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ORIGINAL PAPER

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SUSTAINABLE APPLICATIONS OF PHYTOCHEMICALS AND NUTRITIVE COMPONENTS DERIVED FROM SELECTED UNDERUTILIZED SEEDS: A REVIEW

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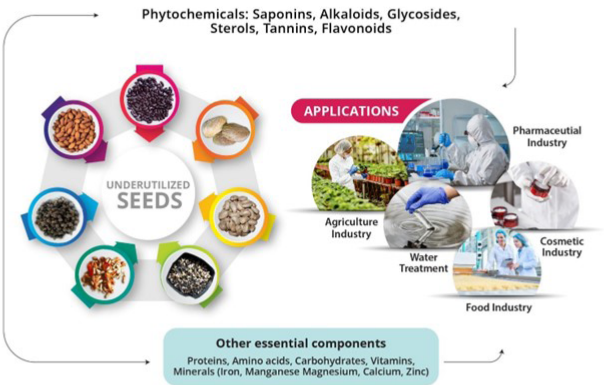
ABSTRACT

There is growing evidence that plant seeds such as jackfruit offer myriad nutritional, livelihood, and health benefits to humans and animals which could be further harnessed in sustainable practices such as farming and human health. However, most of the seeds are discarded and wasted and little research has been done to understand the phytochemicals therein and the nutritive values that seeds offer. As a result, vital chemicals are lost, and their potential for value addition is reduced. Our study contributed to understanding this by employing a non-systematic literature review method where we sourced 219 documents (mainly articles related to plants, seeds, and phytochemicals) and these were sourced from five (5) digital databases: Scopus, Science Direct, PubMed, ResearchGate, and Google Scholar. Our study contributes to scholarship by systematically gathering and synthesizing scholarly literature on 11 tropical seed varieties to analyze the various sustainable applications of phytochemicals and nutritive components found in underutilized seeds such as the Indian almond, tamarind, papaya, mango, pumpkin, Indian gooseberry, custard apple, lemon, as well as shells from cashew nuts, and coconuts and the phytochemicals therein such as phenolics, saponins, alkaloids, tannins, flavonoids, anthraquinone glycosides, and nutrients like proteins, carbohydrates, vitamins, and minerals. Studies have reported that underutilized seeds could offer substantial potential in the food, pharmaceutical, and agricultural industries. Metabolites isolated from these seeds have been employed as colourants, preservatives, flavourings, and nutraceuticals, offering health advantages beyond basic nutrition. Their anti-inflammatory, anticancer, antibacterial, and antispasmodic qualities have drawn significant attention in the pharmaceutical industry. Additionally, they have demonstrated their potential in agriculture as antiparasitic, insecticidal, and antifungal agents. Hence, the compilation of information on the uses of underutilized seeds is essential to set a path to sustainable and innovative solutions. By doing so, waste would be minimized and their potential would be realized.

Keywords: phytochemicals, underutilized seeds, waste, nutrients, sustainability, value addition



Graphical abstract

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PREAMBLE ON UNDERUTILIZED SEEDS

INTRODUCTION

Globally, there is increased evidence that plant seeds especially of tropical plants such as jackfruits, papaya, and almonds among others avail myriad benefits for both humans and animals and thus, utilizing them could be key in availing sustainable benefits. However, in most tropical regions, most of these seeds are discarded as waste thus leading to the loss of the immense phytochemicals and nutrients that they possess. In addition, limited research has been conducted; especially in tropical regions to specifically map out the various phytochemicals and their benefits that are lost when seeds are discarded. Our study contributes to this by exploring 11 plant seeds that are commonly found in tropical regions (and discarded) to inform about their benefits that could be tapped for different purposes.

Underutilized seeds have enormous untapped potential for various pharmaceutical, food, cosmetic, and agricultural uses (Kirubakaran et al., 2002). Even though these neglected seeds are rich in vital elements, they have not been extensively explored (Okonwu, 2019). For example, coconut shells have been regarded as part of food waste during processing (FAO, 2019). Furthermore, it is noted that underutilized seeds are routinely disposed of in landfills, where they decompose and release greenhouse gases (GHGs) (Zaini et al., 2022). Although seed varieties are abundant in nature and highly diverse, most literature about their applications is scattered leading to a dearth of knowledge regarding their bioactive compounds and potential applications (Jaiswal et al., 2022; Magallanes-Cruz et al., 2023). This hinders the development of sustainable and diverse utilization of natural compounds for various industries and communities.

Value-added metabolic compounds derived from food waste and byproducts have attracted a lot of concern, especially in the domain of food security and sustainability (Prakash et el., 2021). Phytochemicals and nutrients available in underutilized seeds are among these metabolites, and several studies have demonstrated their applications (Zaini et al., 2022). Figure 1 illustrates the organization of some phytochemical classes and nutrients commonly found in underutilized seeds.

The potential of underutilized seeds could further be harnessed at a global level as a prospective means for food security, traditional medicine remedy, in agriculture and pharmaceuticals respectively. In addition, seeds have also gained popularity in the cosmetic

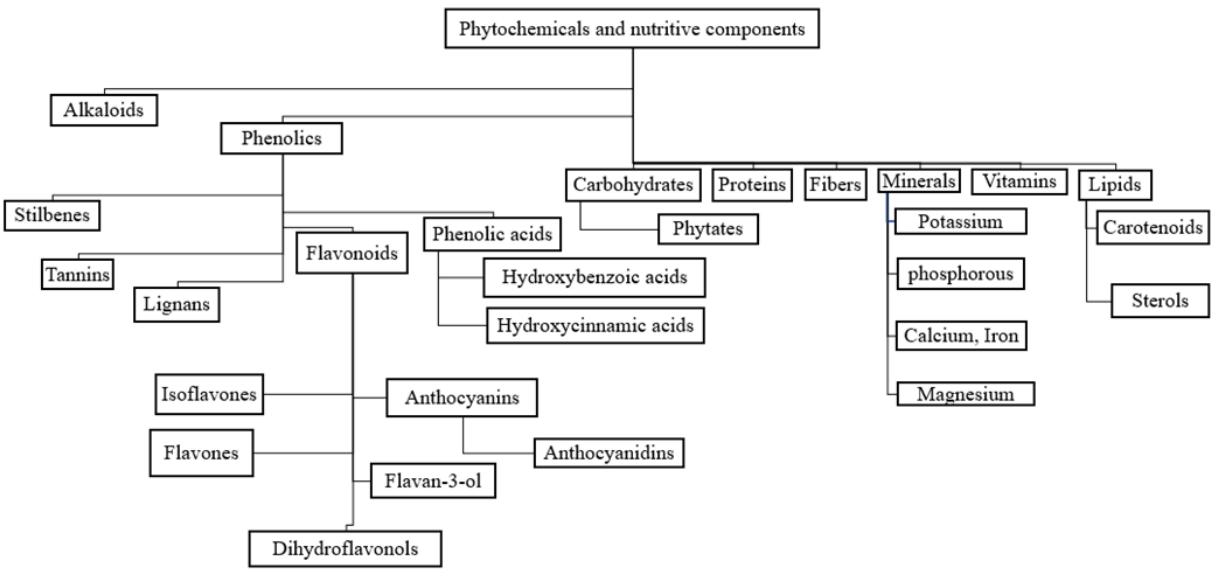

Fig. 1. Classes of phytochemicals and nutrients found in underutilized seeds

industry and water purification plants (Ankegowanda et al., 2020; Bahinipati et al., 2021). In Africa, Asia and some parts of South America, for instance, jackfruit seeds have been employed as a source of carbon for the extracellular synthesis of pullulan by *Aureobasidium pullulans* and polyhydroxybutyrate using *Bacillus sphaericus* (Ranasinghe et al. 2019; Coltelli et al., 2020). Pullulan polysaccharide polymer that is produced when starch is fermented, is increasingly used in the cosmetics industry as a binder and film-forming agent (Coltelli et al., 2020).

In the agri-food value chain, this could add value to agricultural waste products through biotechnological interventions. In Zambia, a study by Chota et al. (2010) validated the effectiveness of *Carica papaya* underutilized seeds, as an efficient anthelmintic against nematodes parasites in poultry chickens-a crucial aspect in boosting the livelihoods of vulnerable and poor rural communities. They further noted that the papaya seeds' anthelmintic effects are primarily due to the presence of carpaine, an alkaloid that expresses an intensely bitter taste and a potent depressive effect. In addition, another study by Verma, Nambiar, and Chinoy (2006) validated papaya seed extracts' anti-fertility, anti-implantation, and abortifacient properties, which made them potential anti-fertility treatment agents. Furthermore, the entire savannah region of West and Central Africa uses papaya seeds to make fermented food condiments, which is a primary seasoning used in soups and stews. Particularly, a fermented food condiment known as *"daddawa"- a* Hausa term is a native Nigerian food with a pungent, ammonia-like aroma obtained during its last stages of fermentation. *Daddawa*, not only adds flavor to food, but also adds calories and protein (Abdulazeez and Sani, 2011).

We thus contend that though there is a gap in understanding the value of underutilized seeds, increased research on such seeds would reveal additional elements like dietary fibre, vitamins, minerals, essential phytochemicals, and other vital elements that could be of value in various industrial sectors (Cervera-Mata et al., 2022). Our study contributes to this discourse by exploring and examining the phytochemicals and nutritional components, with a focus on the valorization of commonly underutilized seeds in India. The review's main innovation is its specific focus on the value-addition aspect of underutilized seeds. Furthermore, it explores the varied industrial applications of underutilized seeds that go beyond traditional food uses and encompasses the pharmaceutical, nutrition, agricultural, and cosmetic sectors. The study emphasizes sustainability by showing how the use of underutilized seeds can reduce waste through their utilization and promote the development of products with value additions, which is in line with the Sustainable Development Goals (SDGs) especially SDG 2 under Target 2.1 and the Food and Agriculture Organization (FAO) four (4) pillars of food security. Highlighting the seeds' pharmacological, agricultural, nutritional and dermatological benefits, provides a special dimension to their possible uses in the effort to achieve sustainable utilization.

With such a new perspective in mind, our study contributes to bridging this gap by exploring literature on 11 tropical seed varieties to analyze the various sustainable applications of phytochemicals and nutritive components found in underutilized. The aim is to bridge the knowledge gap by integrating information and providing an in-depth analysis of the applications of phytochemicals and nutritive components present in the underutilized seeds commonly found in tropical regions especially India. The findings of this study could revolutionize a number of industries by providing environmentally friendly substitutes for current sources of bioactive compounds. Additionally, realizing the significance of underutilized seeds could result in the creation of new products with improved nutritional and medicinal properties. It would further shed light on the underutilized untapped potentials of the seeds and boost further research.

METHOD

Our study employed a non-systematic literature review of 219 documents to gather data on the applications of phytochemicals and nutritive components. These mainly included published papers and grey literature that were readily accessible online, e.g., research reports, published journal articles and books. Searches across various databases, including Google Scholar, ResearchGate, PubMed, Scopus, and ScienceDirect, were used to find the information using key terms like phytochemicals found in a specified seed (see Fig. 2 and Table 1), applications of major phytochemicals,

Table 1. Summary of phytochemicals, essential nutrients and their application

No	Name of seed	Phytochemicals and other essential components	Biological applications	Industrial Applications	References
1	2	3	4	5	6
1.	Cashew (*Anacardium occidentale*)	phenols, anacardic acid, cardol, cardanol, fats, protein, carbohydrates, vitamins, minerals, antioxidants	antioxidant, bactericidal	drug processing, pesticide production organic soil conditioner	Mbatchou and Kosoono, 2012; Akinhanmi et al., 2008; Uchida, 2000
2.	Coconut (*Cocos nucifera*)	phenols, oxyresveratrol, ferulic acid	antioxidant, antimicrobial, vasorelaxant, anticancer, antihypertensive	biosorbent, activated carbon production, fertilizer, structural lightweight concrete production, heavy metal removal	Kumar et al., 2015; Morais et al., 2017; Ashraf and Rathinasamy, 2018)
3.	Jackfruit (*Artocarpus heterophyllus*)	lectins (jacalin & artocarpin), lignans, saponins, tannins, flavonoids, steroids, isoflavones, reducing sugars, cardiac glycosides, fat, dietary fiber, oil, carbohydrates, manganese and magnesium	antispasmodic, antimicrobial, antioxidant, high reducing potential, anticancer	food industry, animal feeds	Fernandez-del--Carmen et al., 2013; Jagtap and Bapat, 2010
4.	Indian almond (*Terminalia catappa*)	fiber, β-carotene, riboflavin, proteins, carbohydrates, olein, stearin, oil, glutelin, gliadin, minerals, palmitic acid, ascorbic acid, myristic acid, linoleic acid, niacin, oleic acid,	aphrodisiac, antibacterial	nutrient supplements, edible oil, biodiesel	Ratnasooriya and Dharmasiri, 2000; dos Santos et al., 2008
5.	Tamarind (*Tamarindus indica*)	proteins, alkaloids, glycosides sterols, saponins, tannins, flavonoids, anthraquinone, cardiac glycosides, phytic acid, minerals	antioxidant	food industry, animal fodder	Fernandez-del-Carmen et al., 2013; Okello et al., 2017
6.	Papaya (*Carica papaya*)	alkaloids, tannins, flavonoids, saponins, cardiac glycoside, anthraquinones, anthocyanosides, reducing sugars, glucotropaeolin, crude protein, crude fiber, fatty acids oil, carpaine, caricin, benzyl isothiocyanate, benzyl thiourea	antibacterial, antidiabetic, germicidal, insecticidal, antihelminthic, hypoglycemic, hypolipidemic, cardioprotective	food industry, natural coagulant, curing sickle cell diseases and poisoning associated renal disorders	Singh et al., 2010
7.	Mango (*Mangifera indica*)	polyphenols, tannins, gallotannins, proteins, sesquiterpenoids, phytosterols, gallic acid, essential fatty acids, carbohydrates, coumarin, ellagic acid, vanillin, phenolic antioxidants, metal chelators, tyrosinase inhibitors, ferulic acid, cinnamic acid, minerals, and vitamins	antioxidants	food industry, animal fodder, cosmetic industry, wastewater treatment	Maisuthisakul and Gordon, 2010; Bahari et al., 2018
8.	Pumpkin (*Cucurbita*)	proteins, oils, phytosterols, waxes, tocopherols, antioxidants, vitamins, fatty acids, oleic, linoleic, palmitic, and stearic acids	antioxidant, antifungal, antidiabetic, antibacterial, anti-inflammation	food industry, animal feeds	Ninčević Grassino et al., 2023; Glew et al., 2023; Tem, 2001; De Carvalho and Caramujo, 2018

Table 1 – cont.

1	2	3	4	5	6
9.	Indian gooseberry (*Phyllanthus emblica*)	alkaloids, tannins, flavonoids, saponins, terpenoids, glycosides, phenolics, linoleic acid, stearic acid, linolenic acid, oleic acid, myristic acid, palmitic acid	antioxidant, antibacterial, antifungal, antidiabetic, anticancer, hydration, water retention	pharmaceutical industry	Kaur and Sharma, 2018; Sriwatcharakul, 2020; Dasaroju, and Gottumukkala, 2014
10.	Custard Apple (*Annona muricata*)	alkaloids, glycosides, saponins, steroids, oil, carbohydrates, amino acids, flavonoids, terpenoides, esters, alcohols, amides, oleic acid, linoleic acid	anti-inflammatory, anti-tumor, antidiabetic	head lice and worm treatment, mosquito larvae destruction	Shashanka et al., 2018
11.	Lemon (*Citrus-limonum*)	terpenoids, phlobatannins, saponins, glycosides, steroids, carotenoid, triacylglycerols, fatty acids, phytosterols, tannins, hesperidin, limonoid aglycones, alkaloids, flavonoids, reducing sugars.	antimicrobial, anti-fertility	food industry, cosmetic industry, pharmaceutical industry	Kuna et al., 2018; Frondel and Peters, 2007; Ambrogina et al., 2020

other essential components found in seeds and their uses, and their availability in India. In this review, the common name and scientific name of the seeds were also noted, phytochemicals and other compounds present as well as their biological and industrial applications were summarized in Table 1.

In this review, a total number of 11 seeds or their parts that are available in India as by-products from domestic or commercial activities were selected. The phytochemicals and other compounds present in these seeds show great potential for use in the pharmaceutical industry, food industry, cosmetic and agricultural sectors (Kalli et al., 2018), though still largely underutilized (Fig. 2).

Fig. 2. selected underutilized seeds commonly available in India

RESULTS

In this section we show the various seed varieties in India. For each seed variety, we document the various phytochemicals and nutritive components present in the seeds. We also show how each seed variety is presently used and its benefits. With this, we further include the level of underutilization for each seed variety so as to recommend sustainability and innovative measures that can be harnessed to realize the benefits of each seed.

Coconut (*Cocos nucifera*)

The coconut is a fruit that grows on the coconut tree. It is classified under the family *Arecaceae*. The leading global producers of coconuts are the Philippines, Indonesia, India, Papua New Guinea, and the Pacific Islands e.g., the Solomon Islands. India, specifically, holds the position of the third-largest producer, with an annual production which amounts to 10.6 million metric tons (Mininel et al., 2014). The major coconut-producing states in India are Tamil Nadu, Karnataka and Kerala (Raghavi et al., 2019). Several studies have documented the value of coconut shells. Reports reveal that coconut shells are a rich source of phytochemicals and nutritional elements that have numerous uses across a variety of industries (Amoako and Mensah-Amoah, 2018). Phenols, saponins, tannins, steroids and flavonoids are among the phytochemicals present in these seeds (Kibria et al., 2018). Additionally, the nutritional elements present include; fibre, fat, protein, carbohydrate, calcium, phosphorous, magnesium, sodium, iron, zinc, and manganese (Ewansiha et al., 2012). Figure 3 shows the phytochemicals and nutrients found in coconut shells and their applications. These compounds provide a healthy and environmentally responsible substitute for artificial additives and supplements.

The phytochemical compounds extracted from coconut shells have been used in a wide range of pharmacological products due to a variety of therapeutic effects they have expressed such as; anti-inflammatory, anti-cancer, antioxidant, antimicrobial, vasorelaxant, and antihypertensive actions (Lima et al., 2015). A study by Pizzi (2021) noted that due to their potent anti-inflammatory properties, tannins are utilized in anti-inflammatory drugs due to the presence of gallic acid. Therefore, coconut nut shells could be a possible source of medications that might be utilized to treat a variety of chronic diseases, such as arthritis and inflammatory bowel disease, which both express inflammation as a common underlying factor. Additionally, the manufacturing of substitute antimicrobial agents is crucial given the rise in antibiotic resistance. In a study that was conducted in Brazil, coconut shell extracts have been shown to have in vitro antibacterial action against foodborne microorganisms. The phytochemical analysis showed that luteolin present in the coconut shells was the main component responsible for the action (Prakash et al., 2018). Hence, this points out the possibility of using coconut shells as a rich source of natural antibacterial agents in pharmaceutical products. Furthermore, Sunilkumar et al. (Sunilkumar et al., 2017) in a study identified and characterized oxyresveratrol from coconut shells. Subsequent research revealed that oxyresveratrol may have anti-cancer effects which inhibit the expression of MMP-2, MMP-9, vascular endothelial growth factor, epidermal growth factor receptors, and cyclooxygenase -2, preventing cell migration, and inducing cell cycle arrest at the G2/M phase. Coconut shells are also utilized in various applications, e.g. the production of activated carbon, a biosorbent material for removing heavy metals like cadmium, which are known to pose health hazards (Jayan and Aryasree, 2018). Early life is a critical period for cadmium exposure and accumulation in the body, with children primarily exposed

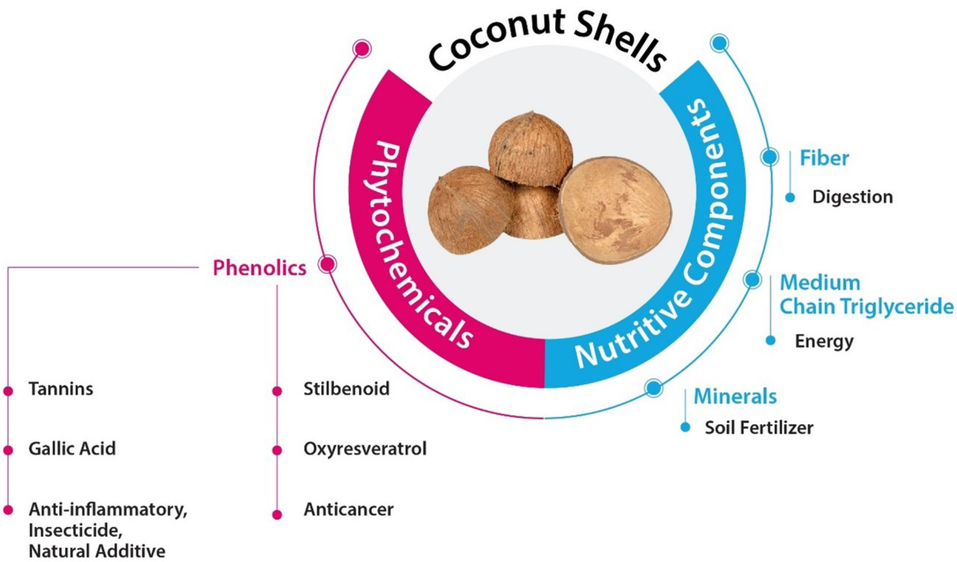

Fig. 3. Phytochemicals and nutritive components found in coconut shell and their uses

through food, environmental cigarette smoke, and household dust. Cadmium buildup in the kidneys can lead to nephrotoxicity and osteoporosis in adults. The risk of lung cancer in adults has also been raised by cadmium inhalation (Chaudhary et al., 2018).

On the other hand, the minerals such as calcium, potassium, and magnesium present in coconut shells have been considered essential for healthy bones, neuron function, and muscular contraction (Bankar et al., 2011). The shell has also been noted to be a good source of dietary fiber, which is vital for good digestion and may lower the chances of developing chronic illnesses like diabetes and heart disease (Sreejamole and Neeraja, 2021). Furthermore, medium-chain triglycerides (MCTs) found in coconut shells have the property of being easily digested and absorbed. This makes them a possible source of energy especially for people who have problems with fat absorption. MCTs can also be used to treat some infections and inflammatory diseases since they have antibacterial and anti-inflammatory properties (Nandi et al., 2005).

In most of the reviewed literature, it is clearly documented that agriculture and agronomic communities have historically underutilized coconut shells, yet new studies have revealed that the nutrients present in coconut shells have been noted to possess soil-fertilizing abilities (Kabir Ahman et al., 2022). By lowering the need for chemical fertilizers, coconut shells can be used as a soil supplement to improve soil porosity, pH, nutrient availability, microbial activity, and overall soil quality, with the potential to increase crop yields. This perspective is further supported by a study carried out in the Philippines found that tomato plant growth and yield were boosted when coconut shell biochar was applied (Manikandan and Nair, 2023). Furthermore, gallic acid is a major metabolite responsible for the insecticidal actions of tannins present in coconut shells (Zhang el al., 2022). Hence, due to these qualities, tannins can act as natural insecticides. Tannin-rich extracts from coconut shells are utilized as biopesticides in organic farming (Shivashankar and Sumathi, 2022). While supporting environmentally responsible pest management techniques, these natural insecticides efficiently control a variety of agricultural pests, such as aphids and caterpillars.

In the food industry, gallic acid has been noted to be a natural food additive. While providing a pure and appealing aroma, it can be utilized as a natural flavor enhancer in a variety of food products like ice cream and baked food products (Sorrentino et al., 2018). It is evident from the studies that coconut shells offer a sustainable source of beneficial phytochemicals that satisfy consumer demands for clean-label products as the food industry looks for more natural and health-oriented ingredients.

In addition, coconut shells continue to be a reliable source of valuable phytochemicals, such as saponins, that satisfy the demand for safe, efficient, and environmentally friendly cosmetic formulations. As customer preferences for natural and sustainable beauty solutions continue to grow, shampoos, face cleansers, and body washes made from the natural emulsifiers and stabilizers contained in coconut shells would be an option (Kibria et al., 2018).

Unfortunately, however, the increased consumption of coconuts and their byproducts has resulted in significant waste production, which has a detrimental effect on the environment. For instance, about 62–65% of the coconut fruits, which are made up of shell and husks, are considered waste because they are inedible and thus are mostly discarded during processing (Singh et al., 2022). The underutilization of coconut shells represents a great opportunity due to the number of vital substances they contain that have numerous possible uses. In this case, we observe and contend that the tapping of underutilized coconut shells could help rural and poor communities in India minimize a set of health issues, especially among the vulnerable and poor communities in agrarian states e.g. Gujarat and West Bengal (Kumar et al., 2015).

Cashew nut (*Anacardium occidentale*)

Cashew is classified within the *Anacardiaceae* family. The leading cashew cultivators worldwide include Brazil, India, Kenya, Vietnam, and Nigeria. In India, the annual cashew production amounts to approximately 0.75 million tons (Mininel et al., 2014). The south Indian states such as Kerala, Karnataka, Tamil and West Bengal are the top cashew-producing states in India (Kumar et al., 2015). This has yielded benefits, especially from the main byproducts of the cashew nut e.g., the cashew nutshell and shell liquid. Studies have reported that cashew nut shell liquid (CNSL) is known for being a rich natural source of phytochemicals such as saponins, alkaloids, flavonoids and phenols like isoprenoid phenols, anacardic acid, cardol, and cardanol (Mbatchou and Kosoono, 2012). The specific composition of compounds may vary depending on the extraction process used, resulting in different ranges of constituents. For example, a study focusing on cold solvent extraction of CNSL revealed a high content of 90% anacardic acid and more than 10% cardol. Anacardic acid can be transformed into Cardanol which can be used in the production of an unlimited number of derivatives including Salicylic acid and anacardic acid esters, along with additional compounds generated from anacardic acid and its derivatives (Das et al., 2004).

In addition to the phytochemicals, CNSL also possess a range of mineral elements which include; calcium, magnesium, potassium, and phosphorus in abundance (Fig. 4) (Akinhanmi et al., 2008).

CNSL-derived metabolites have been confirmed to offer a wide range of applications in various industries. Anacardic acid, the main constituent of CNSL has been shown to have antibacterial, antifungal, and anticancer effects (Morais et al., 2017), making it a potential drug candidate in the pharmaceutical industry. Moreover, it also possesses antioxidant properties that help mitigate inflammation and protect cells from damage (Laxmanaswami and Urooj, 2018). Several clinically significant markers, including nuclear factor B kinase, histone acetyltransferase, lipoxygenase, xanthine oxidase, tyrosinase, and ureases, have been reported to be inhibited by anacardic acid and its related compounds (Sung et al., 2008). Additionally, it has been identified as a potential lead compound for enhancing neutrophil function in innate immune defense (Hollands et al., 2016). Furthermore, anacardic acid has demonstrated the ability to inhibit MMP-2 and MMP-9 activities through the regulation of Sprouty 2, MMP-14, Extracellular MMP Inducer, and Reversion-inducing Cysteine-rich protein along with Kazal motifs (Omanakuttan et al., 2012). In traditional medicine, CNSL is utilized for the treatment of persistent conditions such as long term ulcers (Ashraf and Rathinasamy, 2018). Cardol is another significant phytochemical present in cashew nut shells. Cardol has pain-relieving and antitumor characteristics (Yuliana et al., 2014), making it effective for the treatment of pain and cancer. It has also shown antibacterial characteristics that may aid in preventing the development of dangerous bacteria and fungi (Balouiri et al., 2016). The fact that CNSL, which contains anacardic acid and cardol, has been utilized in conventional medicine raises the possibility that these substances have

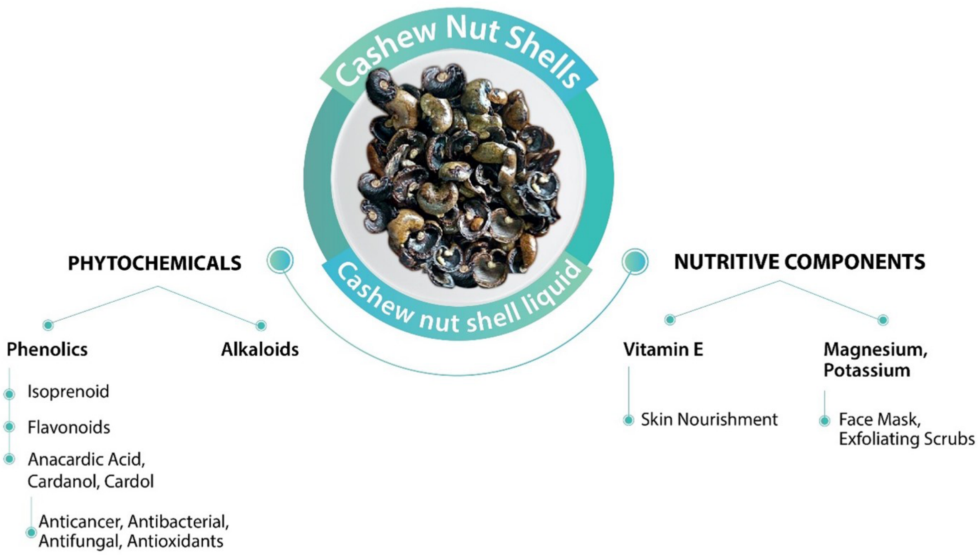

Fig. 4. Phytochemicals and nutrients derived from cashew nut shell liquid and their applications

important therapeutic advantages. To fully utilize the benefits of these natural treatments, modern medicine could benefit from additional research.

Phytochemicals and minerals from cashew nut shells have other industrial uses in addition to their therapeutic applications. In the agricultural sector, cardanol has surfactant capabilities of improving pesticide formulations (Fontana et al., 2015). Adjuvants made from cardanol boost the spread ability and adhesion of agrochemicals to plant surfaces, enhancing their efficacy (Friuli et al., 2020). Furthermore, due to the abundance of mineral elements, CNSL could be used to increase soil fertility and crop productivity as fertilizers (Mgaya et al., 2019). For example, CNSL extract could be utilized to enrich the soil with calcium, phosphorus, and potassium when applied as an organic soil conditioner, which promotes strong plant growth. While calcium and magnesium can support soil water retention and strengthen its structure (Uchida, 2000), when used as an organic soil conditioner, CNSL extract would further be a useful tool for fostering healthy plant growth by enhancing the soil with calcium, phosphorus, and potassium. This strategy incorporates nutrient enrichment advantages with enhanced soil structure and water retention, which are consistent with sustainable farming methods.

In addition to CNSL utilization in agriculture, it has also shown enormous potential in the food sector, even if in this case, cashew nuts themselves are more popular for their uses as food. This observation is further supported by a study by Chen et al. (2023) which reported that anacardic acid; which is a primary product from CNSL could be used as a natural food preservative in the food industry to increase the shelf life of foods like meat and snacks because it has antibacterial and antioxidant characteristics. The study also highlighted anacardic acid's potential to prevent microbial development and enhance food safety in food packaging materials. Therefore, adopting natural preservatives like anacardic acid is in line with the growing consumer desire for safer and more environmentally friendly food preservation techniques, which will eventually be advantageous for both the food industry and consumers. Subsequently, vitamin E and unsaturated fatty acids contained in CNSL can improve the nutritional value of dietary items. For instance, cashew nut oil generated from CNSL can be used as a substitute for cooking oil or as a source of healthful fats in salad dressings (Jayeola et al., 2018). Products made from CNSL are a great complement to a balanced diet. Therefore, including them into the diet is in line with the objective of promoting healthy eating habits and overall well-being.

Numerous nutrients and minerals found in cashew nut shell liquid (CNSL) also have potential uses in the cosmetic sector. A study by Park (2015) reported that vitamin E, which is contained in CNSL, is well known for its skin-nourishing properties. Hence it could be added to moisturizers, serums, and sunscreens to protect the skin against UV rays and preserve its health. Additionally, the study also noted that magnesium and potassium minerals are used in face masks and exfoliating scrubs to promote healthy skin. They help hydrate skin and improve texture. However, the downside has been that about 60% of the cashew nut shell get wasted per kilogram of cashew nut (Patade, 2020) implying that extra benefits that could be obtained from cashew nut shells are increasingly being lost.

Jackfruit (*Artocarpus heterophyllus*)

Jackfruits belong to *Moraceae* family. They are planted and cultivated all over the world, especially in Bangladesh, China, India, Myanmar, Malaysia, the Philippines, Thailand, Vietnam, and countries in East Africa and Latin America. The top exporting nations are Australia, Canada, China, Indonesia, Japan, New Zealand, the United States, and Vietnam (Saha et al., 2022), with over 1.25 million metric tonnes of fruit produced each year. India and Bangladesh are the world's top producers of jackfruit (Balamaze et al., 2019). In addition to the northern Indian states, jackfruits are also commonly found in the southern Indian states of Kerala, Tamil Nadu, and Karnataka. The majority of the world's jackfruit is produced in Tripura, Assam, and West Bengal (Kaustubh and Abhik, 2020). Recent studies have suggested that jackfruit seeds are a good source of valuable biological compounds (Akter and Haque, 2018) including phytochemicals such as saponins, lignans, tannins, flavonoids, steroids, isoflavones, and cardiac glycosides (Gupta et al., 2011). Studies suggests that jackfruit seeds also contain moisture (49.59%), fat (0.4%), carbohydrates (25%), proteins (13.6%), and 206 kcal/100 g of energy. In addition, 1.3 mg/g Magnesium, 1.77 mg/g phosphorus, 1.82 mg/g calcium, 9.72 mg/g potassium, 0.18 mg/g sodium, 0.051 mg/g zinc, and 0.019 mg/g copper (Amadi et al., 2018)

These bioactive compounds present in the seeds have been reported to have, antimicrobial, antioxidant, anti-inflammatory, and anti-cancer properties (Fernandes et al., 2017). Quercetin and kaempferol are among the flavonoids found in jackfruit seeds that would be of great interest to the pharmaceutical industry. The antioxidant quercetin in particular has anti-inflammatory and anti-cancer properties (Rodríguez-Félix et al., 2019). The potential uses of essential nutrients and phytochemicals obtained from jackfruit seeds are shown in Figure 5.

A study conducted on rats found that jackfruit seed extract significantly reduced inflammation in rats with artificially inflicted arthritis (Bantilan, 2018). The ability of quercetin to alleviate inflammation thus opens up possibilities for pharmaceutical interventions aimed at reducing the suffering of individuals afflicted by such conditions. By targeting the inflammatory process, drugs derived from Jackfruit seeds could potentially enhance the quality of life for millions of patients. Quercetin has been sparked by its capacity to stop the spread of cancer cells and trigger apoptosis (Dwitiyanti et al., 2019). Using these natural anticancer agents, innovative cancer treatments and preventative measures may be created in pharmaceutical applications. Jackfruit seed derived phytochemicals have also shown antihypertensive, antiulcer, and anti-ageing health benefits, protecting the body against serious ailments (Ray et al., 2021). Furthermore, the fibre and resistant starch present in jackfruit seeds are processed slowly by the body, hence helping in feeding healthy gut bacteria. It is evident from the studies that jackfruit seeds could be potential raw materials for drug production in the pharmaceutical industry. Potassium is one of the most significant intracellular components as it is needed for its various physiological properties e.g. its ability of maintaining the cell membrane potential (Palmer et al., 2016; Ajayi, 2008). In addition, Jacalin-a lectin is a major protein which takes 50% of the jackfruit seed and it has a characteristic of binding to human immunoglobulin A(IgA) (Fernandez-del-Carmen et. al., 2013). Its unique property of being significantly mitogenic for human CD4+ T cells may make it valuable as a means for determining the immunological state of individuals who have human immunodeficiency virus HIV-1 infection (Jagtap and Bapat, 2012). Researchers and

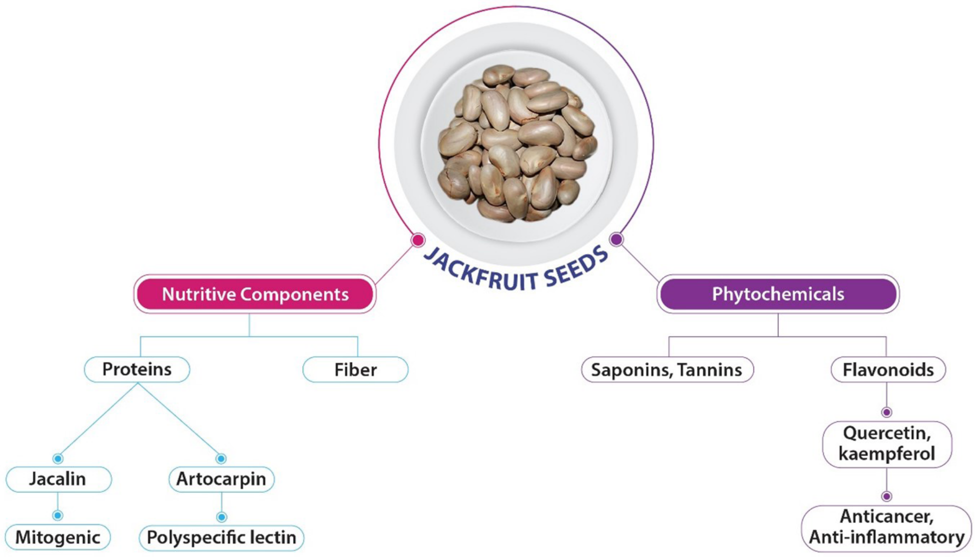

Fig. 5. Applications of phytochemicals and nutrients found in jackfruit seeds

medical personnel would have an insight about how the infection develops and how well treatment plans would work by using Jacalin as a diagnostic tool. The monitoring of HIV-1 infection could be revolutionized by this technology thus creating a potential for the enhancement of patient care. The other lectin is artocarpin, and it is a polyspecific lectin that has been used to react with a variety of monosaccharides (Chowdhury et al., 2012). Based on this quality, artocarpin can be used in a variety of biochemical experiments. It can also be used by researchers to investigate and examine the interactions between lectins and carbohydrates, revealing important details about molecular recognition procedures.

Other applications of jackfruit seeds in the food industry include using the seeds as a nourishing food source. And also incorporating the fruit's bioactive ingredients into a variety of food formulations for their beneficial effects on nutrition and health (Tramontin et al., 2019). Saponins have been used in the manufacture of steroid hormones. Plant-derived steroidal saponins have long been used in a variety of industrial and commercial applications, e.g. as a source of raw materials, and food additives (Gupta et al., 2011). Jackfruit seeds are becoming a subject of interest as a nutritional supplement in a variety of diets. Like in the manufacturing of cereal bars, snacks, and the fortification of flour in baked products (Ranasinghe et al., 2019). The seed powder has also been utilized as a substrate for the manufacture of L-lactic acid using *Streptococcus equinus* (Nair et al., 2016). This makes the seeds a potential raw material to be used in various industries in the manufacturing of value-added products.

The antifungal properties of jackfruit seed extract have been shown to be effective against a number of plant diseases, which may be significant in the agricultural sector. Particularly, Jacalin, a protein found in the seeds, has been proven to have insecticidal capabilities against the cowpea weevil (Fernandes et al., 2017). In the cosmetics industry, phytosterols made from jackfruit seeds are gaining popularity. They are added to skincare products due to their ability to improve skin barrier functions, keep skin moist, and lessen transepidermal water loss (Cruz-Casillas et al., 2021).

Unfortunately, jackfruit seeds are among the waste products during jackfruit processing. In the Karnataka state of India, about 2000 crore Indian rupees of jackfruits get wasted (Karelia, 2019). A study by Hossain (2014) reported that about 15% of jackfruit seeds are discarded and considered as waste. The major contributors to the waste of these seeds are the lack of knowledge about the biological components present and poor technologies for using them in several industries like agriculture, cosmetic and pharmaceutical industries (Akter and Haque, 2018).

Papaya (*Carica papaya*)

Papaya belongs to the *Caricaceae* family. Globally, India is the chief producer of papaya with a production area of 70,100 ha and an annual yield of more than 6 million metric tonnes. It contributes to over 43% of the global production. Karnataka, Bihar, Orissa, West Bengal, Tamil Nadu, Andhra Pradesh and Gujarat are the main states in India where papaya is grown. In 2012–13, the production of papayas contributed 6.6% to India's overall fruit harvest (Bankar et al., 2011; Singh et al., 2010). Studies have reported that products made from papaya seeds are rich in essential compounds and are determined to be beneficial in combating the effectiveness of biological systems (Shaistha and Pattan, 2022; Kumar and Devi, 2017). The phytochemical investigation of papaya seed extract displayed the presence of alkaloids, tannins, flavonoids, triterpenoids as well as saponins. In addition, cardiac glycoside, anthraquinones, anthocyanosides, and reducing sugars were also observed (Nyirenda et al., 2021). Nutritional components present in papaya seeds include proteins, fibre, and vitamins and these have innumerable benefits (Puangsri et al., 2005). To clearly put this into perspective, studies conducted by dos Santos et al. (2014) reported that an intake of 100g of papaya seeds can provide the body with 16%, 127%, 37%, 88%, 135%, 59%, 81%, and 72.5% of potassium, magnesium, iron, zinc, manganese, copper, phosphorus, and calcium, respectively.

In addition, the seed extracts contain potent antibacterial, diabetic, helminthic, insecticidal, germicidal, lipid-lowering, and cardioprotective activities that could be essential in the pharmaceutical industry (El Moussaoui et al., 2001). Due to antibacterial substances present in *Carica papaya* seeds, gram-positive and gram-negative bacteria cannot proliferate (Miraj et al., 2023). As a result, this makes the seeds a potential source of antibacterial compounds. Studies by

Mustikasari et al. (2016) and Saha et al. (2023) revealed that secondary metabolites e.g. terpenoid flavonoids and carpaine alkaloids exhibit antimicrobial properties that are capable of breaking the cell membrane and denaturing proteins; killing the bacterial cell. According to Masfufatun et al. (2019), carpaine also converts microorganism proteins into peptone by digesting them. These findings show the potential to revolutionize the area of antimicrobial research, opening up new opportunities for the development of potent antibacterial drugs and deepening our knowledge of microbial biology and technologies. Furthermore, another study by Sabir (2005) reported that streptococcus mutans' in vitro growth was suppressed by the flavonoid content of *Trigona sp.* propolis. The seeds have lately been linked to treating sickle cell illnesses and kidney problems that are brought by poisoning as noted in a study by Imaga et al. (2009). Figure 6 highlights the applications of phytochemicals and nutrients derived from papaya seeds.

In the agri-businesses value chain, the seeds of papaya have been thoroughly investigated as a source of possible elements recommended for chicken feed among the agro-industrial byproducts. This is due to the considerable amount of protein they possess (Ebruaja et al., 2020). The ripe papaya seed can be used as an alternate protein feed component for poultry, with crude protein levels of 24–30%, in vitro protein digestibility of 80%, and a proportion of 47% essential amino acids. Furthermore, the seed protein could also be utilized in the fortification of cornmeal (Imaga et al., 2009). Another study reported the effectiveness of fiber, oil, and an enzyme myosin present in papaya seeds for their ability to boost poultry's health, metabolism, and other biological processes (Sugiharto, 2020). The adequate amount of nutrients present in papaya seeds proves to be helpful for satisfying the dietary needs of chickens. It makes the seeds an excellent and sustainable alternative for chicken feed, improving the nutrition, well-being, and general poultry productivity. Papaya seed inclusion in poultry diets would not only be advantageous for the poultry business, it would also support efficient and sustainable agricultural methods e.g., in the transition to organic farming.

The bioactive chemicals found in papaya seeds are also employed in a variety of food compositions for their nutritional and health benefits. The seeds are used in the food industry as a nutrient-rich food source. For instance, the monounsaturated fatty acid present in the seeds could be used as an alternative to vegetable oils (Mesquita et al., 2023). The seeds can be dried and processed into a powder. The powder can be

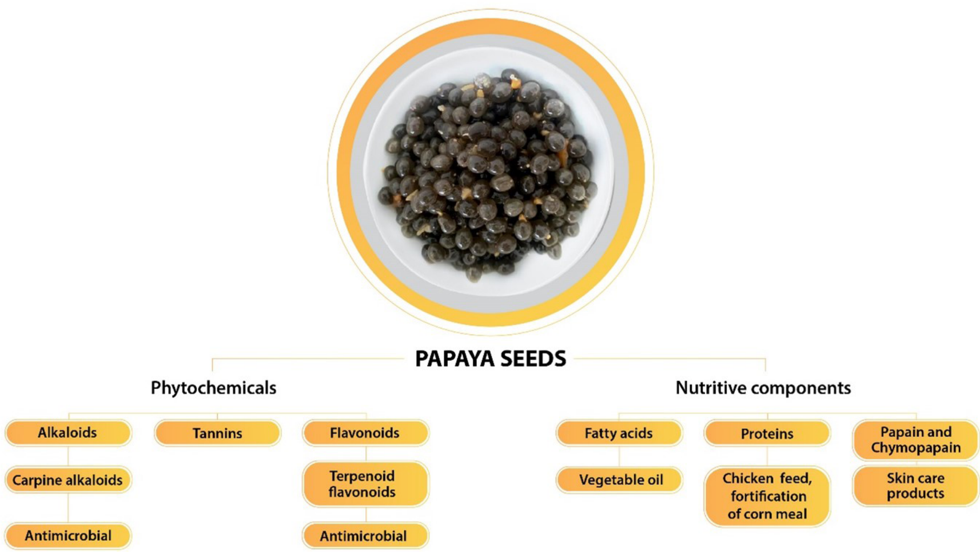

Fig. 6. Phytochemicals and nutrients found in papaya seeds and their applications

added to smoothies and other drinks or used as a spice and flavoring to salad dressings and meat hamburgers (Azevedo and Campagnol, 2014). Papaya seeds have been reported to contain an adequate amount of papain and chymopapain, proteolytic enzymes which help in the breaking down of proteins to amino acids, hence enhancing the process of digestion (Chakraborty, 2021). This implies that papaya seeds as a sustainable and natural source of these enzymes would meet the industry's move towards less expensive, greener options. In the cosmetics industry, papaya seeds are frequently utilized and have great exfoliating qualities (Chakraborty, 2021). With their ability to exfoliate dead skin cells and promote smoother, more radiant skin, papain and chymopapain are vital components for facial masks and skincare products (Ikram et al., 2015). They could be appealing to individuals looking for minimally processed products due to their natural origin.

Unfortunately, even though papaya seeds can be used in various industries with the right techniques, they are typically thrown away as waste (Shaistha and Pattan, 2022). About 25% of the seeds are lost during processing as agriculture waste (Castro-Vargas et al., 2019).

Indian almond (*Terminalia catappa*)

Indian almond is a member of the *Combretaceae* family. Despite having a documented Indian origin, it is also found in Africa and Australia (Anand et al., 2015). The states of Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, and Kerala are among the Indian states that have the best climates for growing almonds (Catherine, 2013). While the commercial uses of *Terminalia catappa* seeds have not been explored, several studies have been reported on the seed's proximate compositions (Ekop and Eddy, 2005). The seeds of Indian almond contain phytochemical compounds such as saponins, flavonoids, steroids, terpenoids, glycosides, carotenoids, alkaloids, anthraquinones and anthraquinone glycosides (Oduro el al., 2009). In addition, the nutritional components that are present in 100 g of Indian almonds include: protein, fat, sodium, potassium, calcium, phosphorus, magnesium, iron, zinc, copper, thiamin, and niacin (2,000 mg, 55,800 mg, 18, 200 mg, 1,130 mg, 10 mg, 6.3 mg, 410 mg, 5.1 mg, and 0.5 mg, respectively) (Catherine, 2013). Other essential compounds include; fiber, β-carotene, water, carbohydrates and fixed oil (Puravankara et al., 2000). Figure 7 illustrates the phytochemicals and nutrients commonly found in Indian almonds seeds and their uses.

The bioactive substances flavonoids, tannins, and alkaloids found in Indian almond seeds are beneficial in the pharmaceutical industry due to their antioxidant, anti-inflammatory, and antibacterial activities (Barreca et al., 2020). The presence of alkaloids provides the seeds with antioxidant properties that have strong

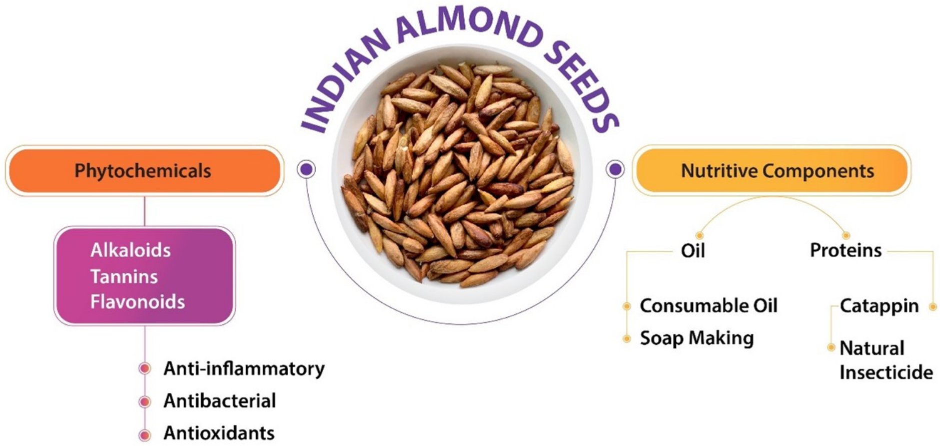

Fig. 7. applications of phytochemicals and nutrients found in Indian almond seeds

physiological effects on biological systems (Oduro et al., 2009). These compounds were noted to have antidiabetic and antihyperlipidemic properties in a study that was conducted on rats, and also extracts also showed hepatoprotective benefits in rats with induced liver injury (Ng et al., 2015). These results deserve attention due to the fact that diabetes and hyperlipidemia are serious health issues that have a big influence on the world's healthcare systems. Additionally, the hepatoprotective properties of Indian almond seed extracts represent an exciting arena for future pharmaceutical study. Natural drugs with hepatoprotective qualities may be extremely important in treating and preventing liver disorders, a rising cause for worry. In Taiwan, the seed is commonly used as folk medicine and is believed to have aphrodisiac and antibacterial properties (Ratnasooriya and Dharmasiri, 2000). This traditional knowledge serves as a starting point for additional investigation into the discovery of potent antibacterial drugs, potentially resolving one of the most important global health issues.

In addition, Indian almond extracts have chemicals that encourage plant growth and can be utilized in agriculture to improve crop growth and development. The insecticidal qualities of the seeds have been employed as a natural insecticide in agrarian communities. The seeds contain catappin protein, which has been demonstrated to have insecticidal qualities against a variety of insect pests (Barreca et al., 2020). According to a study that was conducted on tomato plant, it has been demonstrated that Indian almond extracts have positive impacts on plant development, boosting plant height, stem diameter, and leaf area (Sylvia, 2019). Furthermore, the presence of proteins in the seed makes it a possible source of nutrients that might be added to people's diets to increase the amount of protein and lower the rate of malnutrition in developing nations, including India (Siew et al., 2015). Due to the high oil content, the almond seeds could be considered as an inexpensive source of oil that could be consumable, however, in the cosmetic industry it could be used as an ingredient that would aid soap making (dos Santos et al., 2008).

Nonetheless, the seeds are still not properly acknowledged or used as multipurpose plant products. One of the likely contributing factors to their underutilization is their smaller size and the challenge of extracting them (Odutayo et al., 2021). The seeds frequently get wasted when fruits are plucked or simply disposed of as wastes, leaving them to rot in the environment (Esonye et al., 2019).

Tamarind (*Tamarindus indica*)

Tamarind belongs to the dicotyledonous family. Although it is native to tropical Africa, India is the world's top producer with roughly 0.3 million tons annually. It is also the world's largest tamarind product manufacturer (Abubakar and Muhammad, 2013; Ishaku et al., 2016). The states that are considered to be the main producers of tamarind in India are Madhya Pradesh, Bihar, Andhra Pradesh, Karnataka, Tamil Nadu, West Bengal, Orissa and Kerala (Rao and Mathew, 2012). Primarily, tamarind is commonly used for its pulp while seeds have not been widely utilized despite the fact that they have been proven to be a rich source of biologically active compounds (Bagul et al., 2015). According to a phytochemical study of tamarind seeds, the presence of triterpenes, saponins, lignans, steroids, isoflavones, alkaloids, tannins, flavonoids, anthraquinone glycosides, cardiac glycosides, and phytic acid has been reported (Natukunda et al., 2016). It has also been revealed that tamarind seeds are also sources of other essential components e.g. fatty acids, carbohydrates, fiber, proteins, vitamins and minerals as well as sodium, calcium, iron, magnesium, and phosphorus (Rao and Mathew, 2012). Tamarind seeds can be used in various industries since they contain a wide range of bioactive substances and essential nutrients (Fig. 8).

Tamarind seeds have attracted substantial attention in the pharmaceutical industry due to their exceptional qualities and the potential they offer for a variety of uses. According to a study by Ushanandini et al. (2006), tamarind seeds have been noted to have the capacity of inhibiting the activity of enzymes associated with snake envenomation. The possible consequences of envenomation are hypotension, localized tissue injury, and severe inflammatory reactions (Brown and Rayburn, 2012). Tamarind seed extracts could improve the efficacy of antivenom preparations for snakebites, potentially saving uncountable lives. The flavonoids present in the seeds could help to stabilize highly reactive, potentially dangerous free radicals and reduce the risk of oxidative damage to the cells (Weidmann, 2012). This not only improves general health but may

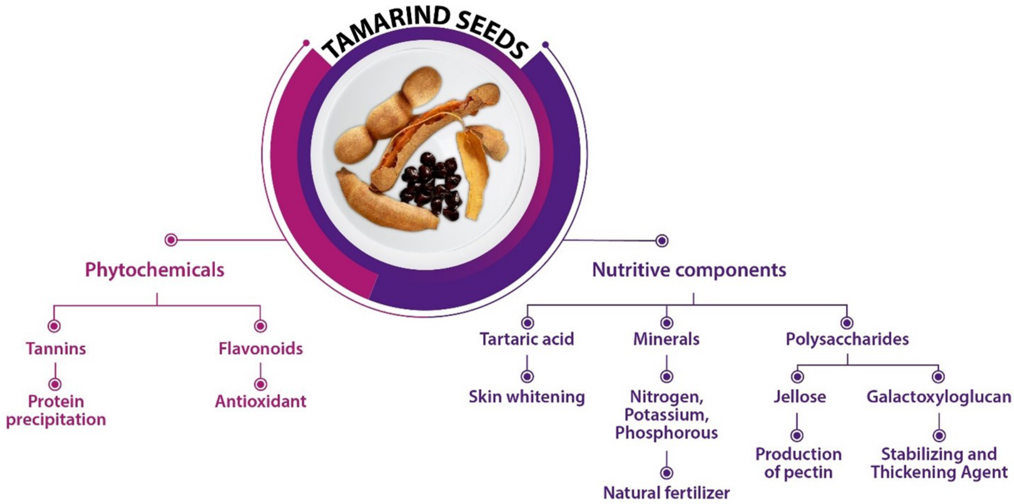

Fig. 8. Applications of phytochemicals and nutrients found in tamarind seeds

also lessen the risk of numerous illnesses linked to oxidative stress, including cancer and cardiovascular conditions. According to Akah et al. (2007), tannins have the unusual capacity to stimulate protein precipitation, a mechanism that occurs when arteries become damaged. By sealing the wound region, this process aids in reducing excessive bleeding. Such a tannic characteristic can be extremely beneficial in medical situations and could possibly promote wound healing more quickly. A study by Shukla et al. (2018) reported that tamarind seeds polysaccharides could be used to create controlled drug delivery systems. Utilizing these natural polysaccharides for drug delivery systems is consistent with eco-friendly and sustainable practices, as opposed to manufactured polymers, which lessens the environmental impact of pharmaceutical production. Moreover, natural resource's affordability may lower the cost at which pharmaceuticals are produced, potentially increasing the population's access to necessary treatments.

Natukund et al. (2016) in a study incorporated tamarind seed powder, mango juice and cookies and concluded that the quantity of bioactive phytochemicals in mango juice and cookies dramatically increased by adding tamarind seed powder, which also boosted the antioxidant activity of the products. These findings have profound implications for the food sector since they imply that tamarind seed powder can be employed as a safe, efficient, and natural way to increase the nutritional value encouraging general well-being. Another study reported that the kernels of tamarind seeds contain a gel forming substance known as jellose a polysaccharide (Bagul et al., 2015). The presence of jellose in the seed nut has led to the production of pectin which is used in the manufacturing of products e.g. jams, jellies, as well as cheese (Arshad et al., 2019). In addition, tamarind kernel powder is frequently employed in the food and pharmaceutical industries as a stabilizing and thickening agent because of the presence of galactoxyloglucan another polysaccharide (Shukla et al., 2018). A study in Asia found that decontaminated and polished tamarind kernel powder commonly called by its trade name glyloid in Japan is processed and accepted for its stabilizing, thickening and gelling characteristics (Thombare et al., 2014).

In the agronomic domain, the nutrients and minerals found in tamarind seeds, such as nitrogen, phosphorus, and potassium, help plants grow and develop (Okello et al., 2017). According to a study by Khushbu, Warkar and Kumar (2019) tamarind seed powder has a beneficial effect on crop yield when used as a soil conditioner. The study further noted that the seed powder can be used as a natural fertilizer, raising the fertility of the soil and giving crops good yields. Besides, the abundance of two different kinds of organic materials, cellulose and hemicellulose, have also been noted in tamarind seeds (Contato et al., 2021). The organic matter can increase soil fertility and crop yields by enhancing soil structure, water retention, and nutrient availability. Tamarind seed-derived organic matter is frequently used in organic farming techniques to support environmentally friendly and sustainable agriculture (Singh et al., 2022). Furthermore, tamarind seeds are valuable resources with a wide range of uses in the cosmetic industry (Waqas et al., 2017). A report by AAVRANI (2022) revealed that tamarind seeds have natural exfoliating characteristics that make them gentle yet efficient agents for skin whitening and the elimination of dead skin cells. This is because they contain alpha hydroxyl acids (AHAs), particularly tartaric and citric acids.

Although there are several possible applications of tamarind seeds, frequently the seeds have been discarded in large amounts as agricultural waste in tamarind pulp industry (Chandra et al., 2018). About 40% of the total amount of seeds is a waste product of the commercial processing of the tamarind fruit (Bagul et al., 2015).

Mango (*Mangifera indica*)

Mango belongs to the *Anacardiaceae* family. Globally the top producers of mango are India, China, Thailand, Mexico, Pakistan, Indonesia, Philippines, Nigeria, and Brazil. Several studies document that India is the world's largest mango producer, producing roughly half of all mangoes worldwide. India produces 19.627 metric tonnes of mangoes annually, making up about 44.14% globally. The states that produce the most mangoes in India are Andhra Pradesh, Uttar Pradesh, Karnataka, Bihar, Gujarat, Maharashtra, Tamil Nadu, West Bengal, Kerala, and Orissa (Gopalakrishnan, 2013; Ashous et al., 2011). Studies have confirmed that the by products from mango processing, particularly the mango seed are a rich source of phytochemicals (Mitra et al., 2013). The phytochemicals found in mango seeds include; phytosterols, carotenoids, tocopherol, polyphenols such as mangiferin, hesperidin, vanillin, penta-o-galloyl-glucoside, rutin, quercetin and kaempferol (Raihana et al., 2015). Additionally, the presence of phenolic acids like gallic acid, caffeic acid, ellagic acid and ferulic acid were also noted (Maisuthisakul and Gordon, 2009). Furthermore, the mango seed consists of 44% moisture, 6% protein, 12.8% fat, 32.8% carbohydrates, and 2% ash (Sagar and Singh, 2016). Figure 9 shows the common essential compounds present in mango seeds and their uses.

Utilizing the seeds in various industries might be a cost-effective approach to lessen the issue of disposing of waste from mango production. Consequently, the pharmaceutical industry would greatly benefit from the biological components that are found in mango seeds. For instance, one study reported that the polyphenol extracted from mango seeds displays antioxidant and anti-inflammatory properties, which could be used in preventing serious ailments such as cancer and cardiovascular diseases (Masibo and Qian, 2008). Mango seed polyphenols' capacity to resist oxidative

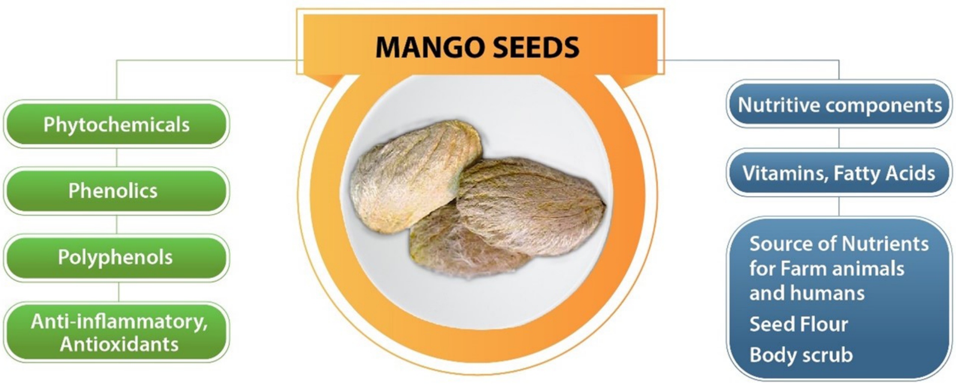

Fig. 9. Applications of phytochemicals and nutrients found in mango seeds

stress and inflammation may be significant in lowering the risk and development of these potentially fatal illnesses. Another study that was conducted on rats with regard to the medicinal properties of the mango seed reported that the seed has the potential to manage diabetes due to its hypoglycemic effect (Khedr and El-badry, 2020). As the globe draws its attention to environmentally safe products, the pharmaceutical industry could leverage this opportunity to tap into the therapeutic potential of mango seeds. Given the prevalence of diabetes worldwide, efforts to create anti-diabetic medications could be strengthened to provide patients with safer and more practical treatment options.

Due to their antimicrobial properties, mango seeds can be used in the development of natural preservatives for food products (Mwaurah et al., 2020). Despite being underutilized, the seed kernel is a promising source of high-quality fat that can be substituted for cocoa butter in chocolates and can also be a source of nutrients for farm animals and humans (Ashoush et al., 2011). Due to the abundance of vitamins and fatty acids especially oleic, stearic, and linoleic acids, mango kernel butter would be a natural raw material in the food industry (Kittiphoom, 2012). The seeds can be used as a natural additive to improve the nutritional profile of products including confectionery, baked goods, and spreads (Gowe, 2015). Utilizing mango kernel butter supports sustainability initiatives in the food sector and also it would reduce waste and promote a circular economy.

In the cosmetic industry, various skin lotions, lubricants, body washes, and soaps can be made using kernel butter and seed oil due to their moisturizing and deodorizing characteristics (Karunanithi et al., 2015). A study by Bahari et al. (2018) supported the value of mango seeds as they were utilized in the formulation of seed flour of two types of body scrub; oil in water and rough salt. The study compared the formulated scrub with other commercially available body scrubs in which a consumer acceptance test revealed that people preferred the oil-in-water formulation of mango seed flour body scrub. This empirical data highlights the usefulness and consumer attractiveness of using components derived from mango seeds in cosmetic products.

Despite mangoes having essential compounds, significant volumes of mango seeds are wasted when the fruits are consumed or processed industrially (Lazzari et al., 2016). In addition, a number of social issues may arise from the improper disposal of waste from the mango agro-industry e.g. the improper disposal of mango seeds has the potential to cause serious environmental issues (Garcia-Mahecha et al., 2023).

Pumpkin (*Cucurbita*)

Pumpkins belong to the family *Cucurbitaceae*. It is generally grown in the tropical regions as well as the subtropical regions of the globe as a vegetable. The largest producers of pumpkin worldwide are the United States of America, Mexico, India and China. India produces about 49,00,000 tons of pumpkin from an area of 45,000 ha (Ahmad and Khan, 2019; Pradheep and Singh, 2015). The main pumpkin producing states in India are Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura (Pradheep and Singh, 2015; Pande and Verma, 2016). In recent years, there has been a rapid expansion of knowledge that has been documented on the benefits of pumpkin seeds due to their potential as a rich source of phytochemicals (Lestari and Meiyanto, 2018). Studies have found that, the main phytochemicals found in pumpkin seeds are polyphenolics, flavonoids, saponins, steroids, carotenoids, squalene, and tocopherols (Šamec et al., 2022). Other studies have noted that pumpkin seeds are rich in proteins, lipids, vitamins, and minerals (Singh and Kumar, 2022). Figure 10 illustrates the common metabolites found in pumpkin seeds along with their applications.

According to Alasalvar et al. (2021) pumpkin seeds have a variety of pharmaceutical properties, including analgesic, anti-inflammatory, anti-diabetic, anti-hypertensive, anti-tumour, immunomodulatory, antibacterial, antiviral, anti-hypercholesterolemic, and intracellular antiparasitic actions. A study by Vanhanen et al. (2005) reported that vitamin E present in the seeds, primarily in the form of -tocopherol has a strong antioxidant effect. According to Marquardt et al. (2013), vitamin E assists in sustaining the integrity of cell membranes and cellular structure by scavenging free radicals. This makes it a possible alternative drug for the prevention of age-related cell damage. Additionally, Ninčević Grassino et al. (2023) in a study observe that beta-carotene, lutein, and zeaxanthin are found in pumpkin seeds, which add to

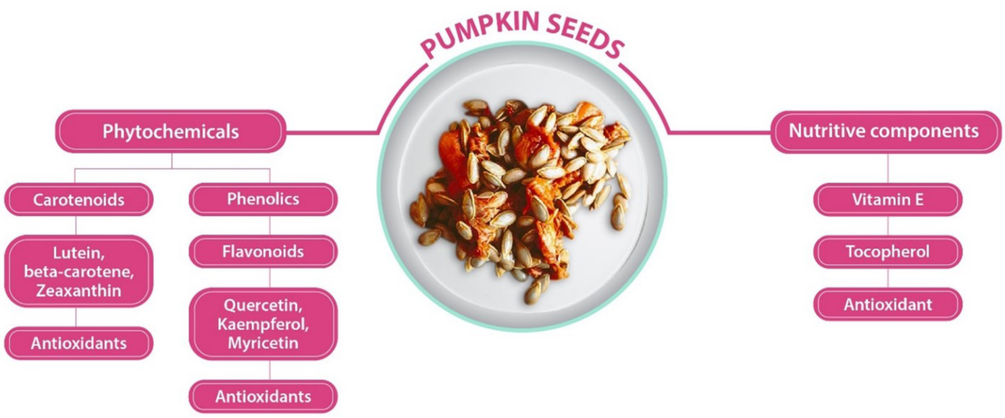

Fig. 10. Metabolites found in pumpkin seeds and their uses

the seeds' vivid colour and have antioxidant effects. Particularly lutein and zeaxanthin support eye health. Pumpkin seeds include flavonoids, such as quercetin, kaempferol, and myricetin, which have antioxidant and anti-inflammatory activities (Singh and Kumar, 2022). The health-promoting qualities of pumpkin seeds are further supported by the presence of flavonoids. Thus, adding pumpkin seeds to one's diet might be considered a useful strategy to take advantage of these flavonoids' positive effects on general health and well-being. Notably, pumpkin seeds have a significant amount of zinc, and with the increase in scientific research on how zinc can act as an oxidizing agent and mediator for enzyme activation, this could help in COVID-19 health emergencies (Hussain et al., 2021). It becomes even more important that pumpkin seeds contain zinc in light of the COVID-19 pandemic, where a strong immune response was essential for recovery and prevention. The body's immune system and capacity to fight viral infections may be supported by ensuring a proper intake of zinc, whether through food sources like pumpkin seeds or supplementation when required.

Furthermore, the potential use of pumpkin seed oil in the cosmetic sector has received a lot of scholarly attention recently (Šamec et al., 2022). In a study by Al-Ghamdi et al. (2017), an efficient antiulcer agent was developed using pumpkin seed oil formulation based on nanostructured lipid carriers. In addition, Šamec et al. (2022) further reported that pumpkin seed oil may help treat menopausal women's cardiovascular issues and conditions brought on by sex hormone imbalance.

Pumpkin seeds are adaptable and can be used to flavor and give nutritional value to a variety of food items. For instance, the seed sub-raw materials can be used to create a variety of products, such as salty snacks and baked goods made by fortifying wheat flour (Patel, 2013). Essential amino acids present in various amounts in pumpkin seeds, makes them a rich source of plant-based proteins (Glew et al., 2016). They are therefore a great option for vegetarians and vegans. Furthermore, phospholipids present in seeds, particularly phosphatidylcholine and phosphatidylethanolamine, have emulsifying qualities and can be employed in food production (Ragajro et al., 2011).

Due to the possible skin benefits of pumpkin seeds and their derivatives, they are used in the production of cosmetics (Lacatusu et al., 2018). As a result of the high quantity of antioxidants and essential fatty acids the seed oil, the seed could be used in skin care products such as moisturizers, serums, and facial masks (Chu and Nyam, 2021). These products may assist to promote skin health. A study by Hajhashemi et al. (2019) reported that, the seed oil can be used in the manufacturing of hair care products like shampoos and conditioners for scalp hydration and rapid development of hair.

The use of pumpkin seeds is thus beneficial in various aspects of human endeavors (Kaur and Sharma, 2018). However, large amounts of seeds are frequently discarded as by products in food processing e.g. in rural communities of India (Patel and Rauf, 2017). Their underutilization is attributed to low demand for the seeds and the lack of knowledge about the benefits embedded in the seed (Bunde-tsegba et al., 2020).

Indian gooseberry (*Phyllanthus emblica*)

Indian gooseberry commonly known as amla in India, is a tropical and subtropical plant that belongs to the *Phyllanthacae* family (Tem, 2001). It is indigenous to India and grows in other countries such as Pakistan, Uzbekistan, Sri Lanka, South East Asia, China and Malaysia (Mandal, 2017). India is the top producer of amla globally. The area of amla cultivation is about 93.17 thousand hectares and the total production of the crop amounts to 1074.60 thousand metric tons per year as of 2017–2018 (Hasan et al., 2016). The state with the leading amla production in India is Punjab (Kaur et al., 2021). The state's outstanding contribution to amla agriculture highlights the country's agricultural landscape's geographical diversity and dynamic nature. Studies have shown that amla seeds are a rich source of fatty acids, including linoleic, stearic, oleic, myristic, and palmitic, as well as alkaloids, flavonoids, saponins, tannins, terpenoids, glycosides, and phenolics (Kaur and Sharma, 2018). Even though amla seeds are not consumed alone as food, they contain nutrients such as proteins, and vitamins like vitamin E, vitamin K and vitamin B (Gupta et al., 2015). The seeds are also rich in fibre and minerals like calcium, zinc, selenium and magnesium (Rayman, 2005). Although amla seeds are not frequently consumed on their own, they are a nutritional powerhouse, containing a wide variety of important elements. Amla seeds can give a considerable nutritional boost and enhance general health and well-being by being used as a supplemental ingredient. Phytochemicals and essential nutrients found in amla seeds have a wide range of applications in various industries (Fig. 11). In the amla processing industry, amla fruit is used for a variety of purposes, while seeds are considered the major by-products (Kaur et al., 2021).

Due to their therapeutic characteristics and rich phytochemical composition, amla seeds offer myriad potential applications in the pharmaceutical industry. Fatty acids are essential in nutrient absorption and in hormone production (Carvalho and Caramujo, 2018). They have been employed as therapeutic adjuncts in injectable and oral formulations to enhance drug absorption, distribution, metabolism, and excretion (Hackett et al., 2013). Additionally, the presence of flavonoids gives the seeds their anti-inflammatory and anticancer properties (Zhao et al., 2015). The seeds also demonstrate antibacterial, antifungal, and antidiabetic, hydration, and water retention effects, and exhibit potential cytotoxicity against MCF-7 breast cancer cell lines (Sriwatcharakul, 2020). The public health is significantly impacted by these characteristics. The seeds may be used to create herbal treatments for bacterial and fungal diseases as well as a different method of

Fig. 11. Applications of phytochemicals and nutrients found in Indian gooseberry seeds

managing diabetes, eliminating the need for synthetic drugs. A study by Kaur and Sharma (2018) reported that, due to the antioxidant properties of the amla seed coat, it may be utilized alone or in combination with other seeds to increase the value of various products. Another study noted that an infusion of the seeds is used as a medication to treat diabetes, and diarrhoea in children, and to lower fever (Dasaroju and Gottumukkala, 2014). This traditional knowledge demonstrates the amla seeds' historical efficacy and safety in treating frequently occurring health conditions.

Amla seeds contain antioxidants that fight oxidative stress, including vitamin C and selenium. The cosmetics industry can provide users with resistance against early skin ageing by including amla seed extracts in their products. Natural antioxidants are utilized in accordance with the rising demand for pure and natural cosmetic compositions (Rayman, 2005). Essential fatty acids included in amla seed oil can strengthen and nourish hair. Amla seed oil's capacity to stop hair breakage, enhance hair texture, and advance general hair health are arguments in favour of its use in hair care products. In addition, Amla oil may lessen scalp inflammation and hence lower oil production, which may aid in sebum management (Chakraborty, 2022) as well as in solving environmental issues. These uses are in line with customer aspirations for items that are healthy, sustainable, and natural. Utilizing amla seeds to their full capacity can result in creative and sustainable cosmetics solutions.

Despite the fact that amla seeds have proven to be excellent sources of essential compounds, they are frequently regarded as waste and are discarded during fruit processing (Kaur et al., 2021). This raises the necessity for additional research and exploration.

Custard apple (*Annona muricata*)

Custard apple belongs to the family *Annonaceae* (Opute et al., 2014). In India it is called soursop because it produces fruits that have a slightly acidic taste when ripe (Shashanka et al., 2018; Asare et al., 2015). Soursop is native to South and North America (Orak et al., 2019; Coria-Téllez et al., 2018), but also widely distributed across the tropical and subtropical regions of the world, including Malaysia and Nigeria and in the Indian subcontinent (Alizade-Harakiyan et al., 2018). In India, it is made available through cultivation with the main producing areas being Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Assam, Andaman and Nicobar Islands (Karthikeyan et al., 2016). The phytochemicals present in custard apple seeds are not limited to alkaloids, glycosides, saponins, phytosteroids, fixed oils, flavonoids, terpenoids, fatty acids such as stearic acid, oleic and linoleic acid (Agu and Okolie, 2017). Among the nutrients that are contained in *Annona muricata* seeds are proteins, essential amino acids, dietary fiber and carbohydrates essential for tissue growth, and body repair (Menezes et al., 2019). Minerals e.g. potassium, sodium, calcium, magnesium, zinc, iron, copper, manganese, lead, and cadmium were also reported (Fasakin et al., 2008). Based on the stated literature, *Annona muricata* seeds hold considerable potential for use in a variety of industries (Fig. 12), due to their abundance of vital chemicals.

Chemical analysis of *Annona muricata* seeds has been conducted in view of isolating a range of phytochemicals that may contribute to potential health benefits (Gajalakshmi et al., 2012). These compounds have been proven to have anti-inflammatory, anti-tumour, antidiabetic, and insecticidal properties, and the seed powder is used to treat worms and head lice (Vijayameena et al., 2013). Besides, it has been demonstrated that the endosperm extract and the whole seed are poisonous to mosquito larvae (Komansilan et al., 2012). According to Sayeed and Ameen (2015), pytosteroid helps the body maintain healthy cholesterol levels, while fatty acids play a significant role in maintaining cellular integrity, promoting brain function and supporting overall health. A class of polyketides (*Annonaceous acetogenins*) have shown promising anticancer effects in preclinical studies by inhibiting the growth of cancer cells, and potentially offering a therapeutical option against various types of cancer (Zorofchian Moghadamtousi et al., 2014). Similar studies demonstrated that custard apple seed extracts have an inhibitory effect on MMP-2 and MMP-9 cancer biomarkers and that it could increase the expression of a few endogenous MMP-2 and MP-9 inhibitors, such as Reversion-inducing Cysteine-Rich Protein with Kazal Motifs (RECK) and Tissue Inhibitor of Metalloproteinase-2 (TIMP-2) (Drishya et al., 2020)

Annona muricata seeds contain acitogenins and annonaceous acitogenins, which have been shown to

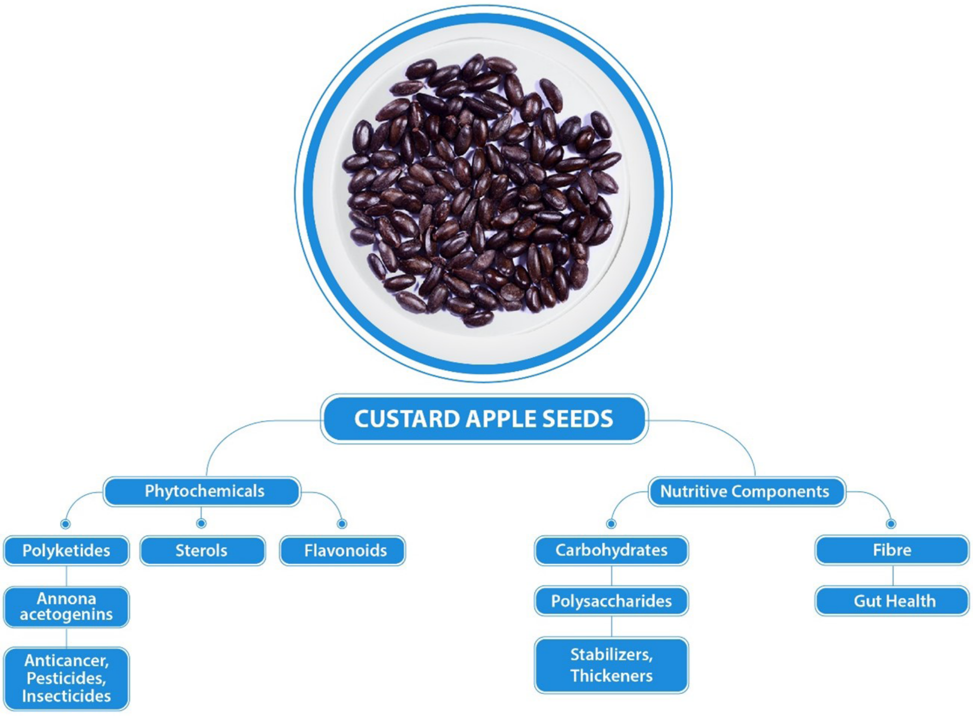

Fig. 12. Metabolites found in custard apple seeds and their applications

have antibacterial and antifungal properties (Aguilar-Hernández et al., 2023). By preventing the growth of spoilage microorganisms, these substances can be utilized as natural preservatives in food products to increase shelf life. Minerals found in custard apple seeds could be used as supplements in diets to enhance the nutritional contents (Menezes et al., 2019). Since custard apple seeds are frequently thrown away as waste, using them as supplements might be a sustainable strategy. Utilizing them helps conserve resources and lessen food waste. Scientific literature has confirmed that the high protein and oil contents present in seeds are desirable for making a variety of foods like beverages, snacks, and baked products (Villacís-Chiriboga et al., 2023). Certain carbohydrates found in the seeds like polysaccharides could be essential ingredients as stabilizers and thickeners to enhance texture, stability and mouthfeel of several food products (Fuentes et al., 2011). Furthermore, the presence of dietary fiber could significantly contribute to the improvement of the digestion process and overall gut health (Menezes et al., 2019).

Additionally, anonaceous acetogenins, have been shown to have insecticidal and pesticidal effects (Padmanabhan and Paliyath, 2015). These elements can be used to create organic insecticides for use in agriculture, lessening the dependency on synthetic chemicals. while proteins could be incorporated in animal feed formulations as a source of essential amino acids for livestock and poultry (Fasakim et al., 2008). A study by Wong et al. (2019), reported that biodiesel was successfully produced from a novel feedstock of *Annona muricata* seeds making the underutilized plant product a candidate for further research related to sustainable energy use and transitions. By exploiting *Annona muricata* seeds and their various components, a range of industries could develop sustainable, long-lasting solutions. Hence the need for artificial additives and chemicals would lessen while improving both good health and a safe environment.

While *Annona muricata* seeds possess a wide range of potential benefits, their setback lies in the fact that they are among the residues discarded during processing (Villacís-Chiriboga et al., 2023). Wastes account for

33% of the entire fruit, with about 5–10% seed wastes (López-Romero et al., 2022). In addition, their bitter flavor and relatively hard texture make them unappealing for direct consumption thus making them less popular in traditional cuisines (Solís-Fuentes et al., 2020).

Lemon (*Citrus limonum*)

Citrus Limon is a member of the *Rutaceae* family and belongs to the genus Citrus (Sharma et al., 2017). The largest producers of lemon are China, the United States, Mexico, India, Brazil, Argentina and Spain (Aguilar-Hernández, 2020). Out of the 116 million tonnes of lemon produced worldwide, India produces about 28.35 lakh tonnes [203]. Andhra Pradesh is India's leading lemon-producing state with a production of 0.69 million MT from 0.05 million hectares and productivity of 15 MT/ha, it supplies over 33% of the nation's total lemon (Chiphang, 2018). Studies have shown that lemon seeds possess diverse phytochemical groups e.g. alkaloids, glycosides, flavonoids, tannins, saponins and steroids (Rahman et al., 2022). Additionally, a number of essential nutrients have been identified in lemon seeds including dietary fibre, which is in abundance, is good for the digestive system and encourages regular bowel motions (Karaman et al., 2017). Due to the existence of these vital compounds, lemon seeds may therefore be useful in a variety of industries (Fig. 13).

In the pharmaceutical industry, lemon seeds have been proven to be a significant source of nutraceutical bioactive substances due to the high concentrations of flavonoids and limonoids (Kim et al., 2013). Flavonoids from lemon seeds have useful properties and can be utilized as supplements for post-exercise recuperation (Narayanam et al., 2021). While limonoids derived from lemon seeds have anti-proliferative and anti-aromatase characteristics that are effective against human breast cancer cells (Kim et al., 2013). Additionally, the results of photodynamic therapy demonstrated that adding salicylic acid from lemon seeds boosts the effectiveness of methylene blue in destroying cancer cells (Jafari et al., 2017). Salicylic acid extracted from lemon seeds has shown higher biocompatibility and a lower risk of side effects than other synthetic substances used in cancer therapies. This represents an important development in the realm of cancer treatment since it might offer a more effective and specialized method of destroying cells that are cancerous.

Studies in female rats have shown that seed oil has a reversible anti-fertility effect, making it a candidate for an anti-fertility drug (Kulicarni et al., 2005). This study offers an opportunity for the production of new contraceptive drugs. It has shown its capacity to provide safer, more flexible, and non-hormonal contraceptive options, addressing an important component

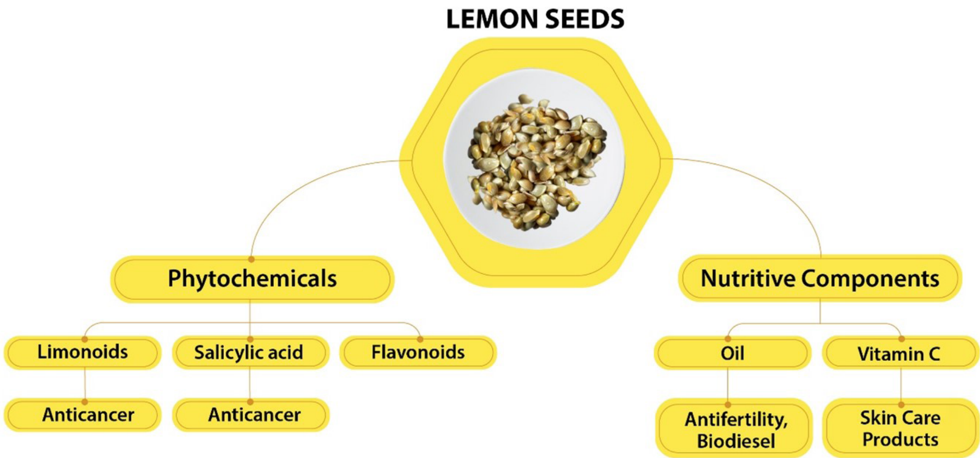

Fig. 13. Metabolites found in lemon seeds and their uses

of reproductive health and family planning. To ensure its efficacy and safety, more research involving human participants is necessary. Furthermore, the seeds also contain a moderate amount of proteins (Buket Karabiber and Yilmaz, 2017), which are essential for maintaining immunological function, repairing tissues, and carrying out other vital bodily functions (Alberts et al., 2018). Vitamin C, a significant nutrient present in the lemon fruit is also found in the seeds. This vitamin is an antioxidant that strengthens the immune system. It promotes the production of collagen and functions as a cofactor in a number of enzymatic processes (Hosen et al., 2020). Minerals like calcium, magnesium, phosphorus, and potassium are also found in the seeds. These minerals are essential for maintaining strong bones, muscles, and proper body structure.

The food industry may find lemon seed oil useful. Numerous citrus oils, including lemon, contain limonene a cyclic terpene (Sun, 2007). Limonene has a sweet, lemon-like scent. It is frequently used in the food industry as an ingredient in products such as beverages as well as for flavoring, dietary supplements, and food preservatives (Kuna et al., 2018). Lemon seed oil, which contains limonene, could be a flexible component that may be used in a variety of food compositions, encouraging product development creativity and innovation. It can also be utilized for both savoury and sweet purposes, satisfying a range of consumer tastes.

The oil from lemon seeds can further be used to make biodiesel due to essential features it possesses such as viscosity and density similar to the European standards (Frondel and Peters, 2007; Sarno and Ponticorvo, 2020). By offering a more sustainable and regionally sourced fuel choice for farm machinery, biodiesel plays an important role in the agriculture sector. The manufacturing of biodiesel from lemon seed oil is a potential strategy for supplying the world's energy needs in the farming industry. It is a strong option in the search for cleaner and more sustainable energy sources. Its conformance with European requirements for viscosity and density, as well as its renewability and minimal environmental impact, makes it suitable. Lemon seed oil biodiesel stands out as a profitable and environmentally beneficial choice as the globe looks for alternatives to fossil fuels.

The need to utilize industrial wastes has grown critical in the context of reducing environmental deterioration and resource depletion which is rapidly expanding. Yet lemon seeds still remain the primary by-product of industrial processing (Ambrogina et al., 2020). In fact, the seed waste accounts for about 20–40% of the whole fruit (Sury et al., 2022).

Table 1 summarizes the phytochemicals and other essential components present in the underutilized seeds or their parts locally available in India. It also highlights their biological and industrial applications.

KEY STUDY FINDINGS AND FUTURE IMPLICATIONS ON SUSTAINABILITY RESEARCH

According to our research, the majority of the 11 tropical seeds we looked at, including jackfruit seeds, have a wealth of untapped phytochemicals and health advantages. Where they are present, however, they are not fully utilized (Gupta et al., 2022; Konsue et al., 2023). In India, 40% of the jackfruit seed production is lost, putting this into context. It is estimated that between 60 and 65 percent of the jackfruit's inedible parts—such as the peel and immature portions—are discarded (Konsue et al., 2023; Thamizlvel et al., 2023; Zhang et al., 2017). About 60% of the entire jackfruit is wasted in most tropical regions, including Uganda, where people only eat the fruit and seeds, or they toss away the pulp. Most tropical regions, including Uganda, squander over 60% of the entire jackfruit as people just eat the fruit and they discard the pulp and seed because it is not widely known how valuable the phytochemical and health benefits are for commercial production (Nakintu et al., 2023; Joy et al., 2022). After the flesh is consumed, the majority of the seeds are likewise thrown away (Joy et al., 2022; Li et al., 2022). This has resulted in 46% of the jackfruit products (notably seeds) being wasted and left underutilized (Watanabe et al., 2023; Kamila et al., 2022). A notably gap is research on the physicochemical properties and phytochemical constituents of most tropical seeds is largely unknown and unavailable (Brahma and Ray, 2022).

Due to poor preservation practices, a significant portion of harvested seeds perish quickly both during production and after consumption (Konsue et al., 2023; Li et al., 2021). The accumulation of bio-waste leads to an increase in emissions and environmental pollution (Li et al., 2022; Akmeemana et al., 2022). According to Joy et al. (2022) and Li et al. (2021), spoilage of these goods results in the loss of important bioactive fruit components such the rind, peel, and outer core as well as antibacterial components that might be utilized in sustainable agriculture techniques. This opens up a new line of inquiry for studying tropical seed research; especially in the main producing areas such as India in order to identify the different phytochemicals and their relative importance.

CONCLUSION

Existing literature shows evidence of the abundance of underutilized seed varieties available in tropical regions such as India. Some seeds, e.g., those from papaya, custard apple, pumpkin, mango, tamarind, cashew nut shells, and coconut shells, continue being underutilized. This is confirmed in studies in other tropical regions such as Uganda where about 60 percent of jackfruit (notably seeds and pulp) are discarded (Nakintu et al., 2023). Even though these seeds are frequently disposed of during processing, they are confirmed to contain valuable compounds. The identified seeds provide a variety of phytochemicals and vital nutrients when taken as a whole. Gathering information on the applications of phytochemicals and nutrients found in these seeds can greatly influence the production of value-added products while providing advantages for commercial benefits. Such initiatives may support the development of novel lead molecules for drugs in the pharmaceutical industry, and valuable items being produced in the cosmetics industry, as well as the agricultural and food industries. We, therefore, suggest that this study would assist the research community in conducting additional studies/research and identifying potential strategies and interventions to support the adoption of more diverse and resilient seed systems. In addition, the study could best inform policymakers to initiate the promotion of the use of underutilized seeds by revealing information about their availability and applications. Furthermore, such would help the local communities to enhance the sustainable use of value-added products to promote their livelihoods through greater nutrition and income generation. We recommend that communities be encouraged to consider the various uses of the abandoned seeds by increasing knowledge among them about their value, which will help to reduce waste.

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DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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