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Exploring Bioactive Compounds in Underutilized Fruit Crops of Arid and Semi-Arid Regions: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Exploring the bioactive compounds in underutilized fruit crops of arid regions reveals a wealth of phytochemicals, including polyphenols, vitamins, polyunsaturated fatty acids, amino acids, and carotenoids. These compounds exhibit significant health benefits, evidenced through both in vitro and in vivo studies, demonstrating antioxidant, anti-inflammatory, antimicrobial, hypolipidemic and neuroactive properties. This review delves into the bioactive compounds found in fruits of arid and semi-arid regions, highlighting their phytochemical compositions and their potential in preventing chronic diseases, thereby enhancing human health. Underutilized fruit crops, typically grown and consumed locally rather than being commercially cultivated or widely traded, offer several

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advantages. They are easier to grow, more resilient to climate change, and exceptionally rich in phytochemicals with medicinal properties. These fruits, such as Indian jujube, Indian gooseberry, bael, and tamarind, among others, are valuable for their high nutritional content and potential to meet the dietary needs of rural populations in arid regions. Local knowledge attests to their nutritional and medicinal benefits, necessitating rigorous study for conservation and nutritional characterization to broaden future food options and enhance functional and nutritional values. This review outlines the ethnobotany, medicinal and nutritional values, biodiversity conservation, and utilization strategies for significant underutilized fruit crops from arid and semi-arid regions. These fruits are rich in diverse phytochemical compounds like flavonoids, tannins, terpenoids, saponins, glycosides, and alkaloids, which are utilized to treat various health conditions in humans and livestock. Their extracts demonstrate a range of activities, including antipyretic, analgesic, anti-inflammatory, anticancer, antimicrobial, antiplasmodial and antinociceptive effects. Highlighting the current research on the nutritional profiling, chemical composition, and potential applications of these fruits, this chapter addresses the knowledge gap concerning the health benefits of consuming arid and semi-arid fruits. This is particularly relevant given the growing interest in "superfoods" and the need for evidence-based public health guidelines to inform consumers about the benefits of polyphenol-rich plant foods in preventing chronic diseases such as cardiovascular disease and cancer.

Keywords: Flavonoids; tannins; terpenoids; saponins; antimicrobial; hypolipidemic; neuroactive.

1. INTRODUCTION

Fruits are an abundant source of natural bioactive compounds, including polyphenols, vitamins, polyunsaturated fatty acids, amino acids, and carotenoids [1]. These compounds are widely recognized for their health benefits, supported by various in vitro and in vivo studies. They exhibit diverse biological activities, such as antioxidant, anti-inflammatory, antimicrobial, hypolipidemic, and neuroactive properties, which contribute significantly to human health [2-3]. This review explores the bioactive compounds in underutilized fruit crops of arid regions, their phytochemical compositions, and their potential in disease prevention and health promotion. The increasing consumer awareness about the health benefits of fruits has led to a significant rise in their consumption as part of a balanced diet. The demand for nutrient-dense fruits has surged globally, driven by their positive effects on immune and metabolic health [4]. This trend has been further amplified by the COVID-19 pandemic, which underscored the importance of maintaining good health through proper nutrition.

In India, major fruit crops such as mango, banana, citrus, guava, and apple dominate the agricultural landscape, covering more than 72% of the total area under fruit cultivation [5]. In contrast, indigenous fruit crops occupy only 6.56% of the area, yet they demonstrate high productivity. Climate change poses a significant threat to the sustainable production of these major commercial fruits, with rising temperatures, increased UV radiation, and extreme weather events like droughts and floods exacerbating the challenges [6-8]. These environmental stresses can lead to heightened salinity, mineral imbalances, and increased vulnerability to diseases and pests [9,10]. Given these challenges, there is a growing need to explore and utilize underutilized fruit crops that are more resilient to climate variations and adaptable to diverse agro-climatic conditions [11]. These indigenous crops, although not widely cultivated or traded, offer several advantages. They are easier to grow, more resilient to environmental stresses, and exceptionally rich in phytochemicals with medicinal properties. These crops can play a crucial role in meeting the nutritional needs of local populations in arid regions, where food security is often a concern.

In the Indian arid zone, around 30 plant species are known for their edible uses, with about 19 bearing horticultural significance. Many of these underutilized fruit crops, such as ber (Indian jujube), kair, aonla (Indian gooseberry), lasora, and phalsa, are richer in minerals, antioxidants, and phytonutrients compared to many commercially grown fruits [12]. Despite their nutritional and medicinal benefits, these fruits are not popular and are sold at low prices in local markets. This is due to a lack of awareness about their nutritive values, limited consumption habits, insufficient research, and inadequate governmental policies for their promotion. Recognizing the potential of these underutilized fruit crops, the Government of India, under the Mission on Integrated Development of

Horticulture (MIDH), has initiated efforts to establish orchards of these species [13]. This initiative aims to enhance the nutritional and socio-economic security of regions by leveraging the nutritional richness, wide adaptability, and medicinal properties of these fruits. Underutilized fruit crops in arid regions are not only important for their nutritional value but also for their role in traditional medicine. These fruits contain a diverse range of phytochemicals, such as flavonoids, tannins, terpenoids, saponins, glycosides, and alkaloids, which are used to treat various health conditions in humans and livestock. Their extracts have demonstrated a range of bioactive properties, including antipyretic, analgesic, anti-inflammatory, anticancer, antimicrobial, antiplasmodial, and antinociceptive effects [14].

This review focuses on the importance of 19 underutilized fruit crops endemic to the arid and semi-arid regions of India. It examines their adaptation mechanisms to stress conditions, genetic diversity, ethnobotany, and medicinal and nutritional values. Additionally, it explores potential strategies for their conservation and exploitation to improve the nutritional and socio-economic security of these regions. Dietary guidelines consistently emphasize the importance of plant-based foods in a healthy diet, with fruits being a primary source of bioactive compounds. Polyphenols, which are secondary metabolites of plants, play a crucial role in this context [15]. They contribute to the color, flavor, odor, and oxidative stability of fruits and have been linked to numerous health benefits. Epidemiological studies suggest that long-term consumption of diets high in fruits and vegetables offers protection against cardiovascular diseases, certain cancers, and diabetes [16]. This review highlights the chemical composition and bioactive properties of fruits from arid and semi-arid regions. It aims to bridge the knowledge gap regarding the health benefits of these underutilized fruits and to provide a foundation for further research and development in this field. By understanding the specific benefits of individual polyphenol-rich fruits, public health guidelines can be improved, ensuring that consumers are well-informed about the health advantages of these valuable fruits.

2. BIOACTIVE COMPOUNDS AND HEALTH BENEFITS OF ARID AND SEMIARID FRUITS

Polyphenols are secondary plant metabolites, naturally occurring within a variety of plant-based foods, with over 8000 identified in plants. They include phenolic acids, which are classified according to the number of phenolic rings containing one or more hydroxyl groups directly linked to an aromatic ring [17]. These can be conjugated with sugar residues or other compounds such as organic acids, lipids, and amines [18,19]. The intake of phenolic compounds varies significantly based on dietary habits, ranging from 100 to 1000 mg/day per person in Europe, and up to 2000 mg/day per person in countries like Japan [20]. Factors such as ripening, growth and harvest conditions, fruit processing, and storage affect the number of phenolic compounds in a specific fruit. The most common phenolic compounds in plant foods are flavonoids, which include flavonols, flavanones, isoflavones, phenolic acids, anthocyanins (ACs), and tannins. These are found in apples, oranges, tea, berries, nuts, and cereals. Phenolic acids, divided into hydroxybenzoic and hydroxycinnamic acids, are common in foods like wheat bran and are often found as esters. Flavonoids are a large group of dietary polyphenols, with about 4000 identified in plants [21,22]. They include flavonols, flavonones, flavanols, flavones, anthocyanins, and isoflavones, which differ in the number and arrangement of hydroxyl groups. These compounds are biologically active and contribute to the color of fruits, flowers, and leaves. Anthocyanins, water-soluble plant pigments, give color to many fruits and vegetables and exist as glycosides. There are six common anthocyanins, with over 540 identified in nature. They vary in the number and position of hydroxyl and methoxyl groups and the identity, number, and positions of attached sugars. Anthocyanins have a wide range of health-related properties [23].

The health benefits of polyphenols depend on both intake and bioavailability, influenced by their chemical structure and absorption throughout the gastrointestinal tract. Aglycones are absorbed in the small intestine, while many polyphenols present in fruits and vegetables as esters, glycosides, or polymers are not absorbed in their native form but can be hydrolyzed by gut enzymes and colonic microflora [24]. Following absorption, polyphenols undergo conjugation in the small intestine or liver, mainly through methylation, sulfation, and glucuronidation, resulting in the presence of aglycones in the blood at low concentrations. The absorption of polyphenols varies, with non-anthocyanin flavonoids being better absorbed than anthocyanins and proanthocyanidins [25].

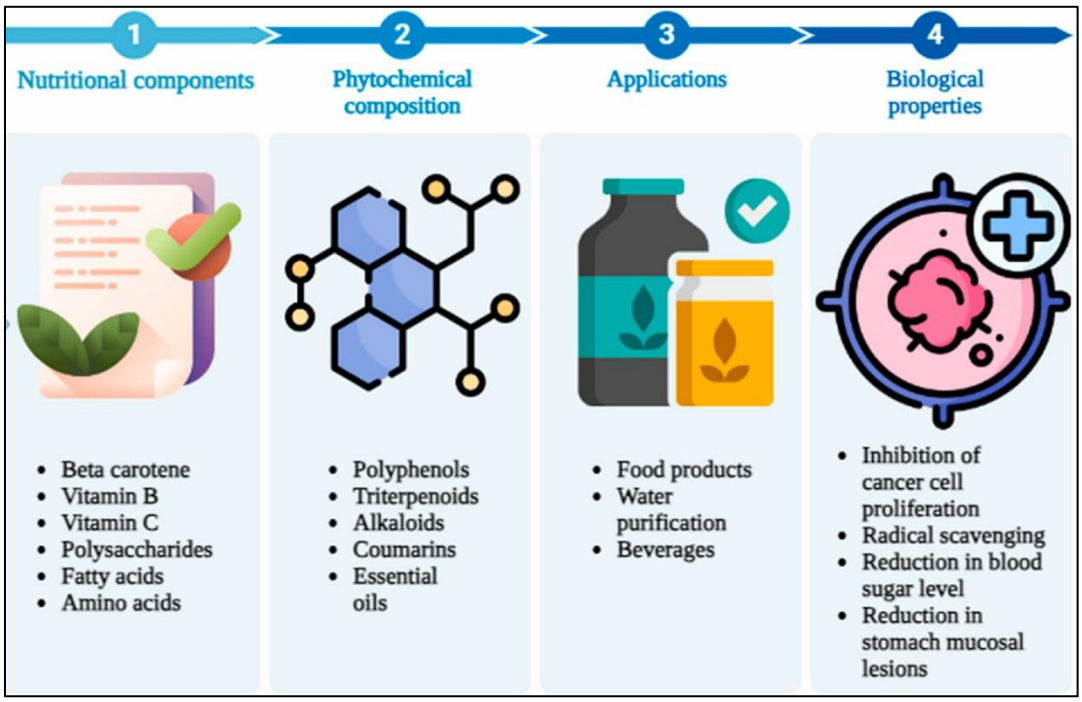

Fig. 1. Nutritional components, its phytochemical composition, application and biological properties of underutilized fruits

Factors such as the food matrix, gender, genetic differences, dietary habits, and gut microflora influence the absorption process. Arid and semi-arid fruits are rich in bioactive compounds that offer significant health benefits. Prickly pears are high in antioxidants and bioactive compounds, providing antidiabetic, antiulcerative, antitumor, antimicrobial, and anti-inflammatory effects. Wood apple contains compounds like bergapten and various acids, contributing to its antioxidant, antidiabetic, antiulcerative, antitumor, and antimicrobial properties [26].

Mulberry is known for its anthocyanins, quercetin glycoside, chlorogenic acid, and polysaccharides, offering antioxidative, anticancer, antidiabetic, and anti-obesity benefits [27]. Pomegranate, with its high antioxidant capacity and phenolic compounds, is effective against chronic diseases like cancers and cardiovascular disease. Olive contains phenolic compounds that provide cardioprotective, antioxidant, and anti-inflammatory properties, with olive oil enhancing heart health. Papaya is rich in saponins, cardiac glycosides, alkaloids, and ascorbic acid, offering anticancer, antitumor, and disease infestation benefits [28]. Moringa is packed with flavonoids and phenolic acids, contributing to its anti-inflammatory, antilipidemic, antihypertensive, and antidiabetic properties. Black currant, rich in phenolic compounds and anthocyanins, provides antioxidant activity, anti-inflammatory, and antihemostatic benefits. The date palm is high in phenolic acids, flavonoids, and carotenoids, offering anticancer, anti-inflammatory, cardioprotective, and antioxidative properties [29]. Fig. 1 Illustrated the Nutritional components, its phytochemical composition, application and biological properties of underutilized fruits. These fruits emphasize the diverse range of bioactive compounds they contain and their significant potential for improving human health through various medicinal and nutritional benefits.

Table 1 showcases various arid and semi-arid fruits, highlighting their bioactive compounds and associated health benefits. Prickly pears (*Opuntia spp.)* are rich in antioxidants and other bioactive compounds, providing benefits such as antidiabetic, antiulcerative, antitumor, antimicrobial, and anti-inflammatory effects [30]. Wood apple (*Feronia limonia*) contains bioactive compounds like bergapten, demethylsuberosin, isopimpinellin, and various acids, which contribute to its antioxidant, antidiabetic, antiulcerative, antitumor, and antimicrobial properties. Mulberry (*Morus spp.)* is known for its anthocyanins, quercetin glycoside, chlorogenic acid, and polysaccharides, which offer

Table 1. Some arid and semiarid fruits along with associated bioactive compounds and their potential health benefits

Fruit	Scientific Name	Bioactive Compounds	Health Benefits	References
Prickly pears	*Opuntia spp.*	High antioxidant capacity High bioactive compounds	Antioxidants Antidiabetic Antiulcerative Antitumor Antimicrobial Anti-inflammatory	[35]
Wood apple	*Feronia limonia*	Bergapten, demethylsuberosin, isopimpinellin, 6-methoxy-7-geranyloxy coumarin, gallic acid, 4-hydroxy benzoic acid, gallocatechin, vitexin, p-coumaric acid, and saponarin	Antioxidants Antidiabetic Antiulcerative Antitumor Antimicrobial	[36]
Mulberry	*Morus spp.*	Anthocyanins, quercetin glycoside, chlorogenic acid, polysaccharides	Antioxidative Anticancer Antidiabetes Antiobesity	[37]
Pomegranate	*Punica granatum*	High antioxidant capacity, phenolic compounds including flavonoids (anthocyanins, flavonols), condensed tannins (proanthocyanadins), and hydrolysable tannins (ellagitannins and gallotannins)	Chronic diseases such as cancers and cardiovascular disease	[38]
Olive	*Olea europaea*	Phenolic compounds, hydroxytyrosol, tyrosol, vanillic acid, oleuropein glucoside	Cardioprotective, antioxidant, and anti-inflammatory properties	[39]
Papaya	*Carica papaya*	Saponins, cardiac glycosides, and alkaloid,ascorbic acid, saponins, tannins, cardiac glycoside, alkaloid	Anticancer, antitumor, disease infestation	[40]
Moringa	*Moringa oleifera*	Flavonoids (myricetin, quercetin, kaempferol) and phenolic acids (cinnamic acid, p-coumaric acid, ferulic acid, caffeic acid, chlorogenic)	Anti-inflammatory, antilipidemic, antihypertensive, antidiabetic	[32]
Black currant	*Ribes nigrum*	Rich in phenolic compounds, high in anthocyanins (delphinidin 3-O-glucoside, delphinidin 3-O-rutinoside, cyanidin 3-O-glucoside, and 3-O-cyanidin rutinoside)	Antioxidant activity Anti-inflammatory Antihemostatic	[33]
Date palm	*Phoenix dactylifera*	High in phenolic acids, flavonoids, and carotenoids	Anticancer Anti-inflammatory Cardioprotective Antioxidative properties	[34]

antioxidative, anticancer, antidiabetic, and antiobesity benefits [27]. Pomegranate (*Punica granatum*) has high antioxidant capacity and a variety of phenolic compounds, including flavonoids, condensed tannins, and hydrolysable tannins, making it effective against chronic diseases like cancers and cardiovascular disease [31]. Olive (*Olea europaea*) contains phenolic compounds, hydroxytyrosol, tyrosol, vanillic acid, and oleuropein glucoside, which provide cardioprotective, antioxidant, and anti-inflammatory properties. Papaya (*Carica papaya*) is rich in saponins, cardiac glycosides, alkaloids, and ascorbic acid, offering anticancer, antitumor, and disease infestation benefits. Moringa (*Moringa oleifera*) is packed with flavonoids like myricetin, quercetin, kaempferol, and phenolic acids such as cinnamic acid, p-coumaric acid, ferulic acid, caffeic acid, and chlorogenic acid [32]. These compounds contribute to its anti-inflammatory, antilipidemic, antihypertensive, and antidiabetic properties. Black currant (*Ribes nigrum*) is rich in phenolic compounds and high in anthocyanins, providing antioxidant activity, anti-inflammatory, and antihemostatic benefits [33]. Lastly, the date palm (*Phoenix dactylifera*) is high in phenolic acids, flavonoids, and carotenoids, offering anticancer, anti-inflammatory, cardioprotective, and antioxidative properties [34]. This table emphasizes the diverse range of bioactive compounds found in these underutilized fruits and their significant potential for improving human health through various medicinal and nutritional benefits.

3. ANTIOXIDANTS IN UNDERUTILIZED FRUITS

Underutilized fruits are a treasure trove of antioxidants, each offering unique compounds that contribute to their health benefits. For instance, Aonla, also known as Indian Gooseberry (*Emblica officinalis*), is a prime example, rich in leucoanthocyanins, gallic acid, and ascorbic acid [41]. These antioxidants are renowned for their ability to neutralize harmful free radicals, thereby protecting the body from oxidative stress and associated diseases. Leucoanthocyanins and gallic acid have been particularly noted for their potential in cancer prevention and cardiovascular health, while ascorbic acid, commonly known as vitamin C, is essential for immune function and skin health [42]. Bael (*Aegle marmelos*), another underutilized fruit, contains unique antioxidants such as marmelosin and psoralen. These compounds enhance Bael's therapeutic properties, making it effective in managing oxidative stress and related conditions. Marmelosin is known for its anti-inflammatory and antimicrobial properties, while psoralen has been used in traditional medicine for its photochemotherapeutic effects, particularly in skin disorders. The presence of these antioxidants makes Bael a valuable addition to a health-conscious diet, offering protection against a range of ailments [43].

Fruits like Ber (Indian Jujube) and Chironji (*Ziziphus mauritiana* and *Buchanania lanzan*, respectively) are also rich in powerful antioxidants. Ber is packed with carotenoids, which are essential for maintaining eye health, boosting immune function, and protecting cells from damage [44]. Carotenoids are known for their role in reducing the risk of chronic diseases, including heart disease and cancer. Chironji, on the other hand, is rich in polyphenolics, which are potent antioxidants that help reduce inflammation and protect against various chronic diseases. These compounds highlight the potential health benefits of incorporating these fruits into one's diet. Jamun (*Syzygium cumunii*) further illustrate the diversity of antioxidants found in underutilized fruits. Custard apple contains a blend of carotenoids and flavonoids, which are beneficial for eye health, immune support, and reducing the risk of chronic diseases [45]. Carotenoids, such as beta-carotene, have been linked to a lower risk of certain cancers and cardiovascular diseases. Flavonoids, on the other hand, have been shown to have anti-inflammatory and neuroprotective effects. Jamun is rich in ascorbic acid and phenolics, contributing to its anti-inflammatory and antidiabetic properties. These antioxidants help combat oxidative stress, enhance immune function, and support overall health. Other notable examples include Jharber (*Ziziphus nummularia*), Kair (*Capparis decidua*), and Karonda (*Carissa carandas*), each offering a unique antioxidant profile. Jharber is rich in phenolics and ascorbic acid, which provide powerful antioxidant effects, supporting overall health and preventing various diseases [46]. Kair contains rutin, tocopherols, and carotenoids, compounds known for their role in reducing inflammation and protecting cardiovascular health. Karonda is packed with phenolics, flavonoids, and anthocyanins, which offer anti-inflammatory, anticancer, and cardioprotective effects. These compounds collectively contribute to the significant health benefits of these underutilized fruits.

Table 2. Various antioxidants found in underutilized fruits

Common Name	Scientific Name	Antioxidants
Aonla (Indian Gooseberry)	*Emblica officinalis G.*	Leucoanthocyanins, gallic acid, ascorbic acid
Bael	*Aegle marmelos L. (Correa)*	Marmelosin, psoralen
Ber (Indian Jujube)	*Ziziphus mauritiana L.*	Carotenoids
Chironji	*Buchanania lanzan*	Polyphenolics
Custard apple	*Annona squamosa L.*	Carotenoid, flavonoids
Jamun	*Syzygium cumunii Skeels*	Ascorbic acid, phenolics
Jharber	*Ziziphus nummularia Burm. f.*	Phenolics and ascorbic acid
Kair	*Capparis decidua (Forsk.)*	Rutin, tocopherols, carotinoids
Karonda	*Carissa carandas L.*	Phenolics, flavonoids, anthocyanins
Khejri	*Prosopis cineraria (Druce.) L.*	Phenolics, carotenoids, saponin
Khirni	*Manilkara hexandra L.*	Quercetin, myricetin, rutin
Lasora	*Cordia myxa L.*	Polyphenols, flavonoids
Mahua	*Madhuca longifolia Koenig*	Ascorbic acid

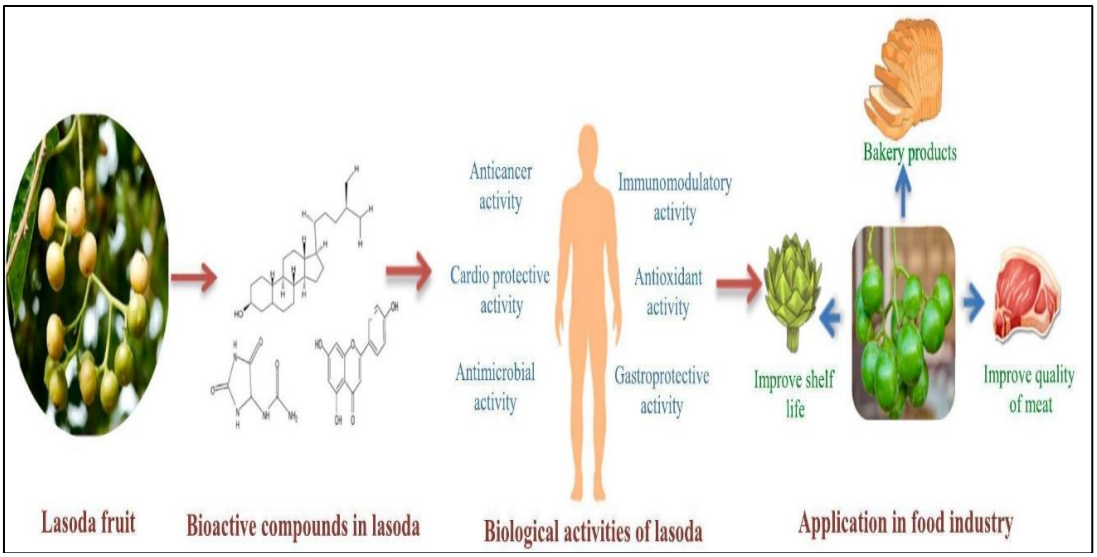

Fig. 2. Underutilized fruit lasoda (*Cordia myxa* L.) its bioactive compounds, antioxidant potentiality and applications in health bioactivities and food [46]

Table 2 further highlights the diverse range of antioxidants found in these underutilized fruits. It lists various fruits along with their scientific names and the specific antioxidants they contain. For example, Khejri (*Prosopis cineraria*) is rich in phenolics, carotenoids, and saponin, compounds known for their anti-inflammatory and antioxidant properties. Khirni (*Manilkara hexandra*) contains quercetin, myricetin, and rutin, antioxidants that support cardiovascular health and have anti-cancer properties [12]. Lasora (*Cordia myxa*) is rich in polyphenols and flavonoids, which provide potent antioxidant and anti-inflammatory effects. Mahua (*Madhuca longifolia*) is noted for its high ascorbic acid content, essential for immune function and skin health [47]. These examples underscore the importance of these fruits in providing essential nutrients that combat oxidative stress and reduce the risk of chronic diseases. Incorporating these fruits into the diet can significantly enhance overall health and well-being.

Lasora (*Cordia myxa* L.), also known as Gonda, Lehsua, Indian cherry, Assyrian Plum, or Bird's Nest Tree, belongs to the Boraginaceae family and is widely cultivated throughout India, thriving in various climates except for high hills and temperate regions [48]. This fast-growing tree is prized not only for its aesthetic value, with a distinctive inverted dome/umbrella crown, but also for its practical uses. The ovate, alternate leaves are utilized as fodder during hot summers when green grass is scarce and are also involved in lac insect rearing. In March, Cordia trees produce white hermaphrodite flowers, followed by green drupaceous fruits that ripen from April to June. Cordia fruits, commonly referred to as Lasora, play a crucial role in local cuisines and diets, particularly during lean periods when other vegetables are less available. They are often consumed as fresh greens or pickled, adding a tangy flavor to dishes. Beyond their culinary uses, Cordia fruits are recognized for their rich nutritional profile. They are natural reservoirs of antioxidants such as carotenoids, ascorbic acid, and phenols, along with essential minerals, crude fiber, proteins, ash, and vitamins [49]. These nutrients not only contribute to human health but also possess medicinal properties, making Cordia fruits valuable in traditional medicine.

Fig. 2 illustrates the underutilized fruit Lasoda (*Cordia myxa* L.), emphasizing its bioactive compounds and antioxidant potential. The presence of carotenoids and ascorbic acid underscores its role in enhancing antioxidant defenses within the body, protecting cells from oxidative damage linked to various chronic diseases [50]. Phenolic compounds found in Lasora contribute further to its health benefits, exhibiting properties such as anti-inflammatory, antimicrobial, and potentially anticancer effects. In traditional medicine, Cordia fruits are utilized for a range of health purposes, including improving digestion, acting as a birdlime (sticky substance for trapping birds), exhibiting anti-tumor and anti-helminthic properties, and serving as diuretics, demulcents, and expectorants. Additionally, extracts from *Cordia myxa* have shown potential in promoting hair growth, highlighting its diverse applications in health and wellness [51]. Overall, the multifaceted benefits of *Cordia myxa* make it a significant underutilized fruit not only in culinary traditions but also in promoting human health through its bioactive compounds and nutritional richness.

4. DIVERSITY AND CONSERVATION OF GENETIC RESOURCES OF INDIGENOUS UNDERUTILIZED FRUIT CROPS

India is recognized globally for its rich biodiversity, harboring approximately 11.18% of the world's documented plant species within just 2.4% of the world's land area [52,53]. The country shares four out of 34 global biodiversity hotspots, including the Western Ghats and Sri Lanka, Himalayas, Indo-Burma, and Sundal regions. These hotspots are home to a significant portion of higher plant species, many of which are endemic. Safeguarding this biodiversity is crucial for humanity, necessitating conservation efforts.

However, indigenous underutilized fruit resources in India have faced challenges. The introduction of exotic fruit species and the prioritization of major fruit crops have marginalized these indigenous varieties. Additionally, the growing population exerts immense pressure on biodiversity, leading to genetic erosion and loss of ecosystems. Traditional societies, farmers, and tribal communities have historically conserved and improved endangered fruit species. Recently, institutional efforts have focused on exploring, conserving, and utilizing these underutilized fruits.

The ICAR-National Bureau of Plant Genetic Resources (ICAR-NBPGR) in New Delhi plays a pivotal role in conserving plant genetic resources in India. Since its establishment in 1976, ICAR-NBPGR has amassed around 440,000 accessions representing 1900 species in its gene bank [54]. It also maintains approximately 3520 accessions of recalcitrant species in a cryo gene bank. Conservation efforts are bolstered by 10 regional stations and 59 National Active Germplasm sites (NAGS) spread across the country, ensuring both in-situ and ex-situ conservation. As of the latest data, ICAR-NBPGR and its collaborative centers account for the conservation of 1717 accessions of underutilized fruit crops. Meanwhile, major research institutions dedicated to underutilized fruit crops in India maintain an additional 1127 accessions in their field gene banks [55]. Furthermore, 357 accessions from eleven underutilized fruit species are preserved through cryopreservation techniques in gene banks. These efforts underscore India's commitment to safeguarding its genetic resources and

promoting sustainable utilization of underutilized fruit crops amidst ongoing environmental challenges.

5. CHALLENGES OF EXPLORING BIOACTIVE COMPOUNDS IN UNDERUTILIZED FRUIT

The exploration of bioactive compounds in underutilized fruit crops of arid and semi-arid regions holds promise for enhancing human health and promoting sustainable agriculture. These fruits, often overlooked in mainstream agricultural practices, possess unique phytochemical profiles that contribute to their potential health benefits. However, embarking on a comprehensive review of these bioactive compounds presents several challenges that need to be addressed to ensure the reliability and impact of the research.

5.1 Challenges in Data Collection and Accessibility

One of the primary challenges in researching bioactive compounds in underutilized fruit crops is the availability and accessibility of data. Many of these fruits have not been extensively studied compared to commercially popular fruits like apples or oranges. As a result, comprehensive datasets documenting their phytochemical composition, nutritional values, and bioactive properties may be sparse or scattered across various sources. This lack of centralized and readily accessible information complicates the synthesis of a cohesive review and may require extensive literature searches and data aggregation efforts.

5.2 Heterogeneity of Research Methods and Standards

Another significant challenge arises from the heterogeneity of research methods and standards used in studying bioactive compounds. Studies on underutilized fruits often vary in methodologies such as extraction techniques, analytical assays, and criteria for identifying and quantifying bioactive compounds [56]. This variability can lead to inconsistencies in reported findings and makes it challenging to compare results across different studies. Standardization of methods and protocols would be beneficial to ensure robustness and reproducibility in assessing the bioactive profiles of these fruits.

5.3 Diversity and Complexity of Bioactive Compounds

Underutilized fruits from arid and semi-arid regions exhibit a rich diversity of bioactive compounds, including phenolic compounds, flavonoids, carotenoids, and vitamins. However, the complexity of these compounds poses challenges in comprehensively characterizing their roles and interactions within the human body. Understanding the synergistic effects and bioavailability of these compounds requires sophisticated analytical techniques and potentially costly experiments [57]. Moreover, the biological activities of these compounds may vary based on factors such as fruit variety, ripening stage, and environmental conditions, adding layers of complexity to their study.

5.4 Limited Understanding of Health Impacts

Despite growing interest in functional foods and nutraceuticals, there remains a gap in understanding the precise health impacts of bioactive compounds from underutilized fruits [58]. While some fruits like pomegranates and olives have been extensively studied for their health benefits, others lack sufficient clinical trials or epidemiological studies to validate their purported effects. Establishing clear cause-effect relationships between bioactive compounds and health outcomes requires rigorous research designs and long-term studies, which may be lacking for many underutilized fruits.

5.5 Socioeconomic and Cultural Considerations

The promotion of underutilized fruit crops as sources of bioactive compounds also faces socioeconomic and cultural challenges. In many regions, these fruits play significant roles in local diets, traditional medicine, and cultural practices. Introducing commercial interests or altering cultivation practices could disrupt these socio-cultural dynamics. Furthermore, the economic viability of cultivating and marketing underutilized fruits as sources of bioactive compounds may be uncertain, especially when compared to established commercial crops. Addressing these challenges requires a balanced approach that respects local traditions while exploring new economic opportunities.

In conclusion, while exploring bioactive compounds in underutilized fruit crops of arid and semi-arid regions offers substantial benefits for human health and agricultural sustainability, it is not without challenges. Overcoming these challenges requires concerted efforts in data collection, method standardization, understanding compound complexity, validating health impacts, and addressing socioeconomic considerations. Despite these hurdles, the potential rewards—enhanced nutrition, sustainable agriculture, and economic opportunities—are significant, making this area of research both challenging and highly promising for future exploration.

6. FUTURE ASPECTS OF EXPLORING BIOACTIVE COMPOUNDS IN UNDERUTILIZED FRUIT

As research into bioactive compounds in underutilized fruit crops of arid and semi-arid regions continues to evolve, several promising future aspects emerge that could shape the trajectory of this field. These aspects not only aim to overcome current challenges but also seek to capitalize on the potential benefits for human health, agricultural sustainability, and economic development [59].

6.1 Advancements in Analytical Techniques and Method Standardization

Future research will likely witness advancements in analytical techniques for studying bioactive compounds. Technologies such as high-performance liquid chromatography (HPLC), mass spectrometry (MS), and nuclear magnetic resonance (NMR) spectroscopy will become more refined and accessible, enabling more precise identification and quantification of complex phytochemicals [60]. Standardization of methods across studies will also improve comparability and reliability of research findings, enhancing the credibility of studies on underutilized fruits.

6.2 Integration of Omics Approaches

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, will play a pivotal role in unraveling the biological mechanisms underlying the bioactivity of underutilized fruit compounds [61]. These approaches will provide comprehensive insights into how genetic variations, gene expression patterns, protein profiles, and metabolite compositions influence the production and function of bioactive compounds. Integrating omics data with traditional biochemical analyses will offer a holistic understanding of fruit bioactivity.

6.3 Focus on Health Outcomes and Mechanistic Studies

Future research will increasingly emphasize mechanistic studies to elucidate how specific bioactive compounds from underutilized fruits exert their health benefits. This includes exploring their interactions with cellular pathways, modulation of biomarkers, and impact on disease prevention and treatment. Longitudinal epidemiological studies and clinical trials will be crucial for validating these health outcomes, establishing dose-response relationships, and ensuring the safety and efficacy of bioactive compounds in human consumption.

6.4 Exploration of Synergistic Effects and Food Matrix Interactions

Many bioactive compounds exhibit synergistic effects when consumed as part of whole foods rather than isolated components. Future research will explore these synergies and interactions within the food matrix to optimize bioavailability and enhance health benefits. Understanding how processing, cooking, and storage methods affect bioactive compound stability and efficacy will be essential for developing functional foods and dietary recommendations.

6.5 Sustainability and Conservation Efforts

Given the ecological importance of underutilized fruit crops in arid and semi-arid regions, future research will prioritize sustainability and conservation efforts. This includes promoting agro-biodiversity, supporting local cultivation practices, and conserving genetic resources through seed banks and ex-situ conservation measures. Integrating traditional knowledge systems with modern agricultural practices will also contribute to preserving biodiversity and ensuring the long-term availability of underutilized fruits [62].

6.6 Commercialization and Economic Viability

To realize the full potential of underutilized fruit crops, future research will explore strategies for commercialization and economic viability. This includes developing value-added products, exploring international markets, and enhancing market acceptance through consumer education and awareness campaigns. Economic analyses and feasibility studies will guide stakeholders in making informed decisions about investing in underutilized fruits as sustainable sources of bioactive compounds.

6.7 Policy Support and Regulatory Frameworks

Governments and international organizations are likely to play a crucial role in supporting research and development in underutilized fruit crops. Future efforts may focus on developing policy frameworks that incentivize research, provide funding opportunities, and establish regulatory standards for the cultivation, processing, and marketing of bioactive-rich fruits. Collaborative initiatives between academia, industry, and policymakers will foster innovation and facilitate the translation of research findings into practical applications.

In conclusion, the future of exploring bioactive compounds in underutilized fruit crops of arid and semi-arid regions is promising and multifaceted. By addressing current challenges through technological advancements, integrated approaches, and sustainable practices, researchers can unlock the full potential of these fruits for improving human health and promoting agricultural resilience in a changing climate. Embracing interdisciplinary collaborations and leveraging emerging opportunities will be pivotal in shaping a sustainable and impactful future for underutilized fruit research.

7. CONCLUSION

In exploring the diverse realm of underutilized fruits, our discussions have illuminated their immense potential as sources of bioactive compounds with profound implications for human health and agricultural sustainability. From the rich phytochemical profiles of prickly pears, wood apples, and mulberries to the antioxidant prowess of pomegranates, olives, and moringa, these fruits offer a treasure trove of compounds like phenolics, flavonoids, and carotenoids, each contributing unique health benefits. The synthesis of our conversations underscores the critical importance of further research into these fruits. By employing advanced analytical techniques and embracing omics approaches, future studies can deepen our understanding of the biochemical pathways and mechanisms through which these bioactive exert their beneficial effects. This knowledge will not only enhance the development of functional foods but also support evidence-based dietary recommendations and therapeutic applications. However, the journey forward is not without challenges. Sustainability concerns, including conservation of genetic diversity and promotion of eco-friendly cultivation practices, are paramount. Addressing these challenges requires integrated efforts across disciplines, incorporating traditional knowledge systems and modern scientific innovations to ensure the resilience and longevity of underutilized fruit crops. Moreover, navigating the path to commercialization and economic viability demands strategic collaborations, supportive policy frameworks, and public awareness campaigns. By fostering partnerships between researchers, policymakers, farmers, and industry stakeholders, we can unlock the economic potential of these fruits while preserving their cultural significance and environmental integrity. The exploration of bioactive compounds in underutilized fruits represents a promising frontier in nutritional science and agricultural sustainability. By harnessing their bioactive potential responsibly and innovatively, we can cultivate healthier communities, promote biodiversity conservation, and build resilient food systems capable of meeting the challenges of a rapidly changing world.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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