Phytochem Rev
https://doi.org/10.1007/s11101-024-09927-x

Environmental, industrial, and health benefits of *Moringa oleifera*

Harshika Mahaveerchand · Abdul Ajees Abdul Salam

Received: 29 September 2023 / Accepted: 9 February 2024

Abstract The rise of air, water, and soil pollution poses a significant threat to global health, leading to widespread disease and premature mortality. Soil health is vital, ensuring the production of safe food, but it is compromised by pollutants such as heavy metals, pesticides, plastics, and excessive fertilization, resulting in the depletion of beneficial microorganisms and subsequently groundwater contamination. Water bodies are polluted due to contamination from industrial effluents, domestic wastewater, agricultural runoff, and oil spillage, further intensifying environmental pollution. On the other hand, atmospheric pollution, characterized by high emissions of gases, volatile compounds, greenhouse gases, not only impacts the climate but also poses serious risks to human health, leading to respiratory diseases, cardiovascular issues, and increased cancer risks. Thus, the strategic utilization of traditional plants emerges as a potent tool for environmental restoration and improving human health. The plants possess natural filtering capabilities, absorbing pollutants from air, soil, and water, thus mitigating their adverse effects. Through phytoremediation, plants can be actively used to extract and remove contaminants, contributing to detoxification and improving water and soil quality. Additionally, plants offer various health benefits. *Moringa oleifera* or the drumstick plant belonging to the *Moringaceae* family is one such indigenous plant with wide applications, that can be grown in extreme arid conditions. Since ancient times, this plant has been used for treating skin infections, anaemia, and blood impurities. This plant thrives in diverse climates addressing over 300 different aliments. Rich in phytochemicals and bioactive compounds, *M. oleifera* serve as a superfood, offering high nutritional values and exhibiting potential for drug development with fewer side effects. Extensive research has elucidated the diverse properties and applications of *M. oleifera*, however, in-depth research is needed to identify bioactive molecules, phytochemicals, and protein compounds involved, which will aid in understanding of the mechanisms of action of the plant's diverse functions. Although studies have reported several of individual *M. oleifera* attributes, there is no comprehensive study available addressing its diverse applications. This review covers the findings of past three decades and provides a detailed outline of *M. oleifera* plant and its various parts, its applications in environmental, industrial, food and health aspects documented to date.

Keywords *Moringa oleifera* · Anti-cancer · Anti-fungal · Anti-parasitic · Anti-viral · Anti-microbial · Bioactive compounds · Biofuel · Coagulation · Computational studies · Neuroprotective effect · Nutritive food ingredient · Phytochemicals · 3D

H. Mahaveerchand · A. A. Abdul Salam (✉)
Department of Atomic and Molecular Physics, Manipal Academy of Higher Education, Manipal, Karnataka 576 104, India
e-mail: abdul.ajees@manipal.edu

protein structural studies · Sustainable agriculture · Water purification · Wound healing

Abbreviations

ABA	Abscisic acid
ACE	Angiotensin- converting enzyme
AChE	Acetylcholinesterase
AEP	Asparaginyl endopeptidase
APAP	Acetaminophen
APP/PS1	Amyloid precursor protein and Human presenilin 1
BACE1	Beta-site amyloid precursor protein cleaving enzyme 1
Bax	BCL-2-asscoaited X protein
BChE	Butyrylcholinesterase
BCL	Burkholderia cepacia Lipase
BCL-2	B-cell lymphoma 2
BMP2	Bone morphogenetic protein 2
CC_{50}	50% Cytotoxicity concentration
CD4 cells	Clusters of differentiation
CREA	Creatinine
CREB	CAMP response element-binding protein
CRL	Candida Rugosa Lipase
CTX-1	Cytotoxin 1
Dilp 2	Drosophila insulin-like peptide
DNA	Deoxyribose nucleic acid
DPD	Deoxypyridinoline
DPPH	“2,2-Diphenyl-1-picrylhydrazyl
EGFR	Epidermal Growth Factor
ERK1/2	Extracellular signal related kinases
FRAP	Fluroscence recovery after photobleaching
GABA	Gamma-aminobutyric acid
HCGC	Human cerebellar granule cells
HIV	Human immunodeficiency syndrome
Hsp 70	Heat shock proteins-70 kilodalton
IAA	Indole acetic acid
IC_{50}	Half minimal inhibitory concentration
IgE	Immunoglobulin E
IgG	Immunoglobulin G
IL-1	Interleukin-1
JNK	c- Jun N-terminal kinase
LPO	Lipid peroxidase
KCL	Potassium Chloride
KOH	Potassium Hydroxide
MAFLD	Metabolic-Associated Fatty Liver Disease
MAPK-8	Mitogen-Activated Protein Kinase 8
MEK/ERK	Mitogen-activated protein Kinase kinase/ Extracellular signal-regulated kinase
MIC	Minimum Inhibitory Concentration
MITC	Methyl isothiocyanate
MOCP	*Moringa oleifera* Coagulation protein
MPTP	1-Methyl-4-phenyl-1,2,3,6-tetrahydropyridine
MTBA	Moringa oleifera tree-based agroforestry
MyD88	Myeloid Differentiation Primary Response 88
NAPQI	N-acetyl-p-ben zoquinoneimine
NASH	Non-alcoholic steatohepatitis
NF-κB	Nuclear factor kappa B
NMDA	N-methyl-d-aspartate
NPK	Nitrogen, phosphorus, potassium
Nrf2	The nuclear factor erythroid 2-related factor 2
Nsp9	Non-structural protein 9
PEA15	Proliferation And Apoptosis Adaptor Protein 15
PGC-1	Peroxisome-activated receptor-gamma coactivator-1 alpha
PPL	Porcine Pancreas Lipase
PSD 95/ SAP90	Synapse-associated protein 90
RMSD	Root mean square deviation
RUNX2	Runt-related transcription factor 2
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SDS-PAGE	Sodium dodecyl Sulfate polyacrylamide gel electrophoresis
SOD	Superoxide dismutase
TGF-β	Transforming Growth Factor – beta
TH	T-helper cells
TJ	Tight Junction proteins
TLR4	Toll-like receptor 4
TNF	Tumour necrosis factor
TNF-α	Tumour necrosis factor alpha
TNF-β	Tumour necrosis factor beta
IL-6	Interleukin 6
IL-1β	Interleukin 1 beta
TRAF-4	Tumour Necrosis Factor Receptor-Associated Factor 4
TRAF-6	Tumour Necrosis Factor Receptor-Associated Factor 6

Introduction

Air, water, and soil pollution stand as major threat to global health, constituting the leading cause of disease and premature death worldwide. Health of the soil is crucial to produce safe, healthy, and sufficient food. Soil pollution is driven by factors such as heavy metals, pesticides, plastic wastes, and overfertilization, resulting in the depletion of numerous beneficial microorganisms. This decline in soil health leads to the leaching of toxic pollutants, ultimately contaminating groundwater (Münzel et al. 2023). Water bodies face contamination from industrial effluents, domestic wastewater, and agricultural runoff, exacerbating environmental pollution. Additionally, the extensive use of crude oil products contributes to soil and water contamination through oil spillage. The atmosphere on another hand, suffers due to high emission of gases, volatile organic compounds, greenhouse gases and particulate matter. These atmospheric contaminants not only affect the climate but also poses serious risks to health and wellbeing of present and future generation (Rather et al. 2023). For example, exposure to polluted air is linked to rise in respiratory diseases, cardiovascular issues, and increased risks of various types of cancer. In total, the interplay of air, water, and soil pollution creates a complex environmental challenge with major consequences for global health, impacting both human and animal life.

In the face of these challenges, the strategic utilization of plants can emerge as a powerful tool in environmental restoration and human health. Plants act as natural filters by absorbing pollutants from air, soil, and water and thus can help in mitigating the impacts of various contaminants. Through processes like phytoremediation, certain plants can actively extract and remove pollutants, helping in detoxification and improving quality of water and soil. Additionally, the initiation of green infrastructure by planting trees can contribute to enhanced air quality by absorbing harmful pollutants and providing oxygen (Khandare and Govindwar 2015). Plants also have various beneficial health properties, and since ancient times various traditional plants were utilized as supplements for curing diseases and boosting immune system. One such extensively known and employed medicinal plant is the "*Moringa oleifera* or *M. oleifera*" also known as the drumstick plant. The *Moringa* genus comprises 14 species belonging to the *Moringaceae* family, commonly known as the horseradish tree. Among these, *M. oleifera* is most widely recognized species. This plant has a history spanning over 2000 years, with its application in health and environmental benefits is documented in 150 BC Indian ayurvedic books. In ancient times, this plant was utilized to treat various problems and issues, including skin infection, anaemia, breathing problems, blood impurities as well as respiratory diseases like bronchitis and cholera (Razis et al. 2014). *M. oleifera* plant is native to India, nevertheless, it has been cultivated in all tropical and subtropical regions such as Central America, North and the South Philippines, Cambodia, Caribbean Islands, and Africa. It grows and reaches 15 m in height, with a diameter of 20–40 cm at chest height (Saa et al. 2019a, b). It is reasonable explanation that this plant is referred to as the "Miracle tree" and "Mother's best friend" for numerous reasons given its potential to heal and cure over 300 different types of ailments. *M. oleifera* is known to thrive in extreme arid conditions, and all parts of the plant, including the leaf, seed, root, bark, flower, seedpod, gum, oil, and fruits, are utilized due to their various environmental applications and multiple health benefits both to humans and animals (Pop et al. 2022). Globally recognized as a 'superfood' due to its high nutritional content, *M. oleifera* is rich in phytochemicals and bioactive organic substances. These compounds are considered suitable alternatives for drug development, offering fewer side effects, and showing synergistic effects. The seeds of *M. oleifera* contain cellotriose, cellotetraose, moringin, sucrose, flavonoid and 2-decenal. Leaves of this plant contain kaempferol, caffeic acid, allose, chlorogenic acid, myricetin, sucrose and niazirin. The bark is a source of eugenol, palmitic acid, 2-chloropionic acid and dibutyl phthalate. Flowers and pulp contain tannin, phenol, saponins and flavonoids. Roots comprise morigin, sucrose, cellotriose, glucotropaelin, methyl 4-caffeoylquinate, and glucotropaelin. *M. oleifera* leaves are particularly rich in vitamins A and B, abundant in β-carotene, and feature provitamin A carotenoids. It contains all the essential amino acids, making it a valuable source of protein (Azlan et al. 2022). The *M. oleifera* seed contain high oil content of approximately 30–40% with 76% polyunsaturated fatty acids, aiding in lowering blood cholesterol levels. Notably, the leaves and seeds of *M. oleifera* are rich in protein, iron, calcium, ascorbic acid, vitamin A, and various antioxidant components, including carotenoids, flavonoids, vitamin E, and phenolics (Abd El-Hack et al. 2018).

The literature contains extensive research documenting the properties and activities exhibited by *M. oleifera*. Research covering its environmental, health, medicinal, phytochemistry, food supplementary, and industrial applications have been thoroughly studied and reported. The primary objective of this review was to establish a structured knowledge base, serving as a reference for future studies in the field. In this review, the author has conducted a comprehensive search, compiling information from animal studies, clinical experiments, and alternative medical investigations, and presents the findings published in the timeframe spanning from 1981 to January 2024. The mechanisms behind each property, including the proteins, phytochemicals, or bioactive compounds responsible, are also discussed in depth. Drawing upon scientific evidence accumulated over the last three centuries, as documented in the literature, this review gathers and emphasizes environmental, industrial, food applications and structural studies pertaining to the *M. oleifera* plant. Remarkably, *M. oleifera* stands out as one of the extraordinary plants, offering numerous applications that proved advantageous for humans, animals, as well as fostering environmental benefits. The organization of this review was structured to provide a thorough examination of plant's diverse applications, categorically addressing its relevance in different domains. By offering a comprehensive review of *M. oleifera*'s potential, this review aimed to be a crucial resource for researchers embarking on further investigations. It would not only enhance the understanding of *M. oleifera* plant but also contribute significantly to the advancement of research endeavours within this scientific domain.

Methods

The data acquisition for this manuscript involved the systematic retrieval of information from electronic databases, specifically Google Scholar (https://scholar.google.com/), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Scopus (https://www.scopus.com/), and ResearchGate (https://www.researchgate.net). Furthermore, the Protein Data Bank (PDB) database (http://www.rcsb.org/) was referenced for obtaining protein structural data pertinent to the *Moringa oleifera* plant and chemaxon-Marvinsketch (https://chemaxon.com/marvin) for obtaining two-dimensional structure details of phytochemicals/bioactive compounds. The search queries utilized in these databases incorporated keywords such as *'Moringa oleifera*,' 'environmental benefits of *M. oleifera*,' 'health benefits of *M. oleifera*,' 'industrial applications of *M. oleifera*,' 'structural and computational studies of *M. oleifera*,' 'proteins and phytochemicals in *M. oleifera*,' 'phytoremediation using *M. oleifera*,' and *'M. oleifera* in disease management and treatment.' Notably, the search encompassed articles published in the timeframe spanning from 1981 to January 2024, focusing on the *M. oleifera* plant (Figs. 1 and 2).

Environmental and industrial benefits from *M. oleifera*

The study of environmental and industrial benefits derived from *M. oleifera* is of paramount importance due to its multifaceted contributions to sustainable practices and industrial applications. *M. oleifera* exhibits remarkable environmental benefits, including its potential for soil remediation through phytoremediation, water purification capabilities, and carbon reduction. Understanding these environmental aspects can lead to the development of eco-friendly solutions for mitigating environmental challenges. Moreover, *M. oleifera* holds significant promise in various industrial sectors, such as agriculture, food, and cosmetics, owing to its rich nutritional content and versatile applications. Investigating its industrial potential can pave the way for the development of innovative products and processes, contributing to economic growth and fostering sustainable industrial practices. Therefore, a comprehensive study of the environmental and industrial benefits of *M. oleifera* is crucial for advancing our knowledge, promoting sustainability, and harnessing the full potential of this plant for the betterment of both the environment and various industries. This section covers the application of this plant in water treatment, improving crop and plant growth, alternative for energy resource in

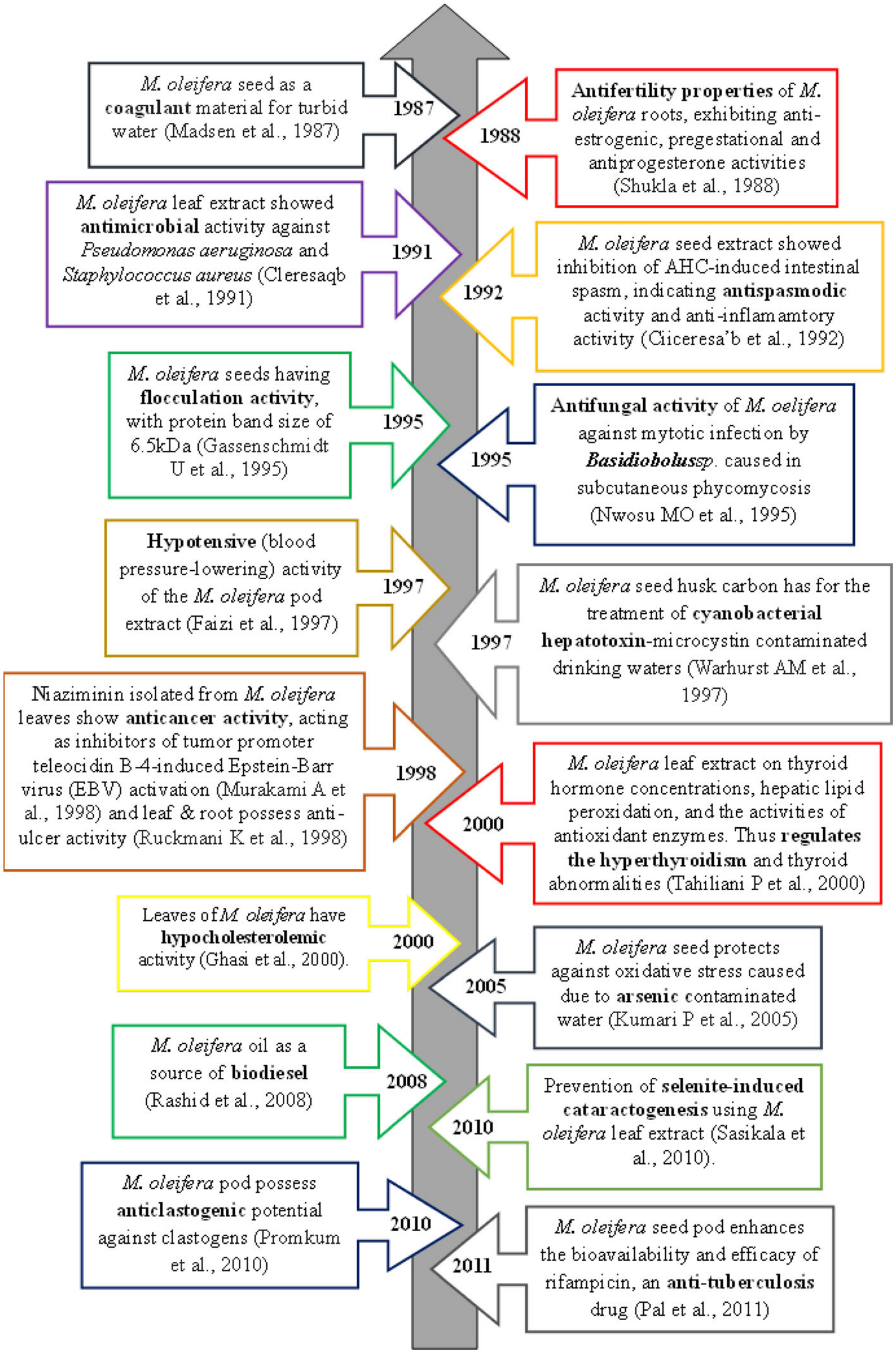


Fig. 1 Chronology showcasing the significant discoveries and identifications of *M. oleifera* over the past three decades

industries and its beneficial nutritive ingredient in food source.

Coagulation properties for water treatment

The generation of contaminated wastewater, primarily attributed to industrial activities, poses environmental challenges due to the presence of various toxic

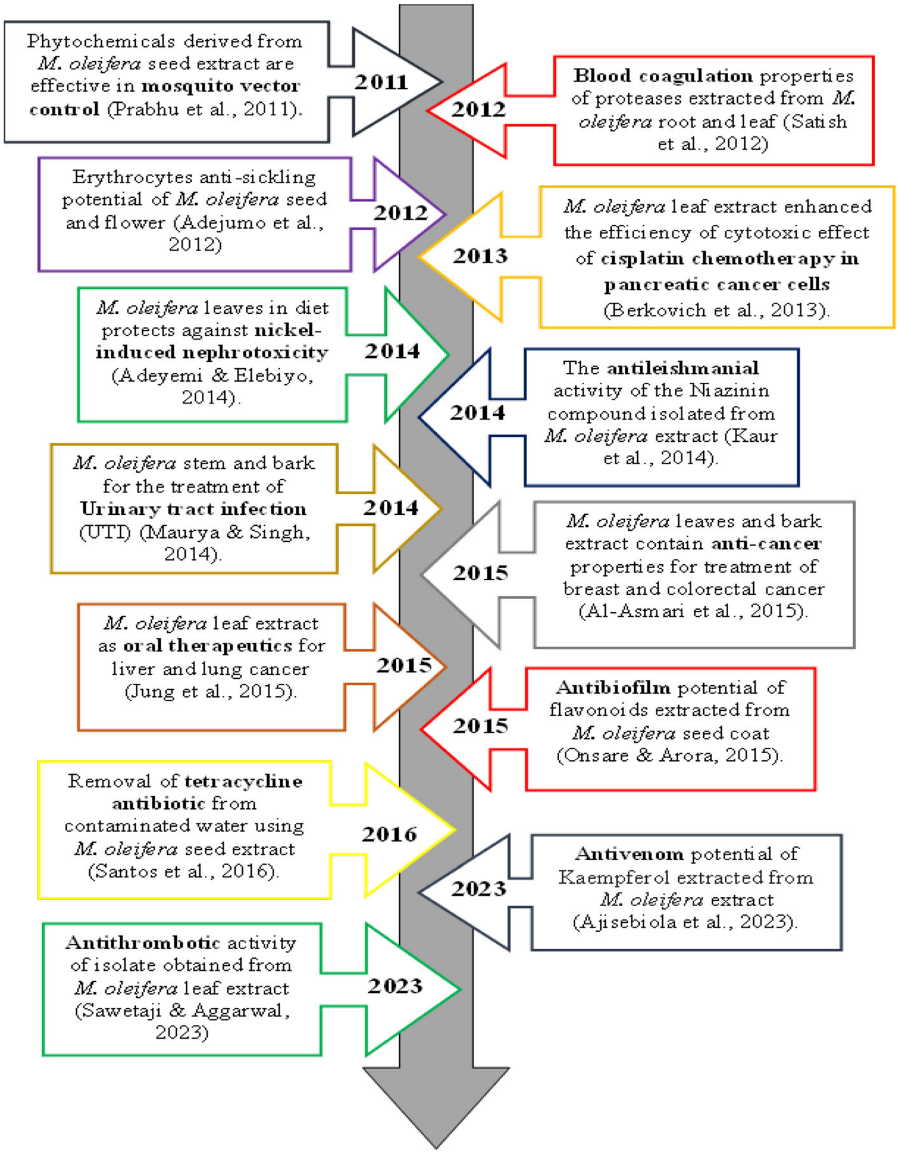


Fig. 1 continued

substances. An integral aspect of water treatment involves the removal of turbidity, a process for which numerous inorganic, natural, and synthetic organic coagulants are employed. Alum, being the most widely utilized coagulant, stands out for its high efficiency, ready availability, and ease of use. However, concerns have emerged regarding potential health risks associated with the extensive use of alum, including links to Alzheimer's disease and related illnesses (Gauthier et al. 2000). In response to these concerns, natural coagulants have been proposed as a viable alternative, playing a pivotal role in the water treatment process (Madrona et al. 2010). Coagulants derived from natural sources have demonstrated promising outcomes, exhibiting efficient coagulation across diverse pH levels and temperatures while generating lesser volumes of sludge (Freitas et al. 2018). For instance, a dosage of 0.15 ml/L of *M. oleifera* seed achieved an impressive 90% turbidity removal within a pH range of 6.3 to 6.5 (Nhut et al. 2021). Furthermore, the application of 0.8 g/L of *M. oleifera* seed extract in acidic wastewater resulted in

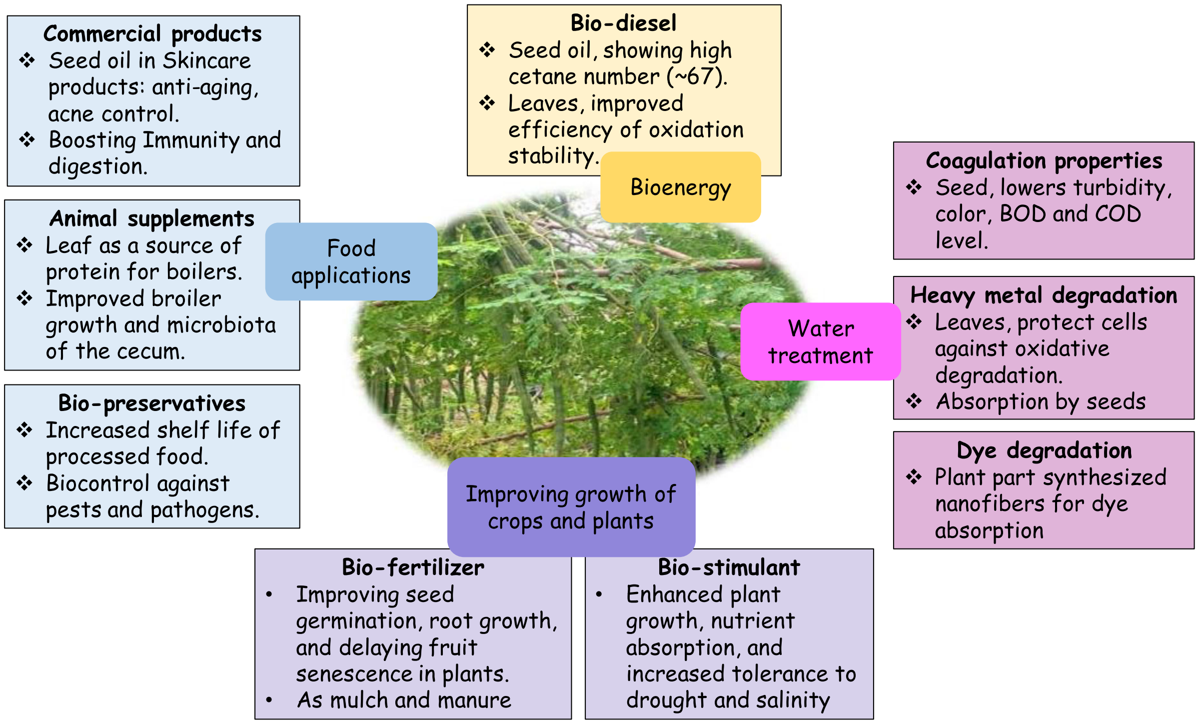


Fig. 2 Graphical representation of environmental, industrial and health benefits of *M. oleifera* parts

significant reductions of 98%, 90.76%, and 65.8% in turbidity, colour, and COD (Chemical Oxygen Demand), respectively. Similarly, in basic wastewater, the reductions in turbidity, colour, and COD were 99.5%, 97.7%, and 65.82%, respectively, with the pH levels after treatment ranging from 7 to 9 (Desta and Bote 2021). The coagulation activity of *M. oleifera* seeds is attributed to cationic proteins, with the flocculation mechanism linked to charge neutralization through protein interaction with negative charges (Madsen et al. 1987). Isolating the protein using 1 M KCl demonstrated 96% turbidity and 82% colour removal efficiency, confirming the stability of KCl salt extract in *M. oleifera* protein extract coagulation capabilities (Madrona et al. 2010). This research underscores the potential of natural coagulants, particularly *M. oleifera*, as a sustainable and effective alternative in water treatment, addressing both environmental and health concerns associated with traditional coagulants like alum.

Effective degradation of synthetic dyes

Synthetic dyes, extensively employed in industries such as textiles, pharmaceuticals, leather, and food, contribute to the emergence of toxic contaminants in wastewater. Approximately 15% of these dyes find their way into wastewater effluents. Due to their complex and stable structures, these dyes present a formidable challenge for degradation, posing harmful effects on humans, animals, and the environment with their inherent toxicity, mutagenicity, and carcinogenicity. Research highlights the efficacy of *M. oleifera* seed extract in addressing this issue, demonstrating a remarkable 98.2% elimination of the synthetic azo dye Direct Red 23 at a concentration of 80 mg/L from textile water effluents (Dalvand et al. 2016). Similarly, activated carbon derived from *M. oleifera* leaves, at a concentration of 0.08 g/100 ml, achieves a rapid 96% degradation of methylene blue dye within 15 min (Rajalingam et al. 2021). Various parts of the *M. oleifera* plant exhibit distinct capabilities in dye removal. The seedcoat efficiently absorbs Acid Blue 9 dye (Buera et al. 2021), while the seedpod or fruit portion effectively removes approximately

91.8% of naphthol blue black dye (Shirani et al. 2018). Additionally, activated carbon derived from the seed-pod demonstrates a noteworthy 90.7% removal of methylene blue dye (Nor Salmi Abdullah et al. 2017). Moreover, the plant's application in the form of electrospun nanofibers, loaded with polyacrylonitrile nanofibers, serves as a biosorbent, successfully removing 85% of Congo red dye within 2.5 h. This method boasts an adsorption capacity exceeding 51 mg/g (Narayan et al. 2022). *M. oleifera* emerges as a versatile and efficient solution in the degradation of synthetic dyes, showcasing its potential for sustainable water treatment practices.

Degradation of oil and heavy metals

The discharge of metallic elements and heavy metals into wastewater due to various anthropogenic activities poses significant environmental challenges. Among these, arsenic stands out as the most toxic metalloid compound, recognized for its potency as a carcinogen and its association with diseases such as cardiovascular and neurological disorders and inducing substantial environmental pollution (Nayek et al. 2023). Arsenic exerts its toxicity by binding to the sulfhydryl group of proteins and enzymes, acting as a substrate for phosphorus in metabolic reactions, disrupting oxidative phosphorylation, and inhibiting and degrading mitochondrial enzymes (Ajees et al. 2011). In response to heavy metal toxicity, *M. oleifera* leaves, rich in antioxidants, play a crucial role in protecting biomolecules. An insightful study on *Cirrhinus mrigala* fish explored arsenic detoxification using *M. oleifera* leaf extract. The fish were divided into four groups (T1 to T4), with T1, T2, and T3 receiving 1/10th of the lethal LC_{50} amount of arsenic along with 0%, 2%, and 4% of *M. oleifera* leaf extract, respectively and T4 were control groups. Enzyme assays measuring superoxide dismutase (SOD) and catalase (CAT) activity revealed improved enzyme activity in groups T2 and T3, showing recovery like the control group. While the group T1 were identified with lowered enzyme activity (Azhar et al. 2023). Cadmium, another pervasive toxic metalloid in the environment, is efficiently absorbed by *M. oleifera* seeds, demonstrating notable absorption efficiency of approximately 85.10% at a cadmium concentration of 25 μg/ml (Sharma et al. 2006). Another study at a cadmium concentration of 0.1 mg/ml maintained a high absorption efficiency of 80% (Abedini and Alipour 2015).

Moving beyond heavy metal remediation, *M. oleifera* proves effective in the removal of oil and grease from wastewater, showcasing a removal efficiency of approximately 82.43% (Magalhães et al. 2021). Additionally, activated carbon derived from *M. oleifera* seeds and pods, administered at a dosage concentration of 2.5 g/L, demonstrates remarkable efficiency of 79% and 87.2% when treating wastewater with an oil and grease concentration of 300 mg/L (Santos et al. 2020).

Sustainable biodiesel production with *M. oleifera*

Bioenergy is a renewable energy derived from organic materials, typically originating from biological sources such as plants, animals, and their byproducts. This sustainable energy source harnesses the energy stored in organic matter through various conversion processes. The primary sources of bioenergy include biomass, biofuels, and biogas. Biomass involves the use of organic materials, such as wood, crop residues, or dedicated energy crops, to produce heat, electricity, or biofuels. Biofuels are liquid or gaseous fuels derived from biomass, commonly used in transportation, with examples like biodiesel and bioethanol. Biogas, generated through the anaerobic digestion of organic waste, primarily consists of methane and can be utilized for cooking, heating, or electricity generation. Bioenergy is considered environmentally friendly as it often involves the utilization of materials that can be replenished, contributing to a reduction in greenhouse gas emissions and promoting sustainable energy practices. The role of bioenergy in environmental conservation is paramount, offering a sustainable alternative to conventional fossil fuels and addressing climate change challenges. Within this context, *M. oleifera* emerges as a distinctive contributor, showcasing its versatility in bioenergy applications.

M. oleifera seed oil emerges as a promising resource for energy production, boasting a rich composition characterized by high levels of monounsaturated/saturated fatty acids (MUFA/SFA) ratio, sterols, tocopherols, and proteins, as detailed in Table 1. Biodiesel, defined as mono-alkyl esters derived from vegetable oil and animal fats, provides a sustainable alternative to conventional diesel fuels.

Table 1 Overview of Sterol, Fatty Acid, and Tocopherol Compounds Found in *M. oleifera* Seed Oil: Concentration Ranges and 2D Structures as Reported in the Literature (References: Anwar et al. 2007; Gharsallah et al. 2023)

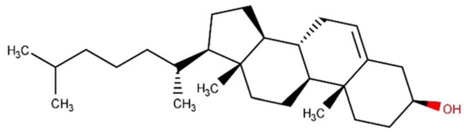
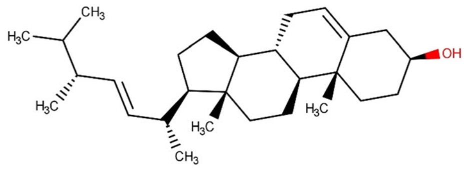
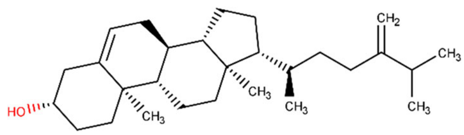
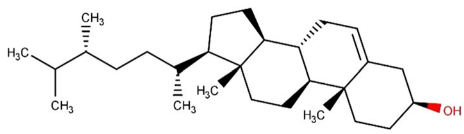
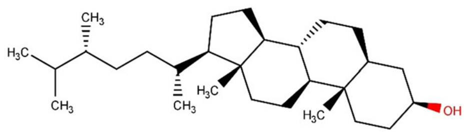
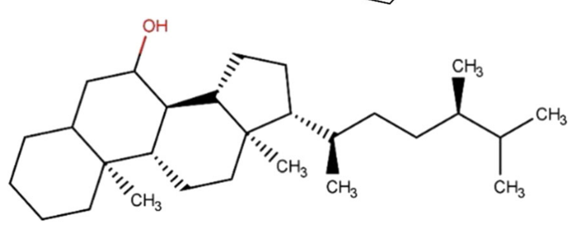
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Choles terol	0.2–0.14	
Brassicasterol	0.06–0.12	
24-methy lene cholestrol	0.14–1.08	
Campesterol	13.87–22.98	
Campestanol	0.03–0.64	
Δ7-campestanol	0.6–0.7	

Table 1 continued

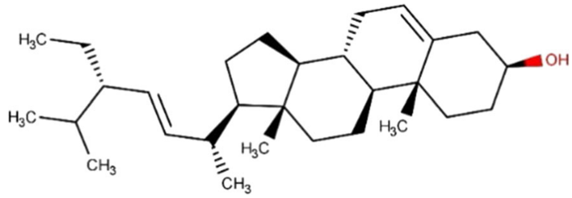
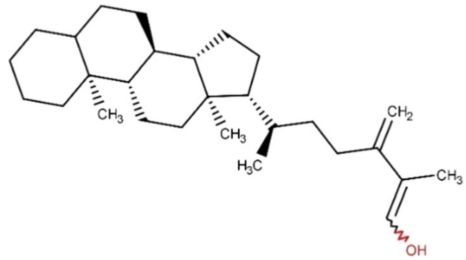
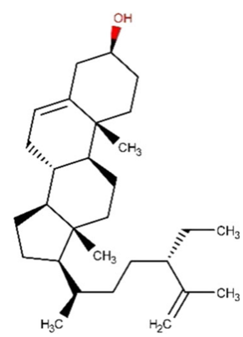
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Stigmasterol	19.28–22.59	
Ergosta dienol	0.01–0.42	
Cleros terol	0.48–2.38	

Table 1 continued

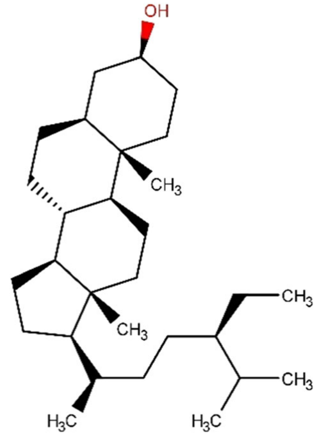
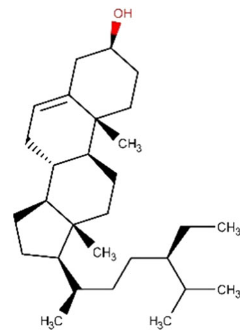
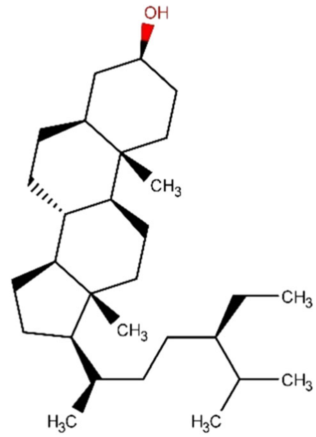
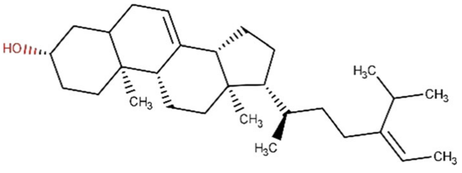
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Stigmastanol	0.55–1.04	
β-sitosterol	45.33–49.12	
Sitostanol	0.75	
Δ 7-avenasterol	0.38–2.43	

Table 1 continued

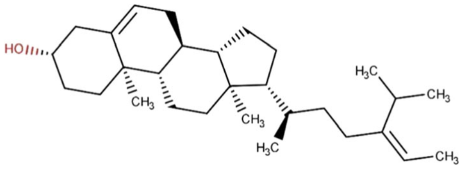
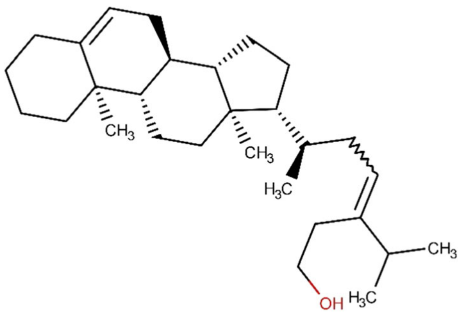
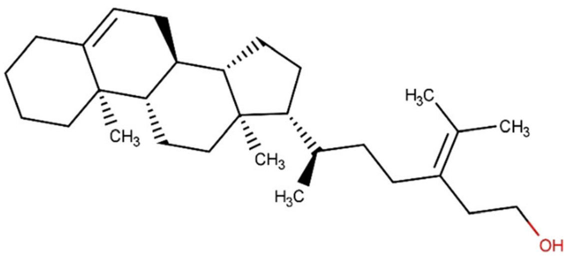
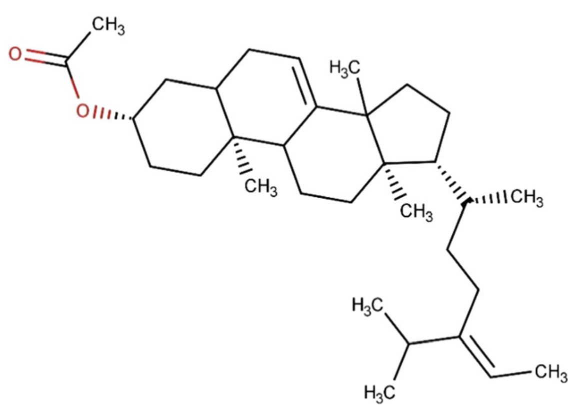
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Δ 5-avenasterol	3.07–12.95	
Δ 5,23-stigmastadienol	0.87, 1.23	
Δ 5,24-stigmastadienol	1.33	
28-isoavenasterol	0.09–0.95	

Table 1 continued

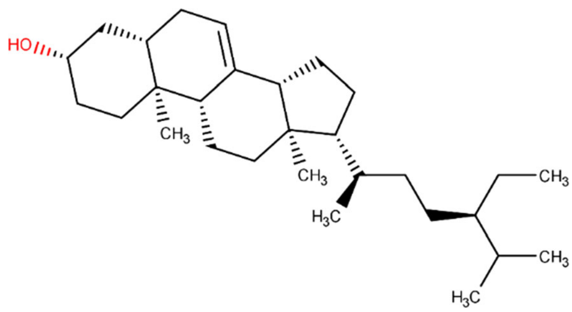
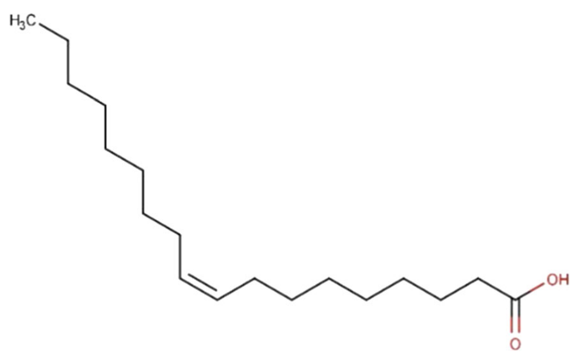
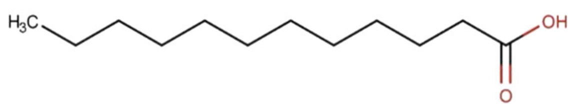
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Δ 7,14-	Stigmastadienol	0.39
Δ 7,14- Stigmastanol	0.44–0.93	
Δ 7-stigmatserol	0.25–1.89	
Fatty acids in M. *oleifera* seed oil (%)		
Oleic acid	70.2–76.16	
Lauric acid	1.89–2.45	

Table 1 continued

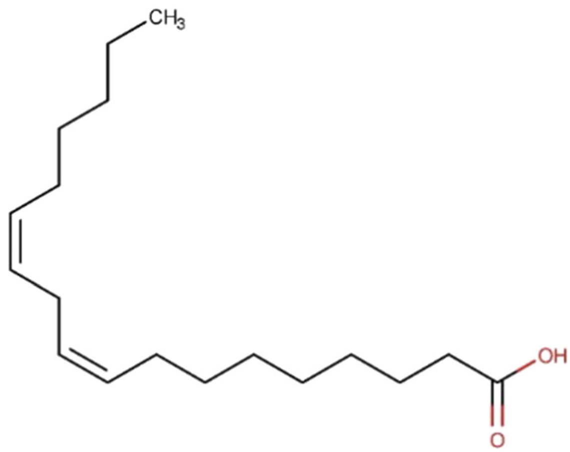
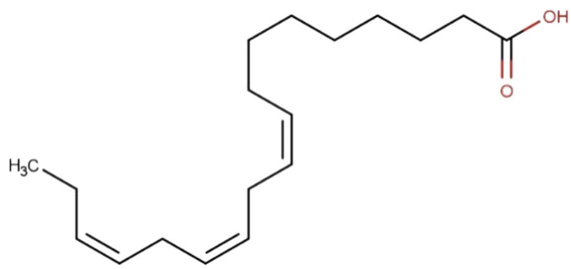
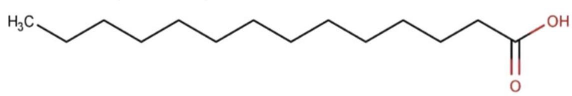
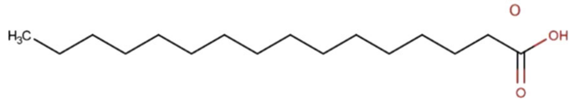
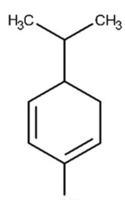
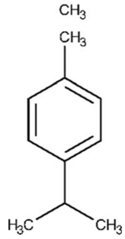
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Linoleic acid	0.05–1.86	
Linolenic acid	0.22–2.08	
Myristic acid	0.75–0.2	
Palmitic acid	5.16–9.90	
α-Phellandrene		
p-Cymene		

Table 1 continued

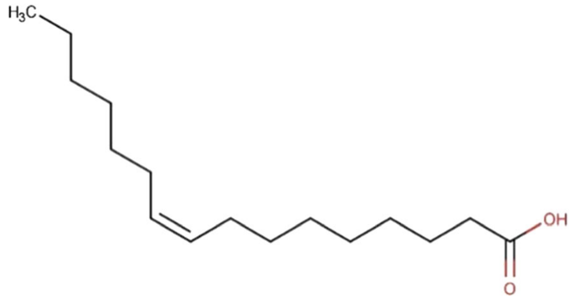
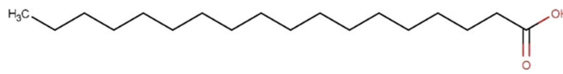
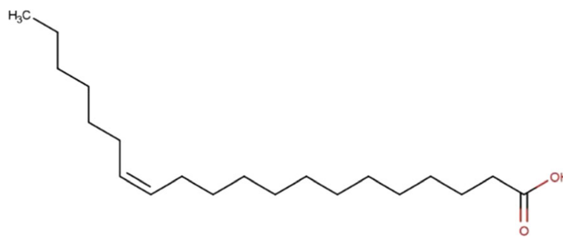
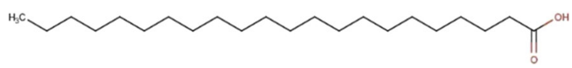
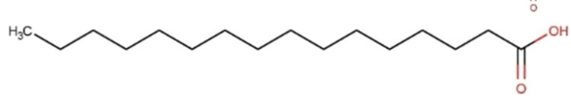
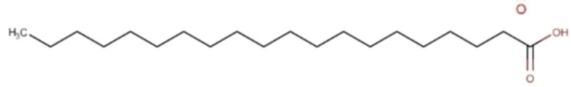
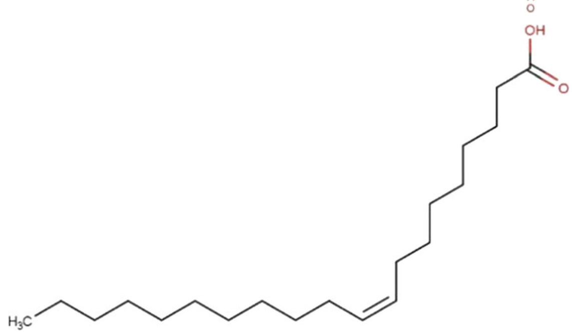
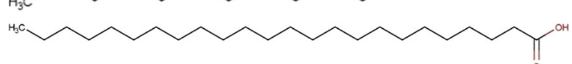
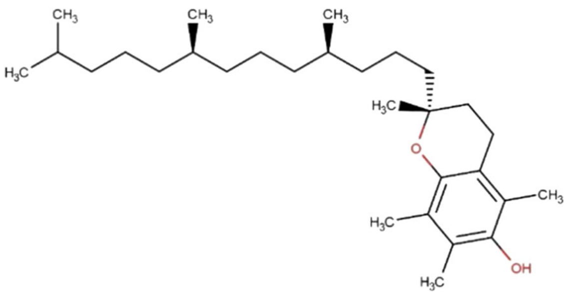
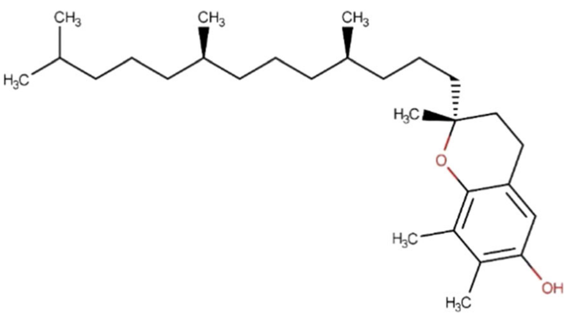
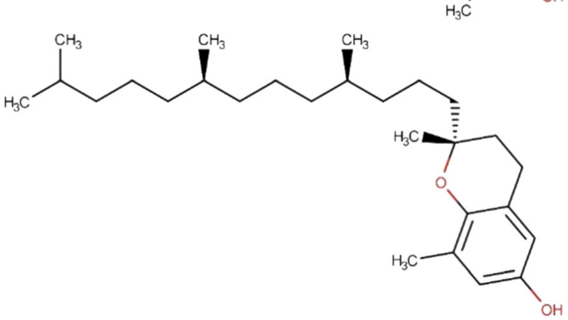
Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Palmitoleic acid	1.31–3.31	
Stearic acid	2.68–6.20	
Paullinic acid		
Behenic acid	5.51–5.96	
Palmitic acid		
Arachidic acid	3.22–5.94	
Gadoleic acid	1.34–2.46	
Lignoceric acid	0.39–0.93	
SFA (saturated fatty acid)	20.46–21.76	–
MUFA (Monosaturated fatty acid)	76.78–78.10	–
PUFA (poly unsaturated fatty acid)	0.40–1.61	–

Table 1 continued

Sterols in M. *oleifera* seed oil (%)	Concentration range	2D- structure
Tocopherols in *M. oleifera* seed oil (mg/kg)		
α-tocopherol	5.05–252.90	
γ-tocopherol	25.40–87.02	
δ-tocopherol	3.55–245.7	

The utilization of *M. oleifera* seeds for biodiesel production proves advantageous due to their elevated oleic acid content, reaching approximately 70%, contributing to superior yield and enhanced oxidative stability. Biodiesel derived from *M. oleifera* oil exhibits a notably high cetane number of 67, an ignition quality characteristic and is valued among the highest observed in biodiesel fuels (Rashid et al. 2008). Furthermore, *M. oleifera*'s leaf residues find application in synergy with soya bean oil for biodiesel production, acting as an antioxidant resource. This dual-source approach not only elevates overall quality but also enhances oxidation stability efficiency by an impressive 265% to 718% against oxidizing agents in rubber seed oil (Granella et al. 2021). The favourable viscosity and acidity index of *M. oleifera* seed oil position it as a viable biodiesel feedstock, contributing to reduced emissions of CO, CO_2, particles, and hydrocarbons. Additionally, by-products of *M. oleifera*, such as seed cake and husks, with their high carbohydrate content, offer potential substrates for bioethanol and biochemical production. The biodiesel production process achieves an impressive 82% conversion rate when operating under optimized conditions, including a reaction temperature of 60 °C, a 1.0 weight percentage of KOH to oil, a rotation speed of 400 rpm, and a methanol to oil ratio of 30 weight percentage (Raman et al. 2018). This underscores the multifaceted utility of *M. oleifera* in the realm of sustainable energy production. Harnessing the potential of *M. oleifera* in bioenergy not only diversifies our energy sources but also contributes significantly to the broader goals of environmental conservation, mitigating environmental degradation and fostering a more sustainable future.

M. oleifera-based agroforestry

Agroforestry is a sustainable land management system that combines the cultivation of trees with crops and/or livestock on the same land. It integrates agriculture and forestry principles, promoting diversity, productivity, and resilience. This practice offers ecological, economic, and social benefits, such as enhanced biodiversity, improved soil fertility, water conservation, and additional income sources for farmers. Various forms of agroforestry include alley cropping, windbreaks, silvopasture, and forest farming. *M. oleifera* based agroforestry constitutes a sustainable agricultural system that integrates the cultivation of trees and crops alongside livestock, fostering ecological and economical interactions among diverse elements. The attractiveness of *M. oleifera* for agroforestry is underscored by its minimal growth time, short rotational period, deep root system, food security potential, and climate-mitigating capabilities (Kumar et al. 2017). A comparative study evaluating land under agroforestry against a monocropping system demonstrated significant benefits, surpassing non-fertilized continuous maize production with a remarkable 44% to 58% superior growth. The rapid establishment of *M. oleifera*, whether through cuttings or seeds, particularly with 1-m cuttings, results in increased pod production from the first year onwards. In favourable conditions, a single *M. oleifera* tree can annually yield 50-70 kg of pods. Integrating *M. oleifera* into intercropping and alley cropping techniques not only provides shade for crops but also reduces soil acidity (Devkota and Bhusal 2020). The adoption of the *M. oleifera* tree-based agroforestry called MTBA system has proven advantageous, contributing to enhanced income prospects, economic stability, cost-effective production, and consistent crop yields (Horn et al. 2022).

Bio-stimulant and biofertilizer potential of ***M. oleifera***

A bio-stimulant is a substance or microorganism that enhances nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality when applied to plants or the rhizosphere. Unlike fertilizers or pesticides, bio-stimulants complement these inputs, improving overall plant health and performance. Various parts of the *M. oleifera* plant, including leaves and seeds, contain bioactive compounds such as vitamins, minerals, amino acids, and plant growth-promoting substances. When applied to crops, *M. oleifera* extracts or formulations stimulate root development, enhance nutrient absorption, and improve overall plant vigor. This utilization of *M. oleifera* as a bio-stimulant aligns with sustainable agricultural practices, leveraging the plant's natural properties to support crop growth and development. It offers an organic and environmentally friendly approach to enhance crop productivity and resilience to stress conditions.

In a study conducted by Granella et al., it was demonstrated that *Freesia hybrida* corms soaked in a 5% *M. oleifera* leaf extract for 24 h exhibited improved morphological, physiological, and yield attributes. The presence of zeatin and cytokine contributed to an increased photosynthetic rate, resulting in a higher number of flowers per stem and more marketable stems per plant (Granella et al. 2021). As we discussed earlier, the utilization of *M. oleifera* leaves as a bio-stimulant is widely recognized for enhancing plant growth, improving nutrient absorption, and increasing tolerance to abiotic stress factors such as drought and salinity. Additionally, it effectively enhances both the productivity and quality of plants in a sustainable manner. The study conducted by Zulfiqar et al. clearly establishes that the preparation of *M. oleifera* leaf extracts is a straightforward and cost-effective process (Zulfiqar et al. 2020). These extracts offer accessibility, eco-friendliness, and serve as excellent sources of organic fertilizer due to their high content of proteins, minerals, essential amino acids, and phytohormones, including gibberellins, IAA (Indole 3 acetic acid), and ABA (abscisic acid).

These compounds play a crucial role in promoting growth-stimulatory activities such as seed germination, stem elongation, leaf expansion, flowering initiation, and fruit development (Zulfiqar et al. 2020).

On the other hand, biofertilizers are substances containing living microorganisms, mainly bacteria, fungi, or algae, that colonize the rhizosphere or plant roots and enhance nutrient availability to plants. These microorganisms facilitate nutrient cycling, fix atmospheric nitrogen, solubilize minerals, and promote plant growth. Common biofertilizers include nitrogen-fixing bacteria like *Rhizobium* and phosphate-solubilizing bacteria. The excessive use of synthetic fertilizers not only degrades the soil and pollutes the environment but is also a costly practice. However, *M. oleifera* offers a viable alternative as it is rich in minerals, nutrients, proteins, phenolics, and fibres. Moreover, it is safe, easy to use, sustainable, and readily available. The study conducted by Mashamaite et al., showed that leaf extract of *M. oleifera* contains auxins, cytokinins, gibberellins, and other phytohormones that aid in seed germination, root growth, and delaying fruit senescence (Mashamaite et al. 2022). Notably, the application of *M. oleifera* leaf extract has been proven beneficial in promoting plant growth and increasing yield in crops such as sorghum (*Sorghum bicolor L.*) and maize (*Zea mays L.*) (Mashamaite et al. 2022).

The rapid growth of industry and increased human activity significantly impacts agricultural soil, affecting plant growth. Among hazardous substances, heavy metals like arsenic, cadmium, and lead pose a significant threat to crops such as rice, maize, and wheat. This study conducted by Shah et al., shown that the utilization of smoke water derived from *M. oleifera l*eaves, containing beneficial compounds like vitamins A and C, riboflavin, β-carotenoids, iron, and phenolics, can effectively reduce the stress caused by cadmium in Basmati 385 and Shaheen Basmati seedlings (Shah et al. 2022). Sustainable agricultural practices using *M. oleifera* leaf extract, containing zeatin and ascorbates applied as pretreatment or foliar spray, promote germination, cell enlargement, bud formation, and root initiation for growing crops such as sorghum, maize, and wheat. The pruning from *M. oleifera* tree, leaves, and oil-extracted seed meal are all used as mulch and manure. Application of *M. oleifera* leaves about 4 tons/hectare gave a yield of 3.60 tons of maize grain per hectare, compared to using NPK (nitrogen, phosphorus, potassium) as fertilizer, which gave a yield of 1.98 tons/hectare (Raman et al. 2018).

The potential of *M. oleifera* as a bio-preservative

Bio-preservatives are natural substances that inhibit the growth of spoilage organisms and pathogens in food, prolonging its shelf life while ensuring safety. *M. oleifera*, with its rich bioactive compounds, emerges as a promising source of bio-preservatives in the food industry. Extensive research has delved into the antimicrobial properties of *M. oleifera*, with a recent review by Jikah and Edoet et al., comprehensively documenting these findings (Jikah and Edo 2023). The *M. oleifera* plant contains bioactive compounds like phenols, flavonoids, alkaloids, and peptides (see Table 3 for the details), which exhibit strong antimicrobial activity against a variety of bacteria, fungi, and even some viruses. These properties make *M. oleifera* an attractive candidate for use as a bio-preservative. *M. oleifera* extracts have shown inhibitory effects on the growth of foodborne pathogens such as *Escherichia coli*, *Salmonella*, and *Staphylococcus aureus*. These extracts can be incorporated into food products to prevent or slow down spoilage, maintaining both the safety and quality of the food (Abdallah et al. 2023). Additionally, *M. oleifera*'s antioxidant properties contribute to the prevention of oxidative processes that lead to food deterioration (Ezz El-Din Ibrahim et al. 2022). The high content of vitamins C and E, along with other antioxidants in *M. oleifera*, helps in preserving the freshness and nutritional value of food (Hodas et al. 2021).

The study conducted by Raman et al., showed that the *M. oleifera* leaf can be incorporated into processed foods, extending the shelf of products, and reducing oxidative rancidity (Raman et al. 2018). Furthermore, dried stored leaf powder retains 50% of their beta-carotene content even after 3 months of storage (Raman et al. 2018). Moreover, the protease inhibitors extracted from *M. oleifera* seed and leaf extracts exhibit potential inhibitory activity against enzymes such as thrombin, elastase, chymotrypsin, trypsin, cathepsin, and papain. This property makes *M. oleifera* a suitable candidate for pharmaceutical applications, acting as a drug with wide-ranging potential. Additionally, these protease inhibitors serve as an effective preservative in the food industry for biocontrol defence protein, protecting plants against infestations by pests and pathogens. seafood preservative against proteolysis, in food industry, and protection of plants against pest and pathogen infestations (Bijina et al. 2011). The utilization of *M. oleifera* as a bio-preservative aligns with the growing demand for natural and sustainable food preservation methods. Its effectiveness against a range of microorganisms, coupled with its antioxidant process, positions *M. oleifera* as an asset in the quest for eco-friendly and health-conscious food preservation strategies (Ayirezang et al. 2020).

Role of *M. oleifera* in the animal food supplements

M. oleifera has gained recognition as an exceptional source of nutrition for animals, serving as a valuable food supplement. The leaves, seeds, and pods of the *M. oleifera* plant are rich in essential nutrients such as vitamins, minerals, proteins, and antioxidants, contributing to enhanced animal health and productivity. As a feed additive, *M. oleifera* is known to improve overall growth, increase milk production in dairy animals, and enhance the quality of meat in livestock. The market value of *M. oleifera* in animal food supplements has witnessed a steady rise due to its proven benefits and growing awareness of its nutritional advantages (Su and Chen 2020). Farmers and livestock owners increasingly integrate *M. oleifera* into animal diets, recognizing its potential to boost immunity, support reproductive health, and mitigate the impact of nutritional deficiencies. As a sustainable and cost-effective solution, *M. oleifera* continues to play a significant role in the animal husbandry sector, reflecting its increasing market demand.

Poultry products are renowned for their rich mineral and protein content, yet the global poultry industry faces challenges from environmental hazards and infectious agents (Ustundag & Ozdogan 2016). Zhang et al., identified the absence of a protein source in broiler chicken feed as a significant issue, highlighting the need for alternatives (Zhang et al. 2023a, b). *M. oleifera* emerges as a viable solution, acting as a feed additive for broilers and laying hens. Apart from being a protein source, *M. oleifera* defends against oxidative stress, inhibits pathogenic bacteria, and moulds, and enhances overall feed digestion. Consequently, the poultry products, including eggs, milk, and meat, exhibit superior quality with health-promoting factors (Abdoun et al. 2023). The benefits extend to cholesterol reduction in eggs and increased shelf life of poultry products due to *M. oleifera*'s strong flavonoid antioxidant capacity (Abo-Elsoud et al. 2022). The impact is not limited to nutritional aspects; *M. oleifera* positively influences chicken growth, carcass characteristics, and microbiota in the cecum, the primary site of intestinal fermentation, enhancing overall broiler performance (Zhang et al. 2023a, b).

In the realm of goat nutrition, where concentrated feeds pose challenges due to scarcity and high costs, *M. oleifera* emerges as a promising dietary supplement. Goats fed with *M. oleifera* leaves experience improved growth performance, enhanced immune status, and a notable increase in antioxidant activity by 10–20%. This dietary inclusion also contributes to reduced total methane emissions, addressing environmental concerns associated with animal feed choices (Leitanthem et al. 2023). As an accessible and cost-effective nutritional resource, *M. oleifera* plays a pivotal role in addressing the nutritional needs of poultry and goats, offering sustainable solutions to enhance productivity and overall animal health.

Commercial non-food products derived from *M. oleifera*

M. oleifera, renowned for its versatility, extends its influence beyond the realm of consumables to the skincare industry. In comparison to other vegetable oils, *M. oleifera* seed oil stands out with a higher proportion of oleic acids and monounsaturated fatty acids. Investigating its impact on human SZ95 sebocytes, lipid-producing skin cells, revealed promising outcomes (Zouboulis et al. 2023). *M. oleifera* seed oil exhibited desirable oil characteristics, concentrating properties that reduce the release of proinflammatory cytokines TNF-α and TNF-β. These cytokines play crucial roles in immunological reactions within cells. TNF-α, known for its proinflammatory nature, influences sebocyte proliferation and sebum secretion, particularly in follicular skin diseases like acne (Sinha et al. 2014). On the other hand, TGF-β signalling regulates lipogenesis in human sebaceous gland cells.

Table 2 Summary of Nutritional Values, Mineral Content, and Amino Acid Profile of *M. oleifera*

Nutritional values in % (per 100 g)	Leaves	Seeds	Fruit Pods
Moisture	7.5	5.32	86.9
Protein	27.1	18.9–37.2	2.5
Fat	2.3		0.1
Carbohydrate	38.2	8.9–9.2	3.7
Fiber	19.2	1.4.–7.7	4.8
Minerals			2.0
Lipids	5.2–7.72	13.4–45.8	1.3
Trace elements (in mg)			
Calcium	2,003	30	30
Magnesium	368	24	24
Phosphorus	204	110	110
Potassium	1,324	235.8	259
Iron	28.2	3.62	5.3
Sulphur	870	0.05	137
Copper	0.57	5.05–5.35	3.1
Sodium	70	107.4	42
Vitamins (in mg)			
Vitamin A-β Carotene	2.26—16.3		
Vitamin B_1–thiamine	2.64	0.05	0.05
Vitamin B_2–riboflavin	20.5	0.06	0.07
Vitamin B_3–nicotinic acid	8.2	0.2	0.2
Vitamin C—ascorbic acid	17.3	120	120
Vitamin E—tocopherol acetate	113	–	–
Choline			423
Amino acids (in g)			
Arginine	5.6–7.4	11.9	8.5
Histidine	2.2–2.5	1.8–2.6	–
Lysine	4.8–5.6	2.0–2.2	3.2–3.3
Phenylalanine	5.7–6.2	3.6–4.7	3.6–3.7
Methionine	1.4–1.8	1.6–2.0	1.5
Threonine	4.0–4.2	2.4–2.6	–
Leucine	7.5–9.2	4.5–5.3	5.6
Isoleucine	4.2–4.8	2.9	2.9
Valine	5.0–6.0	3.3 – 3.7	3.68–3.70
Tyrosine	3.5–4.0	2.2 – 2.4	
Alanine	6.1–6.3	3.9 – 4.7	4.47–4.5
Glutamic acid	10.7	-	15.1–15.2
Aspartic acid	9.1–9.5	4.6 – 5.2	6.88–6.98
Glycine	4.8–5.3	4.6–5.4	4.28–4.34
Proline	2.9–5.2	4.6–5.0	4.61–4.37
Serine	4.1–4.3	2.6–2.8	3.62–3.71
Cysteine	0.6–1.9	2.9–3.3	2.43–2.5

Table 2 continued

Nutritional values in % (per 100 g)	Leaves	Seeds	Fruit Pods
Glutamine	13.0–17.0	16.3–16.9	–

The values given for leaves are summarized from the literature Gandji et al. 2018*;* Dhakad et al. 2019*; and* Islam et al. 2021. *The seeds are from (*Islam et al. 2021*)(*Granella et al. 2021*)(*Saa et al. 2019a, b*) and the fruit pod values are collected from (*Islam et al. 2021*) (*Jikah & Edo 2023*)(*Melesse et al. 2012*). Amino acids proportion details are retrived from (Kumar* Manoj et al. 2022*)(*Owon et al. 2021*)*

These attributes position *M. oleifera* seed oil not only as a promising skincare component but also as an intriguing nutritional prospect (Zouboulis et al. 2023). Beyond skincare, *M. oleifera* finds application in various products aimed at improving digestion, enhancing immunity, reducing acidity and inflammation, muscle relaxation, and boasting anti-aging and antioxidant benefits (Alavilli et al. 2022).

Nutritive food ingredients from M. oleifera

Integrating the nutritional powerhouse *M. oleifera* into food products enhances their profile and introduces multifaceted benefits. *M. oleifera* proves its versatility as a nutritive food ingredient, enriching the protein, mineral, essential amino acid, and fibre content of various cereal-based snacks such as breads, cakes, and pastries (Milla et al. 2021). The *M. oleifera* dry leaf and seed content in these products enhances their nutritional profile (Rathnayake and Navarathna 2015). In the realm of beverages, the leaf extract, whether dried, fresh, or in watery form, emerges as a reliable source of antioxidants, phenolics, and proteins (Bailey-Shaw et al. 2021). Dairy products like yogurt, curd, and cheese benefit from the antioxidant properties displayed by *M. oleifera* components (Trigo et al. 2023). The application extends to *M. oleifera* seed extract as a sprout, offering a valuable source of phenolic and bioactive components. Notably, *M. oleifera* seeds demonstrate high germination rates, ranging from 60 to 100% in both in vivo and in vitro environments (Cirlini et al. 2022). Furthermore, the seed-extracted aspartic-type endopeptidase, with a molecular weight of 45,571 Da, exhibits enhanced thermal and pH stability at 70 °C and this unique attribute finds application in milk coagulation, impacting processes like cheese production (Kumar et al. 2022). The subsequent section delves into the diverse health benefits of *M. oleifera* supplementation in children, shedding light on its potency in addressing various diseases and disorders.

Each part of the *M. oleifera* plant is enriched with various nutrients and compounds such as flavonoids, flavanol glycosides, alkaloid, sterol, terpenes, phenolic acid, glucosinolate and isothiocyanate. The identified compounds *of M. oliefera*, and their concentration, and their presence in different plant parts are summarized in Tables 2 and 3. The nutritional values, minerals and amino acids present in the various *M. oleifera* plant parts are described in Table 2, and various phytochemicals and bioactive compounds identified in *M. oleifera* plant are described in Table 3.

Health impacts of *M. oleifera*

In recent years, the health impact of *M. oleifera* has garnered significant attention from scientists and nutritionists, leading to an in-depth exploration of its potential benefits for human well-being. Recognized for its exceptional nutrient profile, *M. oleifera* emerges as a nutritional powerhouse, boasting a diverse array of vitamins, minerals, and antioxidants. This comprehensive review aims to meticulously examine the health effects associated with *M. oleifera*, substantiating claims with scientific data. From its noteworthy antioxidant and anti-inflammatory properties to its purported role in maintaining blood sugar equilibrium and managing cholesterol levels, we strive to critically assess the breadth of its health-related contributions. The review provides a nuanced perspective by delving into both historical applications and contemporary research findings, contributing to a thorough understanding of *M. oleifera*'s potential impact on human health. Recent review articles authored by Amin et al.,

Table 3 Overview of Phytochemicals/Bioactive Compounds: Concentration and 2D Structures Identified in Different Parts of *M. oleifera* Plant

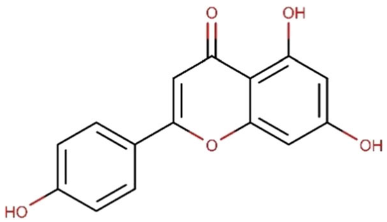
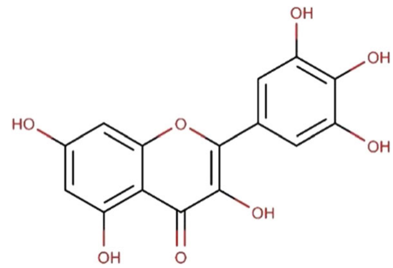
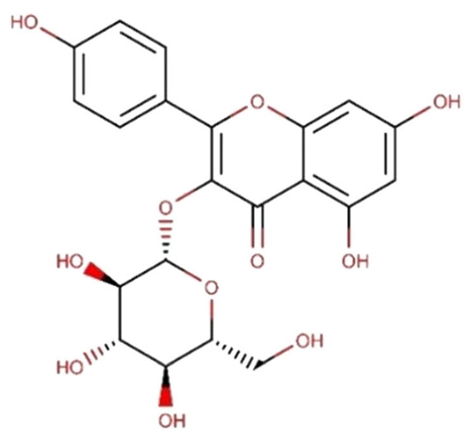
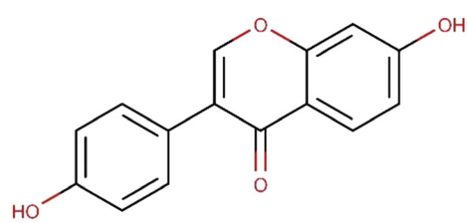
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Apigenin Seed oil concentration: 15.89–16.35 mg/kg	
Myricetin	
Quercetin-3-O-glycoside Concentration = 47.51 mg/kg	
Flavonoids and flavanol glycosides found in leaves	
Phytochemicals	2D structure
Astragalin	
Daidzein	

Table 3 continued

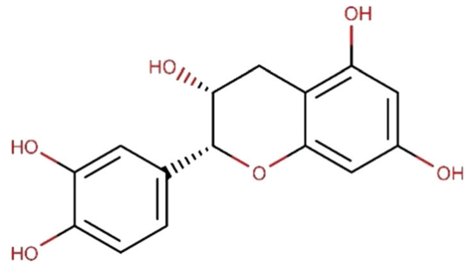
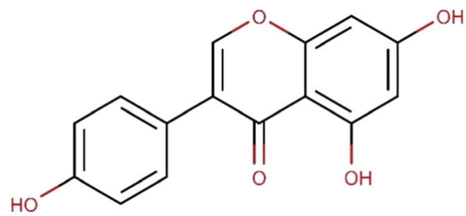
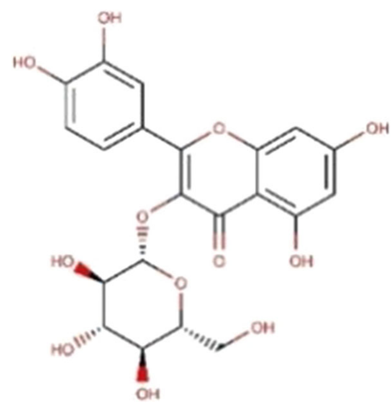
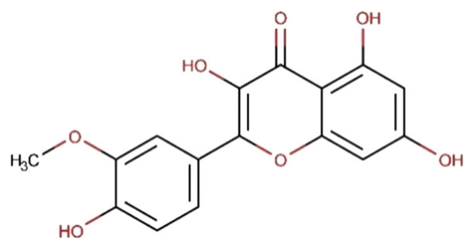
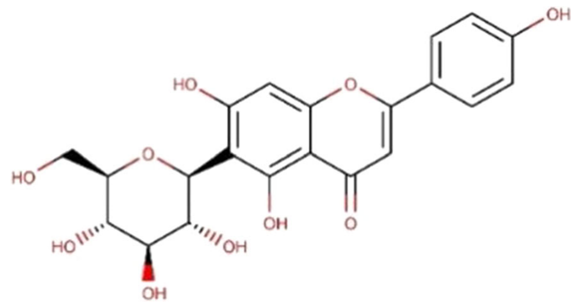
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Epicatechin	
Genistein	
Isoquercetin	
Isorhamnetin	
Isovitexin Leaves concentration: 3.1 -3.3 mg/kg	

Table 3 continued

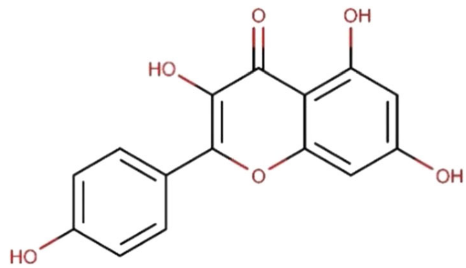
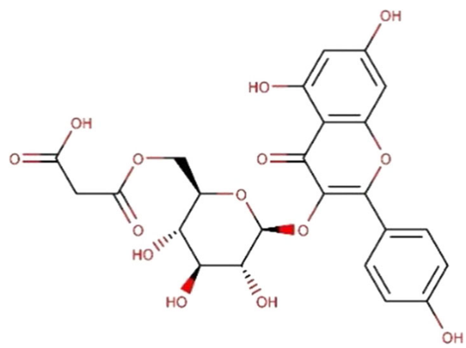
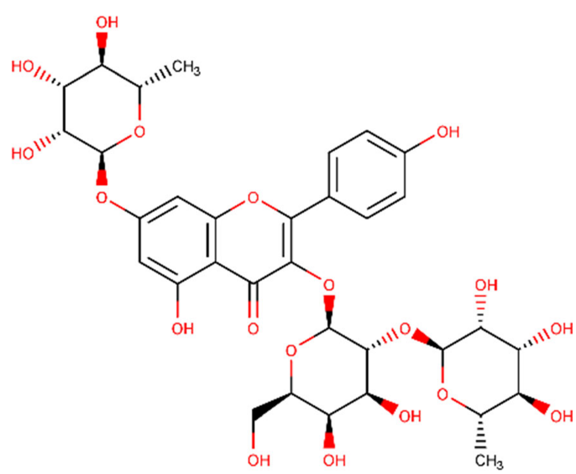
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Kaempferide 3-O-(2″,3″-diacetylglucoside)	
Kaempferide-3-O-(2″-galloylrhamnoside)	
Kaempferide-3-O-(2″-O-galloylrutinoside)- 7-O-α-rhamnoside	
Kaempferol Leaves concentration: 1.9- 2.1 mg/kg	
Kaempferol-3-O-(6″-malonyl) glucoside	
Kaempferol 3-(2″rhamnosyl-galactoside) 7-rhamnoside	

Table 3 continued

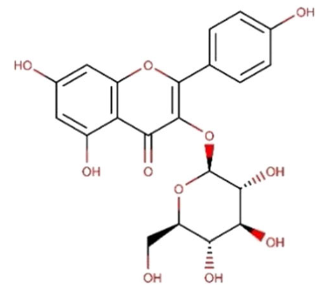
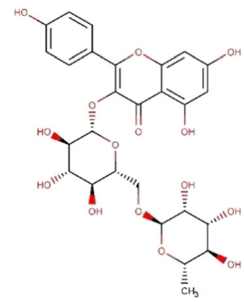
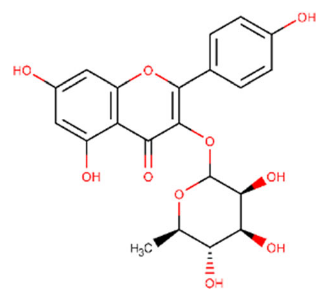
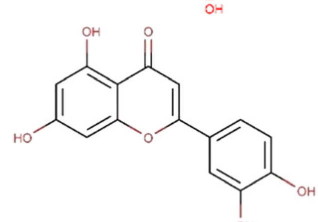
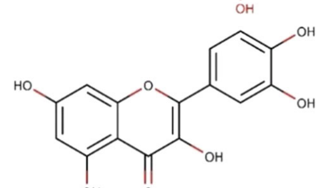
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Kaempferol-3-O-[β-glucosyl-(1 → 2)]- [a-rhamnosyl-(1 → 6)]-β-glucoside-7- O-a-rhamnoside	
Kaempferol-3-O-glucoside Leaves concentration: 13.1–14.5 mg/kg	
Kaempferol-3-rutinoside	
Kaempherol-3-O-α-rhamnoside (3496)	
Luteolin	
Quercetin	

Table 3 continued

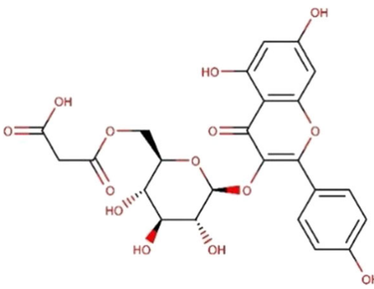
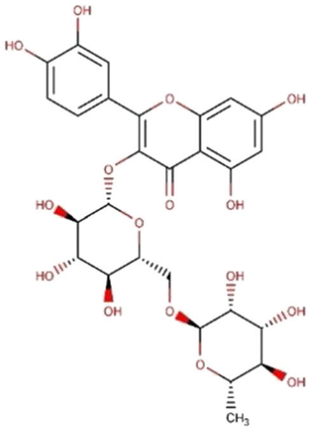
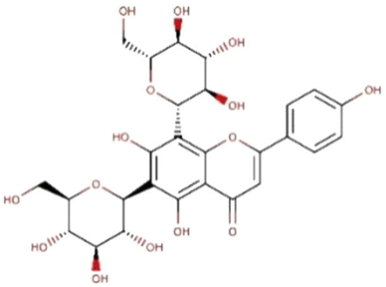
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Quercetin-3-O-(6″-malonyl) glucoside	
Rutin Leaves concentration: 232–248 mg/kg	
Vicenin-2	

Table 3 continued

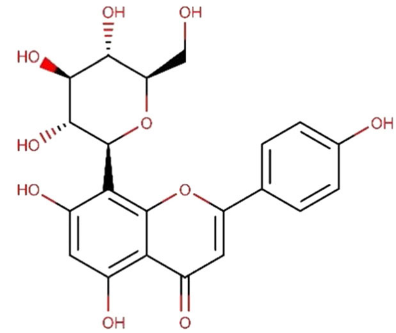
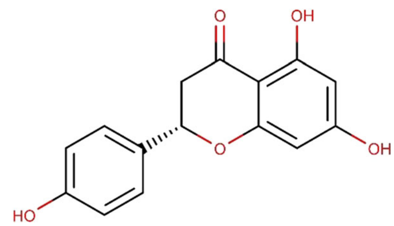
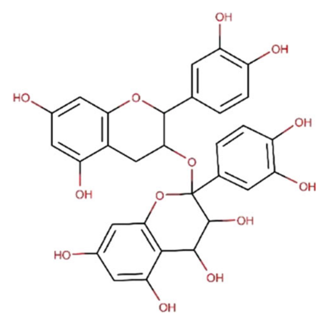
Phytochemicals	2D structure
Flavonoids and flavanol glycosides found in leaves and seed oil	
Vitexin Leaf concentration: 5.4–6.4 mg/kg	
Flavonoids and flavanol glycosides found in seed oil	
Naringenin Seed oil concentration: 20.55–20.95 mg/kg	
Flavonoids and flavanol glycosides found in roots, stem and bark	
Procyanidins	

Table 3 continued

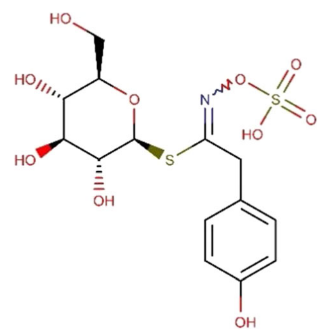
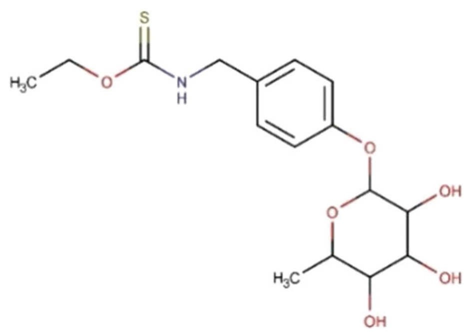
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Glucosinolate and isothiocyanate found in leaves	
4-[(2′-O-acetyl-α-L-rhamnosyloxy) benzyl] glucosinolate	
4-[(3′-O-acetyl-α-L-rhamnosyloxy) benzyl] glucosinolate	
4-[(4′-O-Acetyl-α-L-rhamnosyloxy) benzyl] glucosinolate	
4-[(α-L-rhamnosyloxy) benzyl] isothiocyanate	
4-[(2′-O-acetyl-α-L-rhamnosyloxy) benzyl] isothiocyanate	
4-[(3′-O-acetyl-α-L-rhamnosyloxy) benzyl] isothiocyanate	
4-[(4′-O-acetyl-α-L-rhamnosyloxy) benzyl] isothiocyanate	
Sinalbin	
Glucosinolate and isothiocyanate found in leaves, seed	
4-[(β-D-glucopyranosyl-1- > 4-α-L- rhamnopyranosyloxy) benzyl] isothiocyanate	
Niazimicin	
Glucosinolate and isothiocyanate found in leaves, seed and root bark	
4-(α-L-rhamnopyranosyloxy) benzyl glucosinolate (glucomoringin)	
Class of compound: Glucosinolate and isothiocyanate found in seed	
Benzyl glucosinolate (glucotropaeolin)	
Class of compound: Phenolic acid found in leaves	

Table 3 continued

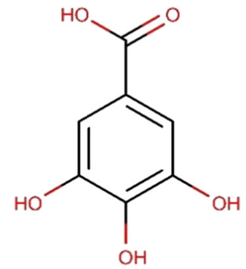
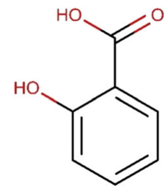
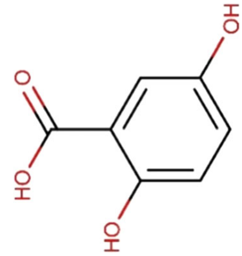
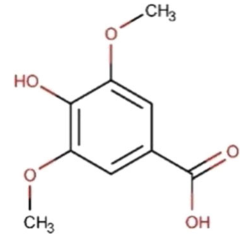
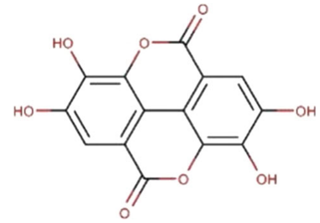
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Gallic acid Seed oil concentration: 0.15–0.25 mg/kg	
Salicylic acid	
Gentisic acid	
Syringic acid	
Ellagic acid	

Table 3 continued

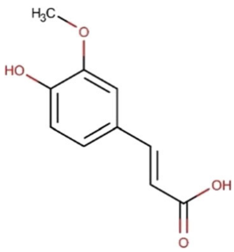
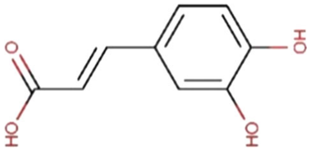
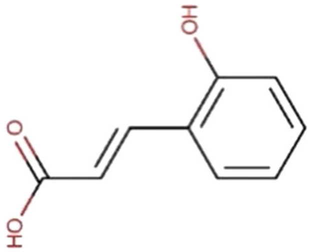
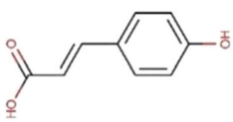
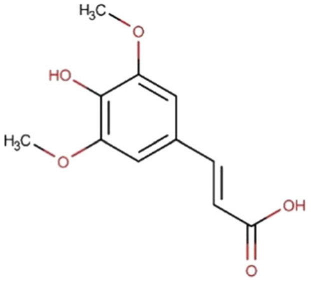
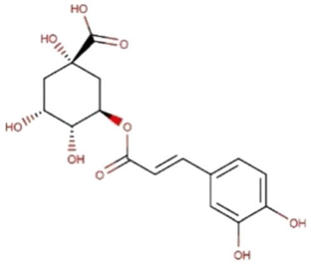
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Ferulic acid Seed oil concentration: 22.22–22.62 mg/kg	
Caffeic acid Seed oil concentration: 4.12–4.48 mg/kg	
Ortho-coumaric acid	
p-coumaric acid	
Sinapic acid	
Chlorogenic acid Leaves concentration: 97–99 mg/kg	

Table 3 continued

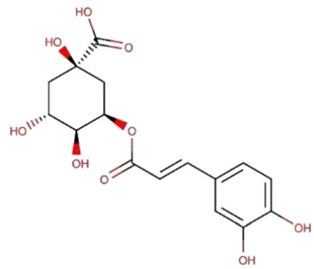
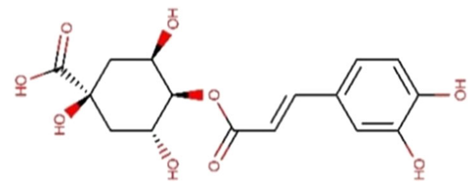
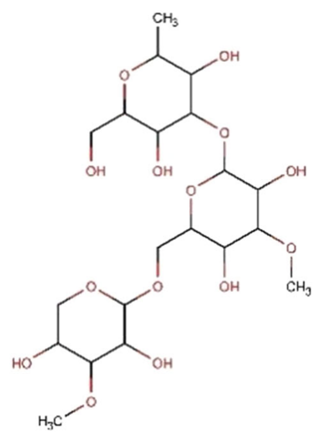
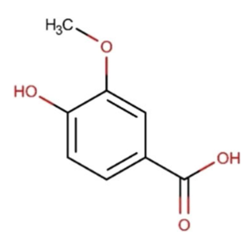
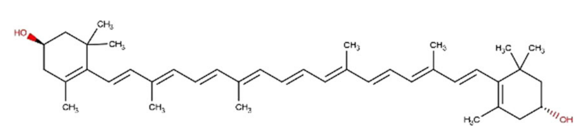
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
Neochlorogenic acid Leaves concentration: 232- 248 mg/kg	
Cryptochlorogenic acid	
Arabinogalactan	
Vanillic acid Seed oil concentration: 0.18–0.28 mg/kg	
Terpene found in seed pod	
All-E-lutein	
All-E-luteoxanthin	
13-z-Lutein	
15-z-β-Carotene	
All-E-zeaxanthin	
Alkaloid and sterol found in leaves	

Table 3 continued

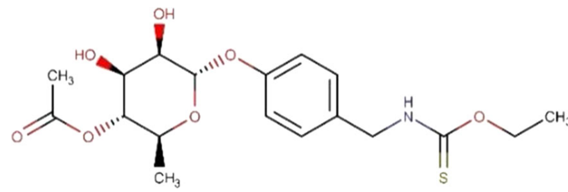
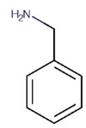
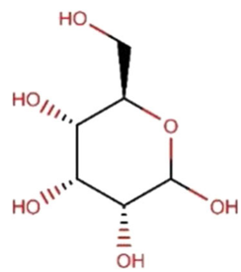
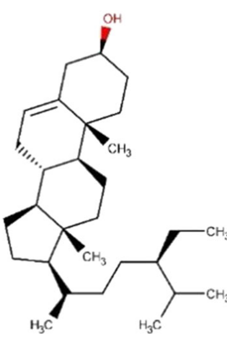
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
4′-hydroxyphenylethanamide-α-L- rhamnopyranoside (Marumoside A)	
3″-O-β-D-glucopyranosyl derivatives (Marumoside B)	
N,α-L-rhamnopyranosyl vincosamide	
Pyrrolemarumine-4″-O-α-L- rhamnopyranoside	
Niaziminin	
Benzylamine	
D-allose	
Benzoic acid 4-O-β-glucoside	
Alkaloid and sterol found in leaves and seeds	
β-sitosterol	
Alkaloid and sterol found in seeds	
O-Ethyl-4-[(α-L-rhamnosyloxy)- benzyl] carbamate	
Pterygospermin	

Table 3 continued

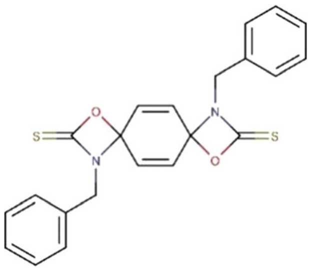
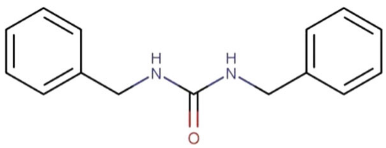
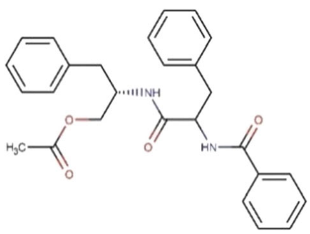
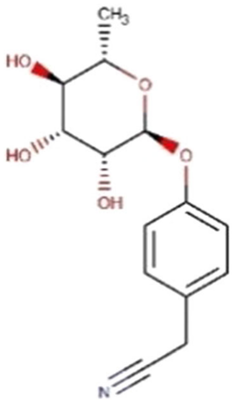
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
	
Alkaloid and sterol found in stem bark	
β-sitosterol-3-O-α-D- galactopyranoside	
Alkaloid and sterol found in roots	
Spirochin	
1, 3-Dibenzyl urea	
Aurantiamide acetate	
N-benzyl, S-ethylthioformate	
Alkaloid and sterol found in leaves and pods	
Niazirin	
Niaziridin	
Alkaloid and sterol found in leaves, fruits and seeds	
Vanillin	

Table 3 continued

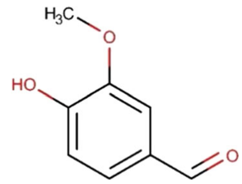
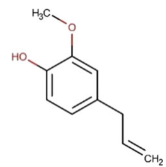
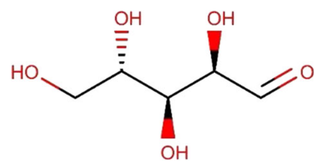
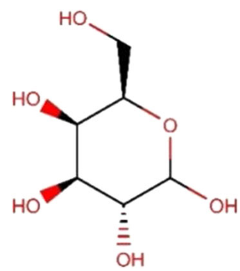
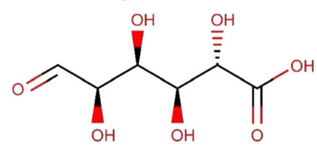
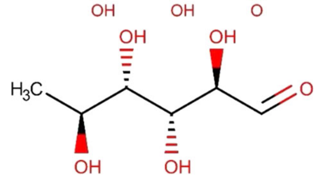
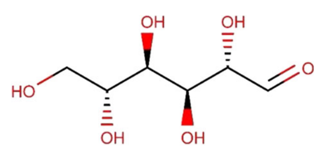
Flavonoids and flavanol glycosides found in leaves and seed oil	
Phytochemicals	2D structure
	
Alkaloid and sterol found in stem bark	
Eugenol	
Alkaloid and sterol found in gum	
L-arabinose	
D-galactose	
D-glucuronic acid	
L-rhamnose	
Aldotriouronic acid	
D-mannose	

Table 3 continued

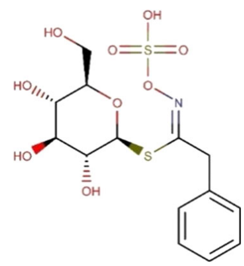
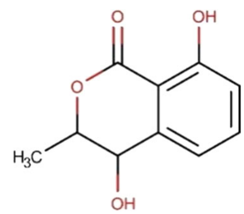
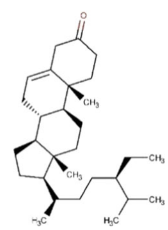
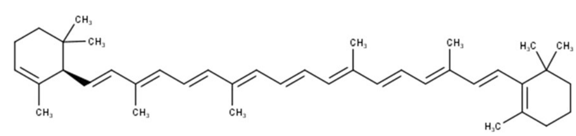
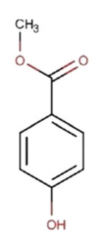
Phytochemicals	2D structure
Flavonoids and flavanol glycosides found in leaves and seed oil	
Leucoanthocyanin	
Alkaloid and sterol found in seeds and roots	
Benzyl glucosinolate	
Alkaloid and sterol found in stem	
4-hydroxymellein	
β-sitosterone	
Octacosanic	
Alkaloid and sterol found in seed oil	
Carotene	
Alkaloid and sterol found in pods	
O-[2′-hydroxy-3′-(2″-heptenyloxy)]- propylundecanoate	
O-ethy-l,4-[(α-1-rhamnosyloxy)- benzyl] carbamate	
Methyl-p-hydroxybenzoate	

Table 4 Health Benefits of *M. oleifera* Plant: Associated Phytochemicals/Bioactive Compounds and Their Mechanisms of Action

Phytochemical	Activity	References
3,4-Dihydroxybenzoic acid	Antioxidant activity	Kamel et al., (2023)
4- [(α-L-rhamnose oxy) benzyl] isothiocyanate	Anti-cancer activity against glioma tumour cells	Xie et al., (2023)
9-octadecenoic acid,	Antimicrobial activity	Afolabi et al., (2022)
1,3-dioxolane		
Apigenin	Antiviral activity against SARS-COV-2 M^{pro}	Sen et al., (2022)
Arabinogalactan, a polysaccharide	Antioxidant activity	Mohamed Husien et al., (2022)
Behenic acid	Antibacterial effect	Oliveira et al., (2023)
B-sitosterol	anti-osteoporosis effect	Khan et al., (2022), Hu et al., (2023), Khan et al., (2022)
Caffeic acid	Antiparasitic activity: by inhibiting egg hatching, larval viability. Neuroprotectant and Antioxidant activity	Azlan et al., (2023), Kamel et al., (2023)
Chlorogenic acid	Antioxidant and anti-inflammatory activity	Kamel et al., (2023), Essa et al., (2012)
Coumaric	Antioxidant activity	Kamel et al., (2023)
Ferulic acid	Anti-inflammatory effect	Mundkar et al., (2022)
Gallic acid	Anti-parasitic activity against equines intestinal nematodes, by damaging the cuticle and intestinal surface of nematodes.Anti-inflammatory, Antioxidant activity	Elghandour et al., (2023) Essa et al., (2012), Younis et al., (2022)
Isorhamnetin	Antiviral activity, SARS-COV-2 protein inhibitor	Sen et al., (2022), Afolabi et al., (2022)
Isothiocyanate	Anti-inflammatory effect and Insulin resistance	Mundkar et al., (2022), Siahaan et al., (2022)
Kaempferol	Antiviral activity, SARS-COV-2 protein inhibitor, Sleep regulation by activating $GABA_A$ receptors, anti-osteoporosis effect, anti-osteoporosis effect, Neuroprotective effect	Sen et al., (2022), Liu et al., (2022), Hu et al., (2023), Khan et al., (2022), Essa et al., (2012)
Luteolin	anti-osteoporosis effect	Hu et al., (2023), (Khan et al., (2022)
Myricetin	anti-osteoporosis effect	Hu et al., (2023, Khan et al., (2022)
Naringenin	Antioxidant activity	Kamel et al. 2023
Niazimicin	Anti-tumour activity	Razis et al. 2014
Niazimicin	Neuroprotective effect	Abdelsayed et al., (2021)
Nonadecanoic acid	Antimicrobial activity	Afolabi et al., (2022)
Oleic acid	Antimicrobial activity, Antibacterial effect	Afolabi et al., (2022), Oliveira et al., (2023)
Palmitic acid	Antibacterial effect	Oliveira et al., (2023)
Quercetin	Antiparasitic activity: by inhibiting egg hatching, larval viability anti-osteoporosis effect, Anti-inflammatory activity, Prevention of memory impairment, Neuroprotective effect, Antioxidant activity	Hu et al., (2023), Khan et al., (2022), Siahaan et al., (2022), Afrin et al., (2022), Essa et al., (2012), Younis et al., (2022)
Sulforaphane (glucosinolate)	Neuroprotective effect	Mundkar et al., (2022)

Abdelazim et al., and Jikah & Edo have comprehensively elucidated the health benefits and diverse applications of *M. oleifera* (Amin et al. 2024; Abdelazim et al. 2024; Jikah & Edo 2023). Amin et al.'s review delve into the antibacterial activities of *M. oleifera*, exploring various phytochemicals, including phenolics, glucosinolates, flavonoids, fatty acids, esters, alkaloids, sterols, and terpenes, with specific focus on their application in dental health (Amin et al. 2024). Abdelazim et al.'s recent review synthesizes biochemical and medicinal significance, highlighting *M. oleifera*'s role in controlling blood glucose levels and diabetes. The plant's richness in fatty acids, amino acids, proteins, polysaccharides, minerals, and vitamins is meticulously detailed (Abdelazim et al. 2024). Jikah & Edo provide a comprehensive overview of *M. oleifera*'s anti-diabetic, anti-sickling, anti-obesity, anti-allergic, anti-atherosclerotic, aphrodisiac, anti-inflammatory, and antihypertensive activities, offering a detailed exploration of its multifaceted health impacts (Jikah & Edo 2023). This section critically discusses various health benefits associated with *M. oleifera*, shedding light on the responsible phytochemicals and bioactive compounds, and contributing to a thorough understanding of its overall health-promoting properties.

Nutritional supplement for children

M. oleifera emerges as a valuable resource in the prevention and treatment of child malnutrition, showcasing various benefits such as weight gain, elevated haemoglobin levels, reduced anaemia, and improved overall nutritional status. The plant's rich composition of essential vitamins A, B, and C, along with crucial minerals like calcium, phosphorus, zinc, potassium, and iron, as well as phytonutrients, makes it a potent solution to combat micronutrient deficiencies and malnutrition in children. These minerals play a pivotal role in supporting physical growth and development in children, as highlighted by Sokhela et al. (Sokhela et al. 2023). In addition to addressing nutritional concerns, *M. oleifera*'s potential impact on allergies and their influence on a child's growth and development is a subject of interest. In a study by Zhang et al. (Zhang et al. 2022), the allergic potential of *M. oleifera* leaf extract was explored through oral administration of allergens to mice. The investigation revealed histopathological modifications, systemic allergy symptoms, elevated levels of specific IgE/IgG antibodies, histamine, mast cells, T_H1-, T_H2-, and T_H17-related cytokine cells, and decreased body temperature. These findings suggest that both in vivo and in vitro allergic reactions can be induced by *M. oleifera* leaf extract. This comprehensive understanding of the potential impacts of *M. oleifera* on children's health encompasses both its positive contributions in addressing malnutrition and the need for cautious consideration in the context of allergies, thereby contributing to a more diversified evaluation of its use as a supplement for children.

Potent source of antioxidant

As a potent source of antioxidants, *M. oleifera* leaves have garnered attention for their rich phytochemical composition. A study conducted by Khalid et al. meticulously characterized the phytochemicals present in *M. oleifera* leaf extract, highlighting their significant antioxidant capabilities (Khalid et al. 2023). Notable antioxidants identified in the study include quercetin, gallic acid, chlorogenic acid, p-coumaric acid, ferulic acid, and sinapic acid, all of which contribute to the plant's robust antioxidant efficacy (Refer Tables 3 and 4 for more detail). These compounds play a crucial role in neutralizing free radicals, thereby aiding in the prevention of oxidative stress-related damage to cells and tissues. The diverse antioxidant activity observed in *M. oleifera* extends beyond the mentioned phytochemicals, providing a comprehensive understanding of its potential health benefits. Further exploration of additional antioxidant activities within the *M. oleifera* plant will be detailed in the subsequent section, shedding light on the holistic antioxidant profile of this remarkable botanical plant. This information contributes to the broader comprehension of *M. oleifera* as a valuable natural source of antioxidants, emphasizing its potential role in promoting health and mitigating oxidative stress-related conditions.

M. oleifera mistletoe association

The *M. oleifera* mistletoe association has been investigated for its impact on antioxidant levels, particularly in *M. oleifera* leaves. This evaluation was conducted using the *Drosophila melanogaster* model organism, initially exposed to a high-sucrose diet that triggered phenotypic responses, disrupted insulin signalling, and led to a redox status imbalance, ultimately inducing a diabetic state. Subsequent exposure to *M. oleifera* leaf extract in the diet resulted in the upregulation of superoxide dismutase (SOD), while the expression of Hsp70 and Dilp2 was downregulated. Consequently, leaves infested with mistletoe in the *M. oleifera* plant exhibited enhanced antioxidant gene activity, showcasing potential health benefits (Oyeniran et al. 2022).

Seed protein hydrolysates

Aderinola et al. demonstrated the efficient antioxidant properties of enzymatically hydrolysed peptides from *M. oleifera* seed protein isolates (Aderinola et al. 2018). The authors have employed various enzymes, including laccase, pepsin, and trypsin, to produce hydrolysates subjected to different antioxidant assays. In the DPPH assay, trypsin hydrolysate exhibited the highest activity (35.99%), followed by pepsin (29.62%) and laccase (24.62%). For the FRAP assay, laccase demonstrated the lowest activity (17%), while pepsin (21%) and trypsin (6%) displayed higher reducing power. In the metal ion chelation assay, laccase (29.5%) and trypsin (19.3%) exhibited significant activity, with pepsin showing fewer notable results. The study suggests the need for further in vivo investigations to confirm the antioxidant properties of protein hydrolysates and explore their potential health benefits (Aderinola et al. 2018). Notably, the laccase isolate displayed the highest angiotensin-converting enzyme (ACE) inhibitory activity, reaching approximately 75.1% (Aderinola et al. 2018).

Antibacterial activity

The *M. oleifera* plant showcases notable antibacterial activity across a broad spectrum of bacteria. A study conducted by Chandrashekar et al. emphasizes the efficacy of *M. oleifera* defatted seed extract and a coagulant protein (measuring < 7.5 kDa) against six pathogens, including *Escherichia coli, Salmonella paratyphi B, Salmonella typhimurium, Shigella flexneri, Salmonella paratyphi A,* and *Kelbsiella pneumoniae* (Chandrashekar et al. 2020). The crude extract, at concentrations ranging from 0.041 to 0.008 mg/ml, displayed significant growth inhibition lasting up to 6 h. Similarly, the coagulant peptide, at a concentration of 0.02 mg/ml, exhibited comparable growth inhibition over the same duration. This experiment suggests that the coagulant protein (< 7.5 kDa) present in the seed extract may be the key component responsible for the observed antibacterial activity (see the sequence and three-dimensional (3D) structure of this protein in Sect. "3D protein structures"). Moreover, the study hints at the potential application of the coagulant peptide in water decontamination, given its ability to inhibit the growth of harmful bacteria, showcasing promising coagulation efficiency. The multifaceted antibacterial properties of *M. oleifera* hold various applications, as elaborated in the subsequent topics.

Anti-biofilm agent in food industry

Addressing the global concern of foodborne illnesses, particularly from contaminated food, *M. oleifera* emerges as a potential solution in the food industry. Milk and dairy products, are often sources of contamination, face challenges associated with undesirable biofilms, particularly those formed by *Staphylococcus aureus*. *M. oleifera* oil, rich in fatty acids like oleic acid, behenic acid, and palmitic acid, demonstrated noteworthy inhibitory (0.5%) and bactericidal (1%) efficacy against *Staphylococcus aureus* biofilms on polystyrene surfaces. This suggests that *M. oleifera* could play a crucial role in ensuring microbial safety during food processing, presenting itself as a widely applicable and safe anti-biofilm agent, as highlighted by Oliveira et al. (Oliveira et al. 2023).

Food packaging applications

In the quest for sustainable alternatives to artificial preservatives in bakery goods, *M. oleifera* stands out as a natural source with potential applications in food packaging. Biobased films derived from *M. oleifera* leaf extracts exhibit effectiveness in extending the microbiological shelf life of wheat sliced bread without the need for synthetic preservation agents. This innovative approach, detailed by Braham et al., not only minimizes the use of synthetic preservatives but also offers a sustainable solution, showcasing the potential of *M. oleifera* in revolutionizing food packaging techniques (Braham et al. 2022).

Dental application

The antibacterial effectiveness of *M. oleifera* extends to dental applications, specifically in addressing gingivitis or periodontal disease caused by microbial infections. Faisal Madhloom et al. conducted an examination of *M. oleifera* seed extract's antibacterial activity against *Porphyromonas gingivalis*, an anaerobic gram-negative secondary pathogen linked to chronic periodontitis (Faisal Madhloom et al. 2022). The study found that a minimum concentration of 12.5 mg/mL was required for inhibitory action and anti-biofilm efficacy against *P. gingivalis*, showcasing the potential of *M. oleifera* in contributing to oral health and disease prevention.

Antiviral activity

M. oleifera leaves, rich in an array of bioactive compounds including benzyl isothiocyanate, chlorogenic acid, quercetin, moringinin, niazimicin, apigenin, chrysin, myricetin, pterygospermінin, squalene, α-tocopherol, and β-amyrin (see the comprehensive list of compounds and their function in Table 3), have demonstrated significant antiviral properties. Specifically, these compounds have been identified for their capacity to impede the growth of the Hepatitis B virus by activating cellular immunity, exhibiting a CC_{50} value of $\geq 200\ \mu g\ ml^{-1}$. Similarly, the bioactive compounds 4-[(α-L-rhamnosyloxy) benzyl isothiocyanate, niazimicin, niaziminin, and β-sitosterol-3-O-β-D-glucopyranoside, present in both *M. oleifera* leaf and seed, manifest inhibitory effects on the Epstein Barr virus-early antigen activation, with a CC50 value of $\geq 100\ \mu g\ ml^{-1}$ (Biswas et al. 2020). Additionally, *M. oleifera* leaf extracts have shown positive effects on HIV-infected patients. Highly active antiretroviral therapy (HAART), a cornerstone in treating HIV-positive patients, aims to maintain viral load below 50 copies/mL, thereby enhancing the life expectancy of individuals with HIV. However, HAART is accompanied by several side effects. In a study involving adult patients, supplementation with *M. oleifera* leaf powder was found to enhance immunological function, increase body mass index, and improve CD4 cell counts in HIV patients undergoing ART. Moreover, the study revealed that *M. oleifera* leaf powder supplementation could reverse the adverse effects of HAART-induced toxicity on testicular form, hormonal profile, and semen quality in adult male Wistar rats. Notably, the phytochemical quercetin emerged as a potential adjuvant for improving the effectiveness of HAART (Ndlovu et al. 2022). This underscores the potential of *M. oleifera* as a protective agent mitigating the side effects associated with HAART while offering additional benefits to HIV patients undergoing antiretroviral treatment.

Antiparasitic activity

Equine piroplasmosis, resulting from single or combined infections of intracellular parasites in bloodstream complexes, poses health challenges in horses. Young horses are susceptible to gastrointestinal parasitism, leading to various intestinal diseases. While synthetic anthelmintic therapies are commonly used, their efficacy is limited, and parasites often develop resistance. *M. oleifera* leaves, rich in tannins and phenols, exhibit remarkable inhibition against the development and hatching of eggs of intestinal nematodes, including *Strongylus sp., Trichostrongylus axei, Strongyloides westeri,* and *Parascaris equorum* (92.8% and 99.0%). Moreover, these compounds cause 100% mortality in second instar larvae at a dose of 5 mg/mL (García-Hernández et al. 2019). The research conducted by Elghandour et al. underscores the significant role of tannins in anti-parasitic activity, exerting damage to the cuticle and intestinal surface of nematodes (Elghandour et al. 2023). Furthermore, gallic acid exhibits noteworthy efficacy, inhibiting nearly 100% of gastrointestinal nematode eggs at a dosage of 1 mg/mL. Saponins play a pivotal role by destabilizing and penetrating egg membranes, while quercetin and caffeic acid contribute to inhibiting egg hatching and larval viability. The synergistic action of these compounds collectively showcases a potent anti-parasitic activity, as elucidated by Elghandour and colleagues (Elghandour et al. 2023).

Antifungal activity

The *M. oleifera* leaf oil extract showed minimum inhibitory effect (MIC) against *Trichophyton rubrum, Trichophyton mentagrophytes, Epidermophyton xoccosum* and *Microsporum canis* with a minimum inhibitory concentration of 1.6 μg/ml, 0.8 μg/ml, 0.2 μg/ml, and 0.4 μg/ml, respectively. Whereas *M.*

oleifera seed oil extract efficient MIC of 0.125 µg/ml against *M. canis*. These are common skin infection causing fungal pathogens (Chuang et al. 2007). Similarly, in a study conducted by shruthi et al., two peptides from *M. oleifera* leaf having antifungal properties against *Alternaria alternata* and *A. brassiciola* with an IC_{50} value of 25.5 µg/ml to 60.43 µg/ml after 24 hour incubation. These two peptides are chitin binding hevein-like peptides, which play a role in plant defence against fungus (Kini et al. 2017). Bismuth metal-based nanoparticles with a size of 25 nm, synthesized from *M. oleifera* leaves, demonstrated anti-fungal activity against *Aspergillus niger, Aspergillus flavus, Candida albicans*, and *Candida glabrata*. The MIC values for the *M. oleifera* leaf extract were 62.5, 62.5, 125, and 250 µg/ml, respectively. In comparison, the bismuth nanoparticles exhibited even stronger anti-fungal properties with MIC values of 250, 250, 62.5, and 62.5 µg/ml, respectively. Thus, *M. oleifera* leaf extract possesses potent antifungal properties, particularly against *Aspergillus niger* and *Aspergillus flavus*, while the bismuth nanoparticles show enhanced efficacy against *Candida albicans* and *Candida glabrata* (Das et al. 2020).

Anticancer activity

M. oleifera, has gained attention for its potential anticancer properties. The plant is rich in bioactive compounds such as flavonoids, polyphenols, and glucosinolates, which are believed to contribute to its anticancer activity. From the literature it is evident that *M. oleifera* extracts may possess anti-proliferative and apoptotic effects, and they may inhibit the growth of cancer cells and induce programmed cell death. Additionally, the presence of various antioxidants in *M. oleifera* is thought to play a role in neutralizing free radicals, which are implicated in the initiation and progression of cancer. Moreover, *M. oleifera* has demonstrated anti-inflammatory properties, and chronic inflammation is often associated with an increased risk of cancer. By mitigating inflammation, *M. oleifera* may contribute to a reduced cancer risk. As discussed in preceding sections, compounds within the *M. oleifera* plant exhibit diverse properties, including antioxidant and anti-inflammatory effects, highlighting its potential as an agent in anticancer activity. In a study conducted by Razis et al., the *M. oleifera* leaf extract, particularly niazimicin, a glucosinolate known as a rhamnose-containing special compound displayed antitumor effects (Razis et al. 2014). The in vivo two-stage carcinogenesis test on mouse skin demonstrated a 50% delay in tumor development, reducing papilloma frequency by 80% at 10 weeks and 17% at 20 weeks of promotion (Razis et al. 2014). Subsequent sections delve into *M. oleifera* plant's effects on various cancer types.

Treatment of non-Hodgkin's lymphoma

The comprehensive study conducted by Kumar Sandeep et al. delves into the profound effects of *M. oleifera* leaf extract on white blood cell lymphoma, utilizing an in vitro model based on Dalton's lymphoma cells (Kumar Sandeep et al. 2023). The key bioactive compound, gitoxigenin, identified in this research, plays a pivotal role in controlling cell growth by modulating the MEK/ERK pathway, which is intricately involved in various intracellular signalling pathways as elucidated by Bedir et al. (Bedir et al. 2021). Additionally, the induction of apoptosis, a crucial mechanism in combating cancer, was explored in the context of changes in mitochondrial membrane potential, in which the betulin compound were found to induce mitochondrial cytochrome c release associated apoptosis (Li et al. 2010). Transitioning to in vivo studies using a mice model, the *M. oleifera* leaf extract exhibited compelling results, inducing cell cycle arrest specifically at the G2/M phase of cancer cells. This pivotal finding signifies a potential mechanism through which *M. oleifera* can impede cancer progression. Moreover, the research illuminated other notable outcomes, including an increase in lifespan, recovery in haematological parameters, and a reduction in both angiogenesis and metastasis. These findings collectively underscore the multi-faceted anti-cancer properties of *M. oleifera* leaf bioactive compounds. The study concluded with a noteworthy observation of the anti-proliferative activity of *M. oleifera* leaf bioactive compounds, quantified by an IC_{50} value of 300 ± 5.60 µg/ml. This value indicates the concentration at which *M. oleifera* leaf extract demonstrates half-maximal inhibitory activity, offering a quantitative measure of its potency in providing protection against cancer, as highlighted by Kumar Sandeep et al. (Kumar Sandeep et al. 2023). This research significantly contributes to our understanding of *M. oleifera*'s potential therapeutic role in combating white blood cell lymphoma, presenting a promising avenue for further investigation and potential clinical applications.

Regulation of glioma cells

M. oleifera seed-based synthetic isothiocyanate compound, named 4-[(α-L-rhamnose oxy) benzyl] or methyl isothiocyanate (MITC), demonstrated potent anti-cancer activity against glioma cancer cells. The mechanism involves increased expression of caspase-3, enhanced Bax: Bcl-2 ratio, induction of S and G2 cell cycle phase arrest, and modulation of protein expression levels, including CDK2, cyclinA2, cyclinE, and cyclinD1. Additionally, MITC activates JNK, a protein involved in the apoptotic pathway, showcasing strong effects against glioma malignant tumor cells (Xie et al. 2023).

Cardio-protective mechanisms in chemotherapy

The administration of cytotoxic chemicals for cancer therapy, commonly known as chemotherapy, often involves potent drugs like doxorubicin, a topoisomerase inhibitor. Doxorubicin acts by disrupting the normal function of nuclear enzymes, specifically topoisomerase I and II, crucial for DNA replication, transcription, and repair. This interference induces transient single or double strand breaks in DNA, leading to more permanent breaks and impeding normal DNA function. While effective against cancer cells due to their rapid division, these drugs also impact rapidly dividing normal cells, resulting in severe side effects, notably cardiotoxicity (Nygren 2001). Among the chemotherapy drugs, doxorubicin stands out for its efficacy against cancer cells but is associated with significant adverse effects, including elevated oxidative stress, suppression of protein and nucleic acid synthesis, cardiomyocyte death, and disruptions in mitochondrial biogenesis. To address these concerns, Pathintingan et al. conducted a pivotal study demonstrating the potential cardio-protective role of *M. oleifera* leaf extract (Patintingan et al. 2023). In this experimental study using Sprague–Dawley rats, *M. oleifera* leaf extract was orally administered at doses ranging from 200 to 400 mg/kg of body weight as a supplement. The results showcased the extract's effective cardio-protective action, particularly through the pathway of mitochondrial biogenesis. The extract mitigated apoptosis, restored the gene expression of PGC-1 (peroxisome-activated receptor-gamma coactivator-1 alpha), and activated Nrf2, a crucial regulator of mitochondrial biogenesis. This concerted action helped alleviate the side effects induced by chemotherapeutic drugs, emphasizing the potential of *M. oleifera* leaf extract as a complementary therapeutic strategy to enhance the safety profile of chemotherapy (Patintingan et al. 2023). This study sheds light on the promising role of *M. oleifera* in minimizing the adverse impacts of chemotherapy on the cardiovascular system, providing a valuable avenue for further exploration in cancer treatment protocols.

M. oleifera based drug delivery system for cancer therapy

In addressing the limitations of non-site-specificity observed in many chemotherapeutic drugs, the development of an advanced drug delivery system has emerged as a pivotal strategy to enhance treatment efficacy. This approach aims to improve the specificity of drug delivery by releasing therapeutic agents in response to tumour-specific conditions such as changes in pH, temperature, enzyme activity, or other unique factors. In a study conducted by Ranote et al., the potential of *M. oleifera* gum nanogel as a novel drug delivery system was demonstrated, particularly for the targeted delivery of doxorubicin (Ranote et al. 2022). The preparation of the *M. oleifera* gum nanogel involved the use of acrylamide and N,N'-methylenebisacrylamide through a process that included γ-radiation, hydrolysis, and subsequent centrifugation. The resulting nanogel showcased an impressive loading efficiency of approximately 98.35%. To assess its effectiveness at the tumor site, the nanogel was subjected to a cytotoxicity study using *Rhabdomyosarcoma*, a tissue sarcoma cell line. In vitro studies further revealed that the release of doxorubicin from the *M. oleifera* gum-loaded nanogel was 91.92% at pH 5.5 and 12.18% at pH 7.4. This approach signifies the potential of *M. oleifera* gum nanogel as a pH-responsive intracellular drug delivery system tailored for anti-cancer therapy. The system demonstrates a high degree of precision in drug release, showcasing its potential to minimize side effects associated with traditional chemotherapy. Thus, the Ranote et al.,'s study, illuminates a promising avenue for the future development of targeted and more effective cancer treatment strategies, highlighting the role of *M. oleifera* in the forefront of innovative oncological research (Ranote et al. 2022).

Management and treatment of metabolic disorders

Metabolic disorders, disruptive to the intricate balance of essential molecules and energy production in the body, present formidable health challenges, encompassing conditions such as diabetes, obesity, and dyslipidemia. Within the realm of potential remedies, *M. oleifera* emerges as a botanical powerhouse, rich in antioxidants such as quercetin, chlorogenic acid, and b-carotene. The robust antioxidant profile of *M. oleifera* assumes a pivotal role in combating oxidative stress, a known accomplice in the development of metabolic disorders. Oxidative stress, often exacerbated in these conditions, finds a formidable adversary in the antioxidative ability of *M. oleifera*. Chronic inflammation, a recurrent companion to metabolic disorders, is another frontier where *M. oleifera* demonstrates its therapeutic potential. Several studies hint that the anti-inflammatory properties inherent in *M. oleifera*, offering a promising avenue for managing the inflammatory facets intricately linked with metabolic conditions. In the intricate dance of blood sugar regulation, *M. oleifera* exhibits promising capabilities. Compounds like isothiocyanates present in *M. oleifera* contribute to enhanced insulin sensitivity and improved glucose metabolism, suggesting a role in maintaining optimal blood sugar levels. Lipid profiles, often perturbed in metabolic disorders, also come under the beneficial influence of *M. oleifera*. Studies indicate a positive impact on cholesterol and triglyceride levels, suggesting its potential in ameliorating dyslipidemia, a common co-conspirator in metabolic maladies. Weight management, a critical aspect of metabolic health, may find support in *M. oleifera*. The plant's potential to induce a feeling of fullness and reduce overall food intake offers a prospective avenue for those seeking assistance in weight control. While the promise of these benefits is compelling, caution is paramount. The efficacy of *M. oleifera* can exhibit variations, and individual responses may differ. Potential side effects and interactions with medications should be carefully considered. As with any supplement or dietary alteration, seeking guidance from a healthcare professional is advisable, especially for individuals with existing medical conditions or those on medications. This section investigates extensive research elucidating how *M. oleifera* may serve as a remedy for various metabolic disorders, providing a comprehensive exploration of its potential therapeutic applications.

Hepatoprotective effects

The hepatoprotective potential of *M. oleifera* leaf extracts incorporated as a supplementary dietary intervention to alleviate the impacts of Metabolic-Associated Fatty Liver Disease (MAFLD). A study conducted by Monraz-Mendez et al. involved subjecting mice to a high-fat sugar diet (60.3% lipids, 21.4% carbohydrates, 18.3% proteins, 2.31% g/v fructose, and 1.89% g/v sucrose) for 16 weeks, inducing Non-Alcoholic Steatohepatitis (NASH) (Monraz-Méndez et al. 2022). Subsequently, *M. oleifera* leaf extract was administered at a dosage of 290 mg/kg of the body weight of mice for 8 weeks. The outcomes showcased an anti-lipogenic effect, exerting a hepatoprotective influence on hepatic genes, microRNAs, and protein expression. Additionally, enhancements in insulin sensitivity, lipid metabolism, and epigenetic modifications linked with MAFLD were notably observed (Monraz-Méndez et al. 2022). In an alternate scenario, the widespread use of acetaminophen (APAP) as an antipyretic and analgesic raises concern about potential liver damage with excessive consumption. This is attributed to an increased synthesis of the toxic metabolite N-acetyl-p-benzoquinoneimine (NAPQI) and diminished antioxidant activity. *M. oleifera* leaf extract, enriched with bioactive compounds quercetin and gallic acid, emerges as a therapeutic ally against APAP-induced liver damage. Younis et al. reported that a daily dietary incorporation of 250 mg/kg of the body weight of *M. oleifera* leaf extract in experimental rats led to elevated concentrations of antioxidant enzymes and normalized liver enzymes functioning. This included parameters such as alkaline phosphatase, aspartate aminotransferase, serum total proteins, albumin, globulin, and total oxidative stress. Notably, the expression of crucial pathways involved in the inflammatory process, namely MAPK-8, TRAF-4, and TRAF-6, witnessed downregulation, underscoring the anti-inflammatory impact (Younis et al. 2022).

The omnipresent threat of heavy metals, pervasive pollutants in air, soil, water, and food, bears neurotoxic and oncogenic repercussions. These elements wreak havoc on blood biochemical markers and induce histopathological changes in kidney and liver tissues. In an experimental mice model, the administration of 300 mg/kg of the body weight of *M. oleifera* leaf extract and 60 mg/kg of the body weight of lead acetate showcased an enhanced and protective impact against the toxicity induced by lead acetate (Melebary and Elnaggar 2023). This emphasizes the potential of *M. oleifera* in counteracting the adverse effects imposed by heavy metal toxicity, marking it as a protective shield in the face of environmental challenges.

Blood glucose regulation

The careful regulation of blood glucose levels stands as a linchpin in overall health, ensuring the body's proper functioning, hormonal equilibrium, and averting complications like diabetes and hyperglycemia. In an interesting experimental study involving rats subjected to a high-fat diet and 20% fructose-laden drinking water, coupled with ethanolic extracts of *M. oleifera* leaf (administered at 1000 mg/kg of the body weight), a remarkable narrative unfolds (Irfan et al. 2022). In comparison to the control group, rats exhibiting metabolic syndrome showcased diminished plasma insulin levels, coupled with the inhibition of inflammatory responses, as illuminated by Irfan et al. in 2022 (Irfan et al. 2022). Beyond glycaemic control, *M. oleifera* leaf emerges as a defender against the intricate landscape of diabetic nephropathy. This condition, marked by non-enzymatic protein glycation, inflammation, oxidative stress, and the accumulation of advanced glycation end-products, finds a formidable adversary in the form of *M. oleifera*. Ahmad et al. investigated the effectiveness of *M. oleifera* leaf extracts in combatting the antiglycation process, positioning it as a viable alternative for the treatment and prevention of diabetes-related kidney dysfunction in diabetic rats (Ahmad et al. 2023). The leaf extract not only showcased utility in enhancing glucose tolerance and managing body weight but also orchestrated positive transformations in serum levels of triglycerides, total cholesterol, creatinine, urea nitrogen, uric acid, and total protein. The comprehensive amelioration extended to renal dysfunctions and morphological enhancements in kidney structure, underscoring the multifaceted therapeutic potential of *M. oleifera* in the realm of diabetes-related complications (Ahmad et al. 2023).

Regulation of lipid metabolism

The delicate balance of various lipids within the human body plays a pivotal role in averting afflictions like obesity and hepatitis. In a seminal study by Roglia et al., the orchestration of miRNA emerged as a potent ally in combating dyslipidemia (Roglia et al. 2022). The investigation unfolded using in vitro pre-obese animal models, strategically supplemented with *M. oleifera* seed extract in their dietary regimen. The consequential panorama revealed a notable reduction in lipid accumulation, coupled with the induction of apoptosis, a testament to the efficacy of *M. oleifera* in mitigating lipid-related disorders. In order to understand the molecular interactions, Roglia et al. pinpointed specific *M. oleifera* miRNAs crucial in safeguarding lipid metabolism integrity (Roglia et al. 2022). Among these, miR159a and miR156c stood out, and acted against the disruptive forces that could lead to lipidaemia. This insightful revelation sheds light on the intricate mechanisms by which *M. oleifera*, through the modulation of miRNAs, emerges as a promising intervention in maintaining the delicate equilibrium of lipid metabolism, paving the way for potential therapeutic applications (Roglia et al. 2022).

Management of PCOD

Polycystic Ovarian Syndrome (PCOD) is a complex hormonal disorder characterized by the production of many immatures or partially matured eggs in the ovaries, eventually developing into cysts. This condition poses risks such as insulin resistance, abnormalities in follicle development, and elevated levels of proinflammatory cytokines like TNF-α, IL-6, and IL-1β. These cytokines, in a cascading effect, activate NF-κB (Nuclear Factor Kappa B). In experimental studies involving PCOD-afflicted Wistar female Rattus norvegicus, a dosage of 500 mg/kg of body weight of *M. oleifera l*eaf extract, rich in the bioactive compound quercetin, was administered (Siahaan et al. 2022). Quercetin, renowned for its potential health benefits, showed significant efficacy in the study. The findings illuminated the extract's effectiveness in inhibiting the formation of Reactive Oxygen Species

(ROS), orchestrating an anti-inflammatory response, and curtailing the activation of NF-κB pathways. Furthermore, the isothiocyanate compound present in *M. oleifera* leaves played a pivotal role in resisting insulin action and hepatic gluconeogenesis. This comprehensive approach culminated in the mitigation of PCOD effects by adeptly addressing oxidative stress, inflammation, and the dysregulation of signalling pathways. Overall, the study by Siahaan et al. underscores the potential of *M. oleifera* as a holistic intervention in managing the multifaceted challenges posed by PCOD (Siahaan et al. 2022).

Neuroprotectant effects and control of neurological disorders

A neuroprotectant is a drug or agent used to protect the structure and function of neurons (nerve cells) in the brain and nervous system. Preventing, reducing, or repairing damage brought on by oxidative stress, inflammation, and other pathological processes is the main objective. Neuroprotectants are of tremendous interest in neuroscience and medicine, especially in the setting of neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and other ailments that cause neuronal damage. Neurological disorders are controlled by controlling or minimizing the symptoms, progression, and underlying causes of nervous system problems. This can involve using therapeutic strategies to reduce symptoms, halt the disease's course, or even repair brain damage. Medications, alterations to lifestyle, and other measures are common control tactics. *M. oleifera* has received interest because of its putative neuroprotective properties. *M. oleifera*'s bioactive substances, which include nutrients, anti-inflammatory agents, and antioxidants, are essential for maintaining brain function and shielding neurons from harm. *M. oleifera* contains antioxidants such as quercetin and chlorogenic acid, which help counteract oxidative stress, which has been linked to the development of neurological diseases. Furthermore, *M. oleifera*'s anti-inflammatory qualities might help to lessen inflammation in the neural system, which might delay the advancement of several neurological disorders. Furthermore, the plant's ability to regulate blood sugar levels and lipid metabolism may benefit illnesses where these characteristics are important, such as diabetes-related neurodegeneration. The studies conducted on *M. oleifera*'s neuroprotective qualities are summarized in this section.

Treatment of Alzheimer's disorder

In the treatment of Alzheimer's disorder (AD), while numerous therapies effectively address neurological disorders, the prolonged use of drugs often results in multiple organ dysfunction. The potential efficacy of *M. oleifera* leaf extract in managing Alzheimer's disease was assessed through an APP/PS1 mouse model (Mahaman et al. 2022). This double transgenic mouse expresses a chimeric amyloid precursor protein and a mutant human presenilin 1, both targeting neurons in the central nervous system and leading to Aβ overproduction. Aβ triggers cascades that induce Tau pathology, neuroinflammation, neurodegeneration, and synapse loss, ultimately causing cognitive deficits. The experimental mouse model, administered 400 mg/kg of leaf extract in 5 mL, demonstrated reduced production of promoting enzymes such as BACE1 and AEP. It also inhibited Aβ protein load while enhancing the levels of proteins involved in synaptic plasticity, such as PSD95 and synapsin1. The extract effectively halted the loss of dendritic spines and neurodegeneration (Mahaman et al. 2022). Quercetin and kaempferol, prominent phenols in *M. oleifera* leaves, have been shown to improve memory, learning, and cognitive functions by increasing the activity of antioxidant enzymes like superoxide dismutase (SOD) and catalase, while significantly reducing lipid peroxidase (LPO) levels (Essa et al. 2012). Gallic acid, a polyphenol and chlorogenic acid (a type of hydroxycinnamate) in *M. oleifera* leaves exhibit significant anti-inflammatory and antioxidant capabilities. These antioxidant activities play a neuroprotective role by inhibiting the activity of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE), thereby preventing their breakdown (Essa et al. 2012). *M. oleifera* demonstrated neuroprotective effects through various mechanisms, including increased blood supply to the brain, preventing brain ischemia (stroke), lowering ROS, and reversing scopolamine drug-induced decreases in phosphorylated ERK1/2 (extracellular signal-related kinases), protein kinases, and cAMP response element-binding protein (CREB) levels in the hippocampus. The extract improved spatial memory and restored acetylcholine levels, effectively halting the progression of Alzheimer's disease (Mundkar et al. 2022).

Treatment of Parkinson's disorder

In the context of Parkinson's disorder treatment, a glucosinolate compound derived from *M. oleifera*, namely sulforaphane, demonstrates promising potential in safeguarding C57Bl/6 mice from the neurotoxic effects of 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP). This protective effect is attributed to sulforaphane's targeting of the transcription factor-like Nrf2. Additionally, sulforaphane exhibits the ability to enhance the survival of nigral dopaminergic neurons, a crucial aspect considering their degeneration in Parkinson's disease. Another noteworthy glucosinolate derivative compound, isothiocyanate, present in *M. oleifera* seeds, showcases anti-inflammatory properties against MPTP-induced damage. This is manifested through a reduction in the production of proinflammatory cytokines, including interleukin-1 (IL-1), toll-like receptor 4 (TLR4), and tumor necrosis factor (TNF) (Mundkar et al. 2022).

Neuroprotective and anti-neuroinflammatory effects

Ferulic acid, a compound found in *M. oleifera* leaves, manifests its neuroprotective characteristics through various processes, including the suppression of amyloid protein precursor (APP), fibril destabilization, and inhibition of amyloid aggregation (Azlan et al. 2023). These mechanisms collectively contribute to the potential enhancement of neuron survival. Notably, ferulic acid upregulates the expression of PEA-15, a phosphoprotein abundant in astrocytes, acting as a robust defence against glutamate-induced toxicity in neurons. Furthermore, ferulic acid demonstrates significant anti-inflammatory properties by mitigating neuroinflammation in presenilin-APP mice. It also plays a crucial role in inhibiting the generation of proinflammatory cytokines such as TNF- and IL-1. Another noteworthy neuroprotectant present in *M. oleifera* leaf extracts is caffeic acid, which is the most prevalent phenolic ingredient. Caffeic acid contributes to bolstering the brain's defence mechanisms by significantly reducing malondialdehyde levels and elevating glutathione levels, an essential antioxidant (Azlan et al. 2023). The combined action of ferulic acid and caffeic acid underscores the potential therapeutic value of *M. oleifera* in neuroprotection and anti-neuroinflammation.

Prevention of memory impairment

Memory loss poses a critical challenge that not only diminishes one's chances of survival but also significantly impacts their quality of life. Working memory, a crucial cognitive system in our brains, facilitates the manipulation and temporary storage of information, including the limited storage of spatial information. The complexity of treating memory loss is compounded by the diminishing effectiveness and increased adverse effects of existing medications. In a study conducted by Afrin et al., ketamine-induced memory impairment was investigated in Wistar experimental rats (Afrin et al. 2022). The rats, treated with an oral dosage of *M. oleifera* leaf extract at 200 mg/kg of body weight following intraperitoneal ketamine administration (15 mg/kg of body weight), demonstrated noteworthy results. The experimental group exhibited significantly fewer working memory errors compared to the memory-impaired group, showcasing the lowest variability of working memory errors among the control groups. Additionally, the identified flavonoid, quercetin, played a protective role against ketamine-induced antagonist activity by enhancing the NMDA subunits (N-methyl-d-aspartate) in the nicotinic receptor (Afrin et al. 2022). These findings underscore the potential of *M. oleifera*, particularly its quercetin content, in preventing memory impairment and preserving cognitive function.

Regulation of sleep

Sleep plays a crucial role in maintaining overall health, and inadequate sleep can lead to drowsiness and increased susceptibility to illness. The GABAergic (gamma-aminobutyric acid) system is a key neurotransmitter system involved in regulating the process of sleep induction, particularly in activating sleep–wake cycles. Traditional treatments for insomnia often involve benzodiazepines and nonbenzodiazepines medications. Unfortunately, these medications are associated with adverse side effects, including amnesia, drug dependence, cognitive impairment, and muscle relaxation (Nesbitt et al. 2014). The flavanol kaempferol, characterized by its diphenyl-propane structure, emerges as a promising alternative. Acting as a positive modulator of GABAA receptors, kaempferol demonstrates its efficacy in an experimental mouse model (Liu et al. 2022). *M. oleifera* seed extract, enriched with the bioactive compound kaempferol, was found to activate the GABAergic system. This activation, characterized by sedative, hypnotic, and anticonvulsant effects, operates through Cl-channel activation in human cerebellar granule cells (HCGC) (Liu et al. 2022). These findings highlight the potential of *M. oleifera* and its kaempferol content as a natural and effective option for regulating sleep without the detrimental side effects associated with conventional medications.

Antiulcer and gastroprotective activity

Antiulcer and gastroprotective activity refers to the ability of substances, such as those found in *M. oleifera*, to protect the stomach lining and prevent the formation of ulcers. These activities are essential for maintaining gastrointestinal health and preventing complications such as gastritis, peptic ulcers, and gastroesophageal reflux disease (GERD). Substances with antiulcer and gastroprotective properties typically strengthen the mucosal barrier, reduce gastric acid secretion, increase mucin production, enhance blood flow to the stomach lining, and exhibit antioxidant and anti-inflammatory effects. Such compounds play a significant role in promoting gastric health and preventing the development of gastrointestinal disorders. *M. oleifera* is renowned for its remarkable antiulcer and gastroprotective activity, making it a valuable resource in addressing gastrointestinal ailments. Research indicates that *M. oleifera* possesses compounds that bolster the stomach's protective lining, mitigating the risk of ulcer formation. These bioactive constituents aid in fortifying the mucosal barrier, reducing gastric acid secretion, and enhancing the production of protective mucus. Furthermore, *M. oleifera*'s antioxidant and anti-inflammatory properties play a crucial role in shielding the stomach from damage and inflammation, thereby promoting overall gastrointestinal health. Extensive mucosal inflammation in the colon characterizes ulcerative colitis (UC), a condition often treated with anti-inflammatory drugs like sulfasalazine, mesalazine, infliximab, and adalimumab, which unfortunately come with various side effects and serious adverse events. *M. oleifera* leaves, rich in polysaccharides such as arabinogalactan, have shown significant antioxidant activity. In a study utilizing a dextran sulfate sodium-induced ulcerative colitis mice model, oral administration of *M. oleifera* polysaccharide substances at doses ranging from 25 to 100 mg/kg of body weight resulted in reduced colonic pathological changes, goblet cell production, crypt destruction, and inflammatory cell infiltration (Mohamed Husien et al. 2022). Additionally, *M. oleifera* leaf exhibited prophylactic efficacy against DSS-induced UC by reducing intestinal damage, suppressing the activation of the TLR4/MyD88/NF-κB signalling pathway, and inhibiting the release of inflammatory cytokines, accompanied by the maintenance of goblet cells and expression of tight junction (TJ) proteins (Mohamed Husien et al. 2022).

Moreover, *M. oleifera* leaf extract has shown promise in protecting against stomach ulcers and inflammation induced by bisphenol-A (BPA), a toxic chemical found in numerous products. Human exposure to BPA primarily occurs through the digestive tract, resulting in decreased gastric mucosal thickness, reduced gastric juice and prostaglandins content in gastric tissues, along with an increase in ulcer area and acid secretion (Abo-Elsoud et al. 2022). In a study by Abo-Elsoud et al., experimental rats were orally administered a combined dosage of *M. oleifera* leaf extract (200 mg/kg) and BPA (50 mg/kg of body weight) for 4 weeks, resulting in increased volume of gastric juice, prostaglandin E2 (PGE2), glutathione (GSH), and interleukin-10 (IL-10, an anti-inflammatory marker) contents, along with enhanced SOD activity. Consequently, the leaf extract demonstrated cytoprotective effects in treating ulceration through its antioxidant, anti-apoptotic, and anti-inflammatory activities (Abo-Elsoud et al. 2022).

Furthermore, intestinal ischemia/reperfusion injury (IIRI) is a condition characterized by insufficient blood flow in the major blood vessels supplying the intestine, leading to bacterial translocation. In an IIRI-induced experimental rat model, *M. oleifera* leaf extract showed protection against epithelial mucosal barrier disruption, bacterial translocation, and hepatic injury. This protective effect was achieved through the downregulation of oxidative stress-mediated caspase 3 activation. Bioactive molecules found in the *M. oleifera* leaf extract, namely hydrazine, 9-octadecenoic acid, 1,3-dioxolane, oleic acid, and nonadecanoic acid, exhibited effective antimicrobial activity (Afolabi et al. 2022). Collectively, these discoveries highlight the potential therapeutic advantages of *M. oleifera* leaf extract in alleviating inflammation, protecting against ulcers, and maintaining intestinal well-being across different disease conditions. These promising findings pave the way for additional exploration and potential clinical implementation in the future.

Promotion of wound healing

Wound healing is a complex process involving multiple stages, including inflammation, proliferation, and tissue remodelling. Challenges in wound healing can arise from various factors such as infection, poor circulation, and underlying health conditions like diabetes. *M. oleifera,* with its rich array of bioactive compounds including vitamins, minerals, and phytochemicals, presents a promising solution to these challenges. Its antimicrobial properties help combat infection, while its anti-inflammatory effects aid in reducing inflammation at the wound site. Additionally, *M. oleifera*'s ability to enhance collagen synthesis and promote angiogenesis can accelerate tissue repair and improve circulation, facilitating faster wound healing. Wound healing and the acceleration of epidermal regeneration are facilitated by *M. oleifera* leaf extracts, showcasing potent capabilities compared to conventional treatments in various studies. In one study, a 100 mg/mL *M. oleifera* leaf extract demonstrated impressive wound closure rates, reaching 93.1% in *Staphylococcus aureus*-infected animals, surpassing gentamycin's performance at 80%. Another study involving a 0.5% *M. oleifera* leaf-based ointment gel exhibited a remarkable 92% wound closure, outperforming silver sulfadiazine at 83% (Muhammad et al. 2016). Furthermore, oral administration of 100 mg/kg *M. oleifera* leaf extract accelerated wound closure in both normal and diabetic-induced rats, achieving closure rates of 92% and 88%, respectively, compared to the control group's 61% and 64% (Azevedo et al. 2018). Additionally, an oral dosage of 300 mg/kg ethyl acetate extracted *M. oleifera* seed extract demonstrated faster wound closure (99.87%) comparable to Vicco turmeric cream (99.90%) on day 14 post-wound (Hukkeri et al. 2006). In another approach, Kamel et al. explored the use of polysaccharide-based hydrogels combined with *M. oleifera* leaf extract for wound healing (Kamel et al. 2023). These hydrogels, known for their ease of synthesis and fluid absorption properties, were synthesized by combining polysaccharides from *M. oleifera* leaf extract with PVA and SA (sodium alginate) to form a *M. oleifera* leaf-based PVA scaffold hydrogel. The leaf extract exhibited significant scavenging activity, with identified polysaccharides including chlorogenic acid, coumaric acid, caffeic acid, naringenin, 3,4-Dihydroxybenzoic acid, and cinnamic acid. In vitro cell scratch studies using 0.4 mg/mL concentration of the scaffold hydrogel on human fibroblasts showed enhanced closure of cell scratches. Additionally, in vivo studies using 1 and 2 mg/mL of scaffold hydrogel demonstrated significant effectiveness in regenerating zebrafish tails after transection (Kamel et al. 2023).

Overall, the findings indicate the potential of *M. oleifera* extract to enhance wound healing across various formulations and dosages in diverse experimental settings. Furthermore, Mohammad shafie et al., in their study reported the toxicity assessments using *M. oleifera* have yielded promising results. For example, topical application of aqueous leaf extracts in a hydrogel form (500 mg) on excision wounds of Wistar rats (200–250 g), administered twice daily for 7 days, showed no signs of skin irritation. Additionally, oral administration to male Swiss albino rats (18–22 g) revealed an LD_{50} of > 5000 mg/kg. Similarly, the application of twigs (10 mg/mL) on wound areas of healthy guinea pigs demonstrated no signs of erythema or edema (Mohammad Shafie et al. 2022).

Management of osteoporosis

Osteoporosis is a bone disease characterized by low bone density and deterioration of bone tissue, leading to an increased risk of fractures. It primarily affects older adults, particularly postmenopausal women, due to hormonal changes that affect bone density. Challenges in osteoporosis management include limited effectiveness of current treatments in preventing fractures, potential side effects of medications, and the need for safe and effective natural alternatives. *M. oleifera* offers potential solutions to these challenges.

Its rich nutritional profile, including calcium, vitamin D, and other essential nutrients, supports bone health and density. Studies have shown that *M. oleifera* extracts have osteoprotective properties, promoting bone formation and inhibiting bone loss. Additionally, *M. oleifera*'s anti-inflammatory and antioxidant properties may help reduce inflammation and oxidative stress, which are associated with bone loss in osteoporosis (Soliman et al. 2021). Furthermore, *M. oleifera* has been found to enhance the absorption of calcium and other minerals essential for bone health, potentially improving the efficacy of osteoporosis treatments (Patel 2013). Its safety profile and minimal side effects make it a promising adjunct therapy or preventive measure for osteoporosis.

The imbalance induced by osteoporosis results in low bone mineral density, degeneration of bone microstructure, and altered bone turnover rates. Several factors contribute to osteoporosis, including decreased estrogenic levels in postmenopausal females and gut dysbiosis, characterized by an imbalance in gut microbiota. *M. oleifera* leaf extract has shown potential in reducing the number of osteoclasts, specialized cells crucial in the bone remodelling process (Hu et al. 2023). Key markers in bone and mineral metabolism include CTX-1 (C-terminal telopeptide of type I collagen), DPD/CREA (Deoxypyrinoline/Creatinine), and U-Ca/CREA (Urinary calcium/Creatinine). The anti-osteoporotic effect of *M. oleifera* leaf bioactive compounds involve improving gut microbiota by increasing the *Firmicutes*/*Bacteroidetes* ratio and *Lactobacillus* abundance. Myricetin and luteolin are credited with regulating MAPK signalling (Hu et al. 2023).Moreover, assessment of 25 and 50 mg/mL of *M. oleifera* leaf extract on the human osteosarcoma SaOS2 cancer cell line revealed enhanced bone cell metabolism, stimulating proliferation, differentiation, and mineralization. Phytochemicals such as β-sitosterol, quercetin, and kaempferol contributed to improved expression of osteoblastic BMP2 and Runx2 genes (Khan et al. 2022).

It is evident that the *M. oleifera*'s multifaceted health benefits highlight the plant's potential as a flexible natural medicine. *M. oleifera* seems to be a rich source of vital nutrients that kids need for healthy growth and development when taken as a supplement. Its high antioxidant content emphasizes its ability to scavenge free radicals, protecting the body from oxidative stress and promoting general health. Furthermore, *M. oleifera* has considerable antibacterial, antiviral, antiparasitic, and antifungal properties, making it a good choice for treating microbial infections. *M. oleifera* demonstrates encouraging anticancer effects in addition to its antibacterial qualities, indicating that it may be able to stop the growth of cancer cells. There is strong evidence that it can control blood sugar levels and enhance metabolic function, which makes it a promising therapeutic option for the treatment and management of metabolic diseases like obesity and diabetes. Because *M. oleifera* is a neuroprotectant, it may be able to lessen the effects of neurological conditions including Parkinson's and Alzheimer's. Furthermore, its antiulcer and gastroprotective effects promote gastrointestinal health by inhibiting ulcer formation and protecting the gastric mucosa. *M. oleifera* is extremely effective at accelerating tissue repair and regeneration, allowing for speedier recovery from injuries. Additionally, continuing studies suggest that *M. oleifera* may help control osteoporosis by slowing down bone loss and encouraging bone growth. In the future, studies on *M. oleifera* may focus on clarifying its mechanisms of action, investigating new formulations for increased bioavailability, and carrying out extensive clinical trials to confirm the plant's medicinal usefulness across a range of demographics. In summary, *M. oleifera* shows promise as a natural medication with a wide range of health benefits. It also presents interesting opportunities for further research and application in both therapeutic and preventative medicine.

Structural and computational studies of bioactive molecules in *M. oleifera* plant

Structural studies, which involve isolation, purification, characterization, and analysis of bioactive molecules, are pivotal for unravelling cellular functions, understanding enzyme metabolism, and laying the groundwork for further investigations aimed at determining the three-dimensional structures of bioactive compounds. Additionally, computational techniques such as molecular docking and molecular dynamics simulations play a critical role in modern drug discovery and structural biology. Molecular docking studies assess the binding affinity of potential ligands to target protein molecules, providing insights

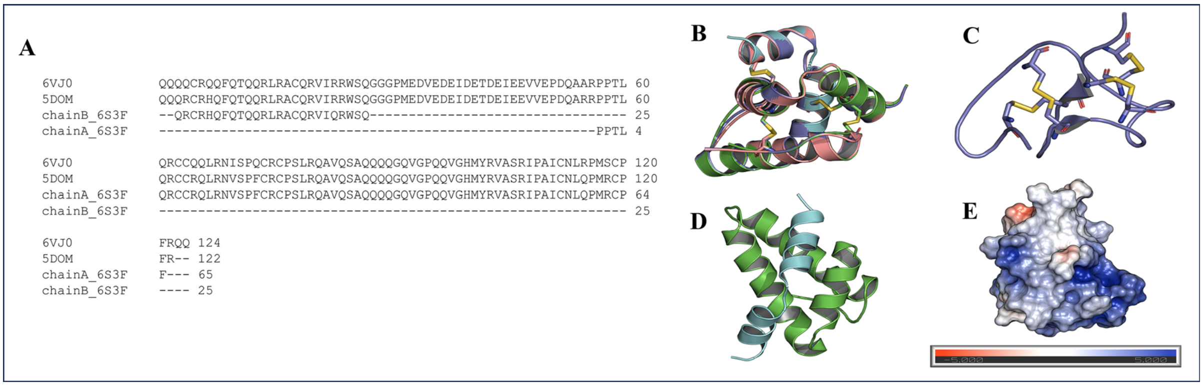


Fig. 3 Sequence and structural of comparison of *M. oleifera* proteins. A) Multiple sequence alignment of *M. oleifera* seed proteins (PDB ids: 6S3F, 5DOM and 6VJ0). B) Overlay of PDB ids 5DOM (purple), 6S3F (green - chain A, and blue - chain B) and 6VJ0 (pink) reveals very similar architectures. C) NMR structure of *M. oleifera* peptide (PDB id: 5WUZ). D) Crystal structure of MOCBP3-4 protein (PDB id: 6S3F), the green and blue colour highlighted are A and B chains, respectively. E) Surface charge distribution of MOCBP3-4 protein, where red, white, and blue represent negative, neutral, and positive charge respectively, with the electrostatic potential outline going from $-5K_BT/e$ to $+5K_BT/e$, where K_b, T and *e* are Boltzmann constant, temperature, and electronic charge respectively

into their interaction mechanisms. On the other hand, molecular dynamics simulations elucidate the dynamic behaviour and conformational changes of biomolecules over time, offering valuable information for drug design and optimization. These computational methods complement experimental approaches, offering cost-effective and time-efficient strategies for exploring molecular interactions and guiding the development of new therapeutics (Santos and Ferreira 2022). In contemporary drug discovery programs, computational methods have gained traction and proven successful in identifying robust molecules prior to synthesis. Traditional drug discovery approaches are expensive and time-consuming, often taking decades to yield results (Zhao et al. 2020). Molecular docking emerges as a particularly valuable tool in designing, evaluating, and comparing new drugs, as it enables the examination of molecular interactions in three-dimensional space, considering various molecular forms and elucidating the factors crucial for pharmacological interactions (Stanzione et al. 2021). *M. oleifera* structural and computational research are critical for understanding its diversified potential. These investigations clarify the bioactive substances found in *M. oleifera*, which helps in the creation of medications for a range of ailments. Environmental rehabilitation operations are also made possible by understanding the structural characteristics of the plant, especially regarding soil and water purification. Moreover, knowledge of *M. oleifera*'s nutritional makeup lends credence to its application as a dietary supplement in the fight against malnutrition. Biotechnological uses, such as the creation of genetically modified varieties and the optimization of agricultural procedures, expand its advantages. Overall, these investigations are critical in realizing the numerous benefits of *M. oleifera* for human health and environmental sustainability. This section addresses the structural and computational studies conducted on various parts of *M. oleifera* to date, evaluating their efficacy and potential applications.

Protein isolation and purification

The isolation and purification of proteins from *M. oleifera* plant extracts involve the extraction of various cationic proteins and peptides. These proteins are then meticulously studied to determine their molecular weights and functions. Various protein extraction methods have been employed for *M. oleifera,* each yielding proteins with different molecular weights and applications. Ion exchange chromatography resulted in proteins with molecular weights of 6.5 and 7 kDa, exhibiting flocculation activity (Gassenschmidt et al. 1995). Protein salting out using ammonium sulphate yielded a 7 kDa protein with coagulation activity (Dezfooli et al. 2016). Chitin binding column and CM Sepharose column purification led to a 23.4 kDa protein, known as Chitin binding protein 2 (Mo-CBP2), demonstrating antifungal activity against *Candida* species (Neto et al. 2017). Alkaline dissolution produced proteins ranging from 6.5 to 13 kDa and 66 kDa, showing coagulation activity (González Garza et al. 2017). Precipitation with ammonium sulphate resulted in a 51 kDa protein with caseinolytic activity (Banik et al. 2018). Solvent extraction at elevated temperatures yielded proteins of 6.5, 14.2, and 29 kDa, displaying oil absorption capacity, foaming capacity, and foam stability (Jain et al. 2019). Freezing and filtration produced proteins of 14 and 16 kDa with coagulation activity (Martha et al. 2016). Exhaustive dialysis yielded proteins ranging from 22 to 66 kDa, exhibiting nematocidal properties against *Meloidogyne* incognita infection (Sousa et al. 2020). Ammonium sulphate precipitation followed by freeze drying resulted in proteins of 20 and 35 kDa, showing foaming property (Du et al. 2022).

3D protein structures

As discussed earlier, protein 3D structures play a crucial role in various biological processes, and their complex arrangements are essential for their specific functions. One area where protein structures are particularly relevant is in water detoxification, where certain proteins can be employed to remove contaminants from water sources. *M. oleifera*, a versatile and nutrient-rich plant, has gained attention for its potential in water purification due to the presence of specific proteins and bioactive compounds. The seeds of *M. oleifera* contain proteins with coagulating properties that can aid in water purification. The primary protein responsible for this coagulation is *M. oleifera* coagulant protein (MOCP). This protein plays a crucial role in flocculation, which is the process of agglomerating or clumping together of particles in water. The coagulation process involves the addition of MOCP to water, causing impurities such as suspended particles and microorganisms to aggregate. Once these impurities form larger particles, they can settle down, making it easier to separate them from the water. As discussed earlier, coagulation-flocculation method is a simple and effective means of water clarification, making *M. oleifera* an attractive natural solution for water detoxification in certain regions where water quality is a concern.

The coagulation properties of MOCP have been applied in various water treatment projects, especially in regions where conventional water treatment methods may be impractical or unavailable. The unique properties of MOCP make them valuable in water treatment, offering an eco-friendly and sustainable solution for communities facing water quality challenges (Muyibi & Okuofu 1995). Continued research on protein structures and their applications in water purification holds promise for developing innovative and accessible solutions to address global water quality issues. MOCP not only exhibits coagulation properties for water purification but also possesses notable antimicrobial activities. This dual functionality makes it a particularly valuable tool in addressing waterborne pathogens and contaminants (Shailemo et al. 2016). The antimicrobial properties of MOCP contribute to the overall improvement of water quality by targeting and eliminating harmful microorganisms. The protein’s unique folding pattern and spatial arrangement of amino acid residues determine its interactions with different types of particles and microorganisms in water. These interactions enable MOCP to effectively neutralize pathogens, contributing to the safety of drinking water. Additionally, the 3D structure influences its ability to aggregate with suspended particles during coagulation-flocculation process. By efficiently binding with impurities, MOCP aids in the settling of particulate matter, improving wate clarity and removing microbial contaminates (Vunain et al. 2019). Thus, understanding the 3D structure of MOCP is vital for optimizing its performance in water purification. The 3D arrangement of amino acid residues in MOCP determines its stability, binding affinity, and overall effectiveness in the coagulation process. Researchers use techniques like X-ray crystallography (PDB ids: 6S3F, 6VJ0, and 5DOM) and nuclear magnetic resonance (NMR) spectroscopy (PDB id: 5WUZ) to elucidate the 3D structure of *M. oleifera* proteins, providing valuable insights for designing enhanced water purification strategies.

Structural comparison of M. oleifera proteins

A detailed structural comparison of *M. oleifera* seed proteins (PDB IDs: 6S3F, 5DOM, 6VJ0, 5WUZ) was conducted to elucidate structural analogies. Sequence-based alignment using the NCBI BLASTp tool (http://blast.ncbi.nlm.nig.gov/Blast.cgi) revealed significant identities among these proteins. Specifically, the reference protein template with PDB ID: 6S3F showed 100% and 91% identity scores with proteins 5DOM and 6VJ0, respectively, as depicted in Fig. 3A. However, the *M. oleifera* peptide with PDB ID: 5WUZ exhibited less sequence identity with MOCP. One of the first protein compounds extracted, purified, and crystallized was Chitin Binding Protein 3-isoform 1 (MOCBP3-1), a 2S albumin storage protein, reported by Ullah et al. (Ullah et al. 2015).. With a molecular weight of 14 kDa and a remarkable heat resistance of up to 98 °C, Mo-CBP3-1 displayed antifungal, antibacterial, and flocculating activities, attributed to the arginine and polyglutamine motifs within its structure. The predicted structure was submitted to the Protein Data Bank (PDB) with the ID: 5DOM, determined at 1.7 Å resolution, and characterized by two α-helical structures (Ullah et al. 2015). Subsequently, Moulin et al. confirmed MOCBP3-1 to be MOCBP3-4, with its crystallized structure (PDB ID: 6S3F) being one of the active compounds responsible for water purification from *M. oleifera* seed extracts (Moulin et al. 2019). The authors also observed more efficient flocculation when using a mixture composition of protein isoforms. Additionally, another crystallized structure with PDB ID: 6VJ0, featuring a resolution of 1.90 Å, was reported. Superimposed images of proteins with PDB IDs: 6S3F, 5DOM, and 6VJ0 revealed root mean square deviation (RMSD) values of 1.86 Å, 1.82 Å, and 0.13 Å, respectively, as illustrated in Fig. 3B. Kini et al. identified two protease peptides, termed 8C-hevein-like peptides, with antifungal properties in *M, oleifera* leaves (Kini et al. 2017). These peptides belong to a family of chitin-binding proteins known for their high cysteine content. Hevein-like peptides play a crucial role in plant defence by binding to chitin, a major component of fungal cell walls. The hevein domain/chitin-binding domain, highly conserved, facilitates the attachment of hevein-like proteins to chitin. In the leaf extract, two main peptide peaks with molecular weights of 4536.71 Da and 4463.76 Da were detected and named morintides mO1 and mO2, respectively, based on the *M. oleifera* mass spectrometry profile. Further analysis revealed that both mO1 and mO2 molecules contained peptides with 44 amino acids. Moreover, mO1 exhibited inhibitory effects on the growth of fungi *Alternaria alternata* and *Alternaria brassiciola*. Morintides demonstrated over 54% sequence identity with 8C-hevein-like peptides, with their structure deposited in the PDB ID: 5WUZ, as depicted in Fig. 3C (Kini et al. 2017).

Docking and simulation studies

Docking and simulation studies have garnered significant interest in the realm of drug discovery, offering an efficient, goal-oriented, and cost-effective approach to screening compound libraries against biological targets (Jakhar et al. 2020). Particularly, there is growing attention towards natural compounds due to their favorable safety profiles and reduced side effects, showcasing diverse therapeutic potential across different disease states (Gupta et al. 2021). Notably, phytochemicals sourced from *M. oleifera* have exhibited enhanced binding affinity and interactions with disease targets associated with various pathological conditions, as elaborated in the subsequent section.

M. oleifera compounds as inhibitor of SARS-CoV-2 proteins

Inhibiting SARS-CoV-2 Proteins: The global health crisis caused by the Coronavirus disease, or SARS-CoV-2, has resulted in economic disruptions and a scarcity of specialized medications, highlighting the urgent need for effective treatment options. Among the three major targets extensively explored for SARS-CoV-2 drug development, the SARS-CoV-2 spike (S) protein, RNA-dependent RNA polymerase, and Mpro protease play a pivotal role in viral replication (Natesh et al. 2021). In a study conducted by Sen et al., computational analysis was employed to evaluate the potential of *M. oleifera* plant phytochemicals as inhibitors against the main protease (Mpro) of SARS-CoV-2 (Sen et al. 2022). Three flavonoids namely isorhamnetin (− 7.1 kcal/mol), kaempferol (− 7.9 kcal/mol), and apigenin (− 8.0 kcal/mol) exhibited superior binding affinity during molecular docking. Notably, these compounds demonstrated similar binding poses to the well-known SARS-CoV-2 Mpro inhibitor, baicalein. Furthermore, the

RMSD values of the bioactive compounds during the 100 ns simulation were found to be less than 3 Å (Sen et al. 2022). In a separate investigation by Muhammad et al., the interaction between two proteins of SARS-CoV-2, namely nsp9 and nsp10—non-structural proteins recognized for their role in promoting IL-6/IL-8-mediated neutrophil chemotaxis and stimulating the host inflammatory response are explored in conjunction with *M. oleifera* bioactive compounds (Muhammad et al. 2021). Apigenin (− 7.1 kcal/mol) demonstrated efficient binding affinity for nsp10, while ellagic acid (− 7.1 kcal/mol) exhibited similar effectiveness for nsp9. Analysis of molecular dynamics simulation behaviour over a 30 ns timescale unveiled varying effects of the ligands on protein docking, as evidenced by RMSD values. Specifically, the ellagic acid-nsp9 complex displayed distinct behaviour, with the RMSD rising to 3.3 Å within the initial 10 ns and subsequently stabilizing from 10 to 30 ns. Conversely, the docking of apigenin perturbed the RMSD of nsp10 over 6 ns, after which both RMSD values stabilized from 6 to 30 ns, showing some fluctuations within a similar range of distance, approximately between ∼ 3.8 to ∼ 5.5 Å (Muhammad et al. 2021).

Fatty acid production from M. oleifera seed oil

Production of fatty acids from *M. oleifera* seed oil was investigated by assessing the catalytic behaviour of commercial lipases including Candida rugosa (CRL), Burkholderia cepacia (BCL), and porcine pancreas (PPL) at a molecular level through molecular docking with major fatty acids from *M. oleifera* Lam oil (Barbosa et al. 2019). Results revealed that CRL exhibited a robust affinity for oleic acid (C18:1), along with stearic acid (− 4.4 kcal/mol) and palmitic acid (− 4.5 kcal/mol). Conversely, BCL demonstrated a higher catalytic affinity for stearic acid (− 5.9 kcal/mol) and equal binding energies for palmitic acid. PPL exhibited a lower binding energy for palmitic acid of − 4.7 kcal/mol. Overall, BCL displayed a preference for stearic acid, directly interacting with its catalytic site, while PPL showed lower affinity and no interaction with the active site, explaining its diminished catalytic performance. CRL emerged as the most effective lipase in hydrolysing *M. oleifera* oil, primarily due to its preference for oleic acid (Barbosa et al. 2019).

Inhibition of epidermal growth factor receptor (EGFR)

EGFR, a member of the ErbB family of receptor tyrosine kinases, plays a pivotal role in various cellular processes such as proliferation, migration, adhesion, survival, and differentiation. Moreover, EGFR serves as a significant therapeutic target in cancer, and mutations or overexpression of EGFR can lead to anti-apoptosis, angiogenesis, and metastasis. In a study by Yousaf et al., various phytochemicals were screened for their potent EGFR inhibition through molecular docking studies (Yousaf et al. 2023). Identified compounds included Delta 7-avenasterol with a binding energy of 9.2 kcal/mol, 24-Methylenecholesterol (− 9.1 kcal/mol), Campesterol (− 9.0 kcal/mol), and Ellagic acid (− 9.0 kcal/mol). Additionally, molecular simulation over 100 ns showed that the compounds exhibited an average RMSD value of Delta 7-Avenasterol (6.1 Å), 24-Methylenecholesterol (8.5 Å), Campesterol (8 Å), and Ellagic acid (7.2 Å) (Yousaf et al. 2023). In summary, structural, and computational studies of *M. oleifera* not only offer solutions to environmental challenges such as water and soil contamination but also contribute to enhancing human health and well-being by providing access to nutritious food sources and natural remedies for various ailments.

Conclusion

Natural resources like water, air, and soil are not only necessary for human survival, but also essential for our everyday activities and overall well-being. But environmental pollution, a ubiquitous problem that directly affects human health and fuels the spread of several diseases, is a serious threat. Due to the constant development of the worldwide population and the rapid expansion of industry, waste generation has reached historic levels, resulting in widespread contamination of land, water, and air with hazardous compounds. These contaminants, which persist in the environment, have far-reaching repercussions, creating significant degradation and decontamination difficulties. The onset of numerous diseases in human populations can often be attributed to a complex interplay of genetic predispositions, lifestyle factors, and exposure to polluted environments. While modern medicine offers a multitude of treatments and pharmaceutical interventions, these often come with a host of adverse side effects, underscoring the need for safer alternatives. Natural plant sources, with their ease of cultivation, non-toxic nature, and compatibility with dietary supplements, present a promising solution. Among these, *M. oleifera*, commonly known as the "Drumstick plant" stands out for its rich history of medicinal use dating back to ancient times. Abundant in essential nutrients such as vitamins, minerals, and amino acids, *M. oleifera* plays a crucial role in fortifying the immune system and promoting overall health and well-being.

Extensive research has disclosed the unlimited benefits offered by various parts of the *M. oleifera* plant. From its effectiveness in water purification to its therapeutic properties in treating neurological and gastrointestinal disorders, *M. oleifera*'s versatility knows no bounds. Particularly noteworthy are its leaves and seeds, which serve as a potent source of protein and calcium, making them invaluable for both human and livestock consumption. The commercial sector has capitalized on *M. oleifera*'s diverse applications, developing a wide array of products across food and non-food categories. This comprehensive review seeks to illuminate the multifaceted advantages of different *M. oleifera* plant parts, highlighting its pivotal role in environmental pollution control and health enhancement. Understanding deep into the plant's diverse phytochemical composition and bioactive compounds, this review provides valuable insights into its therapeutic potential. Structural studies on identified proteins and peptides offer a glimpse into *M. oleifera*'s molecular mechanisms, paving the way for the development of novel synthetic derivatives with enhanced efficacy.

In the global hunger statistics of 2017, Asia stood out, representing 63% of the total population, which is equivalent to two-thirds of the world's populace. Alarmingly, around 821 million people worldwide suffer from undernourishment. Projections suggest that by 2030, approximately 2.2 billion individuals will lack access to effectively managed drinking water. Moreover, the United Nations has outlined 17 Sustainable Development Goals (SDGs), with Goal 2 and Goal 6 specifically targeting the improvement of malnutrition and access to safely managed drinking water for all. These goals are a response to the urgent need for action to enhance water and nutrient quality on a global scale. The comprehensive information and findings presented in this review hold significant implications for both environmental and health applications pertaining to the *M. oleifera* plant. Furthermore, this aligns with the SDGs 4 and 6, which emphasize addressing malnutrition and ensuring access to safely managed drinking water for all, thus responding to the urgent need to enhance water and nutrient quality worldwide, impacting both human and animal welfare. For a more sustainable and advantageous approach, the utilization of plants for environmental protection and water sustainability is paramount. The development of effective treatment methods is essential in this regard. Embracing more eco-friendly and innovative techniques, such as biological methods, is imperative to achieve these goals. The findings presented in this review align seamlessly with these global objectives, emphasizing the critical importance of improving water and nutrient quality on a global scale. Embracing sustainable approaches, such as leveraging plants for environmental protection and water sustainability, is essential in tackling these pressing challenges head-on. *M. oleifera* emerges as a formidable ally in the fight against various global challenges, showcasing remarkable capabilities across a spectrum of applications. From its proficiency in coagulation and flocculation to its potent antibacterial properties, *M. oleifera* holds immense promise as a source of antioxidants and medicinal compounds.

However, a clear understanding of its full potential requires further exploration, including the development of standardized formulations and rigorous safety assessments. While *M. oleifera* offers a plethora of nutritional benefits, its abundance of polyphenols may hinder the absorption of bioactive compounds, underscoring the importance of thorough investigation and safety evaluations. As discussed earlier, the *M. oleifera* plant parts, rich in a wide range of phytochemicals and bioactive molecules, hold significant potential across industries, environmental applications, healthcare, and food production. However, only a limited number of studies have reported the use of standardized formulations of *M. oleifera*, and many of these lack comprehensive details. Furthermore, qualitative analyses aimed at identifying the specific phytochemicals associated with *M. oleifera* are scarce, as are quantitative analyses determining the composition and formulation factors such as particle size of these phytochemicals, along with elucidating the mechanisms of action within *M. oleifera*. For future research endeavours, there is a need to explore the therapeutic potential of *M. oleifera* and its role in various applications such as supplementation or combination therapy. Additionally, safety assessments should be conducted to mitigate potential interferences with other therapeutic actions and to minimize unwanted adverse effects, ultimately optimizing efficacy. Despite the numerous nutritional benefits offered, the significant presence of polyphenols in *M. oleifera* plants can exert inhibitory effects on the absorption of bioactive compounds within the human body. These compounds, known as anti-nutritional factors, impede the absorption of essential nutrients. For instance, conflicting findings regarding iron absorption have been attributed to the high phytic acid content (Gallaher et al. 2017), while calcium absorption is hindered by the elevated oxalic acid content (Pankaja & Prakash 1994) in *M. oleifera* plants. Similarly, glucosinolate and saponin are identified as the primary anti-nutritional factors found in *M. oleifera* seed meal. Hence, there is a critical need to thoroughly investigate each phytoconstituent, including their content and bioavailability. Phytochemicals such as tannins, saponins, oxalates, and phytates, although present in lower quantities, exhibit anti-nutritional effects. However, their concentration can be mitigated through maceration and drying processes. To assess the potential toxicity of *M. oleifera*, numerous experimental studies involving animals and humans have demonstrated the safety of consuming seeds, stems, and bark as nutritional components. Nevertheless, liver function tests have revealed elevated levels of aspartate transaminase (ALT) and alkaline phosphatase (ALP), along with decreased creatinine levels. As a precautionary measure, it is recommended to limit oral intake of *M. oleifera* plants to no more than 70 g per day (Pareek et al. 2023).

In conclusion, *M. oleifera* offers a broad spectrum of applications across various fields, with extensive research conducted on all parts of the plant. Further identification of bioactive molecules, phytochemicals, and proteins present in different plant parts can help elucidate mechanisms of disease prevention and activity at the molecular level. Protein-level studies can provide a foundation for structural information, which in turn can serve as a basis for various future studies. Despite these challenges, *M. oleifera* stands as a source of hope, offering a sustainable, eco-friendly, and efficient alternative for addressing the multifaceted challenges facing our planet.

Acknowledgements Harshika is thankful to Manipal Academy of Higher Education (MAHE) for providing necessary facilities and Dr TMA Pai PhD scholarship. The authors also acknowledge Ms. Thripthi Nagesh Shenoy (Department of Atomic and Molecular Physics, MAHE) and Dr. Afiya Eram (Department of Conservative Dentistry & Endodontics, Manipal College of Dental Sciences, MAHE), for their support.

Author contributions The study conception and design, material preparation, data collection, analysis, and first draft of the manuscript were written by Harshika. M. The study conception and design and critical revision of the work was done by Abdul Ajees Abdul Salam.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal. The authors declare that no funding and grants was received to assist with the preparation of this manuscript.

Data availability The authors are responsible for correctness of the statements provided in the manuscript.

Declarations

Conflict of interest The authors have no competing interest to declare that are relevant to the content of this article.

Ethical approval Not applicable.

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