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Moringa oleifera Lam. leaves as new raw food material: A review of its nutritional composition, functional properties, and comprehensive application

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ABSTRACT

Background: Moringa oleifera Lam. leaves (MOLLs) are recognised as new raw food material with various nutritional factors and phytochemical components. In recent years, a large number of studies have been conducted on deciphering the chemical composition and biological functions of MOLLs. However, the research data on MOLLs are scattered, and the future application trends are not summarised.

Scope and approach: In this review, we recapitulate the nutritional and phytochemical components of MOLLs, including their nutritional components, biological factors, and functional benefits, while emphasising the safety and application of MOLLs as a new raw food material.

Key findings and conclusions: Currently, research has been focused on establishing MOLLs as novel raw food material. MOLLs constitute a variety of bioactive compounds, such as phenolic, flavonoids, protein, polysaccharides, vitamins, minerals. These bioactive compounds exhibit anti-inflammatory, anti-tumour, antibacterial, antioxidant, and anti-diabetic activities. As a promising and economic Chinese herbal medicine and functional food, MOLLs is widely used in the food and pharmaceutical industry. We mainly focus on summarising the findings about the nutritional components, chemical substances, and functional activities of MOLLs and discuss the practical applications of MOLLs as a new raw food material in the food and agriculture industries. Furthermore, this review provides an innovative approach for the application of MOLLs in the food industry and agriculture, discusses the current developments and problems of deep processing products of MOLLs, and provides insights into the future sustainable development options of MOLLs industries.

1. Introduction

Moringa oleifera Lam. belonging to Moringaceae, is a perennial tree widely distributed in the tropical and subtropical regions of Asia, Africa, and Central America. The specific characteristics and planting areas of MOLLs are shown in Fig. 1 (Ahmed, Shehawi, et al., 2021; Arora & Arora, 2021). *Moringa oleifera* Lam. originated in India and was planted in Yunnan, Guangdong, Hainan, Guangxi, Guizhou, Sichuan, and other regions in China. It is known as a miracle tree because of its robust drought resistance, rapid growth, and rich nutrition (Andrew et al., 2018; Hedhilia et al., 2021). Almost all parts of *Moringa oleifera* Lam. including the leaves, roots, seeds, flowers, and barks, are edible and can be used as medicinal resources, based on the reports of its biological role in improving human health (Arora & Arora, 2021; Badwaik et al., 2020; Mutar, Rawi, & Mohammed, 2021).

Moringa oleifera Lam. leaves (MOLLs) are the primary edible parts of *Moringa oleifera* Lam. (Affonfere et al., 2021; Łukaszewska, Toczek, Bujak, Wasilewski, & Baran, 2020). They are rich in nutrients and

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bioactive factors, including polyphenols, polysaccharides, proteins, alkaloids, vitamins, and minerals (Li, Li, et al., 2022; Li, Li, et al., 2022; Mohamed, Azhar, & Elwan, 2022; On, Saenphet, Jaikang, & Sudwan, 2019). MOLLs is known to exert many biological activities, such as regulating hypoglycemic, modulating lipid, antioxidative, antibacterial, antiviral, anti-tumoural, anti-inflammatory, and neuroprotective activities (Nwakulite et al., 2021; Alqurashi & Aldossary, 2021; Shi et al., 2022; González, Moreno, Puican, & Oropeza, 2022; Fatiqin, Amrulloh, & Simanjuntak, 2021; Ahmed, Wareth & Lohakare., 2021). Studies have shown that malnutrition and hunger cause health problems in approximately two billion people worldwide. Moreover, the lack of diversity in diets may lead to nutrient deficiency and aggravate malnutrition (Cuellar, Mejia, & Pina, 2021; Kapil, Deka, Lahkar, & Sharma, 2021; Teclegeorgisha, Aphanea, Mokgalakaa, Steenkamp, & Tembu, 2021). Because of their chemical composition and nutritional characteristics, MOLLs is consumed in many countries around the world. In Africa, MOLLs is a staple food, whereas, in other countries, it is used as a supplement to make bread, noodles, dairy products, and tea drinks to combat hunger and malnutrition (Adetola, Kruger, Ferruzzi, Hamaker, & Taylor, 2021; Govender & Siwel, 2020; Waluyo, Widowati, & Nabillah, 2021; Yasara, Indira, & Wijesekara, 2020; Zula, Ayele, & Egigayhu, 2021). In addition, MOLLs has been approved as a new raw food material in China (Ministry of Health, PRC, 2012; Document NO.19, http://www.nhc.gov.cn/). MOLLs usage has been approved widely in food production and development industries to meet the basic requirements of food because it is harmless to humans (Agunbiade, Famutimi, Kadiri, Kolapo, & Adewale, 2021; Alibade, Batra, Bozinou, Makris, & Lalas, 2021; Altaee & Fadheel, 2021; Cattan et al., 2021).

Currently, research is mainly focused on the isolation and purification of functional factors, identification of their biological activities, and applications of MOLLs as a new raw food material. However, the data from these studies are scattered, and the future application trends of MOLLs have not been summarised, hindering the development and utilisation of MOLLs. Owing to this situation, we reviewed the main nutritional and phytochemical components of MOLLs, summarised the separation and purification processes of different functional factors, concluded the toxicological safety and biological functional activity of MOLLs, and focused on the application of MOLLs in food, agriculture, and other industries. Furthermore, the related products of MOLLs were sorted, and the future development trends of MOLLs are presented in this review.

2. Nutritional characteristics of MOLLs

MOLLs is rich in nutrients (Katmawanti & Mariroh, 2021; Nair, James, Sreelatha, Kariyil, & Nair, 2020). The amount of different nutrients in MOLLs depends on the geographic area, solar radiation, humidity, soil type, and harvest time (Andrew et al., 2018; Arora & Arora, 2021). However, a large number of studies have shown that MOLLs is low in fat and high in protein, carbohydrates, and vitamins. Therefore, MOLLs seems to be a promising nutritional supplement that satisfies the nutritional needs of various groups of people. The specific nutritional contents of MOLLs are shown in Fig. 2.

2.1. Protein and amino acids

MOLLs is rich in protein and has a balanced composition of several amino acids. The protein content of dry leaves is 27.1 g/100 g (DW) and that of fresh leaves is 6.7 g/100 g (FW), which is two times greater than that of milk (Andrew et al., 2018; Arora et al., 2021). Previous studies have found that MOLLs contains mainly 17 types of amino acids (eight essential and nine non-essential amino acids), among which lysine, glutamic acid, cystine, and methionine are prominent, moreover, tryptophan, which is often lacking in many vegetables, is the first limiting amino acid present in MOLLs (Badwaik et al., 2020; Mutar et al., 2021). In addition, MOLLs has high levels of phenylalanine, threonine, leucine, isoleucine, and valine, which help supplement a diet based on soy and beef (Teclegeorgisha et al., 2021). Furthermore, the ratio of essential to non-essential amino acids in MOLLs is close to the FAO/WHO recommended standard value for the amino acid composition of proteins in food (Maheshwaran et al., 2021). Hence, MOLLs has a reasonable composition of amino acids and is considered to be a high-quality and exploitable source of plant proteins.

2.2. Carbohydrates

The total carbohydrate content in MOLLs was estimated to be 8.61%–66.3%. Most of the polysaccharides in MOLLs are composed of glucose, fructose, rhamnose, and xylose (Fernandes et al., 2021; Jimenez, Almatrafi, & Fernandez, 2017). In addition, MOLLs is also rich in dietary fibre, mainly composed of cellulose, hemicellulose, pectin, and lignin. MOLLs polysaccharides are involved in biological activities, including immune regulation, anti-tumorigenic, blood glucose level maintenance, and lipid reduction activities (Badwaik et al., 2020; Teclegeorgisha et al., 2021; Wang et al., 2019).

2.3. Vitamins

Vitamins are trace organic substances that humans obtain from food to maintain normal physiological functions (Andrew et al., 2018). MOLLs is rich in vitamins, especially VA, VB_1, VB_2, VC, and VE. Studies have shown that the content of VB in MOLLs is approximately 4.23 g/100 g (FW), mainly including VB_1 (0.21 g/100 g FW, 2.6 g/100 g DW), VB_2 (0.05 g/100 g FW, 20.5 g/100 g DW), and VB_3 (0.8 g/100 g FW, 8.2 g/100 g DW) (Hoque, Abedin, Kibria, Jahan, & Hossain, 2021; Linda, Laksmiani, Widiantara, & Pawarrangan, 2022). Moreover, MOLLs are a

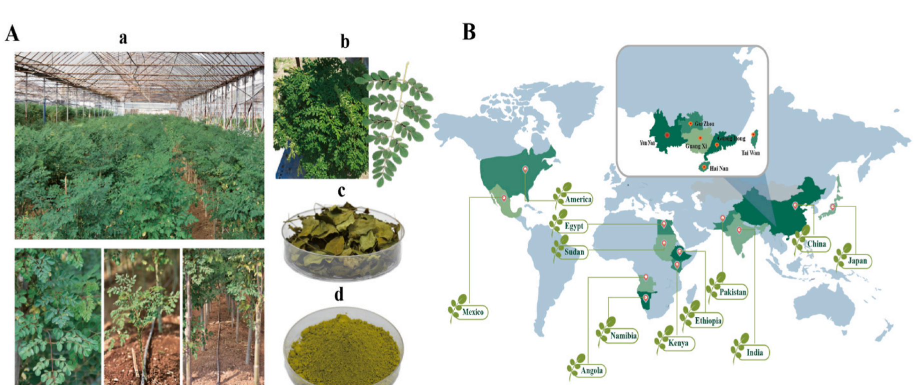

Fig. 1. (A). The Photograps of *Moringa oleifera* Lam. leaves: (a) Plant, (b) Fresh leaves, (b) Dried leaves, (c) Leaves powder; (B). Main production areas of *Moringa oleifera* Lam. leaves in the world.

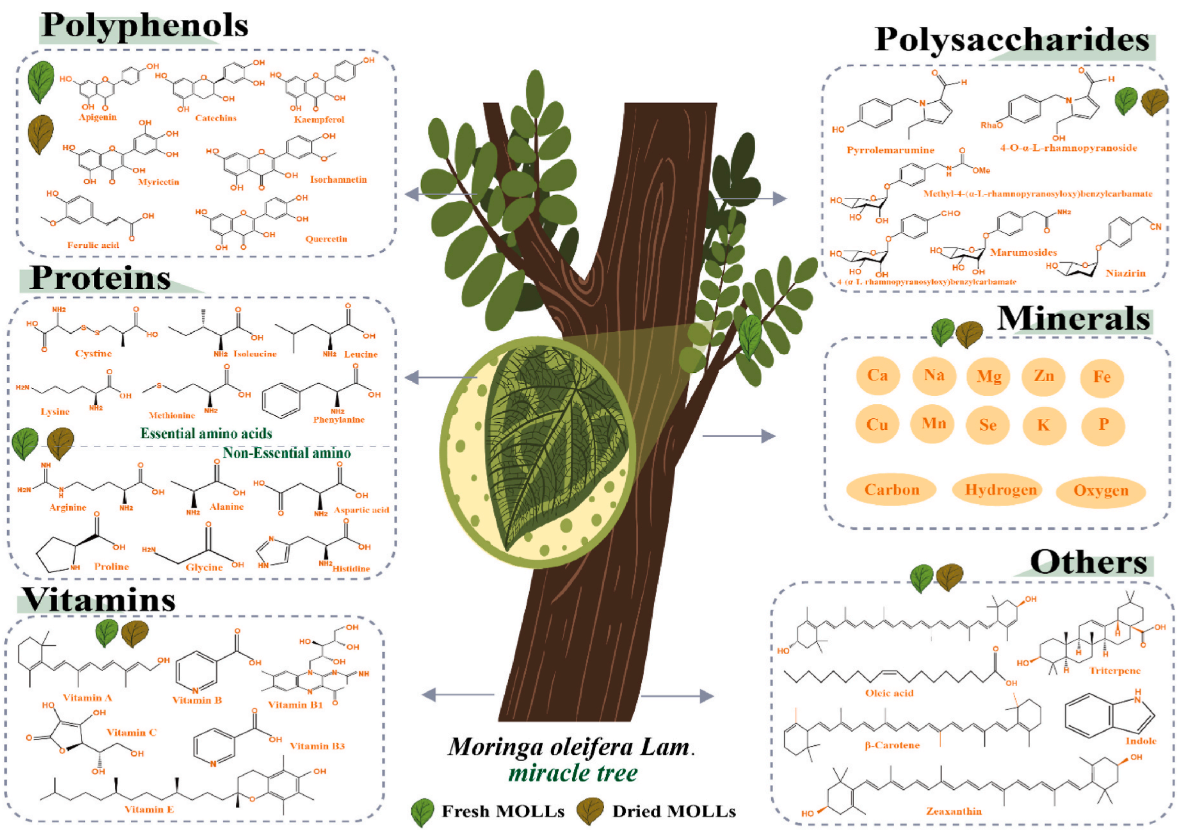

Fig. 2. The chemical structures of nutritional composition and bological factors in *Moringa oleifera* Lam. leaves. For the Proteins in the figure is the main amino acids composition; For the Polysaccharides in the figure is the main monosaccharide composition.

good source of VC. Fresh leaves contain about 2.20 g/100 g of VC, which is seven times more than that of oranges. However, because VC is extremely reactive to heat and oxygen, it constitutes a lower weight in dried leaves (Katmawanti & Mariroh, 2021; Mutar et al., 2021). Nonetheless, freeze-drying technology prevents VC oxidation in MOLLs and improves food utilization efficiency. In addition to carrots, pumpkins, and apricots, MOLLs has been extensively studied for VA richness (6.8 g/100 g FW) (Mohamed, Yousse, Issa, Salam, & Ansary, 2020; Sardar et al., 2021). Fresh MOLLs is a good source of carotenoids, mainly β-carotene. An intake of 11.43 g fresh or 4.62 g dried MOLLs is sufficient to achieve the recommended daily intake of VA. Furthermore, studies have shown that MOLLs is a good source of VE, which is equivalent to the content of VE in nuts (9 g/100 g FW). Drying MOLLs can prevent the loss of VE, and a daily intake of 25 g MOLLs powder can fully pertain to the nutritional needs of different populations (Abatal et al., 2021; Granella, Bechlin, Christa, Coelho, & Paz, 2021).

2.4. Minerals

Minerals are the main elements that constitute human tissues and maintain normal physiological functions and metabolism (Arora & Arora, 2021; Maheshwaran et al., 2021; Mutar et al., 2021). MOLLs contains six macronutrients (Ca, Mg, P, K, Na, and S) and five trace elements (Zn, Cu, Fe, Mn, and Se). The iron content in MOLLs (28.2 g/100 g DW) is 14 times than that in beef and can be used to treat iron deficiency in patients with anaemia. The calcium content (20.03 g/100 g DW) in MOLLs is 10 times than that in milk, while the potassium content (13.24 g/100g DW) in MOLLs is four times than that in banana (Fernandes et al., 2021; Hasrini, Aviana, & Khoiriyah, 2021; Xie et al., 2018). Altogether, MOLLs can be used as a low-sodium and high-potassium supplementary food to meet the need for minerals in humans.

2.5. Effect of different planting conditions on nutritional components of MOLLs

Moringa oleifera Lam. has been a traditionally important edible plant in tropical or subtropical countries. Maturation stages and different planting environments may affect the nutritional and phytochemical characteristics of MOLLs. The effect of different planting conditions on nutritional contents of MOLLs are shown in table S1 and table S2.

2.5.1. Effect of different maturity stages on MOLLs

Qadir, Anwar, Bashir, Tahir, and Mehmood (2022) evaluated the changes in the nutritional content of MOLLs harvested at different maturity stages. The results showed that the total content of phenolic compounds in the extracts of MOLLs harvested at early, middle, and late stages was 95.26 ± 0.89, 60.36 ± 1.14, and 38.22 ± 1.61 mg GAE/g, respectively, suggesting that the phenolic content was the highest in young leaves and the lowest in matured leaves. On the contrary, the flavonoids and protein contents were the highest in mature leaves and the lowest in young leaves. The contents of valine, alanine, leucine, and phenylalanine in late mature leaves were higher than those in early young leaves. In addition, MOLLs is rich in VC, the content of which is 62.66–143.58 mg/100 g and 51.22–150.15 mg/100 g in tender and mature leaves, respectively. Contrary to the content of β-carotene, lipid-soluble vitamins such as VA are higher in mature leaves than in young leaves. However, some studies suggest that the content of carotene in mature leaves is lower than that in young leaves. Therefore, we speculate that the vitamin content in MOLLs may be greatly affected by its origin. The current work also observed significant changes in mineral content in MOLLs at different maturity stages. For instance, the contents of copper, iron, and manganese were higher in the late mature leaves (2.08 ± 0.09 mg/100 g, 58.68 ± 0.39 mg/100 g, and 13.84 ± 0.37 mg/100 g, respectively) than in the early young leaves (0.595 ± 2.08

mg/100 g, 21.96 ± 0.85 mg/100 g, and 5.56 ± 0.48 mg/100 g, respectively). However, the total ash content of MOLLs did not differ significantly between the different maturation periods and cultivation areas.

2.5.2. Effect of different altitudes on MOLLs

At different altitudes, the contents of total phenols, flavonoids, and quercetin in MOLLs cultivated at moderate altitudes were higher than those at extremely low and high altitudes (15–150 m heigh above mean sea level). Owing to the high content of phenols in MOLLs at moderate altitudes, the antioxidant activity in the leaves was better (IC_{50} = 134.5 μg/mL) (Sulastri et al., 2018). Moreover, Kim, Choi, and Shin (2020) compared MOLLs from South Korea and Cambodia and found that the polyphenolic content in Cambodian MOLLs was higher than that in South Korean MOLLs. Using 3T3-L1 cells, it was shown that MOLLs from Cambodia played an anti-obesity role by inhibiting the expression of lipogenesis-related proteins.

2.5.3. Effect of seasonal changes on MOLLs

Furthermore, seasonal changes can also affect the content of polyphenols in MOLLs. The polyphenolic content was higher in MOLLs grown in winter than those grown in summer, possibly due to the unstable degradation of phenols induced by the increase of singlet oxygen upon ultraviolet irradiation. The vitamin composition followed the same trend as the polyphenols, implying that MOLLs grown in winter have higher reduction and antioxidation capacities than those grown in summer (Iqbal & Bhanger, 2006).

2.5.4. Effect of differences in soil nutrients on MOLLs

Soil nutrient loss may lead to a decrease in MOLLs yield. Therefore, *Moringa oleifera* Lam. should be cultivated in a soil of medium-acid to alkaline loam pH, where certain minerals and most vitamins are retained at high concentrations to benefit plant growth. Organic fertilizers combined with animal manure, weeds, and potato crops significantly promoted the growth and development of *Moringa oleifera* Lam., which may be due to the interaction between soil nutrients and growth regulators. Planting in organic soil combined with vermicomposting can induce the production of active alkaloids in MOLLs. In addition, these fertilizers improve the agronomic shape of MOLLs. Taken together, these results support the significance of organic culture and obtaining different metabolites during the industrialisation of MOLLs (Atteya, Albalawi, Bayomy, Alamri, & Genaidy, 2022; Manzano-Gómez et al., 2021).

2.5.5. Nutritional characteristics of MOLLs cultivated in China

Overall, there are mainly 14 varieties of *Moringa oleifera* Lam. worldwide. Currently, four of these varieties have been introduced in China, including Indian traditional *Moringa oleifera* Lam., Indian improved *Moringa oleifera* Lam. (PKM1), PKM1 improved *Moringa oleifera* Lam. (PKM2), and African *Moringa oleifera* Lam. Among them, the polysaccharide content of PKM1 MOLLs was higher than that of PKM2 and African MOLLs, however, the DPPH and ABTS free radical scavenging ability of African MOLLs and PKM1 MOLLs was stronger than that of PKM2 MOLLs owing to the differences in chemical composition and structure. In addition, MOLLs was collected from six different regions (Puer, Lijiang, Chuxiong, Dali, Dehong, and Xishuangbanna) in Yunnan Province, the main producing area of *Moringa oleifera* Lam. in China. The results showed that the contents of protein and polysaccharides in MOLLs from different regions of Yunnan Province were significantly different. The protein content of the Dehong samples was the highest (28.27%), and that of the Dali samples (17.07%) was the lowest. The polysaccharide content of MOLLs from Puer was highest (13.17%) than all of the other samples, while the VC and amino acid contents of MOLLs from Dehong were higher than those of MOLLs from other areas. The contents of polyphenols and flavonoids in the Xishuangbanna and Lijiang samples were the highest, and the calcium content of MOLLs from Dali was the highest. These results promoted Yunnan Province to become the main processing base and research area of MOLLs products in China (Zhu, Yin, & Yang, 2020; Chu, Fu, & Gong, 2016).

Altogether, different conditions affect the nutritional composition and functional activity of MOLLs. These results support the rational selection of suitable planting areas for *Moringa oleifera* Lam. and the appropriate harvesting stages of MOLLs to maximize their functional and nutritional value.

3. Functional factors of MOLLs

Bioactive factors are non-nutritive plant compounds that are beneficial to health. As shown in Figs. 2 and 3, the bioactive factors in MOLLs are mainly polyphenols, protein, polysaccharides and peptides, which can be extracted in many ways. These functional factors play a vital role in mediating the biological activities of MOLLs.

3.1. Polyphenols

Polyphenols are secondary metabolites with high content and wide distribution in plants. Polyphenols in MOLLs mainly include flavonoids and phenolic acids (Adedayo, Luyi, Aladeselu, Oboh, & Boligon, 2018; Lin, J Zhang, & Chen, 2018). Different analytical methods are commonly used to evaluate the polyphenolic content of MOLLs, including HPLC-UV-MS, HPLC-UV, LC-MS/MS, and UPLC-MMS techniques (Bishnoi, Yadav, & Sharma, 2021; Joshi et al., 2022; Mohamed, Yousse, et al., 2020; Sayed, Omar, Emam, & Farag, 2022; Zhu, Yin, & Yang, 2021).

The total phenolic content of MOLLs ranged from 32.93 to 1417 mg GAE/100 g FW. Characterisation of phenols in MOLLs using HPLC showed that hydroxybenzoic acid derivatives (73.475 mg/100 g DW) accounted for nearly 21% of the total phenolic compounds (Teclegeorgisha et al., 2021). Hydroxycinnamic acid derivatives (63.612 mg/100 g DW) accounted for 18%, whereas chlorogenic acid (52.629 mg/100 g DW), rutin (85.15 mg/100 g DW), quercetin pentosidine (80.613 mg/100 g DW), shamrock phenol derivatives (16.11 mg/100 g DW), and quercetin derivatives (49.87 mg/100 g DW) together accounted for approximately 55% of the total phenolic compounds in MOLLs (Vonghirundecha, Chusri, Meunprasertde, & Kaewmanee, 2022); Mutar et al., 2021; Arora et al., 2021). In addition, some research groups used deionized water, ***n***-hexane, ethyl acetate, and n-butanol to extract flavonoids from MOLLs and found that the flavonoid content of MOLLs extracted with ethyl acetate exceeded 89%, whereas the total flavonoid content was 6.2 g/100 g when the leaves were macerated with 70% ethanol (Manaheji, Jafari, Zaringhalam, Rezazadeh, & Taghizadfarid, 2011). Moreover, the main phenolic acids in MOLLs are ferulic acid, catechin, epicatechin, caffeic acid, ellagic acid, gallic acid, gentisic acid, coumaric acid, and syringic acid. These phenolic acids and flavonoids can better scavenge free radicals and protect the body from oxidative stress by reducing lipid peroxidation. Although studies have reported many different types of phenolic compounds in MOLLs, there are still a large number of unique polyphenols to be discovered in MOLLs (Chen et al., 2012; Jimenez et al., 2017; Singh et al., 2009).

3.2. Polysaccharides

Plant polysaccharides have attracted much attention due to their multi-functionality, low toxicity, and fewer side effects. The content of polysaccharides in MOLLs was 15.12 ± 0.65%. Previously, a water-soluble polysaccharides called MOs2-a, isolated from MOLLs, has been shown to have beneficial effects on intestinal microecology in mice, such as increasing microbial diversity, increasing the abundance of beneficial bacteria, and producing beneficial metabolites. MOs2-a may play a prebiotic effect by maintaining the integrity of intestinal mucosa, regulating the composition of intestinal microflora and enhancing the activities of various digestive enzymes to degrade starch, protein and

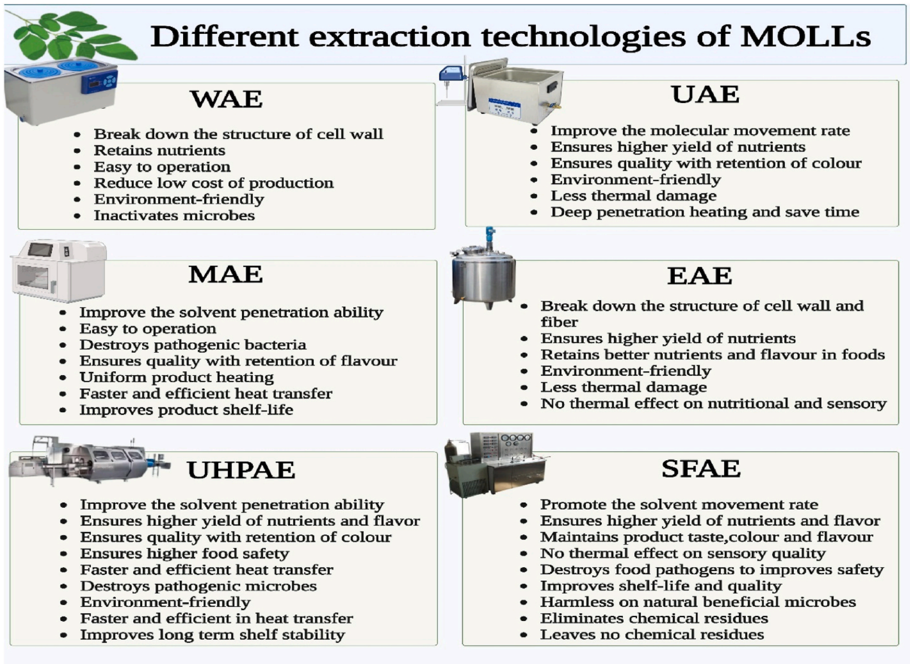

Fig. 3. Different extraction technologies and features for bological factors of *Moringa oleifera* Lam. leaves. WAE: Water-assisted extraction; UAE: Ultrasound-assisted extraction; MAE: Microwave-assisted extraction; EAE: Enzyme-assisted extraction; UHPAE: Ultra High Pressure-assisted extraction; SFAE: Supercritical Fluid-assisted extraction.

lipids of food. Moreover, MOs2-a showed the molar ratio of galactose, D-galacturonic acid, L-arabinose, and L-rhamnose was 1:1:1:1 (Wang et al., 2019). In another study, an antioxidant polysaccharides with a molecular weight of 190 kDa was isolated from MOLLs, it was composed of Ara, Gal, Xyl, Rha, and GlcA with a molar ratio of 64:25:4:3:4. MOLLs contains several special glucosinolates; owing to the presence of a second carbohydrate residue on the aglycone side chain, these glucosinolates exhibit unique characteristics. Moreover, MOLLs also comprises pyrrole glucoside and rhamnoside, which exhibit significant anti-inflammatory activity (Roy et al., 2007).

3.3. Peptides

MOLLs is rich in protein, 100 g of fresh MOLLs can provide 10–50% of the recommended daily protein intake for humans (Benhammouche et al., 2021; Cattan et al., 2021). Some researchers used a multi-enzyme complex to hydrolyse and extract protein from MOLLs, which eventually yielded a protein content of 34.30 ± 0.49 mg/100 g. This enzymatic protein constitutes a wide range of amino acids and can be a good source of essential amino acids. Moreover, based on pea isolates, it was determined that the protein quality of MOLLs was higher than that of commercial protein supplements, and it could be completely digested upon enzymatic digestion by *in vitro* simulation. Anti-nutritional factors may impede the efficient utilisation, absorption, and digestion of proteins, further reducing their bioavailability and nutritional status. However, the extraction of proteins via enzymatic processes may affect their intrinsic structure and impede their ability to be readily absorbed (Paula et al., 2017). In addition, upon fermentation, the protein content and digestibility of MOLLs were increased by 23.4% and 54.4%, respectively, and the contents of other functional factors (polyphenols, polysaccharide) also increased (Dai et al., 2020). The protein extracted from MOLLs by these methods can be used commercially as a protein-rich component in the food industry.

3.4. Alkaloids

Alkaloids with unique structures, such as niazimicin, lupeol, marumoside A, and marumoside B, are also found in MOLLs. Furthermore, alkaloids containing thiocarbamate, carbamate, or nitrile moieties are fully acetylated glycosides that perform a variety of bioactive functions, for example, N-α-L-rhamnopyranosylvincosamide has cardioprotective effects (Gidamis, Panga, Sarwatt, Chove, & Shayo, 2003). However, most of the current studies have focused on the isothiocyanate content of *Moringa oleifera* Lam. seeds. The alkaloids extracted from these seeds have anti-cancerous and antibacterial properties and also regulate glycolipid metabolism, which has practical applications in the future (Chen et al., 2012; Gidamis et al., 2003; Khalila et al., 2020).

3.5. Others

In addition to the above-mentioned active factors, MOLLs contains other functional substances. MOLLs contains edible fatty acids with a content of 8.65 ± 3.24%, of which monounsaturated fatty acids and polyunsaturated fatty acids comprise 4.48% and 52.21%, respectively, and the polyunsaturated fatty acids containing largely was the n-3 type (Jimenez et al., 2017; Mohamed, Yousse, et al., 2020). In addition, MOLLs also contains trace amounts of terpenes, such as luteolin and zeaxanthin. MOLLs is rich in phytosterols, such as flower sterols, glutathione, and lichenosterol, which can increase the secretion of estrogen in pregnant women and prevent malnutrition in infants and children. Notably, MOLLs contains fewer anti-nutritional compounds, such as saponins, oxalates, and phytates, than other plants, hence, the edibility and bio-availability of MOLLs are higher than those of the other plants (Ahmed et al., 2020; Das et al., 2021; Islam, Mandal, & Habib, 2021; Umar et al., 2021).

4. Safety and anti-nutritional properties of MOLLs

4.1. Safety of MOLLs

MOLLs are used as a dietary supplement and plant additive in many countries, therefore, safety for the use of MOLLs as raw material for processed food products is particularly important (Aboulthana et al., 2021). Studies have shown that continuous gavage of MOLLs at a dose of

200 mg/kg for 21 days produced no significant side effects in rats (Altaee & Fadheel, 2021). In addition, in a chronic experiment, gavage of 250, 500, and 1500 mg/kg of MOLLs in mice was still safe (Akter et al., 2021). Gavage of MOLLs at 3200 mg/kg did not produce any mortality in Wistar rats but resulted in reduced locomotion and retardation at a high dose (6400 mg/kg), possibly owing to the high concentration of nitrogen compounds in MOLLs. However, most of the toxicity studies on MOLLs showed no abnormal effects upon the gavage of high-dose ethanol or water extracts of MOLLs. The kidney structure was maintained, and no significant alterations were observed in blood biochemical indexes and reproductivity of the MOLLs extract-fed mice. MOLLs can also regulate glycolipid metabolism and reduce the expression of oxidative stress and inflammatory markers. None histopathological changes were observed in the tissues of mice at MOLLs concentrations as high as 30 times that of typical human doses. There was no acute toxic effect on alloxan-induced diabetic mice upon intraperitoneal injection of *Moringa oleifera* Lam. leaves protein isolate (MO-LPI) (Pappas, Siomou, Bozinou, & Lalas, 2021; Cuellar et al., 2021; Nwakulite et al., 2021; Laoung-on, Saenphet, Jaikang, & Sudwan, 2021). Moreover, a randomized, double-blind, and placebo-controlled clinical study showed that ingesting 2–4 g of MOLLs powder per day did not change the normal renal function of the human body. Long-term consumption of MOLLs may not cause any cumulative toxic effects on the kidney or liver and can promote human insulin secretion and regulate glucose and lipid metabolism (Martínez et al., 2022; Taweerutchana, Lumlerdki, Vannasaeng, Akarasereenont, & Sriwijitkamol, 2017). In summary, MOLLs have a high safety concentration range.

4.2. Anti-nutritional factors of MOLLs

Anti-nutritional factors are a group of basic substances or metabolites produced by plants, which not only affect their nutritional value and palatability but also destroy or hinder the digestion and utilisation of nutrients in the organisms, in turn, affecting human health and growth (Chen et al., 2012; Manaheji et al., 2011). Lectin is a factor that inhibits protein digestion and utilisation. Most lectins can bind to receptors on the surface of the intestinal tract to trigger allergic reactions, disrupt the function of intestinal cells, hinder protein degradation in the digestive tract, change intestinal permeability, and promote faecal excretion, thereby disrupting the digestion and absorption of nutrients. Reports indicated that MOLLs contains lectins (0.265 mg/100 g). Some people may exhibit rash, diarrhoea, vomiting, and other symptoms after eating MOLLs (especially fresh leaves). In addition, MOLLs also contains phytic acid (0.0182 mg/100 g) and tannin (0.22 mg/100 g), which are anti-nutritional factors with strong chelating ability, usually combined with calcium, zinc, magnesium, potassium, and other minerals to form insoluble salts, which easily associate with protein molecules leading to their precipitation. The glucosinolates and alkaloids contained in MOLLs lead to a certain bitter and pungent taste, affecting the palatability of MOLLs. Abundant glucosinolates can stimulate mucous membranes, the long-term or large amount of feeding can cause gastroenteritis and liver bleeding and also affect the absorption of VK in the body (Awodelea, Oreagba, Odoma, Silva, & Sunkalu, 2012; Jimenez et al., 2017).

To improve the digestibility and utilization of MOLLs, eliminate the adverse physiological and biochemical effects of anti-nutritional factors in MOLLs on the organism, and improve the growth performance, the activity of anti-nutritional factors in MOLLs must be passivated or eliminated. MOLLs is usually treated by heating or microbial fermentation (Gidamis et al., 2003), which affects its protein digestibility significantly. Steaming also had a significant effect on the digestibility of constituent MOLLs proteins. The protein digestibility of MOLLs before treatment was 55.4%, which increased to 76.1% upon heating. Moreover, steaming had little effect on phytate but significantly reduced the tannin content (from 0.22% to 0.16%). On the contrary, after microbial fermentation, the content of phytic acid in MOLLs decreased rapidly from 18.31 mg/g to 7.46 mg/g, the content of tannin decreased from 14.60 mg/g to 12.08 mg/g, and the content of glucosinolate decreased from 14.72 mg/g to 10.84 mg/g (Awodelea et al., 2012; Benhammouche et al., 2021; Feitosa, Santos, Gualberto, & Santana, 2020; Paula et al., 2017). In the future, it will be essential to determine the safe daily dosage of MOLLs by studying their residual anti-nutritional factors under different processing conditions and obtaining information through food histology to ensure the safety and nutrition of foods.

5. Health benefits of MOLLs

MOLLs is rich in bioactive components and involved in a variety of functional activities, such as antioxidation, blood glucose and lipid metabolism, anti-inflammatory, anti-cancerous, antibacterial, antiviral, and liver protection, which have become one of the hot spots in food research (Andrew et al., 2018; Arora & Arora, 2021; Nair et al., 2020; Omodanisi, Aboua, & Guntibeju, 2017; Liu et al., 2021). The findings from current research have been summarised in Fig. 4 and Table 1.

5.1. Regulation of glucose and lipid metabolism

Ahmed, Shehawi, et al. (2021) found that after eight weeks of high-fat diet (HFD) feeding, the body weight of rats increased significantly, whereas the body weight of the MOLLs ethanol extract (MOE)-fed group decreased. In the MOE group, the levels of TC, TG, LDL-C, leptin, insulin, and visceral fat in serum significantly decreased, whereas those of HDL-C and serum lipocalin increased. Simultaneously, the liver steatosis of these rats was significantly reduced, and the expression levels of inflammatory factor NFκB-P65 decreased in the liver. Compared to the HFD group, the MOE group had significantly reduced MDA concentration and increased SOD levels in the serum. The results showed that MOE could counterbalance of antioxidant-altered glucolipid metabolism induced by HFD in rats. Another study showed that oral administration of MOLLs extract could upregulate the expression of pancreatic genes *ADIPOQ* and *SNAP-23*, in turn maintaining blood sugar levels by modulating carbohydrate metabolism (Nwakulite et al., 2021). Hamed, Abdin, Rayan, Akhtar, and Zeng (2021) found that the ethyl acetate fraction of MOLLs showed the strongest antioxidative capacity against DPPH and ABTS radicals, with IC_{50} values of 71.9 μg/mL and 54.79 μg/mL, respectively. The IC_{50} value of α-glucosidase inhibition was decreased (0.222 mg/mL). The results of HPLC-ESI-MS showed that the flavonoids from MOLLs had a significant inhibitory effect on α-glucosidase activity and could stably bind to the insulin receptor. The inhibitory activity of flavonoids (100 μg/mL) and acarbose on α-glucosidase activity were 54.41% and 69.17%, respectively. Among them, quercetin and kaempferol were the most important flavonoids in MOLLs. These bioactive components exhibited competitive interactions with two digestive enzymes, in turn, exerting a variety of hypoglycemic and hypolipidemic effects; therefore, MOLLs could be a good choice as special foods for patients with diabetes (Teclegeorgisha et al., 2021). Moreover, in patients with diabetes, after 12 weeks of using MOLLs as a food supplement (six capsules of MOLL powder (2400 mg/day)), the level of blood glucose and hormones of appetite control in patients were improved. The levels of bilirubin, GOT, and GPT in the blood of patients in the MOLLs group increased significantly compared with those in the blood of patients in the control group. In addition, MOLLs capsules inhibited intestinal α-glucosidase activity and maintained the stability of beneficial intestinal flora (Martínez et al., 2022; Taweerutchana et al., 2017).

Furthermore, MOLLs petroleum ether extract (MOPEE) inhibited fat accumulation by preventing adipogenesis and promoting lipolysis. MOPEE (400 μg/mL) significantly downregulated PPARγ expression. Moreover, MOPEE significantly effect the expression of C/EBPα, C/EBPβ, FAS, TC, LDL-C, and AST. UF-LC/MS analysis showed that the α-glycosidase binding strength of MOLE was generally higher than that of pancreatic lipase (Xie et al., 2018). In addition, MOLLs regulates blood glucose levels and reduces lipid concentrations in the blood. These

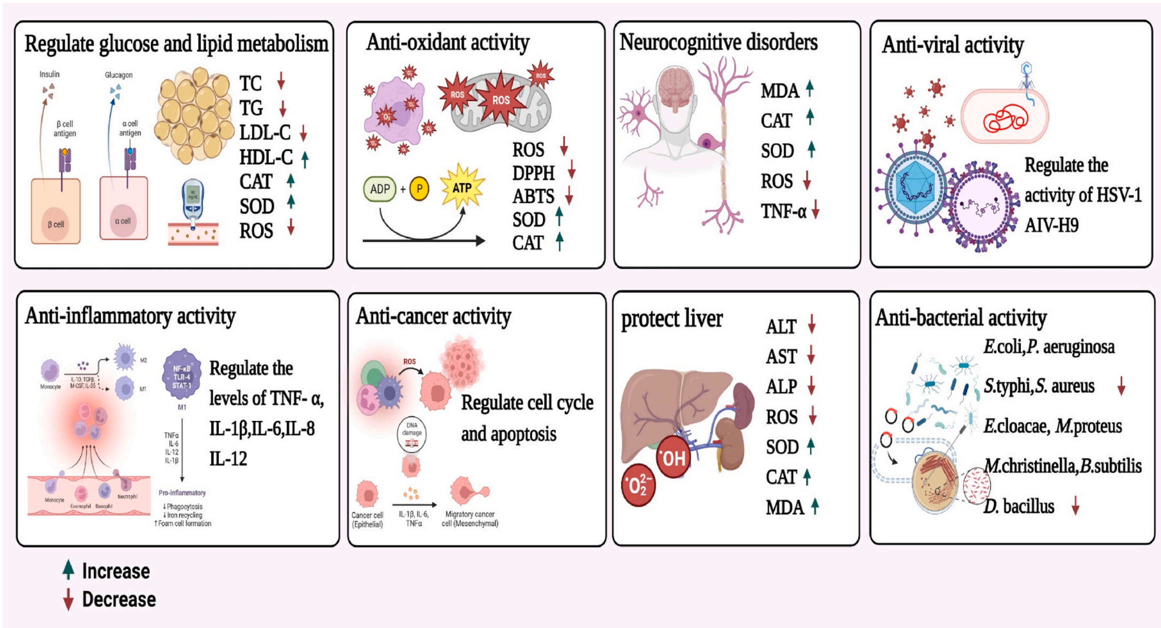

Fig. 4. Biological activities and regulatory mechanisms of *Moringa oleifera* Lam. leaves.

active factors improve the antioxidative capacity. Downregulation of the expression of inflammatory factors (IL-1β, TNF-α, and NO) and adipose markers inhibits liver gluconeogenesis, increases the content of brown adipose tissue in the body, accelerates lipolysis, regulates the level of blood glucose in the body, and thus alleviates the occurrence of diabetes and obesity (Teclegeorgisha et al., 2021; Wang et al., 2019).

5.2. Antioxidant activity

Dysregulation of oxidative stress can lead to the development of many diseases, and natural plant antioxidants can scavenge excess ROS levels. MOLLs is rich in many antioxidant factors and exhibits antioxidant activity both *in vitro* and *in vivo* (Gaxiola et al., 2021). Nair et al. (2020) found that MOLLs aqueous extract, with chlorogenic acid, kaempferol, and quercetin as the main components, has strong free radical scavenging activity, inhibits lipid peroxidation, and protects the body from DNA oxidative damage. Ratshilivha, Awouafack, Toit, and Eloff (2014) measured the DPPH free radical scavenging activity of MOLLs from the same area in different seasons. The results showed that the activity of MOLLs from winter samples was higher than that of MOLLs from summer samples. Nouman et al. (2016) used a 70% methanol solution to extract polyphenols from MOLLs and evaluated their antioxidant activity. The results showed that the IC_{50} value of DPPH free radical scavenging activity was 8.51–31.55 μg/mL, and the activity positively correlated with 3-p-coumaroylquinic acid and apigenin-8-C-glucoside. Verma, Vijayakumar, Mathela, and Rao (2009) also found that MOLLs extract prevents DNA oxidative damage caused by hydroxyl, which inhibits the toxicity of CCl_4, increases glutathione levels, and reduces lipid peroxidation levels. Superoxide dismutase and catalase levels in the serum of MOLLs-treated mice returned to near-normal levels compared with those in CCl_4-intoxicated mice. HPLC analysis showed that the extract contained phenolic acids (gallic acid, chlorogenic acid, tannic acid, and ferulic acid) and flavonoids (kaempferol, quercetin, and rutin). Moreover, protein isolated from MOLLs (MO-LPI) also reduced oxidative stress in diabetic mice (Paula et al., 2017).

5.3. Neurocognitive disorders

Neurodegenerative diseases include Alzheimer's disease and Parkinson's disease. Alzheimer's disease (AD) is an age-related disorder in which cognitive and behavioural characteristics decline due to dysfunction of the choline receptor system. AD is characterized by the formation of β-amyloid plaques. Scopolamine could lead to the loss of spatial memory function in the space exploration escape platform experiment of mice. After gavage administration of MOLLs extract (MO-SD), the spatial memory function of mice improved, and the activity of acetylcholinesterase in the brain decreased significantly. The levels of MDA and TNF-α in the brain of MO-SD mice decreased compared with those in the control group, whereas the level of SOD increased. In addition, the use of scopolamine caused an increase in nitrite concentration in the mice's brains, which was reversed by MO-SD. Moreover, the number of surviving neuronal cells in the hippocampus and prefrontal cortex of the MO-SD group increased. These results suggest that MO-SD can actively regulate the cholinergic system in mice brains and maintain the structural integrity and functional characteristics of neuronal cells by reducing the levels of acetylcholinesterase, oxidative stress, and proinflammatory factors (Onasanwo, Adamaigbo, Adebayo, & Eleazer, 2021). Studies have shown that methanol extract of MOLLs has neuroprotective effects on H_2O_2-induced human neuroblastoma cells by regulating oxidative imbalance and mitochondrial apoptosis. In addition, the extract can reduce lipid peroxidation, increase glutathione levels and antioxidant enzyme activity, prevent mitochondrial dysfunction by regulating calcium levels, and increase mitochondrial membrane potential. Overall, MOLLs as a neuroprotective agent provides the necessary nutrients for a healthy diet (Burgos, Ur Vacas Sánchez, & Serranillos, 2021).

5.4. Anti-inflammatory activity

Inflammation is a reaction of the body against oxidative stress and excessive secretion of inflammatory factors. MOLLs extract inhibited the production of cytokines such as TNF-α, IL-6, and IL-8, which are induced by cigarette smoke or LPS in human macrophages. Moreover, MOLLs also stimulated the immune response in cyclophosphamide-induced immunodeficient mice by increasing the levels of leukocytes, neutrophils, and serum immunoglobulins. Interestingly, upon feeding fermented MOLLs, the mRNA levels of inflammatory cytokines decreased and endoplasmic reticulum stress was reduced in mice, implying that microbial fermentation could enhance the anti-inflammatory properties

Table 1
Health benefits of *Moringa oleifera* Lam. leaves function factors *in vivo* and *in vitro*.

Health benefits	Functional factors	*In Vitro* or *In Vivo*	Model	Molecular pathways	References
Regulate glucose and lipid metabolism	Phenolic and Polysaccharides	*In Vitro* *In Vivo*	Zebrafish test (ZOT); 3T3-L1 cell	Down-regulated the expression of genes that respon for early adipogenesis.	Matsuoka et al., (2022)
Regulate glucose and lipid metabolism	Phenolic and Phenolic acids	*In Vivo*	Wistar rats	Reversed the levels of weight, visceral fatmass, hyperglycemia, hyperleptinemia, hyperinsulinemia, hypoadiponectinemia and dyslipidemia; Decreased the level of lipid peroxidation and hepatic NFκB protein expression; Restored normal hepatic tissue architecture and antioxidant activity.	Ahmed, Shehawi, et al. (2021)
Regulate glucose and lipid metabolism	Phenolic	*In Vivo*	Male wistar albino rats	Increased the expression of *ADIPOQ* gene in serum; Inhibitd carbohydrate metabolism; Reduced blood glucose level.	Nwakulite et al., (2021)
Regulate glucose and lipid metabolism	Flavonoids	*In Vitro*	External digestion	Inhibited α-glucosidase activity by 54.41% and 69.17%.	(Hamed et al., 2021)
Regulate glucose and lipid metabolism	Phenolic and Polysaccharides	Clinical experiment	A double-blind, randomized, placebo-controlled, parallel group intervention study	Significant differences between groups in the rate of change of fasting blood glucose (FBG) and glycated hemoglobin (HbA1c).	Martínez et al., (2022)
Regulate glucose and lipid metabolism	Phenolic	*In Vivo*	Deutsche Denken Yoken mice	Increased in BAT cell density, Increase the experssion of BMP7 protein levels.	Ahmed et al., (2020)
Regulate glucose and lipid metabolism	Isoquercitrin, quercitrin	*In Vivo*	C57BL/6J mouse	Downregulated the expression of adipogenesis-associated proteins (PPARγ, C/EBPα and C/EBPβ), and FAS, Upregulated the lipolysis-associated protein, Increased the degree of phosphorylation of AMPKα and ACC. Reduced the serum levels of TC, LDL-C and AST, Inhibited the adipogenesis and promoting the lipolysis, and this process is related to AMPK activation.	Xie et al., (2018)
Antioxidant	Phenolic and Flavonoids	*In Vitro*	Elisa kit	Decreased the levels of DPPH, FRAP and ABTS activity.	Silva et al., (2014)
Antioxidant	Peroxidase	*In Vitro*	Human neuroblastoma cells	Increased cell viability and reduced free radicals, Decreased the lipid peroxidation; Enhanced glutathione levels and antioxidant enzyme activity; Prevented mitochondrial dysfunction by calcium levels and increasing mitochondrial membrane potential.	Burgos, Ur Vacas Sánchez, & Serranillos, (2021)
Antioxidant	Phenolic and Polysaccharides	*In Vitro*	RAW264.7	Decreased the level of DPPH and ABTS activities; inhibited *S.* aureus and *B.* subtilis; Inhibited NO production and *iNOS* mRNA levels in LPS-induced RAW 264.7 cells.	Guo, Sun, and Zhuang (2019)
Antibacterial	Phenolic and Phenolic acids	*In Vitro*	Pathogenic bacteria	Increased antimicrobial potential against various types of bacteria (Listeria monocytogenes, *B.*subtilis, *E.* coli, *S.* aureus, Bacillus coagulans, Pseudomonas fluorescens).	(Feitosa et al., 2020)
Antibacterial	Phenolic, Polysaccharides and Mg.	*In Vitro*	Pathogenic bacteria	Inhibited Staphylococcus aureus (6.3 mm) and Escherichia coli (6 mm).	(Maheshwaran et al., 2021)
Antibacterial	Phenolic and Polysaccharides	*In Vitro*	Pathogenic bacteria	Against the Staphylococcus aureus strain with zone of inhibition (ZOI) of 30 and 32 mm.	(Islam et al., 2021)
Antiviral	Phenolic	*In Vivo*	Chicks	Protection against Newcastle virus.	Lipipun et al., (2003)
Neurocognitive disorders	Phenolic and Phenolic acids	*In Vitro*	BV-2 microglial cultured cell	Maintained the cell viability; Modulated cholinergic and purinergic enzymes activity.	(Adefegha, Assmann Schetinger, Andrade, & Emanuelli, 2021)
Neurocognitive disorders	Phenolic and Phenolic acids	*In Vivo*	Alzheimer's mice	Decrease the escape latency; Increase the frequency of cross with time spent in the platform quadrant; Ameliorated oxido-infammatory stress, Restored the cholinergic transmission via acetylcholinesterase inhibition and maintains neuronal integrity in the mice brain.	Onasanwo et al. (2021)
Anticancer	Phenolic	*In Vitro*	PC-1 cells, MCF-7 cells and HTC116 cells	Inhibited MCF-7, HTC116 and AsPC-1 cells proliferation at IC50 of 100, 125 and 240 μg/mL after 72 h, Down-regulated of p53 protein expression in all cell lines and down-regulation the levels of c-myc in AsPC-1 cells.	Das et al., (2021)
Anticancer	Phenolic	*In Vivo*	Male CD-1 mice	Decreased the myeloperoxidase activity and lipid peroxidation; Increased the contents of butyrate and propionate; Decreased the level of MCP-1, IL-6, TNF-α; Induced differential expression of genes in colon tissue such as *IL- 2, IL-6, TNF, IL-1β*, and *INF-γ*.	Tiloke et al. (2013)
Anticancer	Phenolic	*In Vitro*	Human melanoma cell lines	Decreased mitochondrial membrane potential; Increased the ratio of Bax/Bcl-2; Activated Caspase-9 translocation.	Do et al., (2020)

(*continued on next page*)

Table 1 (*continued*)

Health benefits	Functional factors	*In Vitro* or *In Vivo*	Model	Molecular pathways	References
Anticancer	Phenolic and Polysaccharides	*In Vitro*	Bone marrow mesenchymal stem cells	Increased the cell viability and proliferation; Decreased the levels of ROS and MDA; Inecreased SOD and GSH-PX activity, the expression of p-Akt and Foxo1protein; Decreased cleaved caspase-3 levels.	(Li, Li, et al., 2022)
Improve constipation	Flavonoids	*In Vitro* *In Vivo*	Kunming mice RAW264.7 436 macrophages	Exhibited the potent anti-inflammatory and improve constipation activity; The IC_{50} values range from 29.3 ± 8.8 μM to 192.4 ± 7.8 μM in LPS-induced RAW264.7; Exhibited potent hypoglycemic activity on inhibite α-glucosidase.	(Jiang et al., 2021)
Improve constipation	Phenolic	*In Vivo*	C57BL/6J mouse	Adjusted the stool number, wet fecal weight and fecal water content to varying degrees to achieve laxative effects; Recovered the colon muscle thickness and mucus, Increase defecation volume and water content of feces.	Li, Li, et al. (2022)
Promoting intestinal health	Polysaccharides	*In Vivo*	ICR mice	Increased the immune and intestinal digestive ability; Increased the leveld of organ index, digestive enzymes; Decreased the levels of TNF-α and diamine oxidase; Increased short chain fatty acid production and lactic acid production.	Wang et al., (2019)
Protect liver	Phenolic	*In Vivo*	Male rabbits	Increased the levels of GSH and reduced the level of MDA; Protecedt the damage of the kidney.	Altaee and Fadheel (2021)
Protect liver	Thymol	*In Vivo*	$CoCl_2$-induced renal injury in rats	Increased the level of SOD and CAT; Reduced the levels of GSH, ROS, MDA, NO, TNF-α, MPO and CRP.	Mohamed, Yousse, Issa, Salam, and Ansary (2020)
Wound healing	Quercetin-O-glucoside Quercetin-O-malonyl glucoside	*In Vitro*	HaCaT cells	Increased the antioxidant, radical scavenging and antibacterial activities.	Pagano et al., (2020)
Calcium supplements	Calcium	*In Vitro* *In Vivo*	Caco-2 cells calcium-deficient rats	Increased the content of calcium (from 2.08% to 4.90%); Increased the level of calcium absorption in Caco-2 cells; In calcium-deficient rat calcium model, MOLF significantly increased the thickness of cortical bone, rat body weight, wet weight and femur bone density; Decreased the osteoclast cells number.	Dai et al., (2020)
Reproductive protection	Phenolic and Flavonoids	*In Vivo*	Male rats	Increased the courtship behavior, seminiferous tubule diameter, epithelium height, epithelium area and spermatogonia; Decreased the levels of DPPH radical, ABTS radical; Inhibited LPO and AGEs formation.	On et al. (2019)

of MOLLs (Mohamed, Yousse, et al., 2020; Xiao et al., 2020).

5.5. Anti-cancer activity

MOLLs contains a variety of anti-cancerous chemicals, such as alkaloids, phenols, glucosinolates, and isothiocyanate, which can be used as natural anti-cancer substitutes in food to inhibit the growth and proliferation of cancer cells. The aqueous extract of MOLLs has anti-proliferative and apoptosis-inducing effects on human tumour cells. This inhibitory effect is achieved by increasing oxidative stress, inducing apoptosis, and causing double stranded DNA breakage. The aqueous extract of MOLLs could inhibit the growth of HepG2 cells, reduce the level of ROS in cells, and prevent tumour growth. In addition, the aqueous extract of MOLLs inhibited the growth of human pancreatic cancer cells Panc-1, COLO-357, and P34 and reduced the expression of IκBα and p-IκBα proteins (Das et al., 2021; Tiloke, Phulukdaree, & Chuturgoon, 2013; Jung, 2014).

5.6. Antibacterial activity

MOLLs showed antibacterial activity. Reports indicated that the MICs of MOLL chloroform extract against *Pseudomonas aeruginosa*, *Escherichia coli*, and *Salmonella typhi* were 20 mg/mL, 10 mg/mL, and 10 mg/mL, respectively (Islam et al., 2021; Naqvi et al., 2021). Busani, Julius, and Voster (2012) found that the aqueous extract of MOLLs showed an inhibitory effect on the quorum sensing of *Purple pigment*. Some research measured the antibacterial activity of the acetone extract of MOLLs, the results showed that the extract had an inhibitory effect on *Escherichia coli*, *Staphylococcus aureus*, *Enterobacter cloacae*, *Micrococcus Christinella*, and *Proteus* at a concentration of 5 mg/mL. In addition, the antibacterial activity of the methanol extract of MOLLs was studied using the agar diffusion method. The results showed that the MOLLs extract had significant inhibitory activity against *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus*, *Dysentery bacillus*, and *Pneumonia bacillus*. Therefore, MOLLs can be used as an antibacterial agent in oral drugs against infections caused by the aforementioned bacteria (Bua-kaew et al., 2021; Sayed et al., 2022; Wang, Long, & Zhang, 2021).

5.7. Liver protection

Fakurazi, Hairuszah, and Nanthini (2008) used MOLLs extract to treat acetaminophen-induced liver injury in rats. The results showed that MOLLs extract improved the deterioration of rat liver cells and significantly reduced the levels of ALT, AST, and ALP, indicating that MOLLs could prevent acetaminophen-induced liver injury by regulating glutathione levels. Pari and Kumar (2002) evaluated the protective effect of MOLLs ethanol extract (200 mg/kg and 400 mg/kg) on liver injury induced by anti-tuberculosis drugs, such as isoniazid, rifampicin, and pyrazinamide, in rats. The results showed that the extract could repair the liver injury by regulating aspartate aminotransferase, alkaline phosphatase, alanine aminotransferase, and serum bilirubin levels. In addition, the levels of liver marker enzymes and lipid peroxidation products increased after feeding rats with aflatoxin B1, whereas the levels of liver marker enzymes and lipid peroxidation products decreased after a dose of aflatoxin B1 along with the MOLLs mixture. Altogether, MOLLs has a protective effect on aflatoxin B1-induced hepatotoxicity (Sharifudin et al., 2013; Suganthi & Parvatham, 2009).

5.8. Antiviral activity

Plants are widely used to treat viral infections. MOLLs can be used as a food supplement for virus disease drugs (Hala, Elmaaty, Farag, Mansou, & Elakkad, 2022). Moreover, MOLLs had inhibitory effects on thymidine kinase-deficient HSV-1 and phosphonoacetate-resistant HSV-1 viruses. Compared to 2% DMSO solution, MOLLs extract (750 mg/kg) could significantly delay the development of skin lesions, prolong the average survival time, and reduce the mortality rate of HSV-1 infected mice. Moreover, the MOLLs extracts had strong antiviral activity against Avian Influenza Virus Type H9 (AIV-H9) at lower concentrations (50 mg/mL) and could be used as safe antiviral agents (Imran et al., 2016; Lipipun et al., 2003).

5.9. Promoting intestinal health

Wang et al. (2019) investigated the effects of polysaccharides from MOLLs (MOs-2-a) on gut microbiota. ICR mice were gavage with MOs-2-a (10 mg/kg, 50 mg/kg) every day. Furthermore, the resulted indicated that immunological and intestinal digestive abilities of mice were significantly improved. Moreover, the villus height and mucosal thickness of the ileum were significantly increased, indicating that MOs-2-a could enhance the immune organ function. In addition, the proportions of *Lachnospiraceae*, *Helicobacteraceae*, *Deferribacteraceae*, *Lactobacillus*, *Helicobacter* and *Peptostreptococcaceae* showed a significant positive correlation. Moreover, some research found a novel

Table 2
Application of *Moringa oleifera* Lam. leaves for food and other development and their special benefits.

Application	Kinds	Special points	Benefits	References
Foods	Fermentednon-alcoholic pearl millet beverage	Lactic acid bacteria were significantly increased.	With beneficial anti-inflammatory and anti-pathogenic properties.	(Jideani et al., 2021)
	Instant porridge	Parameters of colour, texture, and taste, have no significant effect; The energy was 196 kcal/serving.	Rich in vitamins and protein; The product's nutritional value of baby porridge is in accordance with SNI 01-7111.1-2005.	Katmawanti and Mariroh (2021)
	Ice cream	Ice cream with MOLLs showed the highest total phenol and flavonoid contents, Decreased ABTS, DPPH radical scavenging ability, hydroxyl scavenging ability, ferric reducing antioxidant properties, and lowest glycemic index.	It has antioxidant properties, low glycemic index, and acceptable sensory attributes	(Ademosun.et al., 2021)
	Cookie	Rich in vitamins and protein.	Enhance nutritional values such as iron and protein compounds.	(Hedhilia.et al., 2021)
	Tea	Supplementing MOLLs tea with dark tea developed the best flavor.	Increased the levels of caffeine, theophylline, and gallic acid, whereas other key metabolite levels decreased after flowering.	(Zhang.et al., 2021)
	Cake	Protein significantly increased from 5.79% to 8.90%; Ash significantly increased from 1.25% to 1.66%; Fiber significantly increased from 2.70% to 6.98; Carbohydrate significantly increased from 53.0% to 60.88%. fat and moisture content decreased from 20.16% to 13.06% and 17.77%–13.54%, respectively.	Cake enriched nutritional quality and potentially contributed to the improvement of food and nutritional security of the vulnerable populations.	Roni et al. (2021)
	Bread	Bread samples became darker as the concentration of MOLLs was increased whilst nutrient levels increased.	Bread containing MOLLs can be used to contribute significantly to addressing malnutrition, with respect to protein deficiency.	Adetola et al. (2021)
	Noodle	The noodles formulated from 80% durum wheat flour and 20% of MOLLs, the ash, protein, fat, fiber, gross energy, phytate, and tannin content were increased by 39.39%, 10.86%, 153%, 42.2%, 3.43%, 39.83%, and 329.78%, respectively. However, moisture, total bacteria count, and yeast and mold count were decreased by 28.71%, 45.52%, and 55.93%, respectively.	Besides the good nutritional profile and antimicrobial capacity, it has antinutritional content and influences the sensory acceptability of products.	(Zula, Ayele, & Egigayhu.2021)
	Yoghurt	Mango flavored yogurt supplemented with 1% MOLLs has got the highest score in majority of the sensory attributes such as body and texture, flavor, tas.	Enhance nutritional values such as iron and protein compounds.	(Miriam.et al., 2022)
Agricultural	Prolong food shelf life	Improved the antioxidant activity of food, delay the oxidation process; Inhibited the growth of spoilage microorganisms in food, improve food storage stability	Exhibit higher or equivalent antioxidant activity, protect frozen meat products from changes in lipid stability and protein nutritional value.	Rodríguez et al. (2020)
	Plant-derived feed	MOLLs are widely used in poultry feed supplements because of it high nutritional value, rich protein content, low anti-nutritional factor content, and easy digestion and absorption by animals	Increased animal appetite, increased carcass yield, enhanced digestive enzyme secretion, stimulated immune response, and promoted antibacterial and antioxidant properties.	Selim et al. (2021)
	Biostimulants	It can effectively improve the qualitative and quantitative parameters of crop growth, yield and chemical composition, and promote the increase of beneficial microorganisms, which will actively improve the utilization of mineral nutrients by plants.	Increased the contents of vitamin C, folic acid, protein, carbohydrates, fat, fiber, ash and minerals (N, Na, K, Ca, Zn, Mg, Mn, Fe and P) in plants, and reduced the biotic stress effect.	Lungu et al. (2021)
Others	Diesel oil stabilizer	Significantly increase the oxidation stability of oils in biofuels, especially biodiesel, with higher yields and better energy performance than soybean crops	Prolonged controlled induction time and the storage	More et al. (2021)
	Hydrogel adsorbent	MOLLs combined with edible gelatin and other materials to prepare adsorbent	Low-cost biosorbents for removing harmful heavy metal	(Kerdsomboon. Chumsawat & Auesukaree.2020)
	Cosmetics	Sunscreens made from MOLLs alone or in combination with quercetin	Significant ultraviolet protection value	Łukaszewska et al. (2020)

polysaccharides (MOP) from MOLLs with M_W of 104,031 Da. MOP (0, 20, 40, 60 mg/kg) showed significantly effect of decreased the GLU, TC, BUN and MDA levels of C57BL/6 mice ($P < 0.05$), while the contents of SOD and CAT were significantly increased ($P < 0.05$). In addition, the crypt depth in the MOP group were significantly higher than that of control group, indicating that MOP may improve the absorption capacity of nutrients in the intestine. In addition, MOP increased the proportions of *Firmicutes*, *Bacteroides* and *Lachnospiracea*, some research found that *Lachnospiracea* is a beneficial bacterium in the gut that can produce short-chain fatty acids and antimicrobial peptides to resist pathogens. Conversely, MOP decreased the proportions of *Helicobacter*, *Oscillibacter* and *D Ruminiclostridium*, which may produce toxin factors that damage human health. Therefore, MOP could improve the abundance of beneficial bacteria and regulate the intestinal microecological balance (Jiang et al., 2021; Tian et al., 2021).

5.10. Others

Manaheji et al. (2011) found that MOLLs extract was effective in reducing pain in arthritic rats after the gavage of CFA. Other studies also found that MOLLs reversed the MCT-induced thickening of the medial layer by targeting vasodilation and antioxidant activity (Alia et al., 2021; Chen et al., 2012).

6. Application prospects of MOLLs

Moringa oleifera Lam. is a perennial tree with drought resistance and can be an important plant crop in arid and semi-arid areas. It has a long growth cycle and does not require much specific soil, irrigation, or climate conditions, making it easy to survive and grow (Jimenez et al., 2017; Khalila et al., 2020). The present applications of MOLLs are summarised in Table 2, and the current product in the market is shown in Fig. 5.

As a future food crop, *Moringa oleifera* Lam. can be grown on different types of land (especially sandy land) to enhance land usage and improve soil enrichment. MOLLs is the main part of *Moringa oleifera* Lam., widely used in food and agriculture because of its high nutritional value and presence of abundant active ingredients. MOLLs is often used in food as dietary supplements or natural additives (Ahmed et al., 2020; Maheshwaran et al., 2021). In 2018, China's Ministry of Agriculture and Rural Affairs included MOLLs in the Feed Ingredients Catalogue as a high-quality plant protein feed to enhance animal nutrition sources and improve the quality of agricultural products of animal origin.

6.1. Application of MOLLs as a dietary food supplement

With the improvement of human living standards, irrational dietary structure, and increasing consumer health consciousness, there has been an increasing interest in the use of natural plant-based food products with potential benefits. As discussed previously, MOLLs can regulate glucose and lipid metabolism, improve antioxidative capacity and digestion, and delay ageing. In addition, a large number of studies have shown that MOLLs is safe for consumption (Iqbala et al., 2021), therefore, the use of MOLLs as a dietary supplement in developing natural green and healthy foods may soon become a trend in food development industries.

(1) **MOLLs tea:** MOLLs tea is made from MOLLs, which is similar to the preparatory methods of green and black tea, and involves drying, fixing, and crushing the leaves. It can retain the colour and nutrients of MOLLs to the greatest extent. For example, the use of MOLLs as raw material for microbial co-fermentation in the production of brick tea significantly increased the content of alkaloids, amino acids, lipids, and organic acids in the tea (Li, Li, et al., 2022; Zhang et al., 2021). In addition, studies have shown that the mineral content of MOLLs tea is higher than that of other teas (green tea and herbal tea), implying that drinking MOLLs tea often can increase the dietary intake of minerals. Moreover, suitably processing MOLLs can effectively retain the contents of VC, VA, and the antioxidant substances of *Moringa oleifera* Lam. in MOLLs tea (Yasara et al., 2020).

(2) **MOLLs beverage:** MOLLs has been used to prepare different types of beverages. The non-alcoholic fermented millet beverage (PNAPMB) is prepared by *Leuconostoc mesenteroides.* Additionally, the MOLLs millet beverage (MSNAPMB) is prepared by adding 4% MOLLs powder to PNAPMB. The results showed that the contents of protein (from 1.62% to 2.17%), total sugar (from 5.06% to 5.31%), and carbohydrate (from 4.31% to 5.03%) were increased in MSNAPMB compared with those in PNAPMB (Jideani, Ratau, & Okudoh, 2021).

(3) **MOLLs dairy products:** Milk is mainly composed of proteins such as casein and whey, and the main allergens in milk are also

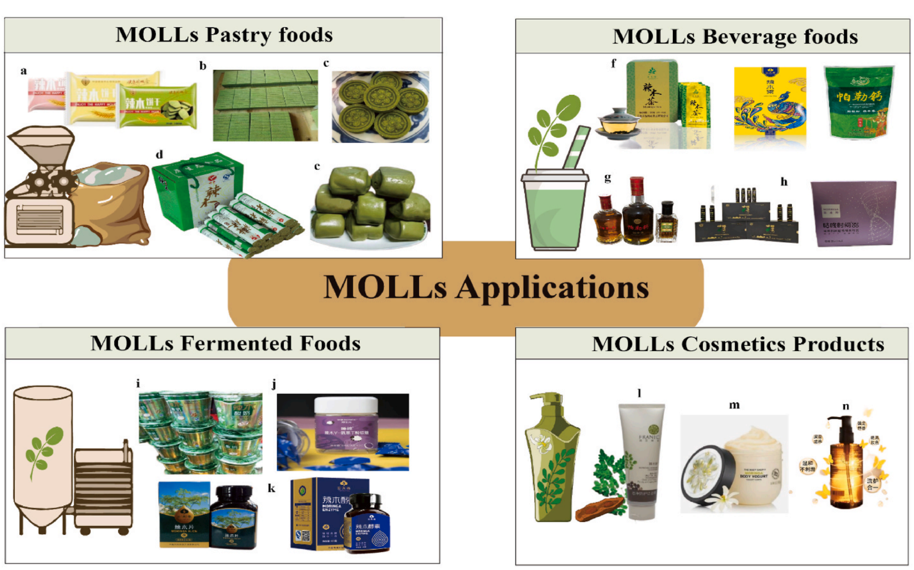

Fig. 5. Application of *Moringa oleifera* Lam. leaves. (A) Application of Pastry foods: (a) Cookies; (b) Cakes; (c) Moon cakes; (d) noodles; (e) Steamed breads. (B) Application of Beverage foods: (f) Tea; (g) Wine; (h) Compound beverage. (C) Application of fermented foods: (i) Yogurt; (j) Candies; (k) Fermented beverage. (D) Application of cosmetics products: (l) Cleansing cream; (m) Body lotion; (n) Makeup removing lotion.

distributed between these two components, for instance, whey protein, whey globulin, and kappa casein. These factors may cause allergic reactions. Thus, in the future, plant milk as an alternative to animal milk can be widely used by consumers. MOLLs is rich in protein, its calcium content is 1.2 times than that of milk, VA content is 1.6 times that of carrots, and potassium and iron content is higher than that of banana and spinach; therefore, MOLLs is a suitable substitute for milk. However, due to the low-fat content of MOLLs, additional fat content (sesame seeds) is needed to meet the human body's nutritional requirements (Waluyo et al., 2021). In addition, MOLLs can also be combined with mangoes and beneficial bacteria, such as *Lactobacilli,* to produce fermented milk. Fermentation further promotes protein degradation and absorption (Saeed, Ali, & Ramzan, 2021). Most importantly, fermented MOLLs supports the viability of lactic acid bacteria, and fermentation reduces the strange and spicy taste of MOLLs, thereby improving the organoleptic quality of regular yoghurt. Ice cream is popular in many countries; however, its sugar and fat content make it a high-calorie product that can easily induce diabetes. Because MOLLs contains natural sugars and antioxidative substances, it can be used as an ingredient in making ice cream. MOLLs ice creams had enhanced polyphenolic content (30.25 GAE/g) and improved ABTS and DPPH radical scavenging ability compared with traditional ice creams (4.13 GAE/g). Moreover, the results of *in vitro* experiments showed that the glycaemic index of the control group was the highest (61.24%), whereas the glycaemic index of the MOLLs ice cream-eating group was 27.14%. Hence, MOLLs dairy products may alleviate post-prandial high blood sugar levels and insulin response and reduce the risk of diabetes and obesity. However, due to the peculiar flavour of MOLLs, excessive addition leads to low acceptability of MOLLs-derived ice creams. Hence, in the future, improvements are needed in the processing of MOLLs to increase its acceptance (Ademosun, 2021).

(4) **MOLLs pastry:** It has become a modern food trend to add nutritional fortification to foods to increase the content of essential micro-nutrients and improve their nutritional quality. Cakes contain high carbohydrates and fats, while other nutrients, including proteins, minerals, and vitamins are fewer. Adding available, cheap, and nutritious edible plants to the cakes can enhance their health and nutritional safety. Many studies have shown that cake made with MOLLs powder is rich in protein, vitamins, and dietary fibre. It has high nutritional value and good taste. Contrarily, the fat content and total calorie intake also decreased (Roni, Sani, Munira, Wazed, & Siddiquee, 2021). Moreover, adding MOLLs to bread or biscuits can increase the content of minerals (especially iron) and folic acid, not exceeding the UL value of food, which can meet the dietary nutrition and safety needs of anaemic people, such as pregnant women (Adetola et al., 2021; Hedhilia et al., 2021; Loa, Hidayanty, Arifuddina, Ahmada, & Hadju, 2021). MOLLs can reduce the *in vitro* starch hydrolysis index (69.3%) of biscuits and improve starch gelatinisation properties. MOLLs biscuits contain fewer resistant starch and higher starch digestibility than ordinary protein cereals, thereby aiding processes such as digestion and absorption in the human body (Loa et al., 2021). Many studies also used MOLLs powder to make different types of noodles (fresh noodles, pasta). Such noodles are rich in nutrition and easy to preserve and meet the dietary needs of many people in different regions. However, because MOLLs contains various types of alkaloids with a peculiar bitter taste, it is necessary to improve the taste of MOLLs-derived cakes (Zula et al., 2021; Rocchetti et al., 2020; Zula et al., 2021).

(5) **MOLLs snacks:** Recently, MOLLs-derived snacks mixed with other plant materials have received extensive attention. For example, sweet and salty biscuits rich in calcium and protein were prepared by mixing MOLLs with coconut powder. Fermented snacks made from cassava flour, soybean flour, and horseradish leaf powder rich in VA provided a new strategy for improving the diet of people with nutritional deficiencies. Snacks are one of the fastest-growing segments of the food industry. However, providing nutrition through the inclusion of fruits and vegetables in puffed snacks is a relatively new concept. Importantly, MOLLs can be easily blended with oats to create extruded puffed snacks with a significantly improved nutrient profile compared to that of commercially available snacks. MOLLs-oat snacks have higher fibre and protein content than typical puffed products, providing a basis for processing vegetable puffed snacks. In addition, MOLLs has been mixed with rice foods to develop instant porridge as an alternative food to prevent malnutrition, and it can also be used as a supplementary food for feeding infants. As insufficient calcium intake affects the basic structure of bones, resulting in developmental retardation in children, MOLLs can be used to attain high calcium content in snacks. As a high-calcium instant porridge, it can meet the recommended daily dietary intake of calcium in most individuals (Katmawanti et al., 2021). Furthermore, cereal porridge mixed with MOLLs and corn is rich in phenols and iron, which can be used as a fortified supplementary food to eliminate malnutrition in specific populations and alleviate oxidative stress damage (Adetola et al., 2021; Ntila, Ndhlala, Mashela, Kolanisi, & Siwela, 2021). The utilisation and commercialisation of this plant in various snacks should be considered.

(6) **Others:** *Pteris multifida* can be used as a potential food to replace fresh laver; however, it is not of the same green shade as the laver. MOLLs powder (8%) was added to *Pteris multifida* to develop an artificial laver with physical properties similar to those of the commercial laver. The results showed that the physical properties of *Pteris multifida* after adding MOLLs were closest to those of commercial seaweed, indicating that MOLLs could be used as a natural colourant in foods while retaining food safety (Andriani, Wulansari, Dewi, & Husen, 2020; Deepa, Ramu, & Rajendrakumar, 2022). In addition, MOLLs can also be mixed with different vegetable oils to prepare microemulsion, strengthen oil stability, and improve the free radical scavenging ability of vegetable oils (Alibade et al., 2021).

Therefore, MOLLs can be added as a food supplement to alleviate malnutrition and increase dietary diversity. In addition, MOLLs is cheap, grows fast, and has a high yield; therefore, it can also be used as famine food.

6.2. Application of MOLLs as an additive to prolong food shelf life

In recent years, MOLLs is considered to be a natural plant additive to extend the shelf lives of food products. In the future, it can be used as a new plant food material to replace artificial additives and improve food safety. The main effects of adding MOLLs to improve the shelf life of food are: **(1)** as an antioxidant, it improves the antioxidative activity of food and delays oxidation; **(2)** as a preservative, it inhibits the growth of microorganisms that spoil the food, thereby prolonging the food storage.

Studies have shown that natural antioxidants from plants exhibit higher or equivalent antioxidant activity, protecting frozen meat products from changes in lipid stability and protein nutritional value. Multiple studies have found that antioxidative components can reduce the degree of microbial spoilage of meat products during storage and prevent meat products from erosion during cold storage. MOLLs contain different types of phenolic compounds, such as rutin, kaempferol, myricetin, quercetin, and isorhamnetin, which can exert antioxidant activity to delay the oxidation process based on their unique hydroxyl group structure (Abidin et al., 2022). The total phenolic and flavonoid contents of hamburgers made by adding MOLLs powder to the chicken were higher than those of the control. Moreover, different concentrations of MOLLs (0.5%–2%) could improve the free radical scavenging ability of chicken hamburgers (45%–85%). In addition, chicken burgers were stored for 0, 2, 4, and 6 d, and the pH value was evaluated. The results showed that the pH values of the chicken burger were stable during all storage periods (0, 2, 4, and 6 d). Unlike the control sample, the chicken burger made with MOLLs could be stored at 4 °C for up to six days (Alqurashi & Aldossary, 2021). Other studies have also suggested that chicken fillets and chicken sausages treated with MOLLs have a long storage period, which may be due to MOLLs being rich in antioxidative factors. This, in turn, improves the antioxidant capacity of foods and reduces the level of microbial activity to prolong the shelf life of products. Moreover, the addition of MOLLs to meat patties can enrich their protein content and enhance their quality characteristics. MOLLs can also effectively delay lipid oxidation and improve the shelf stability of formulated meat products (Mashau, Munandi, & Ramashia, 2021; Khomola, Ramatsetse, Ramashia, & Mashau, 2021; Lungu, Afolayan, Thomas, & Idamokoro, 2021; Mashau, Ramatsetse, & Ramashia, 2021).

MOLLs is also relevant in oils and fats; the induction time required for complete oxidation at 120 °C by mixing MOLLs powder and coconut oil was 36.42 h, which was higher than the control (30.1 h) group and slightly lower than that of the chemical antioxidants, with the actual induction times of 36.53 h and 37.01 h for BHA and BHQ, respectively. These results indicate that MOLLs may enhance the antioxidant activity of oils. When oils containing MOLLs were stored with controls under different conditions (ambient conditions at 30 °C for three months or accelerated heating at 60 °C for 15 days), the PV of the blended oils increased in both cases. The control group had the highest PV of 54 meq/kg after storage at accelerated temperature conditions, and the PV was 23.4 meq/kg upon the addition of MOLLs, indicating that MOLLs can effectively prevent oxidation of the oils. Therefore, MOLLs can be used as a natural antioxidant and as a sustainable alternative to prevent the oxidation of edible oils during long-term storage and extend their shelf lives (More, Gogate, & Waghmare, 2021).

The application of MOLLs in preservation can also be expanded to packaging films. The packaging films do not contain synthetic preservatives but still have good preservation characteristics and delay food browning and spoilage due to microbial growth (George, Oyenihi, Rautenbach, & Bilana, 2021). MOLLs is rich in phenols, polysaccharides, and proteins, and hence, can exhibit better antioxidant and film properties. The application of an aqueous extract of MOLLs on the surface of sliced apples could significantly alleviate the enzymatic browning process and prolong the shelf lives of apples. In addition, MOLLs can also be combined with other foods to make edible films. For instance, papaya and MOLLs have been used as raw materials to make edible films with antioxidant preservation functions. The resultant film was applied to the sliced fruit, which could significantly alleviate the browning reaction of the fruit and inhibit the growth of spoilage microorganisms. Some researchers used MOLLs to make fish-skin-derived gelatin films, which have the ability against *Listeria monocytogenes*. The film was applied to Haoda cheese to increase its antioxidant activity. Therefore, as a new raw food material, MOLLs is good for food matrix packaging materials to prolong the shelf lives of easily oxidisable foods. Moreover, MOLLs can be combined with other antioxidative materials to improve the anti-corrosion ability. Additionally, MOLLs extract has been added to chitosan/polycaprolactone films to improve their antibacterial characteristics. An edible film of MOLLs, chitosan, and carboxymethyl cellulose, used to preserve avocadoes, reduced their respiration rate and delayed their ripening (Rodríguez, Sibaja, Espitia, and Otoni (2020); Matu et al., 2021).

6.3. Application of MOLLs in agriculture

In recent years, plant-derived food additives have been gradually used in animal nutrition due to their beneficial ingredients. These active factors increase animal appetite, increase carcass yield, enhance digestive enzyme secretion, stimulate immune response, and promote antibacterial and antioxidant properties.

MOLLs is widely used in poultry feed supplements because of its high nutritional value, rich protein content, low anti-nutritional factor content, and easy digestion and absorption by animals. Studies have shown that MOLLs benefits the growth of rabbits and improves the nutritional value of meat (Mashau, Munandi, & Ramashia, 2021; Khomola et al., 2021; Lungu et al., 2021). Adding MOLLs (1%–30%) could increase the spleen index of rabbits, length of the digestive tract, absorption area, and nutrient utilization rate of the small intestine. Consequently, MOLLs does not affect the renal function and ketone body metabolism of rabbits. Moyo, Oyedemi, Masika, & Muchenje, 2012 reported that PUFA in MOLLs accounted for about 57% of the total FA, of which α-linolenic acid accounted for 44.57%. Dietary addition of MOLLs can significantly change the fatty acid composition of meat, reduce the content of SFA in meat, and increase the content of PUFA, thereby reducing fatty acid oxidation and fat deposition. Moreover, adding MOLLs to broiler feed can increase the content of antioxidant enzymes in chicken, scavenge free radicals, and improve the oxidative stability of chicken during storage. MOLLs can also improve the embryo survival and growth rate of pregnant animals and protect them from oxidative stress. In addition, MOLLs can improve the quality of animal-derived food. Adding MOLLs to the diet can significantly improve the egg laying rate, egg production, eggshell quality, and Haugh unit of hens, along with retaining the freshness of eggs. MOLLs can also positive affect the lactation of cows and goats (Ahmed, Wareth, & Lohakare, 2021; Selim, Seleiman, Hassan, Saleh, & Mousa, 2021; Afzal, Hussain, & Hameed, 2021; Khan et al., 2021).

Recently, bio-stimulants have attracted attention as natural environmental protection fertilizers. They can effectively improve the qualitative and quantitative parameters of crop growth, yield, and chemical composition to further promote the growth of beneficial microorganisms. The addition of MOLLs (2%, 4%, 6%, 8%, and 10%) significantly increased the contents of VC, folic acid, protein, carbohydrates, fat, fibre, ash, and minerals (Na, K, Ca, Zn, Mg, Mn, Fe, and P) in mushrooms and reduced the effect of biotic stress (Sardar et al., 2021). MOLLs also plays a role in promoting the growth of soybeans and tomatoes. Additionally, treating ornamental plants with MOLLs prompts flowering and sustainable yield growth while replacing the traditional plant growth regulators. A recent study showed that soaking bulbs and geraniums in a solution containing MOLLs extracts before planting can improve their morphology, physiology, and yield. The application of 4% MOLLs could delay the senescence post-harvest of lanceolate by 10 days. These results can be attributed to the presence of antioxidant components, essential nutrients, and growth factors in MOLLs. Therefore, it seems apt to use MOLLs as a source of natural plant hormones in countries producing high-quality flowers and plant appendages (Mutar et al., 2021; Mutar et al., 2021; Sabir et al., 2022; Teclegeorgisha et al., 2021).

6.4. Other applications

Many studies have found that MOLLs significantly increase the oxidation stability of oils in biofuels (Ngom, Ngom, Sackey, & Khamlich, 2020), especially biodiesel, with higher yields and better energy performance than soybean crops. MOLLs was used as an antioxidant resource in soybean oil-derived biodiesel. Research indicated that MOLLs extract (0.5–2.0 g/L) prolonged the oil storage time, and the product had no oxidation loss at 25 °C for 6.5 months. The antioxidant efficiency increased from 265% to 718% (Mohamed et al., 2022). Moreover, some researchers compared the effects of seeds (S-MO) and leaves of *Moringa oleifera* Lam (L-MO) as low-cost biosorbents for chelating harmful heavy metal ions, such as Pb(II), Cd(II), Co(II), and Ni(II), in water. They found that the metal binding rate of L-MO and S-MO biosorbents was very fast, and the equilibrium was achieved within 60 min; however, the adsorption capacity of Pb(II), Cd(II), Co(II), and Ni(II) was higher in the L-MO group than in the S-MO group (Kerdsomboon, Chumsawat, & Auesukaree, 2020).

MOLLs can also be combined with edible gelatin and other materials to prepare a new hydrogel adsorbent that can directly adsorb cationic pollutants in dyes (Benettayeba & Haddou, 2021; Do et al., 2021). Recent studies have shown that MOLLs is also used in cosmetics. For instance, sunscreens made from MOLLs alone or in combination with quercetin have significant ultraviolet protection value and can resist UVB radiation at low concentrations (2%–4%). Clinical application experiments show that MOLLs sunscreens do not cause abnormal skin reactions (Łukaszewska et al., 2020).

7. Opportunities and challenges of MOLLs

As new raw food material, more and more researchers are focusing on MOLLs. MOLLs contains a variety of bioactive compounds, such as phenolic acids, tannins, steroids, saponins, alkaloids, flavonoids, glucosinolates, and glycosides. These bioactive compounds showed anti-inflammatory, anti-tumour, antibacterial, antioxidant, and anti-diabetic activities. As a promising economic Chinese herbal medicine and functional food, MOLLs is widely used in the food and pharmaceutical industries. This review summarised the research progress on the nutritional components, chemical substances, and functional activities of MOLLs and discussed the practical application of MOLLs as a new raw food material in food and agricultural industries. The future developments and trends of MOLLs are shown in Fig. 6.

However, some key concerns regarding MOLLs still need to be investigated through further research: **(1)** As an edible plant, the bitter and astringent taste of MOLLs limits its usage. Therefore, future research must focus on improving the taste to increase consumer acceptance of MOLLs and continuously developing MOLLs-derived functional foods; **(2)** MOLLs contains different anti-nutrients, which interfere with absorption and utilisation in the human body. Therefore, it is urgent to eliminate these effects and carry out safety and toxicology studies of MOLLs constituent anti-nutrients before developing functional foods; **(3)** Based on the rich functional factors constituting MOLLs, the separation of functional compounds, structural identification, discovery of new structural compounds, active function research, and structure-activity relationship research need to be explored. Furthermore,

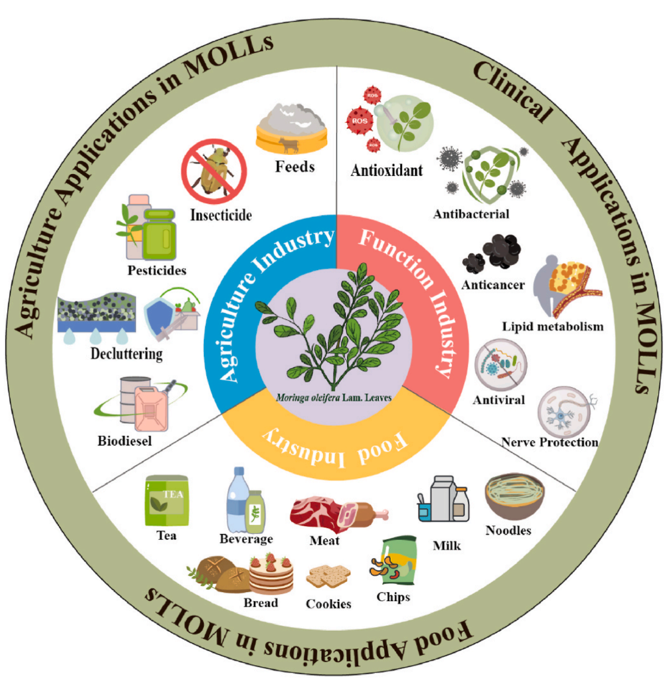

Fig. 6. Future development and applications of *Moringa oleifera* Lam. leaves.

establishing a functional factor database of MOLLs to provide important data for sustainable development is essential; **(4)** MOLLs are rich in factors that contribute to various biological activities; however, most studies focus on the effects of basic indicators on cellular and animal health. Hence, clinical studies examining the changes of these indicators to fully reflect the mechanism of MOLLs' health benefits are needed in the future; **(5)** Although the scale of MOLLs industries continues to develop, comprehensive studies are needed to elucidate the distinct characteristics, nutrient composition, and functional factors contained in the basic structure of the many varieties of MOLLs from different regions; **(6)** The agricultural application of MOLLs lacks relevant standards (national, industrial, group, and enterprise standards). In the future, relevant standards can be formulated according to varying developmental needs; **(7)** As a new raw food material, MOLLs is a new developing industry. The research on processing technical regulations and quality evaluation standards of MOLLs and related products needs to be carried out; **(8)** MOLLs products lack application technology and equipment. In addition, the degree of mechanisation (agricultural planting, harvesting, cleaning, drying, and storage) and industrialisation (drying, milling, grading, and product processing) is still very low. In the future, MOLLs as new raw food material may be the key to the development of emerging health industries; thus, forming an integrated industrial and engineering chain of MOLLs processing industries is essential. In addition, the deep processing of MOLLs products lacks high value, which may affect the development of MOLLs processing industries.

In recent years, with the continuous improvement in people's standard of living and increasing health awareness, the need to explore further extraction technologies, discover biological homeostasis and delivery options, and personalise food nutrition requirements to improve the comprehensive use of MOLLs is vital.

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Declaration of competing interest

The authors declare that there are no conflicts of interest.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2023.05.013.

Abbreviations

MOLLs	*Moringa oleifera* Lam. leaves
FAO/WHO	Food and Agriculture Organization of the United Nations/ World Health Organization
VA	Vitamins A
VB	Vitamins B
VC	Vitamins C
VE	Vitamins E
Ca	Calcium
Mg	Magnesium
P	Phosphorus
K	Potassium
Na	Sodium
S	Sulfur
Zn	Zinc;
Cu	Copper
Fe	Iron
Mn	Manganese
Se	Selenium
GAE	Gallic acid equivalent
PPARγ	Lipogenesis associated protein
ABTS	2,2′-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)
DPPH	2.2-diphenyl-picryl-hydrazyl radical
GC-MS	Gas chromatography coupled to mass spectrometry
HPLC	High performance liquid chromatography
MS	Mass spectrometry
NMR	Nuclear magnetic resonance
TOF	Time of flight
CCl_4	Carbon tetrachloride;
GC	Gas chromatography
MTT	3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide;
Caspase-3	Cysteinyl aspartate specific proteinase 3
Caspase-9	Cysteinyl aspartate specific proteinase 9
HDL:	High-density Lipoprotein
IL-1β	Interleukin 1β
iNOS	Inducible nitric oxide synthase
ALT	Alanine aminotransferase
AST	Aspartate aminotransferase
ALP	Alkaline phosphatase
LDL:	Low-density Lipoprotein
LPS	Lipopolysaccharide;
NO	Nitric Oxide;
TC	Total Cholesterol
TG	Triglycerides
PV	Peroxide values
C/EBPα	CCAAT/enhancer binding proteins α
C/EBPβ	CCAAT/enhancer binding proteins β
FAS	Fatty acid synthase
LDL-C:	Low density lipoprotein cholesterol
AST	Aspartate aminotransferase
HepG2	Human hepatocellular carcinoma cell line;
TNF-α:	Tumor necrosis factor-α;
IL-2	Interleukin-2
NF-κB	Nuclear factor kappa-B;
IL-6	Interleukin- 6
IL-10	Interleukin-10
ROS	Reactive oxygen species
MDA	Malondialdehyde
GSH	Glutathione peroxidase
Bax	Bcl2-associated X protein
Bcl-2	B-cell lymphoma
NK	Natural killer cell
CFA	Complete Freund's adjuvant

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