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REVIEW

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Himalayan fruit and circular economy: nutraceutical potential, traditional uses, challenges and opportunities

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Abstract

The Himalayas, globally acknowledged as one of the four biodiversity hotspots, underscore their ecological significance, boasting abundant flora and fauna. Among these, a diverse array of wild fruits such as *Aegle marmelos, Artocarpus lakoocha, Baccaurea spp., Carissa spp.,* and others provide essential nutrition for local populations. These fruits, rich in bioactive compounds, offer nutraceutical potential, contributing to health aspects like antidiabetic, anti-inflammatory, and anticancer properties. The integration of Himalayan wild fruits into circular practices supports sustainable livelihoods. The responsible harvesting, efficient processing, and value addition of these fruits align with circular principles, striking a balance between conservation and progress. Technologies such as anaerobic digestion, waste-to-energy conversion, and composting can harness waste generated during cultivation and processing, contributing to a circular economy and rural Himalayan community development. Preserving, accessing, and commercializing underutilized fruits can significantly enhance economic prosperity and the quality of life for inhabitants. However, integrating these fruits into agriculture faces multifaceted challenges, spanning social, economic, environmental, agronomic, and political dimensions. Addressing these challenges is crucial for sustainable development, aiming to eradicate poverty, malnutrition, and hidden hunger. Moreover, addressing these challenges is not only vital for sustainable development in the Himalayan region but also for mitigating carbon footprints and tackling issues like poverty, malnutrition, hidden hunger, and climate change. The exploration of these concepts within the Himalayan context holds immense promise for sustainable development and ecological conservation.

Keywords Himalayan fruits, Nutraceutical potential, Carbon footprints, Circular economy, Socio-economic development

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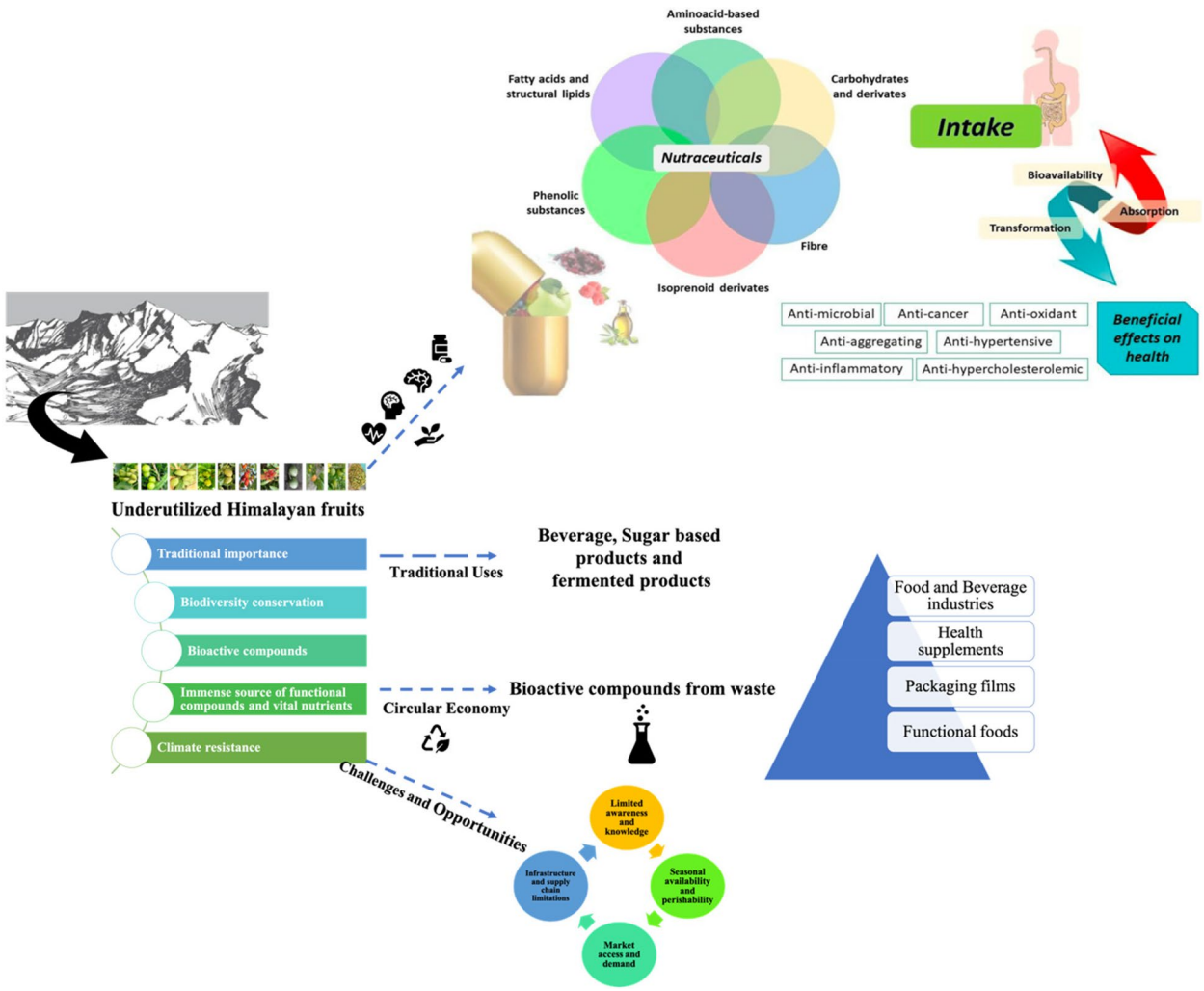
Graphical Abstract



Introduction

The word "Himalaya" translates to "home of snow" in Sanskrit (Him-snow and Alaya-house). It is a mountain range that runs east to west above a height of 8000 m and is north and northeast of mainland India. The Himalayan region is home to the tallest mountains in the world (Bahukhandi, 2023; Bhatt et al. 2023a, 2023b; Da et al. 2023; Timothy & Nyaupane 2022). At lower altitudes, the region experiences an alpine and sub-alpine climate (Salick et al. 2014). There is no flora above 5000 m, and this region is referred to as the Arctic desert or nival zone. People only inhabit the lower altitudes, and mountain pastures serve as valuable resources for flora and fauna (Dvorský et al. 2015; Kunwar et al. 2021). Wild fruit refers to fruits that grow naturally in the wild, without direct cultivation by humans. These fruits are typically found in natural ecosystems, forests, and uncultivated landscapes (Kelle et al. 2020; Kidane & Kejela 2021). The Himalayan region is one of the richest biodiversity areas, which supports over 675 species of wild edible plants that are traditionally known to contribute to meeting the nutritional requirements of indigenous communities (Bhatt et al. 2017; Semwal et al. 2022). Moreover, many wild fruits of the Himalayan region are believed to have numerous bioactive constituents that possess medicinal, health-promoting, and disease-preventive properties (Singh et al. 2022a, 2022b). Indigenous communities of the Himalayan region, such as Sikkim, have well-recognized the potential of Himalayan wild fruits to provide nutritional, medicinal, therapeutic, and industrial values

(Bhutia et al. 2018). With many people in the region struggling for essential food and nutrition (Semwal et al. 2022), Himalayan fruits, if properly identified and utilized, can help improve the livelihood of the region's communities (Padulosi et al. 2002; Rana et al. 2023).

The favorable agro-climatic conditions in the Himalayan region make it home to several rare wild (non-domesticated) and underutilized fruit species (Abdul Kadir et al. 2015; Amin & Nabi 2015; Awasthi 1968). Examples of these rare wild fruits include *Corylus jacquemontii* (Himalayan hazel), *Elaeagnus latifolia* (Bastard oleaster), *Ficus palmata* (Indian fig), *Hippophae rhamnoides* (Sea buckthorn), *Myrica esculenta* (Bayberry), *Olea ferruginea* (Indian olive), *Pinus geradiana* (Chilgoza pine), *Prunus nepalensis* (Sohiong fruit), *Pyrus pashia* (Wild Himalayan pear) *Rubus ellipticus* (Yellow Himalayan raspberry), and *Viburnum mullaha* (Starry viburnum) (Devkota et al. 2023; Lata et al. 2023). Underutilized species in the Himalayan region are crucial for ecosystem quality and can contribute to mitigating climate change (Baliga et al. 2013). Additionally, underutilized fruits have the potential to provide a range of meals and benefits for livelihoods (Jha & Sit 2023a, b; Rather et al. 2023). The North-Western Himalayan region of India is known as an agro-biodiversity hotspot due to the enormous variety of lesser known, underutilized, and valuable ethnomedicinal fruit crops. These natural fruit crops have significant nutritional and medicinal benefits. However, despite their excellent nutritional composition, which is hard to find in nature, these fruit trees are not widely cultivated or cared for.

Extensive research has been conducted on bioactive compounds and the health benefits of wild and underutilized wild fruits (Ismail et al. 2019a, b; 2021). The findings support the bioactivity and health benefits of wild fruits (Rehman et al. 2022). However, it is noted that, despite these bioactive compounds and the proven natural antioxidant activities of Himalayan wild edible fruits, their detailed phytochemical fingerprints have yet to be sufficiently explored (Rana et al. 2023; Rehman et al. 2022). Similarly, Semwal et al. (2022) also noted the lack of detailed investigations into the chemical composition, nutraceutical profile, and health benefits of Himalayan wild fruits. These conclusions were reaffirmed by researchers at the National Institute of Himalayan Environment and Sustainable Development in Uttarakhand, India, who observed that the lack of details regarding antioxidants and health-promoting bioactive compounds has led to the underutilization of edible wild Himalayan fruits.

It is thought that Himalayan fruits have many health benefits, such as the ability to act as antioxidants, anti-microbial, anti-inflammatory agents, anti-allergic agents, anti-spasmodics, chemo-preventive agents, hepato-protective agents, neuro-protective agents, hypolipidemics, hypotensives, anti-aging agents, anti-diabetes agents, anti-osteoporosis agents, DNA damage repair agents, Hence, over the past few years, the demand for nutraceuticals and their therapeutic use has increased (Gupta et al. 2020a; b; Semwal et al. 2022; Singh et al. 2022a, 2022b). Himalayan fruits are considered good sources of nutraceuticals, stimulating their growing demand and interest from a global perspective. This is because of the dynamism of consumers' attitudes towards healthcare. Rather than accepting medical decisions passively, many consumers now prefer to look beyond traditional pharmaceuticals to herbal and food remedies, as well as food supplements (Bachheti et al. 2023; Chacha et al. 2022). These consumer attitudes and trends will continue to boost the nutraceutical food industry and necessitate further exploration of more sources, especially underutilized Himalayan fruits. Furthermore, some publications have reported on the current use of Himalayan fruits for their antioxidant, anticoagulant, anti-inflammatory, neuroprotective, immunomodulatory, antidiabetic, and anticancer effects (Bachheti et al. 2023; Chacha et al. 2022).

While research on the nutraceutical potentials of underutilized Himalayan fruits is still at an early stage, novel bioactive compounds have not been fully identified and characterized (Hailu et al. 2009; Martinho 2021; Thomé et al. 2021). Thus, compounds exerting numerous health benefits have not been fully elucidated. Besides, the challenges hindering the sustainable utilization of Himalayan fruits have not been comprehensively evaluated. This review will highlight the status of the nutraceutical benefits and potential of Himalayan fruits and the challenges hindering their sustainable utilization and promotion. The goal of this review is to showcase the approaches to promoting the utilization of Himalayan fruits as a valuable natural source for nutraceutical and pharmaceutical uses in the region and beyond.

Methods

This review primarily sourced information from over 200 publications. Databases such as Scopus, PubMed, Science Direct, Google Scholar, and Web of Science were utilized to access journals, review papers, books, book chapters, and annual reports. The keywords used in these databases for information retrieval included 'underutilized fruits of the Himalayas,' 'circular economy of fruits,' 'phytochemicals of underutilized fruits,' 'socio-economic and nutritional potential of underutilized fruits,' and various wild edible fruits, specifically focusing on their bioactive and

health benefits. Additionally, we consulted and included other relevant publications in the reference section.

Health promoting potential of the underutilized Himalayan fruits

The Himalayan region is home to a variety of plants and animals, making it a rich supplier of natural resources (Lim 2012a; Kubola 2011; Baig et al. 2021). Nevertheless, wild plants and their fruits play a vital role in the way of life of the locals and communities in the Himalayan region (Khan et al. 2023). Research has shown that Himalayan wild fruits contain significant amounts of biologically active substances, including antioxidants, vitamins, and minerals (Raghavendra 2012). These plants also hold an important position in conventional therapeutic systems, likely due to their rich phytochemical profile (Rymbai et al. 2023). Despite this, there is a lack of thorough research on the chemical makeup, nutraceutical profiling, and health-promoting properties of many Himalayan wild fruits (Semwal et al. 2022).

Many neglected fruit crops offer valuable nutrients that can be used in food and medicine, and they can also be consumed as fresh fruit (Malik et al. 2021). Some of these crops possess attractive qualities, and the local population is aware of their therapeutic and dietary benefits (Saha et al. 2016; Sarkar 2018). However, due to a lack of understanding of their nutritional values, consumption patterns, limited research, and lack of development strategies by governmental bodies, these underutilized fruits are not particularly popular and are sold at meager costs in indigenous markets (Meena et al. 2022).

Most underutilized crops are nutrient-rich and can be grown using low-input agriculture practices (Zargar et al. 2021). Their increased utilization can contribute to improving food security, especially for the local population (Semwal et al. 2022). Additionally, they contain bioactive substances with great potential for use in the pharmaceutical industry (Devkota et al. 2023). The demand for unique and diverse meals made from underutilized crops is growing among consumers worldwide (Hunter et al. 2019). This presents a market opportunity for poor farmers, who historically operated in unfavorable environments, to earn additional income (Bachheti et al. 2023; Rana et al. 2023). Compared to other commercial staple crops, these underutilized crops offer significant benefits and can adapt to harsh environmental and climate changes, including groundwater depletion and desertification (Zargar et al. 2021).

Underutilized fruit species have played a crucial role in regional cultures and ceremonies. By focusing on underutilized and neglected crops, a balanced diet can be provided, micronutrient deficiencies can be combated, and biodiversity can be preserved (Hossain et al. 2021). However, scientific cultivation of these crops is still lacking in the area (Bhatta et al. 2019). Underutilized edible crops have been a significant source of food for humans since the beginning of civilization (Singh et al. 2022a, 2022b). Fruit species, particularly those classified as "underutilized," have significantly contributed to improving human well-being by addressing dietary needs, livelihood needs, household food security, and ecological sustainability. These fruits have also been used in Ayurvedic and Unani medicine for their therapeutic and restorative qualities since ancient times (Akbar 2020). Underutilized fruit species are valuable due to their excellent nutritional composition, which includes fiber, vitamins, minerals, proteins, carbohydrates, flavonoids, antioxidants, phenolics, and carotenoids (Rymbai et al. 2023). These fruits have great nutritional value and unique therapeutic features that can help with common illnesses and provide immunity against numerous ailments. Underutilized fruits may be the solution to closing the gap in battling hidden hunger, malnutrition, and micronutrient insufficiency (Sharma 2011; Singh et al. 2022a, 2022b).

In the northeastern region of India, traditional and indigenous food resources have long been the foundation of the diversity of conventional and domestic food systems (Saha et al. 2014). Underutilized fruits have been a crucial component of traditional diets and have significantly improved the security of various ethnic tribal communities in the area. Tribal people have a deep connection to the forest and are knowledgeable about how to prepare, eat, and store these fruits (Semwal et al. 2022). Underutilized fruits can be consumed fresh, crushed to make juice, jams, or desserts, or dried for use in regional cuisines (Srivastava et al. 2017). In addition to their significant ethnic, socioeconomic, and customary usage, underutilized fruits have many health benefits. Most of these fruits possess potent antioxidant properties, which act as scavengers and help remove free radicals from the body, thus protecting it from chronic and infectious diseases (Angami et al. 2022). Despite unwittingly ingesting a significant amount of nutrition from these fruits, many people are still unaware of their nutritional value (Angami et al. 2022).

Many underutilized fruit varieties are multifunctional trees used in various ancient customs. For example, *Artocarpus lakoocha*'s huge leaves are utilized to prepare green plates for religious festivities in rural areas (Chauvet & Mitra 2023). *Elaeocarpus floribundus* matured fruits are frequently used to make chutneys, pickles, and other traditional foods due to their subacidic flavor (Bhowmick 2011). *Baccaurea ramiflora* fruit is reported to contain antiviral and antioxidant qualities, while its stem bark may have diuretic

characteristics (Goyal et al. 2013). The leaves of *Baccaurea ramiflora* also contain modest amounts of melatonin, which has potential as a health supplement (Padumanonda et al. 2014). Traditional and indigenous food resources, including underutilized fruits, have long been the foundation of regional diets and have contributed to the well-being of ethnic tribal communities. A systematic review on the health-promoting properties of bioactives in common wild fruits grown in the Himalayan region of India is discussed below.

Aegle marmelos Correa (Indian Bael)

Aegle marmelos Correa, commonly known as Indian bael and belonging to the Rutaceae family, has various names in different languages. In Sanskrit, it is referred to as bival, sriphal, or shivadruma, while in hindi, it is known as bel and bael. In english, it is called a "wood apple, stone apple, holy fruit, or golden apple (Pathirana et al. 2020). Bael trees are native to India and can be found abundantly in the Himalayan region, Bengal, Central and South India, Sri Lanka, Myanmar, Thailand, Bangladesh, Laos, Cambodia, and Pakistan (Devkota et al. 2023). This fruit has a long history of use in traditional medicine systems such as ayurveda. Indian bael contains important bioactive compounds, including β-carotene, psoralen, marmin, luvangetin, aurapten, umbeliferone, marmelosin, leucocyanin, aegelinosides a, linolenic acid, tartaric acid, limonene, and linalool. It possesses several nutraceutical properties, such as anti-diarrheal, gastroprotective, anti-inflammatory, and anti-bacterial activities (Baliga et al. 2012). Additionally, studies have reported it's potential hypolipidemic, anti-diabetic, antioxidant, and radioprotective activities (Roy et al. 2011).

Artocarpus lakoocha Roxb (Monkey fruit)

Artocarpus lakoocha Roxb also known as monkey fruit belongs to the family Moraceae. Also known as Lakuch, Kshudra panas, Garnthiphala and Pitanaasha in Ayurveda, the fruit is distributed throughout the Indian subcontinent and Southeast Asian countries and generally cultivated in Western Ghats, West Bengal, Uttar Pradesh and Khasi hills of Meghalaya (Kumar et al. 2010a, 2010b). Some important bioactive with therapeutic properties like Cycloartenone, Cycloartenol, α-amyrin acetate, β- amyrin acetate, Lupeol acetate, Resveratrol, Oxyresveatrol, Tannins and Alkaoids are present in the fruit (Borah et al. 2017; Gupta et al. 2020a, 2020b). Resveratrol present in *Artocarpus lakoocha* Roxb demonstrates anti-cancer, chemoprotective, anti-oxidant, anti-bacterial and anti-helminthic activities (Borah et al. 2017; Kumar et al. 2010a, 2010b). Compounds present in the fruit like β- amyrin acetate and lupeol acetate show anti-hyperglycemic and hypolipidemic activity, which suggests that these bioactive compounds can be used as nutraceuticals (Hossain et al. 2016).

Baccaurea sapida (Roxb.) Meull. Arg. (Burmese grape)

Baccaurea sapida (Roxb.) Mull. Arg. also known as the Burmese grape, belongs to the family Phyllanthaceae. It is known as Mafai in Thai, Latkan in Hindi, Leteku in Assamese, Lerko in Bodo and Bhubi or Lotka in Bengali (Nesa et al. 2018). This fruit is indigenous to the South Asian region and well distributed in the Sub Himalayan tract like Nepal, Sikkim, Assam, Burma, Tripura, Bhutan, Malaysia, Tibet and Andaman Islands (Goyal et al. 2022). *Baccaurea sapida* is a rich source of bioactive phytochemicals like Spidolide A, Picrotoximaesin, Ramifloside, Palmitic acid and Oleic acid (Goyal et al. 2022; Pan et al. 2015). Various studies indicated that *Baccaurea sapida* contains many nutraceutical properties, including anti-fungal, analgesic, anti-diarrhoeal, anti-inflammatory, cytotoxic and neuropharmacological activities (Pan et al. 2015, Amin & Nabi 2015, Nesa et al. 2018).

Carissa carandas (Karaunda)

Carissa carandas, commonly known as Karaunda, belongs to the family Apocynaceae. This fruit is distributed in the Himalayan region of Siwalik Hills, Nepal, Western Ghats, Afghanistan, Sir Lanka, Pakistan, Java, Malaysia, Myanmar and Australia. It is known as Kramardaka in Sanskrit, Koromcha in Bengali, Vakkay in Telegu, Kilaakkaai in Tamil and Karja tenga in Assamese (Singh et al. 2015). *Carissa carandas* fruits are rich in bioactive compounds like cyanadin-3-O-glucoside, carissol, carissic acid, carissone, carinol, Ursolic acid, ascorbic acid, lupeol and β-sitosterol which possesses a lot of therapeutic effect in human health. Studies indicated that fruit extracts of *Carissa carandas* reduce induced oxidative stress, which decreases the symptoms of diabetic nephropathy (Dhodi et al. 2015). In a similar study, the anti-inflammatory activity of dried *Carissa carandas* fruit methanolic extract was established (Anupama et al. 2014). Moreover, the fruit extract demonstrated anti-cancerous activity against human ovarian and lung cancer cells (Singh et al. 2015) and anti-diabetic activity (Itankar et al. 2011).

Citrus medica (Citron)

Citrus medica is popularly known as Citron and belongs to the family Rutaceae. This fruit is widely distributed in India, China, Japan, Australia, Africa and Bangladesh. *Citrus medica* is one of the underutilized fruits that demonstrate nutraceutical potential arising from its

rich-bioactive profile containing flavonoids, terpenes and carotenoids like neoeriocitrin, naringin, neohesperidin, limonene, citral, linalool, β-cryptoxanthin, β-carotene, lycopene, lutein and violaxanthin (Chhikara et al. 2018; Li et al. 2019). Various in vivo and in vitro studies have proven that *Citrus medica* demonstrates anti-cancer, anti-oxidant, anti-inflammatory, cardio-protective, anti-hyperglycemic and anti-microbial activities (Chhikara et al. 2018; Entezari et al. 2009; Menichini et al. 2011).

Dillenia indica Linn. (Elephant apple)

Dillenia indica Linn., popularly known as elephant apple belongs to the family Dilleniaceae. It is found in the sub-Himalayan region and Asian countries like India, Nepal, Bhutan, Malaysia, Laos, Myanmar, Sri Lanka, Indonesia, and the Philippines (Das et al. 2023). It is known as Outenga in Assamese, Chalta and karambel in Hindi, Avartaki, Bhavya, Bharija in Sanskrit, Kattaral, Ugakkay in Tamil and Revadi in Tamil (Rai et al. 2020). The fruit contains many bioactive phytochemicals like betulenic acid, kaempferol, gallic acid, quercetin, neringenin, isohemnetin, dillenetin, sitosterol and dihydrokaempferol, which demonstrates therapeutic effects in humans (Saiful Yazan et al. 2014). *Dillenia indica Linn* fruits show a wide range of therapeutic activities like anti-oxidant activity, anti-cancer activity, anti-diabetic activity, anti-diarrhoeal activity, gastroprotective activity, anti-leukemic activity, hepatoprotective activity, anti-microbial activity, anti-fungal activity (Sharma et al. 2001, Saiful Yazan et al. 2014, Das et al. 2023).

Cyphomandra betacea (Tamarillo/Tree tomato)

Cyphomandra betacea is commonly known as tamarillo or tree tomato. It belongs to the family Solanaceae. This fruit is native to South America from Peru to Argentina but spread later to India, Sri Lanka, Hongkong, Australia, New Zealand, South Africa and China (Guimarães et al. 1996). *Cyphomandra betacea* contains a lot of bioactive compounds like flavonoids, carotenoids, phenolics. Some of the major metabolites which possess therapeutic properties are gallic acid, caffeic acid, vanillic acid, kaempferol, naringin, rutin, quercetin hexoside, β-cryptoxanthin, β-carotene and delphinidin-3-rutinoside (Wrolstad et al. 1974; Mutalib et al. 2016; Suárez-Montenegro et al. 2021). Various researches have proven that *Cyphomandra betacea* fruit demonstrates anti-oxidant activity, anti-cancer activity, anti-proliferative activity, anti-inflammatory activity, anti-cholinergic inhibitory activity and anti-obesity activity (Ali Hassan et al. 2013; Mutalib et al. 2016, 2017; Suárez-Montenegro et al. 2021) which directly implies its high potential in preparation of nutraceutical or functional foods.

Ficus species

Ficus auriculata Lour. (Great Indian fig)

Ficus auriculata Lour, commonly known as the giant Indian fig, Roxburgh fig or broadleaf fig belongs to the family Moraceae. This fig species is indigenous to the Indian Himalayan region, Sikkim, Meghalaya, Nepal, Bhutan, Myanmar, Vietnam, Thailand and South China. It is known as Demur or Doomboor in Bengali, Thebol in Garo, Tiamble, trimmal, phagoora in Hindi, Thaibal in Mizo, Daduri or Triambal in Punjabi (Lim et al. 2012b). *Ficus auriculata* Lour. fruit is rich in useful metabolites like Caffeoylquinic acid, Galloylquinic acid, Gallocatchin-O-hexoside, Trihydroxy-octadecadienoic acid and Linolenic acid (Shahinuzzaman et al. 2021). Since the fruit is rich in various phytochemicals it demonstrates anti-bacterial activity, anti-diabetic activity, anti-microbial activity and anti-oxidant activity which it an important candidate in the nutraceutical industry (Bertoletti et al. 2020; Shahinuzzaman et al. 2021).

Ficus carica Linn. (Common fig)

Ficus carica Linn. is known widely as the Common fig belonging to the family Moraceae. It is native to the sub-Himalayan region, central India and Bengal, Southwest Asia, Mediterranean region and later spread to other parts of the world. It is known as Anjeer or Tin in Hindi, Angira, Anjeer, Phalgu, Rajodumbara or Edumvara in Sanskrit, Fagari in Northern India, Dumur or Angir in Eastern India, Anjoora, Anjira, Chikkapatti in Southern India (Badgujar et al. 2014). The fruit is a good source of phytochemicals like umbelliferone, scopoletin, quinines, cyanidin-3-O-glucoside, cyanidin-3-O-rhamnoglucoside, stilbenes, chlorogenic acid and kaempferolrutinoside. *Ficus carica* Linn. was evaluated and found to be showing anti-cancer activity, immunomodulatory activity, anti-oxidant activity, anti-anemia activity, anti-malarial activity, radical scavenging activity and anti-septic activity (Alamgeer et al. 2017; Badgujar et al. 2014; Barolo et al. 2014; Yang et al. 2009).

Ficus cunia Buch.- Ham. ex Roxb./ Ficus semicordata Buch.- Ham. ex Sm. (Dropping fig)

Ficus cunia Buch.- Ham. ex Roxb./ *Ficus semicordata* Buch.- Ham. ex Sm. is commonly known as Dropping fig belonging to the family Moraceae. It is found in the sub-Himalayan region, West Bengal, Manipur, Nagaland, Assam, Mizoram, Jammu and Kashmir, Odisha, Maharashtra, Central India, Bangladesh, Pakistan, Bhutan, Iraq and Myanmar (Gupta et al. 2018). It is commonly known in various languages as bhui goolar, Chockoithi, khanayo, khaina, putkal, dumur, heibong and joharphal (Gupta et al. 2018; Gandhi et al. 2019). The major classes

of metabolites present in this fruit are flavonoids, phenols, tannins and saponins (Gandhi et al. 2019). The *Ficus cunia* fruit is evaluated and found to have various therapeutic activities like anti-diabetic activity, anti-oxidant activity, anti-fungal activity, anti-diarrhoeal activity, gastroprotective activity and anti-hyperbilirubinemia activity (Sheikh et al. 2015, Gupta et al. 2018).

Diploknema butyracea (Roxburgh) H. J. Lam. (Indian butter nut)

Diploknema butyracea (Roxburgh) H. J. Lam. is commonly known as Indian butternut in English and it belongs to the family Sapotaceae. It is native to the sub-Himalayan tracts of India, Tibet, China, Nepal, Bhutan, Sri Lanka and Bangladesh. It is known as Chyuri in Nepali, Madhupuspa in Sanskrit, Phulwara, Madhuca in Hindi, Gophal in Bengali and Yika Shing in Bhutanese (Bhattarai et al. 2021; Chhetry et al. 2022). *Diploknema butyracea* fruit is rich in phytochemicals like α-Amyrin acetate, β-Amyrin acetate, Erythrodiol monopalmitate, Oleanolic acid palmitate, α-spinasterol and β −spinasterol (Awasthi et al. 1968, Devkota et al. 2012). The seed and the fruit are rich in fats and have been used by the local communities for preparing butter which is known as Chiuri gheu/ghee or Phulwara ghee in local languages, which is used for cooking as well as lighting lamps (Bhattarai et al. 2021). From various types of research, it has been proven that the fruits of *Diploknema butyracea* carry anti-microbial activity, gastroprotective activity, anthelmintic activity, anti-oxidant activity and are also used traditionally for headache, burns, rheumatism, pimples and boils (Bhattarai et al. 2021; Chhetry et al. 2022; Das et al. 2022,).

Myrica esculenta Buch.– Ham. ex D. Don (Himalayan bayberry)

Myrica esculenta Buch.– Ham. ex D. Don which is commonly known as Himalayan bayberry belongs to the family Myricaceae (Bhatt et al. 2023a). This fruit is native to India and found in the sub-Himalayan tract, Sikkim, Assam, Arunachal Pradesh, Manipur, Mizoram, Meghalaya, and Nagaland as well as in other countries like China, Nepal, Bhutan, Bangladesh, Sri Lanka, Japan, Pakistan and Vietnam (Kabra et al. 2019). It is known as Ajoore, Nagatenga in Assamese, Soh-phi in Khasi, Kayachaal, Kaiphal in Bengali, Kobuli, Katphala in Nepali, Kathphala, Krishnagarba, Aranya, Mahavalkala in Sanskrit, Kapha, Kaiphal in Hindi, Kandujai kai in Kannada, Maruta in Malayalam and Marudam in Tamil (Sood et al. 2018). Beneficial phytochemicals that are detected in the fruits are Gallic acid, Coumaric acid, Chlorogenic acid, Catechin, Caffeic acid, trans-cinnamic acid and Myricetin (Rawat et al. 2011, Sood et al. 2018). Various studies revealed that fruits of *Myrica esculenta* have antioxidant activity, anti-inflammatory activity, anti-microbial activity, anti-tumor activity, analgesic activity and anti-cancer activity which indicates that the fruit is rich in therapeutic properties (Rawat et al. 2011; Saini et al. 2013, Sood et al. 2018).

Phyllanthus emblica L. (Indian gooseberry)

Phyllanthus emblica L. is commonly known as Indian gooseberry and belongs to the family Phyllanthaceae. It is known as Amla in Hindi and is found in the tropical and subtropical areas of India, Indonesia, Malaysia and China. This fruit is used in various traditional medicine systems like Ayurveda, Unani, Tibetan and Chinese medicine systems (Liu et al. 2008). *Phyllanthus emblica* fruit contains many useful phytochemicals like phyllantidine, phyllantine, chebulagic acid, chebulinic acid, emblicanin a, ellagic acid, emblicanin B, kaempferol-3-O-a-L-rhamnopyranoside, kaempferol-3-O-a-L-rhamnopyranoside and quercitin. The fruit shows various health benefits like anti-inflammatory activity, anti-cancer activity, hepatoprotective activity, cardio-protective activity, anti-oxidant activity, anti-microbial activity and immunomodulatory activity (Ahmad et al. 2021; Liu et al. 2008).

Rosa canina L. (Wild rose)

Rosa canina L. is commonly known as Wild rose or dog rose belonging to the family Rosaceae. It is distributed in Asia, South Africa and the whole of Europe (Tabaszewska et al. 2020; Polumackanycz et al. 2020). Various metabolites those are detected in *Rosa canina* hips are Vitamin C, *p*-coumaric acid, vanillic acid, *p*-hydroxybenzoic acid, protocatechuic acid, quercitin, quercitin-3-O-glucoside, gallic acid, catechin, epicatechin, quinic acid, lycopene, β-carotene, β-cryptoxanthin and anthocyanins (Razungles et al. 1989; Nađpal et al. 2016, Tabaszewska et al. 2020). Research done on rose hip has proven that it possesses anti-inflammatory activity, cytotoxic activity, antidiabetic activity, anti-oxidant activity, anti-osteoarthritic activity, anti-proliferative activity and gastroprotective activity, which proves its therapeutic potential (Daels-Rakotoarison et al. 2002; Christensen et al. 2008; Orhan et al. 2009; Lattanzio et al. 2011; Tumbas et al. 2012).

Rubus species

Rubus fruticosus L. (Blackberry)

Rubus fruticosus L. which is known as Blackberry worldwide belongs to the family Rosaceae. It is native to Europe and found throughout Asia, South and North America, Northern parts of Pakistan and also cultivated in the valley of Kashmir, Assam and Tamilnadu (Verma et al. 2014, Schulz et al. 2019; Bhatt et al. 2023b). *Rubus*

fruticosus fruit is a good source of anthocyanins, flavonoids and phenolics. The phytochemicals which are present in the fruit are Vitamin C, Cyanidin-3-glucoside, Cyanidin-3-xyloside, Cyanidin-3-maxaloylglucoside, Cyanidin-3-dioxaloylglucoside, Quercetin, Kaempferol, Catechin, Epicatechin, Myricetin, Rutin, Gallic acid, Caffeic acid and Ellagic acid (Schulz et al. 2019). The major health benefits reported for *Rubus fruticosus* fruit are anti-oxidant activity, anti-inflammatory activity, antimicrobial activity, anti-diabetic activity and anti-cancer activity (Verma et al. 2014, Schulz et al. 2019, Amini et al. 2021). Preparations made of blackberry juices with milk and water elevate plasma ascorbic acid content and other supplements help in improving immunity (Zia-Ul-Haq et al. 2014).

Rubus ellipticus Smith. (Yellow Himalayan raspberry/golden Himalayan raspberry)

Rubus ellipticus Smith. widely known as the yellow Himalayan raspberry or golden Himalayan raspberry belongs to the family Rosaceae. It is native to tropical and subtropical regions of India and found in the sub-Himalayan regions, and lowlands of India, Nepal, China and Sri Lanka (Schulz et al. 2019; Lata et al. 2023). *Rubus ellipticus* fruit contains vital phytochemicals such as gallic acid, ellagic acid, catechin, chlorogenic acid, β-carotene, ascorbic acid, caffeic acid, ferulic acid, 3-hydroxybenzoic acid, 4-hydroxybenzoic acid, vanillic acid, m-coumaric acid, cyanin, phloridzin and kaempferol (Schulz et al. 2019; Kewlani et al. 2023a, 2023b). Due to the presence of this wide range of important phytochemicals the fruit demonstrates various health-promoting activities like antioxidant activity, chemopreventive activity, anti-cancer activity, anti-diabetic activity, nephroprotective activity, antiproliferative activity, wound healing activity and antimicrobial activity (Ahmad et al. 2015; Muniyandi et al. 2019; Saini et al. 2014; Sharma et al. 2010, 2011) which makes it a potential candidate for nutraceutical industry.

Rubus niveus Thunb. (Mysore raspberry/Ceylon raspberry/Hill raspberry)

Rubus niveus Thunb. is widely known as Mysore raspberry or Ceylon raspberry or Hill raspberry and belongs to the family Rosaceae. It is native to tropical and subtropical India and found in the temperate Himalayan region of India, central and western China, Thailand and the Philippine Islands (Schulz et al. 2019). The major phytochemicals detected in the fruits of *Rubus niveus* are gallic acid, catechin, chlorogenic acid and β-carotene (Badhani et al. 2015, Schulz et al. 2019). Various researches documented that *Rubus niveus* fruits possess anti-cancer activity (Muniyandi et al. 2019), anti-oxidant activity (Ahmad et al. 2015; Muniyandi et al. 2019) and gastroprotective activity (Nesello et al. 2017).

Rubus occidentalis L. (Black raspberry)

Rubus occidentalis L. which is commonly known as Black raspberry belongs to the family Rosaceae. It is known as Cho Mei in Chinese, Farmboisier De virginie in French, Schwarze Himbeere in German, Koru Mirasu Berii in Japanese and Manila Zagadochania in Russian (Lim & Lim 2012b). *Rubus occidentalis* is found in North America, Europe (Czech Republic, Poland, Slovakia and Russia) and in Eastern Asian countries (Kula et al. 2016). This fruit is rich in important polyphenols like cyanidin-3-O-rutinoside, cyanidin-3-O-sambubioside, quercetin, myricetin, kaempferol, gallic acid, salicylic acid, caffeic acid, ellagic acid, ellagitannins, catechin, epicatechin, ferulic acid and *p*-coumaric acid (Johnson et al. 2011; Teegarden et al. 2019). Due to the presence of phenolic and flavonoid, *Rubus occidentalis* exhibits anti-cancer activity and anti-proliferative activity (Johnson et al. 2011, Kula et al. 2016), anti-oxidant activity, anti-microbial activity (Krauze-Baranowska et al. 2014), anti-diabetic activity (An et al. 2016), hypolipidemic activity and anti-inflammatory activity (Lim et al. 2020; Park et al. 2021).

Terminalia chebula (Myrobalan)

Terminalia chebula is commonly known as Myrobalan in English and belongs to the family Combretaceae (Jha & Sit 2023a, b). It is known as Harard in Hindi, Abhaya in Sanskrit, Allalekai in Kannada and Hezi in Chinese. *Terminalia chebula* fruit is native to India, Nepal, Bangladesh, Myanmar, Pakistan, Vietnam and Western China (Jha & Sit 2020, 2021, 2022; 2023a, b). It is found throughout the sub-Himalayan tract from the Ravi river to West Bengal and Assam and also in Central India, Chennai, Mysore and Southern Mumbai (Sharma et al. 2011; Sultan et al. 2023,). The health-beneficial phytochemicals present are chebulagic acid, casuarinin, chebulic acid, gallic acid, Di-O-galloyl glucose, corilagin, punicalagin, ellagic acid, rutin, caffeic acid, vanillic acid, ethyl gallate and methyl gallate (Pfundstein et al. 2010; Sultan et al. 2023). This fruit is used in various traditional medicine systems like Ayurveda and Unani which base is proven by scientific research showing its anti-oxidant activity, anti-ulcerogenic activity, anti-cancer activity, hepatoprotective activity, cardio-protective activity, anti-diabetic activity, anti-fungal activity, anti-viral activity, hypolipidemic activity and hypercholesterolemic activity (Feng et al. 2021; Kumar et al. 2006; Na et al. 2004; Saleem et al. 2002; Sharma et al. 2011; Sultan et al. 2023).

Importance of Underutilized Himalayan fruits

Reducing carbon footprints and improving the ability of the agro-industries

The two most crucial sustainability concerns for modern agriculture are reducing carbon emissions and enhancing the energy efficiency of crop rotation. Evaluating agricultural efficiency and profitability in terms of carbon footprint and energy budgeting is crucial for effective resource utilization and conservation (Moraditochaee 2012; Soni et al. 2013). Sustainability in agricultural systems depends on reducing carbon footprints and improving energy use (Singh et al. 2016). To meet the increasing demands for food and fodder from human and livestock populations, carbon emissions and energy usage in agricultural systems are steadily increasing. This involves extensive use of fertilizers, chemicals, fossil fuel-powered farm machinery, electricity, and other inputs (Chaudhary et al. 2009; Fadavi et al. 2011; Mishra et al. 2019).

The effective crop yield in agriculture relies significantly on energy. Commercial energy sources, such as fossil fuels, pesticides, and machinery, have significantly contributed to increased agricultural productivity since the green revolution while also posing a threat to the ecosystem (Guignard et al. 2017; Kumar et al. 2019; Sharma & Singhvi 2017). Various energy sources, including direct and indirect (such as chemicals, irrigation, and machinery), renewable, and non-renewable, are used in agricultural operations (Hitraj & Suttles 2016). Finding energy-efficient inputs and manufacturing processes will help reduce environmental hazards and promote sustainable agriculture by protecting natural resources (Erdal et al. 2007). Assessing the energy budget of different crop cultivation operations helps identify inefficient farm inputs and practices, providing an opportunity for farm planners and policymakers to develop strategies for increasing efficiency. Many scientists have already calculated carbon indices, such as the carbon sustainability index and the carbon efficiency ratio, as well as energy indices, such as energy use efficiency, productivity, profitability, nutrient energy ratio, and human energy profitability, in various field crops (Manoj et al. 2022). Underutilized Himalayan fruits can contribute to reducing carbon footprints and improving industry performance in several ways, as follows:

Sustainable cultivation

Underutilized Himalayan fruits flourish naturally without rigorous cultivation. Farmers reduce their carbon footprint by growing them without synthetic fertilizers, herbicides, or irrigation (Devkota et al. 2023).

Biodiversity conservation

Many natural Himalayan fruits are underutilized. Biodiversity conservation is promoted by growing and eating these fruits. This protects ecosystems, carbon sinks, and the environment (Rana et al. 2023).

Carbon sequestration

Forests and natural habitats that sustain underutilized Himalayan fruits are vital to carbon sequestration. These fruits help trees and plants absorb carbon dioxide, lowering greenhouse gas emissions and climate change (Bachheti et al. 2023).

Reduced food waste

Underutilized Himalayan crops have shorter supply chains than popular ones. Their consumption reduces food waste during shipping, storage, and distribution. This reduces food waste-related carbon emissions (Das et al. 2022, 2023).

Value-added products and local enterprises

Using underutilized Himalayan fruits in juices, jams, and dried fruits can boost local enterprises. These sectors may provide jobs, boost economic growth, and improve regional industry, contributing to sustainable development. Recognizing and using underutilized Himalayan fruits may establish a sustainable, eco-friendly food system that minimizes carbon footprints, benefits local people, and encourages environmental stewardship (Da et al. 2023).

Evaluating agricultural efficiency in terms of carbon footprint and energy budgeting allows for better management and promotes sustainable practices. The reliance on commercial energy sources, pesticides, and machinery has significantly increased agricultural productivity but has also posed risks to the ecosystem. Finding energy-efficient inputs and processes can mitigate environmental hazards and protect natural resources (Bhatt et al. 2023a, 2023b; Rana et al. 2023; Semwal et al. 2022).

Assessing the energy budget of crop cultivation operations helps identify inefficiencies and provides opportunities for improving overall efficiency. Scientists have developed various indices to measure carbon and energy performance in field crops, offering valuable insights for farm planners and policymakers. Utilizing underutilized Himalayan fruits can play a role in reducing carbon footprints and improving industry performance (Devkota et al. 2023).

By prioritizing sustainable practices and promoting energy-efficient approaches, agriculture can meet the growing demands for food and fodder while minimizing environmental impacts. Emphasizing a holistic approach that balances productivity, profitability, and

environmental stewardship will contribute to the long-term viability of agricultural systems.

Opportunity for a new source of bioactive compounds

Untapped Himalayan fruits might be a significant source of bioactive substances. Bioactive compounds are extra-nutritional substances obtained from biological sources and exhibit the potential for modulating various metabolic processes. They are usually found in minute quantities but have significant physiological, immunological, and behavioral effects (Hamzalıoğlu & Gökmen 2016). The various bioactive compounds predominantly found in plants include alkaloids, terpenoids, flavonoids, organosulfur compounds, coumarins, nitrogen-containing compounds, phenolics, etc. Various biologically active compounds have been isolated from plants and their role as immunostimulatory, anticancer, antimicrobial, antibiofilm, anti-inflammatory, antioxidant, etc. activities have been demonstrated as well (Rather et al. 2021a, 2021b, 2021c; Stéphane et al. 2021). Even though numerous projects are underway to increase the production of a few domesticated crops, nutritional security remains a source of concern. Efficient utilization of wild fruit species has been proposed as a substitute (Bharucha & Pretty 2010; Bhatt et al. 2000; Chivandi et al. 2015). Here are some ways that they can help:

Rich biodiversity

The Himalayan area is renowned for its abundant biodiversity, which includes a vast range of unexplored fruits. A wide variety of bioactive substances, such as antioxidants, phytochemicals, vitamins, and minerals, are present in these underutilized fruits and may have important health advantages (Lata et al. 2023).

Distinctive composition

Underutilized Himalayan fruits frequently have distinctive nutritionals that set them apart from regularly eaten fruits (Malik et al. 2021). These distinctive characteristics may lead to the identification of new bioactive substances with potential medicinal uses.

Traditional knowledge

The Himalayan region's local populations have a thorough awareness of the long-established applications of underutilized fruits (Upreti et al. 2010). Researchers can use their traditional knowledge to help them discover fruits that may contain bioactive chemicals and their particular health advantages.

Sources that are natural and sustainable

Making use of underutilized Himalayan fruits as a source of bioactive compounds fits with the growing need for components that are natural and sustainable. These fruits can offer a sustainable and environmentally friendly supply of bioactive chemicals, which is something that consumers are increasingly looking for as alternatives to manufactured substances (Bachheti et al. 2023).

Nutraceutical applications

Application in the creation of nutraceuticals, functional foods, nutritional supplements, and even pharmaceutical formulations are possible for the bioactive chemicals produced from underutilized Himalayan fruits (Bachheti et al. 2023). They can aid in enhancing human health and resolving several medical issues.

Value addition and economic opportunities

It may be created by extracting bioactive components from underutilized fruits, which paves the way for the creation of value-added goods and presents the business potential for growers, processors, and entrepreneurs. This might support sustainable development in the area by enhancing local livelihoods and the economy (Donno & Turrini 2020).

Conservation of biodiversity

By concentrating on underutilized Himalayan fruits for bioactive chemicals, local plant species are encouraged to be preserved, preserving the biodiversity of the area (Lata et al. 2023). This strategy promotes sustainable agriculture and aids in preserving conventional farming methods and regional ecosystems.

It is critical to make investments in scientific research, encourage knowledge sharing between communities and researchers, support the infrastructure for cultivation and processing, and make market access and regulatory frameworks easier to fully realize the potential of underutilized Himalayan fruits as a significant source of bioactive compounds. By doing this, these fruits can reach their full potential and aid in the creation of novel bioactive chemicals that have a variety of uses that are good for both the environment and human health (Devkota et al. 2012, 2023). Studies on the bioactive compounds in a few wild edible fruits have been stimulated by this accomplishment in the Himalayan region, where a variety of underutilized natural resources are said to play a crucial role in preserving the region's subsistence livelihoods and may be essential to nutritional stability. For instance, numerous plant genera with economic viability as functional food have been identified, including *Sorbus domestica* and *Rosa canina* (Egea et al. 2010). However, despite their proven potential as natural antioxidants (Bhatt et al. 2013; Rawat et al. 2014), Himalayan plants have not received the same attention. Fruits are the best reservoir of natural antioxidants

and are well-known for preventing cardiovascular and degenerative diseases (Bhatt et al. 2017).

Traditional uses of Himalayan fruits

Wild edible plants have historically played a significant role in socioeconomic and health-related spheres, and they continue to hold great importance in rural Uttarakhand (Upreti et al. 2010). To comprehend the importance of culturally valuable plants, consider how historical, cultural, environmental, religious, and spiritual components may be crucial determinants of socioeconomic issues. Eating plants also has some conventional and modern uses in nutraceuticals for physiological health (Kumar et al. 2018; Namrata et al. 2011). As a result, numerous ethnobotanical studies have concentrated on the influence of socioeconomic and cultural factors on the understanding and utilization of plant species. To encourage human adaptability and a variety of gourmet options, a vast and varied assortment of wild, uncultivated plants and their parts (such as leaves, shoots, roots, fruits, seeds, and flowers) are consumed daily. They offer an affordable source to meet the nutritional demands of rural and semi-urban civilizations across countries and geographies (Jones 2017; Rowland et al. 2017). They are abundant in fiber, proteins, vital minerals, micronutrients, and vitamins, enhancing food quality and variety (Ogle 2001). Even now, especially in remote, economically impoverished places, wild food acceptance and consumption persist (Zehra et al. 2022). Wild edible tree species are traditional sources of nuts, fruits, edible oil and beverages (Suresh et al. 2014; Sharma et al. 2017). The ethnobotanical applications of a few Himalayan fruits are given below (Table 1):

- *Rubus ellipticus Sm.* (Yellow Himalayan raspberry): Those hiking in the mountains can find them everywhere and are used as a significant source of energy (Tsewang 1995; Manandhar et al. 2002).
- *Prunus persica (L.) Batsch* (Peach): Jellies, jams, and sweets frequently contain plums as an ingredient. Even now, dry plums are used as dried fruit. In medicine, it aids in the healing of wounds (García-Gallegos et al. 2020).
- *Myrica esculenta Buch.-Ham. ex D. Don* (Hairy bayberry): The stone and its bark are said to be helpful in heart debility, edema, and hemoptysis, in addition to being therapeutic in a wide range of diseases treated with specific fruit decoctions. A wax coating on the fruit can be removed by scorching the fruit with boiling water. It is claimed that it is applied among the local populace to treat ulcers (Bhatt et al. 2023a; Kabra et al. 2019).
- *Berberis asiatica Roxb. ex DC.* (Kilmora): Due to similar qualities to those of turmeric (Andola et al. 2010), these fruits are utilized in antibacterial, wound healing, hepatoprotective, and cytotoxicity therapies, among other things (Sher et al. 2021). They are also known as "Daruharidra" or Wood Turmeric in Ayurveda medicine. The plant produces a good amount of alkaloids, among which the most extensively researched phytoconstituents are those of the isoquinoline type, such as berberine, palmatine, jetrorrhizine, and columbamine (Bisht et al. 2022).
- *Pyracantha crenulata (Roxb. ex D.Don) M.Roem* (Himalayan firethorn): These fruit byproducts and extracts can be utilized as preservatives. In addition, they possess anti-hypertensive, coronary vasodilator, and cardio-tonic characteristics. Arteriosclerosis, hypertension, paroxysmal tachycardia, myocardial weakness, and Burgor's disease have all been treated with it. The antioxidants in these fruits can help control blood pressure, lower cholesterol, and lessen the adverse effects of free radicals on our bodies. In addition, the fruits serve as an appetizer and aid in rejuvenating elderly persons. The leaves have been utilized to make herbal tea, lotions for sunburn, and various facial treatments. During periods of profuse bleeding, the shrub's bark is employed. Ginkgo and Pyracantha leave together is a cognitive tonic. The stem bark can help with fevers, particularly malaria. It is nutritious because it is high in beta-carotene, iron, potassium, and antioxidants (Kewlani et al. 2023a, 2023b; Singh et al. 2022a, 2022b).
- *Prunus armeniaca L.* (Apricot): The fruit, rich in carotene and vitamin C, offers a nutritious food source that can be consumed raw, as jam, dried, or cooked with meat. Moreover, the kernels can be consumed, squeezed to create almond oil, or utilized medicinally. Current research suggests that cancer may be treated differently using the amygdalin derived from apricot kernels (Kitic et al. 2022; Nadaf et al. 2023).
- *Rosa canina L* (Wild rose): The plant contains high levels of antioxidants and vitamin C and is utilized to prepare syrup, tea, and marmalade. It grows naturally to produce vitamin C, and the fruits have been consumed as a tea to cure viral infections and conditions of the kidneys and urinary tract (Bağci & Keskin 2022; Ognyanov et al. 2022).
- *Ficus auriculata Lour.* (Giant Indian fig): 50–100 ml of fresh leaf juice mixed with water consumed for about ten days might be used to treat digestive issues (Adhikari et al. 2023). Bark and root possess anthelmintic and hypoglycemic properties (Meitei et al. 2022). Also, the liver and kidney insulinase activities were said to be inhibited by the extracts.

Table 1 Summary of underutilized Himalayan fruits, their pharmacological properties and products prepared from it

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Aegle marmelos*	*Rutaceae*	Marmelosin, Luvangetin, Aurapten, Psoralen, Marmelide, Tannin, coumarins (alloimperatorin, zanthotoxol, imperatorin, xanthotoxol, isoimperatorin, umbelliferone, marmelide, scopoletin, marmelosin, scopolentin, marmesin, psoralen-a, scoparone, marmin, methyl ether, psoralen), tannins (4,7,8-trimethoxyfuro-quinoline, skimminianine); alkaloids (aegelenine, halfordinol, aegeline, ethyl cinnamate, aegelinosides A, ethyl cinnamamide, aegelinosides B, dictamine, fragrine); phenolic acids (gallic acids, p-coumaric acid, 2,3-dihydroxy benzoic acid, vanillic acid, chlorogenic acid); organic acids; flavonoids (rutin); tocopherols; and carotenes	Antidiabetic activity, hepatoprotective activity, antimicrobial activity, analgesic anti-inflammatory, & antipyretic activity, antifungal activity, anticancer activity, antispermatogenic activity, antiulcer activity,	Preservatives, powder, jam, wine, slab, and syrup, sherbet, murabba	Sharma et al. (2022)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Artocarpus lakoocha*	*Moraceae*	Cycloartenone, Cycloartenol, α-amyrin acetate, β-amyrin acetate, lupeol acetate	Antihyperglycemic, hypolipidemic, antiatherosclerotic, anti-inflammatory activity, help in decreasing mechanical sensitization hypersensitivity oedema, antioxidant antihyperlipidemic, decrease the threat of non-communicable diseases such as coronary heart disease, diabetes, cancer and neurodegenerative ailment, antioxidant activity	Curries, pickles, chutneys, sauce and drug development due to its medicinal value	Gupta et al., (2020a, 2020b)
 *Baccaurea*	*Phyllanthaceae*	Furfural, Furazandiamine, Benzeneacetaldehyde, 2-Furancarboxylic acid, Thiopivalic acid, 2-Propanamine, 4H-Pyran-4-one, 2-Mercaptophenol, 3H-Pyrazol-3one 1,2,-dihydro-1,2,5-trimethyl, 1,3-cyclohexanedione, Butyric acid, 4-Hepten-3-one, 5 methyl, D-Allose, 1,6- Anhydro-beta-D-glucofuranose, Cyclodecene, Palmitic acid, Eicosanoic acid, Lauric acid, Acetamide, Ethyl oleate	Prevent and reduce the risk of chronic diseases such as inflammation, liver diseases, obesity, diabetes, cardiovascular diseases, and cancer	Jam, juice, and vinegar, pickled fruit	Debnath et al.(2022); Mann et al. (2016)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Carissa spp*	*Apocynaceae*	Nortrachelogenin, carinol and carissanol, carissone, cryptomeridiol and β-eudesmol, Lupeol, oleuropein, β-amyrin	Antioxidant activity, analgesic, anti-inflammatory and antipyretic activities, wound healing properties, antibacterial, antiviral, antiprotozoan, antifungal activities, antidiabetic, antilipidemic and antileptic activity diuretic, anticancer	Jams, jellies, marmalades, squash, sauces, syrups and chutneys. Indian pickles, fruit salads, topping for cakes, puddings and ice cream, soup, pies and bread	Patel (2013)
 *Citrus medica*	*Rutaceae*	Neoeriocitrin, naringin, neohesperidin, apigenin di-C-glucoside, diosmetin di-C-glucoside, rhoifolin, chrysoeriol 7-O-neohesperidoside, limonene, citral (geranial and neral), geranyl acetate, neryl acetate and monoterpenic hydrocarbon mycrene. B-pinene, γ-terpinene, α-terpinolene and trans-α-bergamotene, βcryptoxanthin, β-carotene, cis-violaxanthin, lycopene, lutein, xanthin, violaxanthin,	Antioxidant activity, antimicrobial activity, anticancer property, antihyperglycemic effect, cardioprotective potential	Natural food colour, stabilizer, citron zest for the preparation cookies, whipped cream, in meringues and vanilla puddings essential oils	Chhikara et al. (2018)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Cyphomandra betacea*	*Solanaceae*	Fibre, iron, ascorbic acid and beta carotene, Gallic acid, Caffeic Acid, Chlorogenic Acid, Ferulic Acid, Rutin,Kaempferol rutinoside, Kaempferol	Improves immunity, helps to cure ulcer, prevents the formation of kidney stones and also treat metabolic diseases, maintains blood pressure and glucose level, may prevent free radicals	Jam, sauce, pickles	Suganya and Kalpana (2022); Liu et al. (2022)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Dillenia indica*	*Dilleniaceae*	Proanthocyanidins and 3,5,7-Trihydroxy-2-(4′-hydroxybenzyl)-chroman-4-one, ascorbic acid, tannins, malic acid, arabino galactan, betulin, betulinic acid, and flavonoids	Manage different ailments such as diabetes, inflammations, diarrhea, cancer, ulcer, infectious diseases, hematic disease, hepatic problems, dental problems, cardiovascular problems, hyperlipidmia and others, treats fever, constipation, diarrhea and stomach pain, anti-inflammatory	Jams, jellies, pickles, chutneys, and juices	Ahamed et al. (2022)
 *Diospyros spp*	*Ebenaceae*	β -carotene, α-carotene and cryptoxanthins, as vitamin A precursors, β-cryptoxanthin, dihydrocaffeic acid 3-glucuronide, caffeoylquinic acid, catechin and quercetin-3,4-diglucoside, lutein, astaxanthin, and zeaxanthin	Antioxidant, free radical scavenging, anti-inflammatory,, antimicrobial,, antidiabetic, and, neuroprotective activities	Used in breads, jams, pastas and yoghurts as functional ingredients	Smrke et al. (2019); Ferreira da Vinha et al. (2021); Kaur et al. (2022)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Ficus spp*	*Moraceae*	Chlorogenic acid, tocopherol, β-amyrin, stigmasterol, campesterol, oleic acid, isoamyl laurate and ϒ tocopherols, cyaniding3-O-glucoside, cyaniding-3-Orhamnoglucoside, saturated fat, cholesterol, sodium, insoluble sugars, protein, beta-carotene, ascorbic acid, calcium and iron	Antioxidant and antimicrobial, antibacterial activities. Prevents cardiovascular diseases, respiratory, neurodegenerative and cancer, laxative, antispasmodic, and anti-inflammatory	Juice, paste and dried fruit	Abdussalam (2020); Shahrajabian et al. (2021)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Elaeocarpus sikkimensis*	*Elaeocarpaceae*	Caotenoids, anthocyanin, flavonoids, Ascorbic acid, alkaloids, flavonoids, tannins, glycosides, and ellagic acid derivatives	Antioxidant, anti-inflammatory	Edible fruit	Bhutia et al. (2018)
 *Diploknema butyracea*	*Sapotaceae*	Flavonoids, tannins	Antioxidant, anti-Inflammatory, analgesic, antiseptic properties, and as hemostatic pharmaceuticals	Jams, jellies, pickles, chutneys, juices, herbal medicine	Tiwari et al. (2020)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Eriolobus indica*	*Rosaceae*	Procyanidin dimer, chlorogenic acid, procyanidin B2, (-)-epicatechin, isoastilbin, astilbe diglucoside, quercetin-3-O-glucoside, 3-hydroxy phloretin-glucose xylosides, quercetin-3-O-glucoside isomer, avicularin, avicularin isomers, quercetin-3-O-rhamnoside, phloretin-glucose xyloside, 3-hydroxy phlorizin, phlorizin, phlorizin isomer and phloretin-glucose rhamnoside. Notably, chlorogenic acid, 3-hydroxy phloretin-glucose xylosides, quercetin-3-O-glucoside, quercetin-3-O-glucoside isomer, avicularin, phlorizin and phloretin-glucose rhamnoside, protocatechuic acid, catechin, chlorogenic acid, caffeic acid, (-)-epicatechin, p-coumaric acid, ferulic acid, rutin, hyperin, phlorizin and quercetin, rutin, hyperin and phlorizin	Antioxidant property, Anticancer property, Lipid-lowering property, Anti-diabetic property, Anti-inflammatory property	Jelly, pickles etc	Zeng et al. (2022)
 *Myrica esculenta*	*Myricaceae*	Tannin, ascorbic acid, Gallic acid, Catechin, cholorogenic acid, *p*-coumaric acid, caffeic acid, trans-cinnamic acid, ellagic acid, Myricetin	Analgesic, anxiolytic, antiallergic, antidiabetic, antimicrobial, antihypertensive, antiulcer, antioxidant and anti-inflammatory properties, antiasthmatic, anticancer, antioxidant, hepatoprotective, chemopreventive, hypotensive and wound healing activity	Eaten raw, delicious taste, used in preparing refreshing drinks, jam, jelly, etc. Pectoral, sedative, fruit wax is used externally for ulcers	Sood et al. (2018); Bhatt et al. (2017)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Phyllanthus emblica*	*Phyllanthaceae*	Mucic acid gallate, mucic acid lactone gallate, monogalloylglucose, gallic acid, digalloylglucose, putranjivain A, galloyl-HHDP-glucose, elaeocarpusin, and chebulagic acid	Antidiabetic, antimicrobial, anti-inflammatory, and immune-regulating activities, inhibits the growth of cancer cells and reduces DNA damage, neurological protection, digestive tract protection. Used as aperients, carminative, diuretic, aphrodisiac, laxative, astringent and refrigerant. Useful in anaemia, jaundice, dyspepsia, haemorrhage disorders, etc	Juice, powder, dried candies, Fruits eaten raw and used for processed products such, jams, jellies, pickles, etc	Yang and Liu (2014)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Rosa spp.*	*Rosaceae*	B-carotene, α-cryptoxanthin, lutein, lycopene, rubixanthin, α-Tocopherol, Vitamin E, Vitamin C, quercetin, kaempferol, and ellagic acid possess in vitro inhibitory activity toward tyrosinase, linoleic acid, flavonoids, triterpenoids, and phytosterols, Galactolipids	Prevent or treat flu, cough, stress, sore throat, and pneumonia, used as a tonic, tranquilizer, diaphoretic, antioxidant, anti-inflammatory, treats hyperlipidaemia, diabetes, arthritis, diarrhea, renal disturbances, hepatotoxicity, antitumor activity	Jams, marmalade, juices, syrups, vinegar, jellies, and wine	Pashazadeh et al. (2021); Al-Yafeai et al. (2018); Sabitov et al. (2021)
 *Rubus spp.*	*Rosaceae*	Cyanidin-3-glucoside, cyanidin-3-sophoroside, cyanidin-3-glucoside, Ellagic acid, catechin, caffeic acid, gallic acid, epicatechin, quercetin, lambertianin C, kaempferol	Antioxidant, antimicrobial, anti-inflammatory, anti- cancer activities	Food colourant, bakery products	Žlabur et al. (2021); Schulz and Chim (2019); Bhatt et al., (2023a, 2023b)

Table 1 (continued)

Fruit	Family	Nutraceutical/Bioactive compounds	Bioactive /medicinal Properties	Products	Reference
 *Terminalia chebula*	*Combretaceae*	Chebulanin, chebulinic acid, 1,6-di-O-galloyl- β-D-glucose and Casuarinin, aschebulic acid, chebulagic acid, corilagin, mannitol, gallic acid, ellagic acid, tannic acid, ethyl gallate, and ascorbic acid	Cytoprotective, antidiabetic, antioxidant, antibacterial, anti-arthritic, hypo-cholesterolaemic, anti-inflammatory, analgesic, anti-depressant, antifertility, antiandrogenic activities, Antihypertensive effect, Antiulcer activity	Food preservatives, salads	Sabir et al. (2020)

Fruit extracts have antitumor properties. Hypotensive activity has been reported from the leaves (Adhikari et al. 2023).

- *Aegle marmelos (L.) Corrêa* (Indian bael): The fruit can be consumed fresh or dried. If the juice is fresh, it is filtered, sweetened, and used for sharbat as a drink. Typically, the sun-dried, stiff, leathery slices of dried fruit are submerged in water after being cut into slices. The fruit pulp has a degreasing effect. According to Quisumbing, bael fruit removes scum from vinegar production (Sharma et al. 2022).
- *Rubus occidentalis L.* (Black raspberry): It has plenty of anthocyanins, which are excellent for making natural colors and are also helpful in treating cancer. The leaves can be added to herbal teas, either fresh or dried. It is used in herbal medicine and has an astringent flavor (Meng et al. 2022).
- *Ficus carica L.* (Common fig): All components are employed in the native medical system to treat various illnesses, including cancer, colic, indigestion, diarrhea, sore throats, coughs, bronchial issues, and inflammatory, cardiovascular, and ulcerative diseases (Hajam & Saleem 2022). Plant milk can be coagulated using the sap's latex.
- *Rubus niveus Thunb.* (Mysore raspberry/Ceylon raspberry/Hill raspberry): The fruits can be eaten raw or with ice cream, sugar, and cream. They work well for producing jam, jelly, pies, and tarts. For later usage, the fresh fruit can be quickly frozen (Chauhan et al. 2016; Singh et al. 2023).
- *Phyllanthus emblica L.* (Indian gooseberry): The plant as a whole is commercially significant. Frequently utilized parts include dried fruit, nuts or seeds, leaves, roots, bark, and flowers. Although dried fruit is also utilized, fresh ripe fruits are typically used (Saini et al. 2022). It is recognized as one of the finest vitamin C sources and is abundant in minerals and polyphenols. An energy booster, aperient, antiviral, antifungal, and antibacterial, antitumor in gonorrhea, analgesic, and skin fairness to prevent nausea and vomiting, and hepatoprotective are some examples of therapeutic usage (Gul et al. 2022).
- *Carissa spinarum L.* (Wild karanda): The Mundas, a tribe of Chhota Nagpur, utilize it in conjunction with the roots of a few other medicinal plants to cure rheumatism. It has a potent purgative effect and is a component of certain purgative medicines. Roots in higher doses are helpful for the fatal due to excessive purging (Roy et al. 2023).

The local communities are effective resource managers. Hence, if the domestic market has maintained the environmental system's capacity for resilience, indigenous consumption methods are frequently considered sustainable. The mountain viewpoint includes indigenous cultural systems and ancient survival techniques, which are undervalued in the path toward modernization. Integrating traditional knowledge systems with cutting-edge technologies is the biggest challenge of the upcoming generation to slow down the rate of degradation of the environment (Kala 2006). Fruits of *Rose brunonii Lindle* are used in traditional medicine as a "blood purifier, to encourage wound healing, and to treat infectious infections" (Ishaque et al. 2022).

Scientific studies on the bioactive potentials of wild fruits from the Himalayas

Bioactive compounds are foods' extra-nutritional constituents present in minute quantities and provide myriad health benefits that are beyond the product's basic nutritional value (Hamzalioğlu & Gökmen 2016). Their health-promoting and disease preventing effects have been the subject of numerous investigations (Ismail et al.,). So far, their beneficial physiological, behavioral, and immunological effects have been confirmed, leading to increased efforts to discover more bioactive compounds. Bioactive compounds comprise several classes of compounds grouped based on structure and function, including phenolics, carotenoids, vitamins and minerals (Hamzalioğlu & Gökmen 2016).

To date, only a few of the Himalayan wild fruits were subjected to comprehensive characterization of the bioactive constituents. For instance, a study conducted by Bahukhandi et al. (2023) employed *Elaeagnus latifolia* L. berries, fresh and dried, collected from Chaudas Valley in Pithoragarh district. This study focused on analyzing the polyphenolics-antioxidant properties of these berries in various solvents. Findings indicated that studied parameters varied significantly ($p < 0.05$) across solvents. In contrast to dried berries, fresh berries were discovered to be a powerful source of polyphenolics (phenolics 1.65; flavonoids 1.35; flavonols 1.21; tannins 1.49; and proanthocyanidins 1.21 mg/g, respectively) and antioxidants (ABTS 2.55; DPPH 2.74; FRAP 2.25; OH• 1.16; NO• 1.19 mM AAE/100 g). It was observed that the moderate polarity of the solvents (ethanol, methanol) was suitable for utilizing the species' full potential. Results also showed that fresh and dried fruit berries are natural sources of many favorable health compounds (polyphenolics, antioxidants, and other bioactive components). They should be used to prepare nutrient-dense foods that will help reduce the prevalence of malnourishment.

Agar well diffusion was used to evaluate *Rose brunonii's* methanolic extract against two gram-positive and

three gram-negative bacteria. The plant extract had the lowest antibacterial activity against *Bacillus subtilis* (MIC = 250 ± 7.2 µg/mL), while *Klebsiella pneumoniae* showed the highest antibacterial potential (94 0.3 mm inhibitory zone, MIC = 62.5 ± 1.1 µg/mL). The lethality test on brine shrimp was used to measure the crude methanolic extract's cytotoxic potential. The plant extract had a dose-dependent cytotoxic impact at $p < 0.05$, F (3,8) = 1.58, and LD_{50} of 220.95 ± 1.03 µg/mL. Potato disk anticancer bioassay was used to assess antitumor potential. Maximum tumor inhibition for *R. brunonii* fruit extract was 72.73% at 1000 µg/mL, with an IC_{50} of 655.65 ± 0.03 µg/mL. A first phytochemical investigation showed that the extract is rich in phenolics but free of alkaloids. *R. brunonii* was found to have total phenolic and flavonoid levels of 66.73 ± 3.89 µg/mg GAE and 46.51 ± 0.96 µg/mg QE, respectively (Ishaque et al. 2022).

Further research is needed to explore and identify additional bioactive compounds in various food sources. This will deepen our understanding of their health benefits and potential applications in developing functional foods and dietary interventions. Moreover, comprehensive characterization of bioactive compounds is still required.

Challenges and opportunities for sustainable utilization

Traditional knowledge aids in identifying traditional foods, such as underutilized crops and wild crops, which can significantly mitigate food insecurity by resurrecting and examining the rich bio-cultural dietary practices that helped local traditional cultures construct their food systems throughout history (Haq et al. 2022). The partnerships between academia and the public–private sectors for fundamental and applied research on these species will encourage native communities to commercialize such fruits for consumption purposes and small-scale industries by developing minimal-cost technologies (Devkota et al. 2023). The challenges faced by farmers can be categorized into three main groups: environmental challenges, socioeconomic challenges, and agronomic challenges. Environmental challenges encompass factors like unpredictable rainfall patterns, extreme temperatures, hailstorms, frost, water scarcity, soil erosion caused by landslides, and pollution resulting from emerging industries. Socioeconomic challenges include limited and fragmented land ownership, widespread poverty, high investment costs, and a lack of alternative income sources. Agronomic challenges involve cultivation and production difficulties, including soil erosion, low productivity, pests and diseases, conflicts between humans and wildlife, and the erosion of traditional ecological knowledge (Mishra et al. 2021).

Figure 1 depicts the challenges and opportunities in the field of sustainable utilization of underutilized Himalayan fruits. To tap into these opportunities and address the challenges, collaboration among farmers, government agencies, research institutions, non-governmental organizations, and the private sector is crucial. Together, they can promote awareness, provide training and capacity

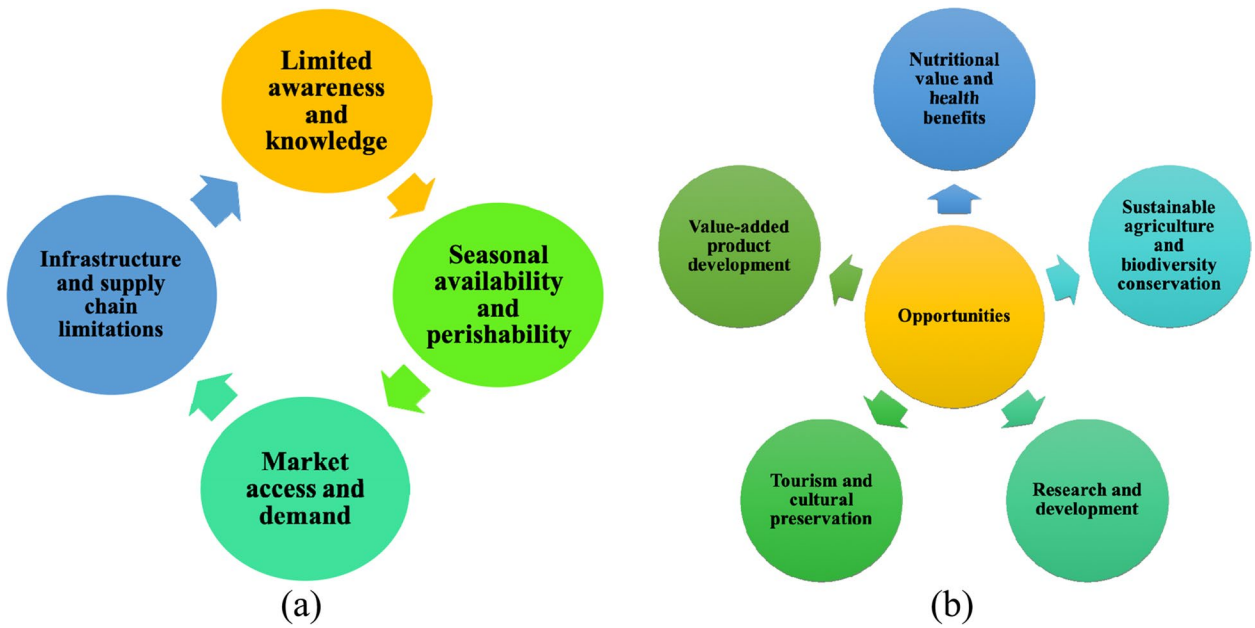


Fig. 1 **a** Challenges; **b** Opportunites towards sustainable utilization of underutilized fruits

building, improve infrastructure, develop value chains, and create a conducive environment for the sustainable utilization of underutilized Himalayan fruits (Bachheti et al. 2023; Devkota et al. 2023).

Although the underutilized fruit species show promising attributes for sustainable agriculture, their incorporation into conventional agriculture is quite challenging. Underutilized crops are facing various social, economic, environmental, agronomic, and political challenges hindering their propagation and inclusion in agricultural practices (Lata et al. 2023). Very little attention is being paid to them as compared to that of major staple crops. The other challenges regarding the cultivation of underutilized fruits include rapid urbanization and conversion of agroforest land into landfills, dumping sites, etc., unavailability of propagating materials including seeds, population explosion, and many more. Ignorance towards indigenous knowledge and farmer's reluctance to shift from local crops to new crops are some of the major challenges faced by underutilized fruits (Li et al. 2020). Low market values, absence of market infrastructure, adverse effects of climate change, inefficient system for propagation material, absence of scientific study and research, etc. are some other major challenges faced by neglected and underutilized crops. For sustainable development and to overcome such challenges various important steps need to be taken at both public and government levels (Padulosi et al. 2002; Rana et al. 2023). Government organizations should prioritize the conservation of underutilized fruits and general masses need to be informed about the uses, nutritional and medicinal values of such fruits. Public awareness should be created among the masses. Ex-situ conservation strategies need to be developed to avoid their genomic erosion (Rehman et al. 2022). Although such fruits are reported to contain essential micro and macronutrients and have the potential to address hidden hunger limited attention is paid to their propagation or domestication (Singh et al. 2022a, 2022b). Therefore, their adoption in conventional agricultural practices and domestication needs to be addressed which could be attained through the incorporation of their ethnomedicinal value in the scientific literature, creating opportunities for opening enterprises for their advertisement and popularity, emphasizing strategies for their conservation, developing plant nurseries, involving mass media for creating awareness, framing of government policies, increasing funding by government and non-government organizations for supporting scientific research, carrying out research for metabolite profiling and validating ethnomedicinal values, etc. (Bachheti et al. 2023; Chacha et al. 2022). Their cultivation and consumption ensure the eradication of global malnutrition and food insecurity for achieving the goal of sustainable development (Meena et al. 2022).

Underutilized Himalayan fruits have great nutraceutical potential, but they also provide problems and opportunities for sustainable use. A few of them are briefly discussed:

Limited scientific research

Few Himalayan fruits have been extensively examined for their nutraceutical potential. Lack of scientific study on their bioactive components, health benefits, and safety profiles may limit their development and marketing as nutraceuticals (Bachheti et al. 2023).

Standardisation and quality control

Making nutraceuticals from underutilized Himalayan fruits safe, potent, and consistent is difficult. To achieve regulatory and customer expectations, extraction, dosing, and quality control processes must be standardized (Devokta et al. 2023).

Cultivation and availability

Growing underutilized fruits to suit nutraceutical demand is difficult. Large-scale production of these fruits may be affected by their growing needs, seasonal harvests, and availability.

Market acceptability and customer awareness

Customer trust and acceptance of nutraceuticals made from underutilized Himalayan fruits require good marketing and consumer education. Awareness of their distinct health advantages and differentiation from standard nutraceuticals might be difficult (Rana et al. 2023).

Role of Himalayan fruits in attaining circular economy

The escalating challenge of meeting the demands of a burgeoning global population (Circle Economy 2021) underscores the imperative to boost food production by an estimated 5.1 billion tonnes before 2050 (FAO 2017), imposing significant strain on agricultural ecosystems and potentially causing adverse environmental impacts (Aznar-Sánchez et al. 2018). Agricultural activities contribute over 90% to land-related environmental impacts (Kusumastuti et al. 2016; Aznar-Sánchez et al. 2019), making the agriculture sector a substantial contributor to material and carbon footprints (21.3 billion tonnes and 10 billion tonnes of CO_2 equivalent, respectively, in 2019) (Circle Economy 2021). In response, the circular economy (CE) emerges as a transformative approach to curbing resource consumption and waste generation, thereby enhancing economic performance and

mitigating agriculture's ecological footprint (Velasco-Muñoz et al. 2021). Unlike the traditional linear model, CE's regenerative nature fosters sustainable agro-food systems through waste-to-bioproduct transformation. CE principles can address climate change, potentially reducing emissions by 5.6 billion tonnes of CO_2 equivalent by 2050, preventing arable land degradation, and conserving freshwater. Economically and socially, CE principles in the food chain could boost the EU's GDP by 0.1% by 2030, generating jobs and increasing farmer profitability (European Commission 2018). CE practices, such as regenerative approaches in potato cultivation, may reduce GHG emissions, biodiversity loss, and agricultural costs. Transitioning from linear to circular economic models necessitates innovative, technological, and sustainable processes, particularly in the nascent field of circular food production (de Boer & van Ittersum 2018). Circularity assessment becomes pivotal, especially in resource-intensive phases like crop production within the agro-food chain. Focusing on arable crop production, this study examines activities, procedures, and nutrient flows associated with agricultural practices to describe CE for each or selected fruit, promoting CE-based circularity (Van der Wiel et al. 2019). The strategic intervention of CE in crop production can drive sustainable practices, transforming the agricultural landscape towards lasting prosperity and reducing environmental impact. In the context of underutilized Himalayan fruits, this study aims to explore the application of CE principles for each or selected fruit, leveraging their regenerative and resource-efficient qualities. Often overlooked, these fruits represent a valuable natural resource that can be seamlessly integrated into a circular system, aligning with CE principles to minimize waste and maximize resource value throughout their lifecycle. Underutilized Himalayan fruits align seamlessly with these principles in several ways:

Resource efficiency and by-product utilization

Underutilized Himalayan fruits offer an abundant source of nutrients that can be harnessed efficiently. Circular economy practices advocate for the utilization of resources in a way that minimizes waste and maximizes its value. These fruits can be utilized not only for their edible parts but also for by-products like peels, seeds, and pulp. By incorporating these by-products into various value-added products with the help of technologies like anaerobic digestion, waste to energy conversion, composting and vermicomposting, mechanical biological treatments and animal feedings such as natural dyes, biogas, fertilizers, animal feed, or biodegradable packaging materials (Osorio et al. 2021). The circular approach ensures a comprehensive utilization of the fruit, creating a regenerative cycle that reduces waste.

Local production and consumption

Circular economies promote localized production and consumption to reduce the environmental impact associated with long-distance transportation. By focusing on underutilized Himalayan fruits within their native region, carbon emissions from transportation are minimized (Osorio et al. 2021). This also reinforces the connection between local communities and their environment, fostering a sense of ownership and responsibility for sustainable resource management.

Value addition through processing

Circular principles encourage the transformation of raw materials into higher-value products. Underutilized Himalayan fruits can undergo processing to extend their shelf life and create a diverse range of products such as jams, jellies, juices, and dried fruits. These value-added products not only enhance economic returns for local communities but also reduce food waste and contribute to increased market demand (Devkota et al. 2023; Donno & Turrini 2020).

Closing the loop through waste management

Circular economies prioritize the reduction and proper management of waste. Fruit waste and by-products can be channeled into composting systems, where they contribute to nutrient-rich soil amendments. Additionally, these by-products can be utilized for the generation of biogas or biofuels, further minimizing waste and promoting a closed-loop system (Bachheti et al. 2023; Osorio et al. 2021).

Supporting local livelihoods

Circular systems emphasize the importance of creating sustainable livelihoods within communities. Integrating underutilized Himalayan fruits into local production systems can lead to employment opportunities in harvesting, processing, marketing, and distribution. By diversifying income streams and empowering local entrepreneurs, circular practices contribute to improved economic resilience and well-being (Rana et al. 2023).

Ecosystem resilience

Circular economies align with principles of ecosystem health and conservation. Utilizing underutilized fruits within circular systems encourages sustainable land management practices, prevents overexploitation, and promotes biodiversity conservation. This holistic approach contributes to the resilience of the fragile Himalayan ecosystem (Devkota et al. 2023; Rana et al. 2023).

Innovation and collaboration

Circular economies thrive on collaboration and innovation across various sectors. The integration of underutilized fruits encourages partnerships between farmers, researchers, businesses, and policymakers. This collaborative ecosystem fosters innovation in product development, technology adoption, and market access, leading to the sustainable scaling of circular practices (Martinho 2021).

Technological advancements

Modernization of traditional technologies of fruit and vegetable processing into more promising advancements like irradiation, pulse electric field, high hydrostatic pressure, freeze drying, modified atmospheric packaging (MAP), vacuum packaging plays a lead role in preserving the underutilized fruits and increasing its shelf life (De Corato 2020). Further, advances in the commercialization and marketing of agro products and the usage of technologies like computer vision and artificial intelligence (AI) help to mitigate hurdles regarding food processing, farming, smart irrigation and plant data analysis (Kakani et al. 2020).

Transformative practices

Explorations and technological advancements in the agro-processing sector especially in the interior areas of the Himalayan region would empower the farming communities to overcome the challenges and promote the sustainable cultivation of high-value underutilized fruits. These transformations in the traditional practices would also foster economic growth by improving productivity, preservation and marketing of the underutilized Himalayan fruits (Bisht 2021). Government policies will also play a vital role in incentivizing these farming communities and ultimately improving the nutrition and health of the entire population (Martinho 2021).

In summary, underutilized Himalayan fruits provide a tangible avenue for implementing circular economy principles in the region. By maximizing resource utilization, reducing waste, supporting local economies, and promoting ecosystem health, these fruits offer a compelling opportunity to create a more sustainable and resilient future for both communities and the environment in the Himalayas.

Consumer acceptance and policy measures and institutional-industrial partnership

Consumer and food relationships are influenced to a large extent by the former's attitude toward the latter following the risks and benefits assessment. Moreover, consumer characteristics, food marketing strategy, new technologies, food image, and sensory attributes influence consumer perception of foods. Most importantly, health concerns can significantly affect these relationships between perceptions and attitudes (Martinho 2021). Health goals motivate consumers to make healthy food choices, and those reflective and cognitive characteristics shape consumption (Thomé et al. 2021).

In the case of nutraceutical food or products, consumer acceptance is essential to promote a sustainable increase in their utilization. Key factors such as consumer characteristics, product characteristics, and purchasing capacity influence the acceptance of nutraceuticals. The level of awareness and consumer understanding of the health benefits of nutraceuticals seems to influence consumer acceptance. Thus, exploring the nutraceutical benefits of Himalayan fruits and their sustainable utilization will depend on a deeper understanding of behaviors and characteristics such as consumers' knowledge and health status. Consumers' lack of awareness of the clinical evidence and the high cost of nutraceutical products were some barriers that may hinder their acceptance (Teoh, Ngorsuraches, & Chaiyakunapruk, 2020). On the other hand, surveys to identify the key factors motivating consumers to use nutraceutical products. The result revealed that perceived health benefits and safety are the key driving factors for some consumers' utilization. However, highly educated consumers were reported to place a strong premium on health claims verified by the government, while little value was placed on non-verified claims by producers of nutraceutical products (Hailu et al. 2009).

Underutilized fruit species, according to Jaenicke and Hoschle-Zeledon (2006), are those that portray a vast amount of agro-biodiversity, have a significant capability to promote food security and nutrition, health (nutritional/medical), revenue generation, ecological benefits, and the fight against the hidden hunger brought on by micronutrient deficiencies. These fruit species are not commercially farmed or traded widely, are less well-known to people, in lower demand on the market, and are less appetizing; they are found in abundance in forests and practically every garden without much care or attention. Its distribution, cultivation, and usage have also received scant attention (Semwal et al. 2022; Singh et al. 2022a, 2022b). These ignored, under-exploited, and undervalued fruit species are also referred to as under-utilized fruits. Several fruit species are underutilized but have significant nutritional benefits. These fruit varieties can be used as a substitute food when there is a food shortage and are regarded as the most beneficial dietary supplements. These species were classified as "underutilized" because, although widespread locally, they are restricted to their geographic region due to a lack of scientific knowledge (Hailu et al. 2009; Martinho 2021; Thomé et al. 2021). The availability of these fruit species throughout the

year and their ability to thrive in hostile environments and threatened habitats are further benefits. In an area, particularly north-eastern India, where most farmers are resource-poor and practice farming under such circumstances, such strength of underutilized fruits is advantageous (Bachheti et al. 2023; Chacha et al. 2022).

Underutilized fruits are the primary means of support for rural people and a critical factor in addressing the malnutrition issue. These fruit crops are essential for preserving and promoting cultural and culinary diversity, enhancing the sustainability of agriculture via lowering inputs, reducing the risk of overdependence on a small number of key staple food crops, assisting the poor for subsistence and income, using marginal and wastelands for agricultural uses to fulfill the ever-growing need for food and more (Bachheti et al. 2023; Chacha et al. 2022). These nutrient-dense fruits can be used to make jam, jelly, juice, pickles, and other value-added goods, providing revenue for rural residents and resulting in a wealth of opportunities for community growth and improved means of subsistence (Bhutia et al. 2018). In addition to providing a stable source of income, these fruits have significant economic ability and are essential in rural areas because they supplement diets with nutrients. Most of these species are said to contain a balance of vitamins, minerals, and numerous phytochemical compounds vital for maintaining good health in humans (Semwal et al. 2022; Singh et al. 2022a, 2022b).

Future trends

It can boost nutraceutical research, product development, commercial potential, conservation, health, and multidisciplinary cooperation. A few of them are briefly discussed:

Further research

In-depth studies on Himalayan fruits can assess their bioactive compounds, nutritional composition, health benefits, and nutraceutical uses.

Nutraceutical product development

The review can help generate nutraceuticals from underutilized Himalayan fruits. Researchers and food producers may use the data to create functional foods, dietary supplements, and natural components for health-promoting goods. Research institutes, universities, and industry can explore the nutraceutical potential of underutilized Himalayan fruits. Joint research, technology transfers, and information exchange can improve science, formulation, and product commercialization (Das et al. 2022, 2023; Devkota et al. 2023; Semwal et al. 2022).

Commercialization and market opportunities

With growing customer interest in natural and healthy products, underutilized Himalayan fruits may be commercialized as nutraceutical components. The evaluation may help entrepreneurs, farmers, and enterprises explore market potential, customer demand, and value chain analysis (De Corato 2020).

Conservation and sustainable agriculture

Locals have historically consumed remote Himalayan fruit. The evaluation might emphasize saving these fruits, fostering sustainable agriculture, and helping local farmers. Nutraceutical manufacture from underutilized fruits supports sustainable agriculture and native plant species. These fruits help with biodiversity, endangered species, and sustainable farming. It may also illuminate the environmental effects of planting and harvesting, supporting sustainable methods for long-term fruit supply (Da et al. 2023; Das et al. 2023).

Health and wellness

The review can promote the nutritional and health advantages of underutilized Himalayan fruits. It may help consumers, healthcare professionals, and policymakers understand how these fruits may prevent and treat various health concerns. This understanding can help integrate these fruits into diet guidelines, public health campaigns, and wellness programs (Das et al. 2022).

Collaboration and multidisciplinary research

The complete study may help dietitians, food scientists, pharmacologists, and other professionals collaborate. Collaborations in biochemistry, pharmacology, agronomy, and food technology can lead to multidisciplinary studies on Himalayan fruits' nutraceutical potential (Rana et al. 2023).

Addressing difficulties and seizing opportunities is necessary to sustainably exploit the nutraceutical potential of underutilized Himalayan fruits. Increased research and funding, cultivation and processing infrastructure, formulation standardization, regulatory support, consumer education, and strategic partnerships between agriculture, healthcare, and nutraceutical stakeholders can achieve this. These fruits can help meet the need for natural, sustainable nutraceuticals while helping local populations and maintaining Himalayan biodiversity (Semwal et al. 2022).

Conclusion

In conclusion, underutilized Himalayan fruits, hold promise as Future Smart Foods (FSFs) due to their resilience, availability, economic viability, and nutrition.

These fruits can serve as sources for nutraceuticals and pharmaceuticals, while waste from their cultivation and processing can be repurposed in line with the circular economy. To valorize bioactives from underutilized fruit processing by-products, efficient extraction techniques, biotechnological approaches, and waste-to-energy conversion can be employed. Collaboration with local industries and community engagement are vital for sustainable practices, fostering regional economic development in a circular economy. Recognizing underutilized fruits offers multiple benefits, from diversifying meals to creating livelihoods and improving health. These foods have the potential to combat malnutrition, poverty, and hunger. The FAO's Future Smart Food Initiative underscores the importance of integrating underutilized foods into conventional agriculture. The future necessitates the cultivation, marketing, and consumption of underutilized foods for a sustainable and nutritionally balanced world.

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