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Minor goes diviner: Functional, prebiotic, probiotic and bioactive properties of underutilized fruits

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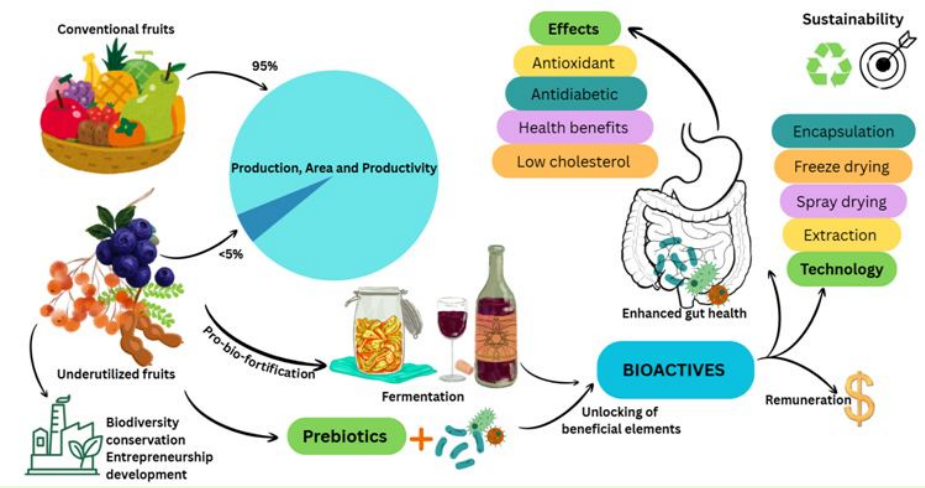
Abstract

The very unpopular opinion persists that arid regions cannot produce fruits of higher nutritional value and have been underestimated for decades. The arid regions are highly neglected from a fruit cultivation point of view. This review shall focus on the neglected crops with high potential as prebiotic, probiotic, and functional foods. The arid zone crops like Kaphal (*Myrica esculenta* Buch.-Ham. ex D.Don), Cluster figure (*Ficus racemosa* L.), Sea buckthorn (*Hippophae rhamnoides* L.), Bael (*Aegle marmelos* (L.) Corrêa), Timru (*Zanthoxylum armatum* DC.), Phalsa (*Grewia asiatica* L.), Khirni (*Manilkara hexandra* (Roxb.) Dubard), Peelu (*Salvadora oleoides* Decne.), Kair (*Capparis decidua* Forssk.), Silver Date (*Phoenix sylvestris* L.), Prickly pear (*Opuntia ficus-indica* L.), Manila tamarind (*Pithecellobium dulce* Roxb.), Lasoda (*Cordia myxa* L.), Mulberry (*Morus alba* L.), Chironji (*Buchanania lanzan* Spreng.), *etc*., are focused for their nutraceutical and functional properties. The consumption of these fruits is very rare nowadays, but have immense potential for planned promotion and expansion of their cultivation area. These fruit crops have high nutraceutical values. These fruits are capable of surviving in unsupportive climate conditions and have the ability to produce some unique phytochemicals that are only possible in the specific climatic conditions received. On the grounds of nutrition demand, barren lands, affected soils, and extreme climate conditions, it is important to reintroduce these species to their habitats. Health benefits of the fruits are well known, but the modern concept of 'eat more fruit' has been concentrating only on a few fruits; the window needs to be widened with the inclusion of minor fruits.



1. Introduction

Fruits are considered one of the first few things that humans consumed for survival. The times when hunting was a notorious job and exhaustive, along with risks, humans turned to cultivate food for themselves. Fruits in those days were sourced from nature itself. The intentional interventions made today's list of fruits that are seen in markets. A handful of fruits are dominating the entire world's fruit market. The technological advancement in fruits like bananas, mangoes, guava, grapes, mandarins, oranges, and limes has led to an increase in market share. Cluelessly, this transformation of fruit choices wiped out some of the very important fruits that have the potential to be celebrated as health super masters. These fruits now get a meaner title like 'minor', 'underutilized', 'forgotten', or

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'orphan'. These fruits are vaguely called minor fruits just because of their scale, but these fruits hold immense potential to be a super food that is nothing less than a tonic for a healthy life. Helplessly, the area under these fruits is depleting at a faster pace and is getting substituted by the mainstream fruit crops, leading to extinction from the sight of common people. Within a similar landscape, the concept of superfoods is gaining huge attention these days, but the Gen-Z audience is exploring it in synthetic products. The so-called 'underutilized fruits' are bestowed with some of the rarest and most beneficial properties. Exploration of fruits with a scope of 'functional superfood' is in the budding stage and has a long journey of scientific exploration. Such fruits, when inspected for the prebiotic, probiotic, and bioactive aspects, make the results shockingly interesting (Meena *et al*., 2022).

'Functional foods' is a term of very recent origin that gained momentum due to health awareness, probably after the COVID-19 pandemic. Functional foods are a spectrum of food products that have the ability to reduce the severity of diseases by improving health through bioactive compounds present in the food (Temple, 2022). Certainly, fruits are a superior source of bioactive compounds that come along with some of the unique health benefits. The demand for functional foods has crossed the production levels and now has become a premium commodity, but underutilized fruits having even higher potential are very rarely exploited for their benefits. The growing demand for conventional strategies would not help with a long-term sustainable sourcing of functional foods. The novel practices like value addition, post-harvest processing, and logistics need to be developed to exploit the limited resources to the maximum. The use of microbes in the food industry has gained momentum in the form of fermented beverages and pickles. Prebiotic food has a greater demand due to its known effect on gut health. Prebiotics are the substrate for microbes in the gut that are a kind of packaged parcels of nutrients that are simplified by the microbes in the gut. The probiotics, on the other hand, are already simplified food substances that actively contain microbes that also enhance the count of the same strain in the gut. The consumption pattern has evolved, and diet now demands probiotics in a supplemental manner due to increased uptake of calorie dense fast-foods. The presence of beneficial microbes and the substrate is important for healthy digestion and proper bowel movement. The human gut houses trillions of microbes that include bacteria, fungi, archaea, *etc*. Viruses may sound astonishing, but are present in the form of bacteriophage. In a total sense, microbial association in digestion, immunity, and health plays a decisive role in sound and healthy living. Medical case studies state that ageusia (a condition), which is probably due to side effects of antibiotic drugs consumed in case of fever, causes loss of beneficial microfauna of the gut, making the food unloving or tasteless. Antibiotics are the major culprits that cause loss of beneficial bacteria in the gut. Studies prove that such a condition worsens the health issues even if medicines are consumed. Ultimately, microfauna of the appropriate type and quantity must be present to have better digestion, immunity, and health (Badjakov *et al*., 2008).

Due to limited technological interventions and climatic conditions, arid fruits are obtained in a particular season, limiting their window for year-round availability. Consumption of the fruits can be a source of bioactives, prebiotics, and probiotics only if they are consumed in the right season, right quantity, and right stage. Aspects related to fruits, highlighting important nutritional factors, shall be evaluated based on prebiotic characteristics like fiber content, water content, sugar, acidity, minerals, vitamins, cholesterol, *etc*. The immunological aspect of fruits has been discovered, proven, and validated through research. While references from the potential interference of microbes for elevating levels of nutrition and exploiting minor fruits for the unexploited section can be explored for probiotic properties. Perhaps, the presence of some unique bioactives makes the fruit an exceptional source of rare medicine, and beneficial properties can be a substitute for increasing the threat of degenerative diseases among generations. The review aims to study the beneficial impact of prebiotics, probiotics, and bioactives that make a fruit a functional food. The review focuses on Kaphal (*M. esculenta*), Cluster fig (*F. racemosa*), Sea buckthorn (*H. rhamnoides*), Timru (*Z. armatum*), Phalsa (*G. asiatica*), Khirni (*M. hexandra*), Peelu (*S. oleoides*), Kair (*C. decidua*), Silver date (*P. sylvestris*), Prickly pear (*O. ficus-indica*), Manila tamarind (*P. dulce*), Lasoda (*C. myxa*), Mulberry (*M. alba*), Chironji (*B. lanzan*), *etc*.

2. Nutrition for a healthy gut: Prebiotics

Food as a whole cannot be directly absorbed by the body. It requires biological interventions of enzymes and microorganisms. Bacteria not only help in balancing the gut pH but also make the availability of micro molecules in food easier to absorb. Fruits in the form of food are one of the largest sources of "Prebiotics", the substances that are a sort of substrate for the biological creatures, typically some beneficial fauna in our body. Prebiotics are as beneficial as food in the body, performing the breakdown of macromolecules into available substances that are essentially derived from the activity of enzymes and biomes. Gut health has a unique correlation with the food that is consumed. Fruits, with their unique combination of prebiotic substances, make acceptance easier (Davani-Davari *et al*., 2019). However, research is now focused on developing fiber-free fruits (insoluble fibers) that are depleting the levels of fiber in fruits. Such selection procedures may sound terrifying, but another aspect that is even more terrifying, that is seedless fruits. Seeds of several fruits like Chironji (*B. lanzan*) are a rich source of tannins, healthy fats, antioxidants and have anticancer properties too. Consumption of seed also provides beneficial minerals that cannot be found in any other food source in that denser amount.

The majority of underutilized fruits, in fact, fruits as a whole, are a rich source of carbohydrates, fibre, metabolites, and a larger chunk of moisture. The fruits are interestingly a poorer source of fats and a moderate source of proteins. The consumption of fruits in the daily diet is significantly important for reaching the minimum of the essential diet requirements. This dietary requirement can be fulfilled from conventional fruits, but minor fruits bring a twist and diversity to the consumption pattern (Figure 1).

2.1 Moisture

The most underestimated factor of fruits that is most required during heat, where the fruits become a source of hydration. The fruits in such a scenario have roles like maintaining the water balance of the body and, at the same time, regulating the solute concentration in the body. Water, being an excellent solvent for soluble fibre, pigments, phenols, and tannins, plays an important role in the better absorption of nutrients in the fruit. Among the conventional fruits, Watermelon (*Citrullus lanatus*) may sound the richest source of moisture, but

minor fruits like Lasoda (*C. myxa*), Phalsa (*G. asiatica*), Mulberry (*M. alba*), *etc*., have a competent moisture content averaging around 80-90%. The higher moisture content also brings some disadvantages, like reduced shelf-life, diluted taste, and the requirement of extra care during logistics. The moisture content comprising the majority of fruit weight is susceptible to being lost, causing physiological loss in weight. The lower moisture level also comes with advantages like enhanced shelf-life, concentrated form of nutrients, and reduced susceptibility to pests and diseases. Fruits like Avocado (*Persea americana*) are poor in water content, and a similar status is observed with fruits like Chironji (*B. lanzan*) that carry very little moisture content, balanced by the presence of lipids (Phogat *et al*., 2020). The substitution of moisture by lipids also adds some healthy fats that are essential for the human body, just like avocado. The water activity of the fruits determines their storage ability and their ability to resist pathogens. The importance of moisture increases when fibre consumption is accompanied, as fibre needs hydration to act well. Water also facilitates proper bowel movement and prevents untimely fermentation of food in the gut that further leads to gas and indigestion (Zambrano *et al*., 2019).

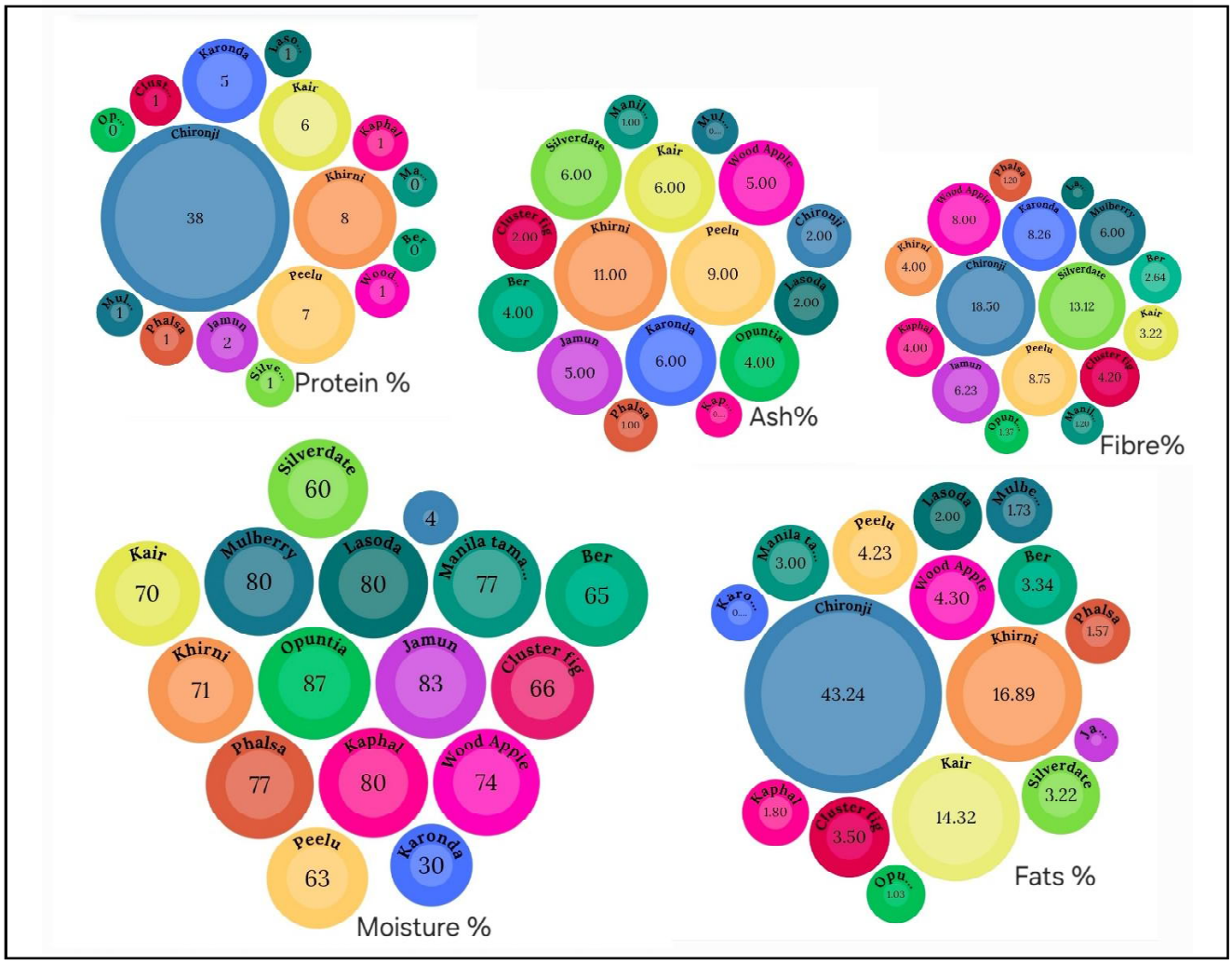

Figure 1: Circle chart depicting the biomolecules in minor fruits, emphasizing to understand the highest content with the largest spread.

2.2 Carbohydrates

Carbohydrates are major components after moisture, invariably present in all fruits. The 3 major types of carbs are simple carbs, complex carbs, and undigestible complex carbs. Simple carbs, or simply just sugars, are the simplest form of carbs received from fruits in reasonable quantities. Carbohydrates are also rich in calories indirectly energy aspect is also rich. Fructose, glucose, and sucrose are prominent sugars found in fruits. Fruits like Bananas (*Musa* spp.), Mangoes (*Mangifera indica*), Dates (*Phoenix dactylifera*), and Pineapple (*Ananas comosus*) are high in carbohydrate content. Simultaneously, some of the carbohydrate-rich fruits are also seen in the minor section in the form of Silver date (*P. sylvestris*), Khirni (*M. hexandra*), *etc*., presenting an alternative to conventional fruits. But the fruits in the minor category gain importance for their ability to manage those carbohydrates at the same time (Panaskar *et al*., 2023; Patil *et al*., 2018; Sajadimajd *et al*., 2019). The fruits typically break down complex sugars like starch into a more accessible hydrolyzed form that can be easily absorbed by the body.

2.2.1 Fructans

These are natural polysaccharides made from fructose units and accounts to be the major contribution as probiotics in the diet. It is made available from fruits, vegetables, and cereals. The gut bacteria break down the larger molecules, and it has health benefits, but when consumed in excess quantity, they may cause diarrhea, bloating, abdominal pain, and uneasiness. The probable cause of these effects can be stated as the fermentation of these substances that releases a large amount of gas like CO_2 and methane. Persons having irritable bowel syndrome (IBS) need to control the intake of these substances (Varney *et al*., 2017).

2.2.2 Galacto-oligosaccharides

Bananas, Berries (Blueberries, Raspberries), Longan tend to be some of the richest sources of Galacto-oligosaccharides (GOS). However, dairy products have even higher content of GOS, but for those being lactose intolerant or vegan, can take fruits as alternatives for sourcing GOS. GOS are known to improve gut health by increasing the beneficial microbes in the gut and additionally improve bowel movement and suppress constipation to a greater extent. It also lowers the pH of the gut and facilitates mineral absorption in the gut. Some side effects may be seen if consumed in excess. The symptoms might be in the form of gas, bloating, flatulence, *etc*. (Jovanovic-Malinovska *et al*., 2014).

2.2.3 Starch and glucose-derived oligosaccharides

These compounds are typically modified starch and glucose chains that can prevent their digestion in the upper digestive system and are flown to reach the colon for fermentation. One of the basic types in this class is resistant starch, a starch that is a polysaccharide in nature and has prebiotic properties. Starch is sometimes seen with doubt, but deep down, it is necessary to know that the place of processing in the human body also plays an important defining role, drawing a thin line between starch and resistant starch. Resistant starch is a great functional food element as it performs fermentation in the colon region and produce large number of short-chain fatty acids that are crucial for colon health. Additionally, resistant starch gives natural alternative for increasing fecal bulk and enhancing detoxification (Hu *et al*., 2025). Resistant maltodextrin (RMD) is a water-soluble fiber that is highly prone to the fermentation process. It also promotes the activity of bifidobacteria in the gut. It also reduces the chances of constipation by making stools wet with moisture absorption (Watanabe *et al*., 2018). Polydextrose is another type under this class that controls the growth of bifidobacteria. Isomalto-oligosaccharides, being a similar example, have similar properties. Some fruits may provide resistant starch that is beneficial in diabetes, but at the same time, they contain other forms of sugars that indirectly can cause an increase in blood sugar levels for a shorter time (Sajadimajd *et al*., 2019). Kaphal (Wild bayberry) is a rich source of crude fiber, crude protein, and carbohydrates, making it ideal as a prebiotic. Timru contains significant fiber (27.53%) and carbohydrates (36.48%), acting as a prebiotic that aids in intestinal disorders (Mishra *et al*., 2023). Lasoda has approximately 4.5% pectin (soluble dietary fiber), which acts as a prebiotic for gut health-promoting bacteria (Tripathi, 2020).

2.2.4 Pectic oligosaccharides

Pectic oligosaccharides (POS) are the basic components from the fruits that are rich in pectin content, where fruits like Guava (*Psidium guajava*), Jackfruit (*Artocarpus heterophylus*), Citrus peel, Figs (*Ficus racemosa*), Pomelos (*Citrus maxima*) account for some of the richest sources of POS. POS are short-chain carbs made of pectin. Its significance as a prebiotic is highlighted because it is selectively fermented in the colon, making it stimulative to bifidobacteria and lactobacilli. The mode of action is, however, similar to other prebiotics. Additionally, POS have the ability to enhance immunity due to their control over gut-associated lymphoid tissues. Bael demonstrated superior prebiotic activity, showing positive growth for *L. paracasei*, *L. plantarum*, and *L. rhamnosus*. It outperforms standard Fructo-oligosaccharides due to its abundance of sucrose (27.98%), fructose (2.49%), and glucose (1.641%). Phalsa can be considered highly prebiotic due to sugars (5.73 to 7.95%) and fiber content in the pomace (over 32%), which adds volume to stools (Siriwardhana *et al*., 2024). The mucilage of Sea buckthorn supported *Bifidobacterium lactis*, yielding the best results in yogurt fermentation (Izquierdo-Cañas *et al*., 2016). The sap of Silver date (Neera) is a rich source of natural sugars and amino acids, useful for digestion (Khadka *et al*., 2024).

2.3 Fibres

Fruits stand as an easily digestible source of prebiotics since they adequately provide fiber and carbohydrates that are a kind of substrate for gut microbes (Pop *et al*., 2021). Other than fruits, vegetables may sound like a good source of prebiotics, but have limitations when dealing with consumption acceptance. Underutilized fruits like Timru, Silver date, and Peelu are some of the competitive sources of fibres competing directly with leading fruits like Jackfruit, Guava, Apples (with skin), *etc*. The probiotic aspect has a deep relation with the fibre content of the fruits. The major role of fibre as a prebiotic is the structure that stays intact in the gut, providing roughage with locked nutrients for the gut microbes to feed upon. Fibres present in food are basically of two types: soluble and insoluble. Soluble fibres are readily solubilized and form a viscous substance that, in return regulate the biomass of the food consumed. Humans now lack the ability to digest complex fibres like cellulose and lignin; this ability vanished with the consumption of cooked food. The reduced intake of fibre in the current scenario is leading to modern lifestyle diseases like piles in the younger age. The supplemental fibre intake in the form of isabgol or laxatives could lead to heavy consequences, hampering the diet habit, leading to the exclusion of fruits from the diet. Thanks to minor fruits, there still exists some scope for bounce back of these fruits for their exceptional fibre content, providing the nutrient-rich laxative options. Bael and Silver date can be included in the daily diet for fulfillment of the fibre requirement. The mucilage of the fruits has a special ability to form a part of fecal matter that smoothens the bowel movement (Munshi *et al*., 2011). Fruits, when consumed with the skin provided maximum fibre in the case of Khirni, Phalsa, *etc*. The fruit wastage from the processing industry, especially for minor fruits, can be turned into fibre-rich supplements that would add more value to the crop. The fruits that are grown in arid regions are fundamentally rich in fibres, for being able to withstand tough climatic conditions. Fibre intake is limited when fruits are processed into beverages. The consumption of fibres can be enhanced by the preparation of yogurt smoothies, or fruit can be added to the yogurt for enhanced consumer acceptability. Fruit-based yogurts are popular with Strawberry, Blueberries, Mango, *etc*. But, the fruits like Peelu, Lasoda, Cluster fig also have a

similar scope for expansion into fibre-rich probiotics, especially with dairy combination (Begum and Bukya, 2024; Tak *et al*., 2024; Varshney *et al*., 2025).

2.4 Protein

Protein is an essential building block of the human body, including enzymes, hormones, *etc*. The fruits in this regard are a poor source of protein. However, some hidden gems like Chironji turn out to be one of the richest sources of protein that any fruit has. Consumption of Chironji (10 g) every day can meet approximately 20% daily dietary requirement of protein for an average human of 80kg weight (Ulhas *et al*., 2023). However, the prime aspect that needs to be considered is that fruit is also rich in fats, a warning for its limited consumption. Similarly, other fruits like Khirni and Kair are high sources of plant-based protein. This can successfully target the vegan conscious audience. However, those having allergies to nuts need to figure out their consumption accordingly. These fruits are excitingly a very tough competition in the protein aspect as well. The protein demand from both the young and old generations is rising at a greater pace, to which chemical-based and dairy-based protein powders are gaining a huge market. A similar scope can be seen for enhanced acceptability of minor fruit-based protein products for meeting the demand of the target audience.

2.5 Lipids and fatty acids

Fats are a concentrated source of energy that, when provided through fruits, are in the form of oleic (MUFA-monounsaturated fatty acids), linoleic (PUFA-polyunsaturated fatty acids), linolenic (omega-3), palmitic (saturated), and stearic acids. The fatty acids present in fruit help to reduce bad cholesterol and efficiently provide the required fats in an adequate quantity. Technically, fruit pulp is not a good source of fats, but the seeds, to some extent, are a good source of fatty acids, and that can be observed through the fat content of seeds like Peelu and Chironji. Peelu seeds are a rich source of oil, ranging around 40% that is also rich in lauric acid (20%), and can potentially contribute as a great substitute for coconut oil (Farag *et al*., 2021). The supply of fats from Avocado is almost 12-15%, and fruits like Peelu or Chironji can provide similar nutrition in lesser quantities. There is also an option for the folks who want to go with less fat fruit. The pulp of Peelu itself is a healthy alternative with meager amounts of fats. Silver date, Phalsa, Manila tamarind, and Prickly pear are good options for the calorie-concerned population. The fruit with lesser-known nutritional values is having solution for both fat-rich and non-fatty fruits at the same time. The fatty acids present in fruit act as a conditioner for the food eaten and later on cause ease in bowel movements (Bae, 2014). The advantage of fruit is not limited to, but also includes enhanced lubrication for bone joints and relief from pain.

2.6 Minerals

Minerals are directly associated with normal physiological functions, where minerals like calcium are associated with bone health, healing action, and tooth health. While iron plays an important role in maintaining blood health, preventing anemia. Similarly, sodium, phosphorus, and potassium maintain the electrolytic balance in the body, additionally maintaining the neural health and proper functioning of the cells. Fruits, especially minor fruits, grow on varied landscape and house these essential minerals that can in turn be utilized by the body cells and have a significant impact on health (Table 1).

Table 1: Nutrients and radical scavenging activity of various minor fruits

S. No.	Fruit	Protein (%)	Fat (%)	Fiber (%)	TPC (mgGAE/g)	FRAP ($mMFe^{2+}/g$)	DPPH IC_{50} (mg/ml)	References
1	Kaphal	3.4	1.10	6.9	115.9	42		Kabra *et al*., 2019
2	Cluster fig	3.5	0.8	4.2	230	37.80	1.278	Begum and Bukya, 2024
3	Phalsa	1.57	0.9	1.2				Khan *et al*., 2019
4	Khirni	16.89		8.26	8.113	0.69	0.665	Panaskar *et al*., 2023; Parikh and Patel, 2017
5	Peelu	4.23	7.19	8.75	5.98			Varshney *et al*., 2025
6	Kair	14.32	6.02	6.19				Alrasheid *et al*., 2018
7	Silver date	3.22	0.61	13.12	212.94	2.122	0.58	Saha *et al*., 2017
8	Opuntia	1.03	0.40	1.37	4090		14.60	El-Mostafa *et al*., 2014
9	Manila tamarind	3	0.4	1.2	3.1	50.7	35.7	Murugesan *et al*., 2019; Vargas-Madriz *et al*., 2020
10	Lasoda	2		0.3	137.56	33.86		El-Nashar *et al*., 2025; Tripathi, 2020
11	Mulberry	1.73	0.48-0.71	6	3360.5			Hu *et al*., 2025; Imran *et al*., 2010
12	Chironji	43.24	38	18.50		18.90		Khatoon *et al*., 2015

3. Microbes in the gut: Probiotics

Fruits as a whole do not contain any probiotic microbes. This statement may not sound true when the external layer is considered, as several foreign microbes harbour on fruit peel. However, fruits of all kinds are a substrate for the probiotic bacteria, which, upon fortification, can make the fruit serve its role in a better way. The methods of converting simple fruits into prebiotics are in the hands of beneficial bacteria outside the human body. Fermentation is the way that can turn fruit juices into probiotics outside the human body. However, the presence of prebiotics is mandatory for such a reaction to take place. The fruit-based probiotics can be made either by fermenting them or adding them to some finished fermented products like cheese, curd, or yogurt, enhancing the nutritional quality of other products (Ranadheera *et al*., 2018). Both ways of inculcation of beneficial bacteria into the food can break down the molecules into Short-chain fatty acids that are easy to digest and impart nutrition. For this venture, bacterial strains like *Lactobacillus plantarum*, *L. paracasei*, *L. rhamnosus*, and yeasts like *Saccharomyces cerevisiae* are considered. The mode of action of probiotics is pretty much the same as prebiotics; however, the major difference observed is that prebiotics perform major activity inside the body, while probiotics have already started their work outside the body before consumption. The probiotics may be classified in following types:

- **Malolactic fermentation:** Due to the metabolism of lactic acid bacteria (used in the wine industry). Malic acid is converted into L-lactic acid by the process of decarboxylation.
- **Probiotic dairy products:** Dairy-based products used in the development of probiotics. They produce short-chain fatty acids that have a beneficial impact on the human gut and improve insulin sensitivity.

3.1 Biotransformation

Mulberry fruits fermented with *Streptococcus thermophiles* and *L. plantarum*, the anthocyanin content was actively degraded by 43-46% and bio-transformed into highly beneficial polyphenols like chlorogenic and caffeic acid, which improve cardiovascular health. Similar studies have a deep scope while dealing with other minor fruits (Cheng *et al*., 2016).

3.2 Fermentation and bacterial strains

A carbonated beverage prepared from minor fruits and fermented with *L. acidophilus* has a shelf life under refrigeration with high consumer acceptability. Additionally, the fermentation with *L. plantarum* along with skim milk significantly increased the fruit's antioxidant levels and total phenolic content. Sea buckthorn has been successfully fermented into yoghurt using *L. bulgaricus* and *Streptococcus thermophiles*. Further research indicates that using *Bifidobacterium lactis* as a prebiotic yielded the best results. Fermentation by *L. plantarum* can also transform the juice into a cholesterol-lowering beverage. Prickly pear or Opuntia pulp fermented with *L. fermentum* is used to preserve the fruit pulp. This process degenerates harmful compounds such as 4h-Pyran-4-one and furan, making the beverage more wholesome and palatable. Cluster fig juice can be fermented with *L. delbrueckii*, which breaks down the contents into simpler molecules for better digestion. The process works best when the juice is symbiotic with inulin.

3.3 Pickling and preservation

Pickling of fruits is a popular method that improves antioxidant capacity and replenishes electrolytes in the human body. It acts as an appetizing agent, though it should be consumed in limited quantities, considering its high acidity. Lasoda is commonly processed into a spicy pickle in arid regions or used as an additive in mango pickles. Peelu fruits in unripe form are used to make spicy pickles in parts of Rajasthan. Unlike other parts of the world, brine pickling is rarely practiced in India; more emphasis is given on oil and spice-based pickles. The newer generation, however, being more aware, demands brine-based pickles.

3.4 Dairy and culinary products

Cluster fig pulp has a unique grainy texture resembling granola, making it a potential functional additive for milk products like yoghurt, shrikhand, and lassi. The flavor of the cluster fig resembles that of fig in dairy products. Peelu fruits are also processed, and a protocol has been developed to prepare squash that aids in preventing heatstroke, enhancing their consumption widely in summers. Chironji pulp (20-40% of the fruit) is very little in quantity; it is sweet and used to make Squash and RTS (Ready-to-Serve) drinks, and has limited popularity in the native regions. Prickly pear cladodes (pads), often mistaken for leaves, are processed into flour, which can substitute corn and wheat flour in bakery products as it retains similar yeast-friendly activity in breads. The fruit pulp is processed into jams, jellies, syrups, and candies, highlighting its scope for cultivation (Chakraborty *et al*., 2011).

4. Bioactive compounds

Bioactive compounds are the basic components that plants produce to serve functions like attraction for insects and birds, defense mechanisms, reflex action, *etc*. Compounds like flavonoids, polyphenols, tannins, anthocyanins, alkaloids, *etc*. Phytochemicals are more or less associated with plant defense mechanisms. The phytochemicals produced by plants are most of the time beneficial for humans, carrying protective and preventive properties for various diseases. Phytochemicals are also responsible for the unique flavor that fruit retains and have a unique ecological relation with insects and birds that are involved in the lifecycle of the plant. These plants have a well-known advantage for propagation through the seeds eaten by birds and animals and then dispersed by the means of fecal matter. The minor fruits seen in the wild are the result of these efforts only. The volatile compounds, pigments and season of availability make the life cycle of the plant complete. Fruits studied in this review belong to arid, semi-arid climate zones that account for a significant area of the terra firma that needs to be studied for functional aspects. Prominently, these fruits house some of the interesting arid fruit crops. The unattended prevalence and lesser market share mark the reason for their unthankful coronation of "minor fruits". The fruits found in arid regions are prone to extreme climate and temperature, along with biotic stress. The natural evolution of these fruits gained them enhanced immunity in the form of protective secondary metabolites that are none other than bioactive compounds. Secondary metabolites are highly beneficial in most of the cases, except for some, where they form toxins and are not suitable for human consumption, especially some compounds like alkaloids and amygdalin that are potentially toxic to humans. Some beneficial metabolites also exist that have great demand for their

protective abilities, like antioxidants, anticancer, antitumor, antirheumatic, hepatoprotective, antimicrobial, *etc*. Along with these functions, metabolites also form some of the essential nutritional factors, like vitamins and phenols. Compounds like anthocyanin and carotenoids, which are popular pigments with hidden properties like free radical scavenging and antiageing, have immense demand from the conscious community. Detailed bioactive components are listed in (Table 2).

Table 2: Bioactive compounds present in the minor fruits

S.No.	Fruit crop	Bioactive compounds present	References
1	Chironji	High protein content, oils, minerals.	Khatoon *et al*., 2015
2	Cluster fig	Flavonoids (quercetin, luteolin, rutin, apigenin, luteolin-7-o-glucoside, catechin, epicatechin).	Munira *et al*., 2018
3	Kair	Glucocapparin, isothiocyanate aglycone.	Khare, 2007
4	Kaphal	Cyanidin-3-o-glucoside, myricanol, myricitrin, predelphindins, quercetrin, isoquercetrin, proanthocyanidins, polyphenols.	Agrawal *et al*., 2024; Shri and Sood, 2018
5	Khirni	Phenolic acids: Gallic, catechol, vanillic, hydroxycinnamic, ferulic, coumaric acids. Flavonoids: Catechin, epicatechin, epigallactocatechin, quercetin, kaempferol.	Parikh and Patel, 2017
6	Lasoda	Pectin (soluble dietary fiber), secondary metabolites.	Tak *et al*., 2024; Tripathi, 2020
7	Manila tamarind	Amino acids: Lysine, valine, phenylalanine, tryptophan. Vitamins: Ascorbic acid, thiamine, riboflavin. Other: Anthocyanins.	Pío-León *et al*., 2013; Vargas-Madriz *et al*., 2020
8	Mulberry	Anthocyanins (Cyanidin-3-glucoside), pectin. Bio-transformed polyphenols: Chlorogenic acid, cryptochlorogenic acid, caffeic acid, ferulic acid.	Cheng *et al*., 2016; Imran *et al*., 2010
9	Peelu	Salvadorine, salvadourea, alkaloids, trimethylamine, cyanogenic glycosides, tannins, saponins, lauric acid (in seeds)	Farag *et al*., 2021; Varshney *et al*., 2025
10	Phalsa	Amino acids (aspartic acid, glutamic acid, valine, leucine), calcium.	Elhassan and Yagi, 2010; Singh, 2025
11	Prickly pear	Phenolics: Quercetin, isorhamnetin, kaempferol, luteolin, isorhamnetin glycosides. Fatty acids: Palmitic acid, oleic acid, linoleic acid (Omega 3).	Messina *et al*., 2021
12	Sea buckthorn	Flavonoids, fatty acids, phytosterols, vitamins (A, C, E).	Olas, 2016; Stobdan *et al*., 2010
13	Silver date	Phenols, flavonoids, alkaloids, tannins, terpenoids, carotenoids, vitamins, and amino acids.	Jain *et al*., 2018
14	Timru	Linalool (46.65% of aroma compounds), terpenes, alcohols, phenols, and flavonoids.	Khaing and Moe, 2021; Xiao *et al*., 2025

5. Health benefits

5.1 Antidiabetic

The fruits with lower molecular weight carbohydrates, can counteract diabetes and act as a powerful antidiabetic agent. Glycemic index was studied when glucose was considered as a standard; fruits like Watermelon, Pineapple, Mango, Kiwi, *etc*., resulted in a higher glycemic index, showcasing a higher sugar spike upon consumption. Upon similar grounds, fruits like Cluster figure carry a significantly lower glycemic index. Various citrus species also retain a lower glycemic score. Lower glycemic index directly correlates with health conditions like lower sugar spike, regulated blood pressure, and balanced obesity. While anthocyanins and cyanidin-3-O-glucoside contribute to antidiabetic properties in wild bayberry (Agrawal *et al*., 2024). Similarly, Sea buckthorn-based fermented juice regulated pancreatic lipase activity and cholesterol micellar solubility, aiding in metabolic syndrome treatment (Olas, 2016).

5.2 Antioxidant

The lifestyle has become lethargic, and a root cause for the lifestyle disorders is the ROS, which certainly causes irreparable damage to the human body. The symptoms are visible in the form of poor heart health, early ageing and failure of essential organs. Minor fruits like Opuntia (Prickly pear) have an antioxidant activity of 4,090 mgGAE/g by virtue of quercetin and isorhamnetin. While Mulberry has about 3,360.5 mgGAE/g radical oxygen scavenging activity due to the presence of anthocyanins (cyanidin-3-glucoside). The Mulberry has an even higher amount of anthocyanin compared to the Strawberry. In Cluster fig, the presence of antioxidants is more concentrated in the skin compared to the pulp of the fruit, signifying the inclusion of fruit skin in the consumption too.

5.3 Anticancer

Fruits, when consumed for nutraceutical purposes, also exhibit some miraculous properties, like the regulation of cell growth. The excessive multiplication of cells, a cancer condition, can be administered by

minor fruits. While Karonda (*Carissa carandas*) ethanolic extract successfully treated cervical (HeLa), Breast (MCF-7), and Hepatocellular carcinoma (HepG-2) cell lines. Kaphal fruits inhibited growth and caused death of breast cancer cells (MDA-MB-231). The advantages of minor known fruits underline the need for fruit consumption, particularly among women (Makarova and Zyriax, 2023).

5.4 Other health benefits

Cardioprotective, antiobesity, antimicrobial, anthelmintic, hepatoprotective and tooth health enhancement come ex-gratis with minor fruits. The age-old tradition of brushing teeth with Peelu sticks and maintaining oral health has now disappeared, but can be reintroduced for its added advantage. Sea buckthorn is popularly recommended for heart patients and also as a preventive agent. Phalsa also retains similar properties. The presence of antibacterial properties in Cluster fig has been confirmed, and its application in infection-relieving ointments is also validated (Dubey *et al*., 2018). Inflammation regulatory and antiobesity properties have also been validated in Cluster fig. Tribal communities are aware of the health benefits of Timru and hence consume these fruits in the bearing season. Successful studies were undertaken for antibacterial activity of various plant part extracts (Phuyal *et al*., 2020). Young shoots are also used as a toothbrush for healthy gums. The fruit juice of Kair can act against *Vibrio cholera*, a cholera-causing pathogen in humans. The seeds are antibacterial due to the presence of glucocapparin and isothiocyanate aglycone of glucocapparin. Unani medical science observes Kair as a carminative, aphrodisiac, appetizer, cough, and asthma-relieving medicinal plant. Ayurveda also presents this fruit as beneficial in urinary tract infections and fighting ulcers, vomiting, and piles. The ability of fruit to be antidiabetic, sedative, anticonvulsant, cholesterol controlling, and antioxidant capacities have been validated (Singh *et al*., 2010).

6. Possibilities for technological intervention in minor fruits

Due to the perishable nature and seasonal availability of these fruits, various processing and value-addition methods need to be undertaken to enhance the shelf-life and commercially viable minor-fruit-based products. Different methods are possible with respect to post-harvest management of the fruits, considering the range of methods like spray drying, emulsification, freeze drying, chemical-based encapsulation, electro-spraying, *etc*. These methods also have an advantage while dealing with flavors that are fruit-specific, extending the application to perfumery with fruits. The technological interventions not only limit the post-harvest losses but also provide audience-specific solutions based on minor fruits.

6.1 Extraction

Extraction of bioactives from the fruits can be a suitable solution for year-round access to specific bioactives in concentrated forms and can be consumed as per needs. It is highly beneficial for those who cannot avail themselves of fruits in season or are allergic to other complementary bio-ingredients. Hot water extraction is possible by keeping the fruit pulp in 70-80ºC for 30 min and then precipitating in acetone, yielding a dry mass of 14% (Patil *et al*., 2018). Microwaves in the range of 300 MHz to 300 GHz are also used for the extraction of bioactives (Zainuddin *et al*., 2021). Microwaves generate a high frequency of vibrations that cause agitation of polar molecules, leading to the buildup of pressure, causing disruption of the cell wall and penetration of solvent into the cell. Dry extraction is also possible in fruits like Bael (*Aegle marmelos*), where the fruit is dried, and the mucilage is collected (Banu *et al*., 2021). While cold water extraction of bioactives involved soaking for 24 h at 280ºC, extracting up to 15% (Ibrahim *et al*., 2016).

6.2 Encapsulation

Micro and nano encapsulations have a spectrum of applications that need to be evaluated for their ability to comprehend targeted biomolecules or phytochemicals for concentrated sourcing of the same. Fruits, especially the minor ones, are rich in beneficial phytochemicals that are sensitive to thermal and photo degradation. Lasoda fruits, considering their high phytochemical status, encapsulation with alginate based nano particles have provided them with high resistance against thermal degradation, preserving the fruit's nutritional status for a longer period in adverse conditions (El-Massry *et al*., 2021). Several conventional fruits have been attempted for chitosan-based encapsulation, especially in grapes, mangoes, and apples, marking an important direction for the processing of minor fruits in a similar way.

6.3 Spray drying

The novel method of conservation of nutritional status of the fruit has the ability to retain the color of the product with relatively very low water content and higher bulk density, making the product suitable for industrial applications. Spray drying, an arm of encapsulation, enabled the underutilized fruit like prickly pear to obtain a free-flowing powder-like substance that has high demand in the processing industry as juice powders (Obón *et al*., 2008).

6.4 Freeze drying

The process of exposing the fruit substances to extreme cold temperatures with the aim of reducing or stopping the physicochemical changes of the fruits is known as freeze drying. Research conducted on mulberry for freeze drying and hot-air drying compared to fresh fruits revealed that the fruits showed negligible reduction in TSS, amino acids, and soluble protein content. However, hot-air drying resulted in a significant reduction in the same factors. A similar trend was observed with flavonoids, polyphenols, resveratrol, chlorogenic acid, and anthocyanin content. Antioxidant ability did not increase when compared to fresh fruits, but had remarkable retention in the freeze-drying process. The freeze-drying retains almost 95% of the original properties of the fruits (Wang *et al*., 2023).

6.5 Beverages and wines

Karonda fruit can be processed into wine containing approximately 7.8% alcohol and 4.50 mg/l of ascorbic acid. The process has been standardized and has been well accepted by the consumers. Silver date sap (Neera) is fermented into 'Toddy', a natural probiotic fermented beverage. Wine prepared from the sap contained 10-14% alcohol after a week of fermentation. The colored wine prepared from Karonda is also rich in antioxidants. Due to rich pigmentation, Phalsa is also suitable for making coloured wines, which are often blended with Grapes (*Vitis vinifera*), Pomegranate (*Punica granatum*), or Aonla (*Emblica officinalis*) to improve the profile of the wine.

6.6 Waste valorization

Along with processing, there comes a range of waste products, potentially by-products that may be utilized for obtaining the much

more valuable resource. The skin, pomace, and the seeds are the most wasted parts; they can find their place in the form of valuable products. The seeds of Khirni, Peelu, Lasoda, Silver date, and Prickly pear are a great source of micro nutrients and minerals. Comprising the importance of the seeds as a source of oils can add more value to the fruit itself. The pomace that primarily comprises non-soluble fibres carries a significant amount of unextracted fragments of the pulp. The fibre-rich alternatives are possible through the processing of the pomace. Skin, being one of the prominent sources of anthocyanins and other pigments like carotenoids, contributes a lot to the fruit's nutritional value and needs to be valorized with the right value. The skin is also rich in fibres and can be used as a natural food additive or coloring agent for food products.

7. Factors giving minor fruits a cutting edge

- Most underutilized fruits easily grow without much care.
- Potentially carry genetic traits for tolerance and resistance towards abiotic stress.
- The fruits impart resistance due to secondary metabolites that are themselves the beneficial elements.
- The fruits are high-yielding when exposed to suitable conditions.
- Fruits have the potential to create their place in the market with a prime focus on their nutraceutical values.
- The fruits have very few explored post-harvests processing protocol that creates an opportunity to obtain the most benefits from the products.
- The nutraceutical properties of the fruit enable these fruits to be health protective agents.
- Climate-resilient agriculture is possible with minor fruit crops.

8. Future perspectives and research gaps

The need for nature-friendly practices in the treatment of diseases is gaining popularity. The demand for functional foods is very high, but the supply is very low. There needs to be some attempts in the commercialization of the plant products to deliver the exact required functional ingredient to the needy. Sourcing of the functional factors is possible through conventional fruits, but the focus on the arid region also needs to be concentrated to derive more of the nutritional benefits possible. The pros of the underutilized fruits have been successfully highlighted, which may promote awareness among consumers, leading to increasing demand, as seen in the recent trends of the health and nutrition sector. Awareness of functional foods is on a full boom, and demand from consumers is also rising, as in the initial stage. The development of the market also depends on the production aspect. More competitive production management practices can be useful to create a space for a budding domain in the fruit sector. Enhanced storage, management, and logistics protocols need to be developed for highly perishable fruits. Parallely, it is necessary to fortify the produce of underutilized origins into novel processed products that shall include, but not be limited to, pro-bio-fortification. In this regard, a greater number of beneficial strains of microbes that have a beneficial impact need to be evaluated and utilized. The shelf life of fruits, already being a concern, needs to be addressed by involving a biotechnology approach to retain the pros but eliminate the unwanted factors from the fruits to serve a larger audience base.

9. Conclusion

The underutilized fruits are slowly coming into the landscape and have immense potential to replace the conventional fruits with the virtue of their nutraceutical, bioactive, and functional properties. Use of advanced technologies shall be introduced to bring highly neglected fruits under cultivation, and initiatives need to be undertaken to quantify and estimate the contents of the functional ingredients in the fruit, as well as associated parts, at the same time. It again comes into focus that the probiotics cannot only make food simpler to absorb but also impart health benefits like unlocking polyphenols and the release of certain amino acids when undergoing bioactivity. Bioactive compounds of the fruit, either positive or negative, can be regulated for their presence using specific microbes, eliminating the risk of toxins that come along. Value addition is a sector that has no end, and it also has the ability to sustain the importance of the alleged minor fruit crops. The reason for fruits not getting acceptability is hidden within their notorious characteristics like taste, flavour, spines, texture, availability, *etc*., which need to be addressed on a biotechnological scale. The time has come when the diet needs to be incorporated with prebiotic and probiotic food products as a part of a balanced diet. According to Ayurveda, all plants have some or the other hidden medicinal value; the one who knows all knows the medicine. Awareness is the key that can unlock the potential for expansion in this sector. Breeding of such fruits may not only give them a better quality but also a supernumerary compensation to the farmers. Year-round availability may be beneficial for fetching elite prices and meeting customer demand. Now, it is time to give these fruits a wider frame of appreciation and endorsement so that a newer version of fruits secures their place on the plates of commons.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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