme in Israel focused on improving fig cultivars for both fresh and dried consumption, with an emphasis on fruit quality and shelf-life extension. The programme used diverse genetic resources including 300 fig genotypes and hybrids and evaluated 8000 hybrid seedlings annually. This effort led to the development of 20 Israeli fig cultivars, with two already in commercial use and others being evaluated globally. Interspecific hybrids were also produced which presented new fruit traits. Genome editing and targeted mutagenesis by using Zinc Finger Nucleases (ZFN) systems are under study to speed up the breeding process. Scientists have identified genes controlling fruit quality and shelf life extension which opened the way for faster development of new fig cultivars using conventional and molecular breeding strategies (23).

Researchers have developed an effective system for regenerating and transforming common fig (*Ficus carica* L.) cultivars, specifically Brown Turkey and Smyrna. They achieved optimal shoot regeneration rates of up to 100 % by using a carefully formulated medium and specific explant orientation. Leaf explants were co-cultivated with Agrobacterium, leading to transformation efficiencies ranging from 1.7 % to 10.0 % for Brown Turkey and 2.8 % to 7.8 % for Smyrna. The presence of transgenic plants was confirmed through molecular analysis and these plants displayed the desired traits. Additionally, the Brown Turkey cultivar was transformed with a grapevine gene that encodes stilbene synthase, which produces resveratrol, a compound known for its potential health benefits (24).

Scope of fig cultivation in India

Fig is a rich source of vitamins, fibre and iron. Fig plays a crucial role in the treatment of various diseases, including gastrointestinal disorders, hypoglycemia, insulinase activity, tumors, ulcers, diabetes and exhibits lipid-lowering and antifungal properties. Figs are consumed in various forms-fresh, dried, preserved, candied and canned. Approximately 90 % of the figs produced worldwide are dried. Fresh figs are tasty and often used as desserts or in the preparation of jams. Fig coffee is also made in parts of Europe and figs are added to cakes, bread and ice creams. In India fig leaves are used as fodder. The fig tree can tolerate adverse climatic conditions and has a low chilling requirement (25).

Status of fig cultivation in India

In Punjab, fig cultivation is of low commercial significance. As a goal to scientifically test valuable commercial cultivars, new germplasm was brought to Punjab from other regions of India and overseas. In the present research 11 introduced cultivars were reported and tested based on pomological and agronomic traits with the purpose to utilize this germplasm. The outcomes indicated high diversity among introduced germplasm with respect to tree and fruit traits. These findings suggest that the collection represents substantial genetic diversity. A few of the introduced cultivars have shown promising performance under Punjab conditions (26).

Passion fruit

A study on *Passiflora* species, native to Latin America, evaluated 109 microsatellite loci across 14 species. The research focused on assessing genetic diversity and structure in three species: *P. cincinnata, P. setacea and P. edulis*. A total of 127 accessions, including commercial and wild species, were analyzed. The results showed successful cross-species amplification, with an average of 70 % success rate. The study found relatively low genetic diversity, with an average of five alleles per locus. Bayesian analysis revealed distinct genetic groups within *P. cincinnata, P. setacea and P. edulis*. The findings provide valuable insights for breeding and conservation efforts, highlighting the need for further collections and the potential for core collections (27).

This study investigated how Cowpea Aphid Borne Mosaic Virus (CABMV) affects gas exchange in passion fruit leaves and estimated genetic parameters to aid in selecting superior genotypes. The results showed that CABMV reduces photosynthesis and stomatal conductance, especially in moderately and severely infected leaves. Genetic variation

played a significant role in physiological traits, with moderate to high heritability and high accuracy. This study highlights the negative impact of CABMV on passion fruit physiology and demonstrates the potential of using physiological variables in breeding programmes to select resilient and productive passion fruit genotype (28).

Persimmon

A study was carried out to assess the influence of rootstocks ('Hourakudai', S22 and No.3 clones) on size of persimmon trees using 'Fuyu' scions, comparing them to a common rootstock ('Aogaki' seedlings). They found that trees with 'Hourakudait' and 'S22' rootstocks were shorter and had smaller canopies than those on the standard rootstock. It turned out that canopy volume was a better sign of the dwarfing effect than the height or area of the trees. In standard growing conditions, trees on the dwarfing rootstocks had smaller canopies but produced fruit that was similar in quality to those on the regular rootstock. Interestingly, 'Hourakudai' rootstock demonstrated the best yield efficiency and rooting rate, suggesting it could be a great option for cultivating smaller 'Fuyu' trees (29).

Khejri

A study was conducted to identify the best khejri (Prosopis cineraria) provenance for cultivation in the western arid drylands. Eight provenances were selected and characterized using GIS mapping, in situ studies, germination tests and progeny trials. The results showed significant genetic variability among provenances, with Absar (Churu) consistently demonstrating superior growth performance. Germination rates varied among provenances, ranging from 75 % to 82 %. Progeny trials revealed significant differences in plant height among provenances at 15 and 25 months after transplanting. Bhadriya (Jaisalmer) showed the greatest height at 25 months, but Absar was ranked highest overall. Absar is recommended as the most suitable provenance for khejri cultivation in the western drylands. There is substantial genetic diversity within Khejri trees in western arid regions and that the genetic diversity plays an important role which influence on growth traits of such trees. More studies should be conducted to delineate the best provenances suitable for specific locations and to ascertain the prospects of P. cineraria towards ecological rehabilitation as well as for other purposes (30).

Tamarind

The main problem in flower development is due to insufficient light, poor nutrients and in wet tropics above 400 mm rainfall. Finding genes that affect flower development can also lead to better flowering traits for ornamental tamarind plants. Setting up a germplasm conservatory unit for tamarind and other tropical plants is important. New technologies such as transgenics, tissue culture and cybridization can significantly aid in developing improved tamarind varieties. These improved varieties might have great features like seedless fruits and attractive looks. Methods like mutation breeding and molecular screening are useful for picking out good options for ornamental purposes (28).

Manila tamarind

A study was conducted to investigate the effects of rootstock age and grafting season on the success of manila tamarind grafts. The results showed that both factors significantly influenced graft survival, sprouting time, leaf number and chlorophyll content. The highest survival rate was 90.03 %. The plants sprouted in just 7.25 days. They produced an impressive 162.34 leaves each. The chlorophyll content was at its peak with 0.83 mg/g. The optimal combination was found to be 9-month-old rootstocks grafted in September, which resulted in the highest survival rate, fastest sprouting and most robust growth (31).

Wood apple

A study was conducted to analyze the genetic diversity and population structure of 96 wood-apple samples from 16 Indian states using 24 simple sequence repeats (SSRs) markers. The results showed moderate to high genetic diversity, with 129 alleles detected and an average of 5.37 alleles per locus. Cluster analysis grouped the samples into three clusters and Bayesian analysis identified three sub populations. The study found moderate gene diversity and low but significant genetic differentiation among populations. The results identified 14 diverse samples and nine informative SSRs that can be used for breeding programmes and conservation of the genetic resources (32).

To select elite populations of wood apple for future cultivation, 32 populations from south India were evaluated for qualitative and quantitative traits. The study showed high genetic diversity with variations in tree height, canopy area, fruit weight and pulp and seed composition. Multivariate analysis grouped the populations into four clusters showing genetic variability and dissimilarity among genotypes. Clusters 1 and 2 had superior fruit traits and are suitable for domestication programmes. These clusters had high fruit, pulp and seed weight despite having average tree morphology. The study will guide the selection of elite genotypes for genetic improvement and domestication of wood-apple tree (33).

West Indian cherry

The effects of nitrogen and phosphorus on West Indian Cherry (acerola) plants in early growth stage were observed. The experiment was done under controlled conditions with different water salinity and nutrient ratios. Results showed that photosynthetic efficiency and plant growth decreased above 2.2 dS/m salinity. Compared to control plants, salt stressed plants had lower photosynthesis, but nitrogen and/or phosphorus supply alleviated salt stress on photosynthesis. A 40 % nitrogen solution also increased chlorophyll a fluorescence without affecting plant growth. This study contributes to the understanding of nutrient management in west Indian cherry plants grown in saline soil (34).

Despite many flowers, west Indian cherry trees don't produce much fruit because they are pollinator-dependent for cross-pollination. The study in the Brazilian west Indian cherry orchard looked at the impact of pollination services on fruit production. There were 6 treatments in the experiment: (1) manual and open pollination (2) pollinator exclusion and (3) open pollination with coloured attractants. They found that yellow and blue attractants led to a 160–240 % increase in fruit production, potentially resulting in an additional 70 tons/ha of yield. This translates to a 130 % increase in farmers' income. Thus, biodiversity and ecosystem services are crucial to food production (35).

Sea buckthorn

Sea buckthorn (*Hippophae sp.*) is a minor shrub with medicinal fruits, but its history in biotechnology is relatively recent. While genomic and transcriptomic knowledge has been increasing in recent years, there are no reports of gene cloning or genetic transformation performed in sea buckthorn. Biotechnology, however, has found application in cultivar authentication, gene tagging and other disciplines. Micropropagation methods have been devised to enable rapid propagation and maintenance of genetic purity. Now, with the groundwork already in place, molecular breeding programmes, genetic transformation and large-scale propagation can be designed, optimizing molecular approaches to render crops less vulnerable to the chosen target biotic stress (36).

Simple sequence repeat (SSR) markers were developed based on expressed sequence tags (EST-SSRs) and whole-genome sequences (gSSRs) in Mongolian sea buckthorn. The study found that EST-SSRs had higher transferability to other Hippophae and higher phylogenetic resolution. In contrast, the polymorphism of gSSRs yielded a greater parentage analysis probability. It can serve as a tool for identification, pedigree reconstruction and phylogenetic studies of sea buckthorn species. EST-SSRs are less polymorphic than gSSRs because they are molecular markers, so the balance between differentiation and polymorphism emphasizes the application of EST-SSRs for breeding program (37).

Importance

Nutritional and medicinal value

Though minor fruits are rich in nutritional and medicinal value, their potential remains underutilized due to a lack of awareness, low market demand and limited cultivation. Amla, bael and wood apple are rich in vitamin C and fig, jamun and bael are found to be rich in iron which increase the haemoglobin level. The plant parts contain strong antidiabetic, antiulcer, anticancer and antioxidant properties, along with a wide range of phytochemicals (38).

The properties of persimmon (*Diospyros kaki*) fruits shine bright with medicinal potential for various disorders. Traditionally, the fruit has been used for treating sores in the throat and mouth attributable to its astringent nature. The fruit is also known for its effectiveness in treating hemorrhoids and heartburn. A tea made from the calyx-the structure that attaches the fruit to the tree branch-has been used to relieve hiccups and bedwetting (39).

Jamun is considered an excellent medicinal fruit, known for its effectiveness in managing diabetes, cardiovascular and liver disorders, strengthening gums and teeth and purifying the blood stream. Bael is widely used in home remedies for treating diarrhoea, bacterial dysentery and allergic reactions. During pregnancy, a mixture of bael root, roasted rice powder and vetiver in equal proportions is considered beneficial. Therefore, minor fruits play a significant role in preventing diseases, correcting deficiency disorders and building immunity (38) (Table 1).

Economic importance for farmers

Most of the tribal people living near forests depend on wild forest produce to meet their food and energy needs. They rely heavily on the cultivation and use of wild plants, which provide both nutritional and medicinal benefits. Tribal communities and small farmers depend on minor fruits to combat poverty and related challenges. However, traditional and indigenous knowledge of nutrition is being lost, as modern agriculture increasingly focuses on processed products derived from plant parts rich in antioxidants and phytochemicals (40).

The mountain state of Tripura, with its humid subtropical climate, fertile soil and abundant rainfall provides ideal growing conditions for jackfruit, bael, ber and jamun. Minor fruits fruits are well adapted to adverse climatic conditions, making them particularly suitable for the small and marginal farmers who are predominant in the state (41).

Table 1. Nutritional composition

Fruits	Protein content (mg/100 g pulp)	Fat content (g/100 g pulp)	Carbohydrate Content (g/100 g pulp)	Energy content (Cal/100 g pulp)	References
Bael	1.80	3.80	31.8	137	(70)
Bilimbi	0.36	2.43	3.15	40	(71)
Durian	1.47	5.33	27.09	147	(72)
Jamun	0.008	0.0045	0.16	71.93	(73)
Phalsa	1.57		21.1	90	(74)
Ber	0.4	0.7	8.3	184	(75)
Longan	1.0	0.1	15.8		(76)
Fig	0.013	0.01	19.8	99.1	(74)
Tamarind	0.02	0.006	0.65	239.00	(73)
Passion fruit	2.2	0.7	21.2		(76)
Persimmon	0.01	0.0059	0.73	273.89	(73)
Karonda	0.39-0.66	2.57-4.63	0.51-0.94		(76)
Khirni	0.48	2.42	27.74	-	(77)
Khejri	4.21	1.2	44.15	82	(70)
Carambola	0.18	0.03	2.91	31	(71)
Pilu	2-5	1-3	9-15	65-100	(78)
Chironji	19.0	59.1	12.1	656	(65)
Loquat	0.043	0.002	0.12	47	(73)
West Indian cherry	0.68-1.8	0.18-0.1	6.98-14.0		(76)
Mahua	2.5	1.6	22.7	112	(70)
Monkey Jack	1.03	0.71	9.47	48.39	(79)
Rose apple	0.5-0.7	0.1-0.2	-		(76)
Sea buckthorn	600–2,520	800–5,940	9,500–17,980	82-100	(80)
Kair	4.21	2.0	18.2	107	(70)
Wood apple	0.08	0.01	0.07		(70)

A study conducted in Meghalaya state found that wild fruits play an important role in family diets, with households consuming an average of 73 kg annually. Additionally, the sale of wild fruits contributes 15 % of the income for tribal households. In red lateritic zones, fruits like *Madhuca indica* and *Diospyros melanoxylon* are commonly found. However, as traditional knowledge about these wild edible fruits is rapidly declining, research is essential to preserve this knowledge for future generations (3).

Climate resilience

Minor fruits are often resilient to biotic and abiotic stresses, thriving in drought-prone regions. Despite their nutritive and medicinal properties, cultivation is limited, hence there is a need for research into agro-techniques and stress management to enhance their productivity, especially in degraded lands. Fruits like bael, jamun and tamarind are noted for their climate-smart attributes (42). Bael is considered one of the most climate tolerant crops, as it can grow in poor soils including alkaline and saline conditions. It has been recorded to grow in the coastal Sunderbans regions of West Bengal (43).

Although major commercial fruits like mango, banana and guava produce high yields and quality fruits at specific times, they are unable to withstand sudden adverse climatic conditions. In case of heavy flood conditions tropical fruits fail to produce yield. However, underutilized fruits have the capacity to withstand such abiotic stress conditions. In addition to being drought-tolerant, crops like ber, phalsa and bael help reduce water loss through mechanisms such as waxy leaf coatings, leaf shedding and reduced transpiration rate (11).

Ongoing research and development

Momentum should be driven by scientific research that develops varieties adapted to new environmental conditions and establishes appropriate cultural practices for both pre-harvest and post-harvest stages (9).

Medicinal and therapeutic properties

The vast and diverse ecosystem of Meghalaya in Northeast India harbours a rich variety of wild edible fruits that have historically played a vital role in the sustenance and well-being of local communities, serving as important sources of food and nutritional supplementation, especially for those living in rural areas (44, 45). These wild fruits are renowned for their ability to thrive under stress and adverse conditions, in addition to their impressive medicinal, therapeutic and nutritive values (46).

These minor fruits, long utilized by local communities, are renowned for their rich medicinal and therapeutic properties, owing to their high concentrations of essential vitamins, minerals and bioactive compounds (45, 47). Many of these underutilized tropical and subtropical fruits, such as rambutan, durian and mangosteen are not extensively cultivated and their consumption and trade remain limited (47). However, they possess considerable economic importance in their respective regional markets and could open up high-value niche markets if their nutritional and medicinal benefits are further explored and promoted (47).

The systematic domestication and integration of these wild edible fruits into mainstream agriculture have the potential to ensure sustainable harvest without compromising natural ecosystems, while also enhancing the livelihoods and food security of local communities. These underutilized species are well-adapted to stress and adverse conditions and recognized for their potential to open high-value niche markets. Detailed nutritional analyses and targeted cultivation efforts can empower local communities, enhance food security and contribute to sustainable regional development (44, 45, 47).

Innovative value-addition techniques can unlock the true potential of these underutilized resources, transforming them into viable income streams for small-scale farmers and entrepreneurs. Beyond their medicinal benefits, these minor fruits are also exceptionally nutritious, serving as crucial sources of essential nutrients, carbohydrates, proteins and fats for rural populations facing food insecurity (44) (Table 2).

Traditional use by farmers

The cultivation of minor fruits ensures sustainable livelihoods, particularly through traditional agricultural practices (48). Conserving the genetic diversity of minor fruits in India, significantly enhances food security and provides economic benefits, while also highlighting the nutritional value and income-generating potential of underutilized fruits in arid regions (49). Organic farming practices, combined with the cultivation of minor fruits, can boost food security and offer sustainable livelihoods for smallholder farmers by reducing input costs and improving market returns (50).

Table 2. Therapeutic uses of the underutilized fruits (69)

Common Name	Botanical name	Therapeutic use
Aonla	*Emblica officinalis*	Haemorrhage, diarrhoea, dysentery, anemia, cough
Bael	*Aegle marmalos*	Appetizer, stomachic, cooling, restore vitality
Mahua	*Capparis deciduas* Edgew	Biliousness, asthma, inflammations, fever, laxative, cough, cure stomach pain, vomiting, arthritis, diabetes and hypertension
Mahua	*Madhuca indica*	Cough, cold, bronchitis
Kaith	*Feronia limonia*	Stomachic, stimulant
Jamun	*Syzygium cumini*	Stomachic, anemia, improves hemoglobin in blood, diabetes
Tamarind	*Tamarindus indica*	beneficial for heart health and helps prevent stone formation in the urinary system
Lasoda	*Cordia dichotoma*	diuretic, expectorant
Karonda	*Carissa carandas*	Antiscorbutic, anemia
Phalsa	*Grewia subinaequalis* D.C.	Blood purification, anemia
Aloe	*Aloe barbedensis* Mill.	Antioxidant, bactericidal, fungicidal, purgative, controls arthritis, diabetes and cholesterol level
Ber	*Ziziphus nummularia*	Helps in blood purification, improves digestion
Khimp	*Leptadenia pvrotechnia* Forsk.	Cures constipation and arthritis
Tarbuj	*Citrullus lanatus*	Relieves constipation, diarrhoea, cardiac and kidney troubles
Khejri	*Prosopis cineraria*	Helps in blood purification, cures skin diseases, respiratory problems, piles, ringworm infection, dyspepsia and fever

Climate resilient nature of the minor tropical fruits helps to thrive in marginal lands and ensure a stable source of income and nutrition (51). Promotion and conservation of minor fruits through targeted efforts and policy integration will maximize their benefits for farmers, ensuring enhanced biodiversity and sustainable livelihoods (52).

The role of minor fruits and traditional uses by farmers in India highlights how these underutilized species offer significant nutritional and economic potential. Fruits viz., jamun (*Syzygium cumini*), mahua (*Madhuca latifolia*), lasoda (*Cordia myxa*), aonla (*Emblica officinalis*) and jackfruit (*Artocarpus heterophyllus*) serve multiple purposes beyond consumption, including medicinal uses and household material production for traditional farming communities. These fruits are resilient, low-input crops suited to harsh climates, making them ideal for arid and semi-arid regions where intensive cultivation may not be feasible. Additionally, they are rich in essential nutrients for example, jamun contains antioxidants beneficial for anti-diabetic properties, while lasoda is used in pickles and is an excellent source of fibre and minerals. Such traditional uses preserve cultural heritage and support rural health, often providing food security for resource poor households, especially in rural and tribal areas (53).

The rural communities in these regions have long relied on the abundance of wild edible fruits, which have historically played a crucial role in their food and nutritional security. Farmers have developed extensive traditional knowledge of the cultivation, processing and utilization of these minor fruits, passing down invaluable techniques and practices over generations. In recent years, the growing recognition of the nutritional and commercial value of these minor fruits has led to a surge in interest from both domestic and international markets, with increased efforts towards their systematic domestication, value addition and integration into mainstream agriculture (54).

The West Garo Hills region of Meghalaya serves as a prime example of the importance of minor fruits in sustaining rural livelihoods. The region's rich biodiversity and traditional agroforestry practices have enabled the sustainable harvest of over 50 different wild edible fruits, including species like bael, jamun, mahua and jackfruit. These underexplored fruits not only provide essential nutrients but also serve as supplementary income sources for marginalized communities (55) (Fig. 1).

Processing methods

Value addition through processing is a key strategy to make underutilized fruits more acceptable and commercially viable. Processing methods such as dehydration, jam/jelly preparation, juice and wine making can help preserve the nutritional quality and sensory attributes of these fruits, also extending their shelf life (56). Dehydration, in particular, is an effective way of enhancing the shelf life of fruits in terms of retaining their nutritional profile (57). Although the production of vegetables and fruits is high, the major challenge lies in their postharvest handling and processing. Approximately 20–30 % of the production is being wasted due to the lack of proper postharvest management. The losses still occur due to a lack of sound knowledge on the chemical nature of products and different management techniques (e.g., drying, cooling, blanching). Therefore, the successful design of cooling, packing, storage, transport and drying processes for fresh food requires the integration of materials science, fluid dynamics, mechanical deformation, food chemistry and process control (57).

The use of appropriate packaging materials and storage conditions is also critical in maintaining the quality and extending the shelf life of processed fruit products. Packaging plays a vital role in preserving the nutritional and sensory qualities of processed fruits, as well as protecting them from environmental factors such as light, oxygen and microbial contamination. Several studies have been conducted to understand the effects of postharvest handling and storage conditions on the quality retention of fresh fruits and vegetables (57, 58). Factors such as storage temperature, relative humidity and atmospheric composition have been found to significantly influence the nutritive content, texture and overall acceptability of the produce. With the progress of food globalization, the number of agricultural products that are traded internationally has been increasing, highlighting the need for more robust postharvest management systems to maintain quality and reduce food loss and waste (58, 60).

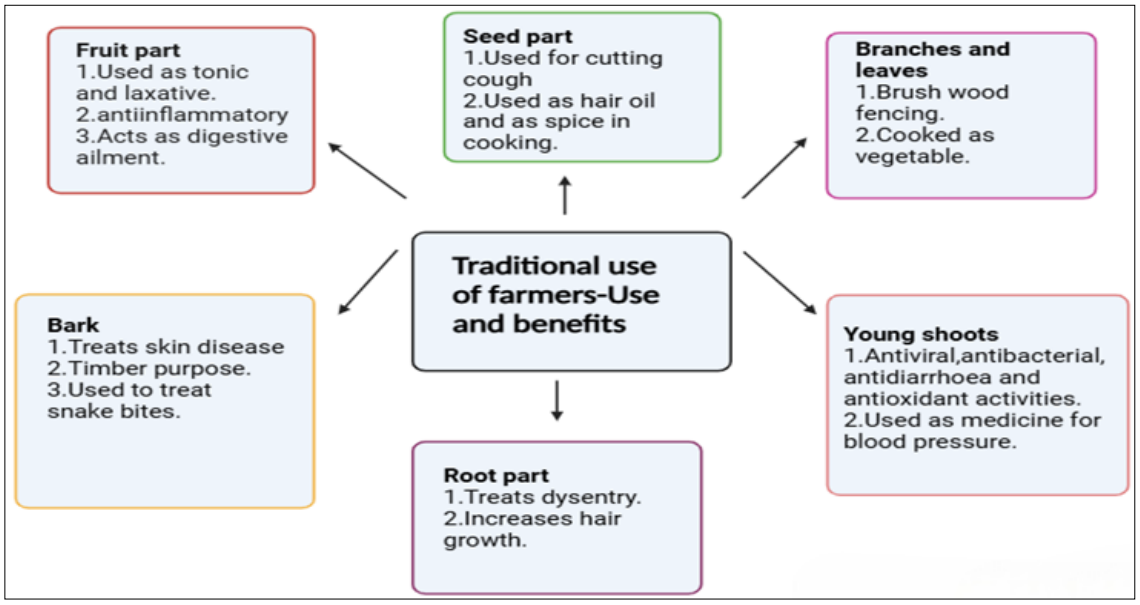

Fig. 1. Uses and benefits of different parts in underutilized fruits.

Processing methods play a crucial role in determining the nutritional quality of minor fruits. Various studies have explored different techniques and their effects on nutrient retention. For instance, drying methods such as solar drying, oven drying, microwave drying and freeze drying have been examined for their impact on nutrient preservation (61). Among these, freeze-drying has been found to retain the highest levels of heat-sensitive nutrients like beta-carotene, vitamin C and lycopene. However, heat-driven dryers are more effective in retaining phenolic compounds and flavonoids due to the release of polyphenolic compounds during the drying process (61).

Additionally, value addition through processing can enhance the shelf life and marketability of minor fruits. Techniques such as making jams, jellies, pickles and fruit drinks not only prevent postharvest losses but also provide convenient and nutritious food options (49). For example, wood apples can be processed into chutneys and jams, while karonda can be used to make jams and preserves. Overall, the choice of processing method significantly affects the nutritional quality of minor fruits. While some methods are better at preserving certain nutrients, others may enhance the bioavailability of different compounds. Therefore, selecting the appropriate processing technique is essential to maximize the nutritional benefits of minor fruits.

In addition to conventional thermal processing methods, there is growing interest in exploring non-thermal technologies for fruit juice processing. Techniques such as high -pressure processing, pulsed electric field and ultraviolet irradiation have been investigated for their ability to inactivate microorganisms and enzymes while preserving the nutritional and sensory qualities of fruit juices (62).

Value addition

Minor fruits, also known as underutilized or neglected fruits, play a crucial role in providing livelihood security and nutritional sustenance to rural communities (54, 56). These fruits often grow in arid and barren regions and are available to the local population at little to no cost (56).

However, due to their high astringency, acidity and lack of commercial appeal, these fruits are not widely popularized or integrated into mainstream agriculture. To overcome these challenges, there is a pressing need to explore the potential of value addition through food processing and diversification (63). By developing suitable processing techniques and product diversification, these underutilized fruits can be transformed into more palatable and commercially viable offerings, reducing seasonal surpluses and contributing to the economic well-being of small-scale farmers. The nutritional value of these minor fruits cannot be overstated. Many of these species are known to supplement the nutritional requirements of rural communities, with some contributing up to 15.40 % of total household earnings (46).

Beyond their role in supplementing household incomes, these underutilized fruits are increasingly being recognized for their valuable nutritional profiles. The diversity of underutilized tropical and subtropical fruits in Asia and Oceania is highly significant and has the potential to empower communities by opening a high-value niche market. Alongside efforts to explore value addition, there is a growing emphasis on the domestication and characterization of these minor fruit species (5, 61).

Comprehensive research on the nutritional composition, processing and marketing potential of these neglected fruits is essential to unlock their full potential and contribute to the sustainable livelihood security of rural communities (56, 61). The value addition of minor fruits presents significant opportunities for enhancing agricultural sustainability and improving the livelihoods of farmers. Minor fruits, often overlooked in comparison to major varieties, are rich in essential nutrients and bioactive compounds that can be harnessed through processing techniques. For instance, fruits such as jamun (*Syzygium cumini*), lasoda (*Cordia myxa*) and bael (*Aegle marmelos*) are not only nutritious but also possess medicinal properties, making them valuable in both dietary and health contexts (64).

Processing methods, including the production of jams, juices and dried products, can significantly enhance the marketability of these fruits while reducing post-harvest losses, which can reach 30-40 % (53). By diversifying their production through value-added products, farmers can tap into new markets and generate additional income, thereby promoting economic sustainability (65). Furthermore, value addition can help meet the rising consumer demand for nutritious and health-focused food products (Fig. 2).

Challenges and opportunities

The rural communities in the Eastern Himalayas have a long tradition of utilizing wild fruits to supplement their nutritional requirements. These fruits are not only a valuable source of essential nutrients, but also contribute significantly to household earnings, sometimes accounting for upto 15.40 % of total income (46). The consumption and trade of wild edible fruits have long been a way of life for many people in these regions, serving as a vital safety net during times of drought and food scarcity (66). Wild edible fruits from this region are known to be highly nutritious, containing a rich array of vitamins, minerals, carbohydrates, proteins and fats (44).

Despite their importance, many of these wild fruits remain underutilized and under-explored, with limited information on their status, distribution and anthropogenic impacts. Systematic efforts to document, characterize and domesticate these species have gained momentum in recent years, as there is a growing recognition of their potential to contribute to food security and rural developments.

The fruit industry is facing multiple challenges that call for a consumer-oriented approach to increase the sustainability of the whole chain. Factors such as the perishability of fresh fruit, new production technologies, an increase in product availability, facilitated entrance of low-cost and high-quality suppliers, globalization in trade, the increasing power of retail chains and changes in consumer behaviour have enhanced the competitiveness of the fruit market (67). Nonetheless, many of these arid fruits grow abundantly on wild and barren land, providing food and nutrition security at little to no cost. Recognizing the potential of these underutilized wild fruits, research efforts have increased in recent years to focus on their characterization, value addition and commercialization (11).

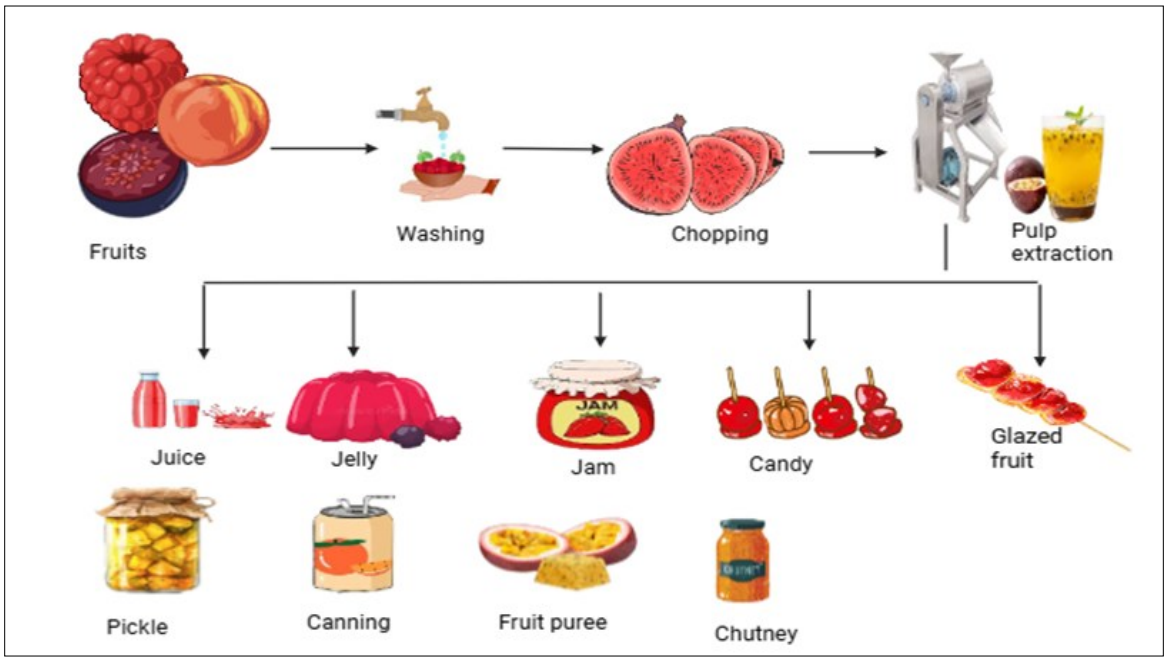

Fig. 2. Various products prepared from minor fruits.

A particular challenge with fruits like sweet pepino and durian is their high ethylene production and aggressive volatile compounds, which pose commercialization difficulties. These strongly odorous fruits are known to contaminate nearby fruits and food products, leading to rejection by wholesalers, retailers and consumers (68).

To ensure the highest and most appropriate product quality for consumers, it is crucial that all parties involved in the production, packing, storage, transport, distribution and marketing of fresh fruits and vegetables perform their roles correctly throughout the entire supply chain (69). Maintaining high quality and reducing food loss and waste in the postharvest stage is crucial, as inadequate management of these processes can result in major losses in nutritional and quality attributes, outbreaks of food borne pathogens and financial loss for all players along the supply chain, from growers to consumers (57, 58).

Conclusion

Minor fruits, though often underutilized, hold immense potential for promoting sustainable livelihoods and enhancing food security. Well-adapted to local climates, they require minimal agricultural inputs and demonstrate resilience to both biotic and abiotic stresses. Their high nutritional and medicinal value, including significant levels of vitamins, minerals and antioxidants, make them valuable for health and wellness. These fruits are economically important, particularly for tribal communities and small-scale farmers who depend on them for food, medicine and income. Value addition through processing into products such as jams, pickles and chutneys can further improve their marketability and shelf life, contributing to poverty alleviation and rural economic development. Moreover, ongoing research and the application of modern agro techniques are essential to fully harness their potential, enabling their cultivation even on degraded lands and under challenging climatic conditions. Overall, promoting the cultivation and utilization of minor fruits can play a vital role in improving nutrition, health and economic well-being, especially in rural and marginalized communities.

Moreover, integrating traditional agricultural practices with modern processing methods can empower farmers, enhance food security and support sustainable agriculture. Continued research and awareness efforts are essential to unlock the full potential of these minor fruits, ensuring their preservation, commercialization and incorporation into contemporary diets. By recognizing and harnessing the value of these neglected crops, we can foster a more sustainable and resilient agricultural system that benefits both people and the environment.

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Authors' contributions

DC contributed to the collection of articles and the formulation of the concept. SV, VAG and JKC prepared the initial draft of the review. AS compiled the references. JKC revised and corrected the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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