DOI: 10.54083/BRT/7.3.2025/68-77

Bio. Res. Today 2025, 7(3):68-77

Biotica Research Today

e-ISSN: 2582-6654

March, 2025

Article ID: RT1730 **Review Article**

Moringa oleifera: A Multifunctional Natural Agent for Cancer Prevention and Therapy

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Open Access

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Conflict of interests: The author has declared that no conflict of interest exists.

How to cite this article?

Christopher, S.E.N., Tomaskinova, J., Christie, S.A.D., 2025. *Moringa oleifera*: A Multifunctional Natural Agent for Cancer Prevention and Therapy. *Biotica Research Today* 7(3), 68-77. DOI: 10.54083/BRT/7.3.2025/68-77.

Abstract

Moringa oleifera, often referred as the "miracle tree," has received attracted significant attention in recent decades due to its multiple therapeutic properties and unique phytochemical profile. Recent studies indicate that various extracts and bioactive compounds isolated from *M. oleifera* have potential anticancer activity *in vitro*, *in vivo* and *in silico* toward diverse types of cancer. This review summarizes recent evidence on the anticancer effects of *M. oleifera*, with emphasis on its underlying molecular mechanisms, such as modulation of critical signaling pathways like JAK2/STAT3, downregulation of oncogenes (*e.g.*, c-myc and p53) and apoptosis. There are several preclinical studies on the antitumor efficacy of curcumin in lung, colon, breast, liver and oral cancers, which, on the other hand, have been innovative approaches like nanoparticle formulations and molecular docking studies, that have made it possible to depict its bioactivity. This review demonstrates how *M. oleifera* contains nutritional value while discussing its capability to function with conventional anticancer treatments as an additional prevention and therapeutic approach. Our preclinical study holds promise but multiple hurdles related to extract availability and standardization of preparation and strong clinical evidence remain to be solved. The growing evidence demonstrates *M. oleifera* could serve as a new therapeutic candidate against different cancers but oncological testing of these findings needs more population-based clinical research.

Keywords: Anticancer activity, Apoptosis, Cancer prevention, *Moringa oleifera*, Molecular docking, Nanoparticle

Introduction

The quick increase of cancer-related fatalities remains uncontrolled by newly developed treatments thus making it a leading chronic disease over the world. The research of natural products and medicinal plants attracts much interest because scientists seek anticancer agents that are both efficient and less toxic and more affordable. Of these, the plant native to the Indian subcontinent, *Moringa oleifera* has quickly emerged as the most promising candidate, given its wide nutritional and medical properties that are widely cultivated across the globe.

Traditionally, the different parts of *Moringa oleifera* (leaves, seeds, roots and pods) have been used in traditional medicine since ancient times. Recent scientific research focuses on leaves because they contain high concentrations of vitamins together with minerals and antioxidants as well as bioactive compounds such as flavonoids and alkaloids and polyphenols (Arora and Arora, 2021; Bibi *et al.*, 2023). This diversity of phytochemicals offers a fertile ground for diverse pharmacological actions, including, but not limited

Article History

RECEIVED on 29th October 2024 RECEIVED in revised form 01st March 2025 ACCEPTED in final form 07th March 2025

to anti-inflammation, anti-redox and immunomodulatory effects, which ultimately play key roles in the control of carcinogenesis.

Recent findings have started to clarify the unique anticancer mechanisms of *M. oleifera*. For example, studies of its alkaloid extracts have shown potent anti-tumor activity in non-small-cell lung cancer models *via* the modulation of the JAK2/STAT3 signaling cascade, a pathway recognized as central to the proliferation and survival of cancer cells (Xie *et al.*, 2021). Furthermore, crude aqueous extracts of *M. oleifera* leaves have shown the ability to down-regulate the oncogenes BRCA1, mta-1, c-myc and p53 in multiple cancer cell lines, indicating a mechanism of action that may be useful in a wide variety of malignancies (Pappas *et al.*, 2021).

The therapeutic potential of *M. oleifera* is not limited to a single type of cancer. Some results in different cancer models are promising in preclinical studies. For example, *M. oleifera* leaf extract-synthesized silver nanoparticles have exhibited remarkable efficacy in a rat model of chemically induced colon cancer (Aboulthana *et al.*, 2021), and a breast cancer study demonstrated its promising activity through direct cytotoxic effects and synergistic interactions with conventional chemotherapeutic agents (Masarkar *et al.*, 2023; Moremane *et al.*, 2023). In addition, molecular docking studies along with ADMET (absorption, distribution, metabolism, excretion and toxicity) profiling analyzed binding affinities and pharmacokinetic properties of *M. oleifera*-derived compounds as anticancer agents, thus further supporting their development in that direction (Aja *et al.*, 2021; Saputri *et al.*, 2022).

This review is an attempt to summarize and consolidate the current state of knowledge concerning the anticancer potential of *M. oleifera* focusing on the molecular mechanisms associated with its bioactivity, preclinical evidence in diverse cancer models, as well as novel technological approaches to maximize its therapeutic efficacy. In doing so, we additionally highlight the challenges and limitations of the current research landscape while outlining pathways towards the eventual clinical translation of *M. oleifera* as a complementary agent in cancer therapy.

The following sections explore *M. oleifera*'s historical background alongside its phytochemicals and cancer prevention capability followed by preclinical investigations of its potential alongside nanotechnology research and proof of binding. It also analyzes the challenges of implementing this plant for cancer care solutions along with possible solutions. *M. oleifera* research provides a detailed molecular insight into its actions that supports its role in integrative oncology practice.

Historical and Ethnopharmacological Perspectives

Traditional medicine has employed *Moringa oleifera* for various uses since long time. The ancient writings of South Asia document how *Moringa oleifera* served three medical purposes, such as fever treatment, wound management and digestive disorder remedy. Every section of the Moringa plant has traditional medical applications since people use leaves and pods as vegetables while also using bark and roots for medicinal preparations. Traditional Indian and folk medicine refer to *Moringa oleifera* as "Shigru" because of its proven properties against oxidative stress together with its ability to decrease inflammation and promote general health benefits. The plant species *Moringa oleifera* commonly known as the "miracle tree" offers various therapeutic uses worldwide. According to Rode *et al.* (2022), this tree gains its status due to its nutritional benefits while providing anti-inflammatory alongside antimicrobial and antioxidant effects and anticancer and antihypertensive properties as well as hepatoprotective features with anti-ulcer benefits and antifertility attributes and diuretic effects.

Research conducted in recent times has proven some of the long-standing traditional views. Modern scientific studies have revealed how *M. oleifera* contains multiple bioactivities that exhibit strong anti-cancer properties. Research demonstrates a relationship between traditional utilization of this compound for inflammation control because it blocks important inflammatory mediators like NF-κB, TNF-α and IL-1β (Chis *et al.*, 2024). *M. oleifera* stands out in integrative medicine since it functions as both a nutritional supplement and a medical treatment. Research expands historical traditional medicine applications of *Moringa oleifera* by identifying which particular phytochemicals create its therapeutic benefits.

Phytochemical Composition and Bioactive Constituents

1. Overview of Nutritional and Phytochemical Profiles

Moringa oleifera contains various bioactive compounds playing a significant role in its wide range of medical treatment possibilities. The leaves contain high amounts of vitamins A, C and E, minerals like calcium, potassium, iron and a host of antioxidants, in particular. All these parts together contribute to the scavenging of free radicals and reduction of oxidative stress, which is important in the initiation and progression of cancer (Arora and Arora, 2021; Srivastava *et al.*, 2023).

2. Bioactive Compounds and Their Pharmacological Implications

Various phytochemical groups identified in *Moringa oleifera* function by multiple mechanisms to combat cancer cells are:

- *Flavonoids and Phenolic Compounds*: These antioxidant substances stop oxidative DNA damage caused by stress in the body. *M. oleifera* flavonoids disrupt cell communication pathways which control both cell development and programmed cell death functions. Research shows that antioxidant compounds in *M. oleifera* cause cancer cells to stop active cell cycles along with triggering programmed cell death (apoptosis) (Singh *et al.*, 2022).

- *Alkaloids*: Research shows that *M. oleifera* alkaloid extracts show important antitumor effects in lung cancer because they control JAK2/STAT3 signaling, which controls cell growth and survival (Xie *et al.*, 2021). Alkaloid compounds can link up with different molecular targets, which strengthen their complete anticancer capabilities.

- *Saponins and Terpenoids*: The compounds exhibit both anti-inflammatory properties together with immunomodulatory

characteristics. The ability of mesenchymal stem cells to regulate immune responses together with their anti-inflammatory properties holds great value for cancer patients whose persistent inflammation may increase tumor development (Arora and Arora, 2021).

• *Glucosinolates*: Multiple parts of the plant contain glucosinolates accompanied by their hydrolysis products, which participate in both detoxification processes and carcinogen metabolism regulation. Glucosinolates activate different phase-II detoxification enzymes to help prevent cancer development (da Silva *et al.*, 2021).

• *Vitamins and Minerals*: *M. oleifera* contains high levels of vitamins along with essential minerals which helps the anticancer outcomes because they strengthen immunity and shield cells from damage caused by oxidation (Bibi *et al.*, 2023).

3. Synergistic Effects of Phytochemicals

In many ways, one of the most intriguing things about *Moringa oleifera* is the potential synergy among its myriad bioactive constituents. The anticancer properties of individual components are considerable; however, it is their combination in the whole extract that may provide additive and/or synergistic properties that add on to their therapeutic effect. Such synergism may explain the down-regulation of oncogenes and apoptosis induction in several cancer cell lines, observed in reports of crude aqueous extracts of *Moringa oleifera* leaves (Pappas *et al.*, 2021).

Collectively, the varied phytochemical composition of *M. oleifera* creates a solid foundation for its anticancer potential. The interaction of these compounds, such as antioxidants, alkaloids, flavonoids and secondary metabolites, on malignant cells appears to have a cytotoxic property, in addition to modifying important pathways involved in carcinogenesis. *M. oleifera* is considered a potential natural resource in extractions for anticancer therapy due to the rich chemical contour presented. The collection of bioactive compounds possesses several components that demonstrate powerful anti-inflammatory properties essential for cancer progression reduction.

Anti-Inflammatory and Immunomodulatory Properties

The anti-inflammatory characteristics of *M. oleifera* serve as the primary mechanism through which this plant shows anticancer potential during tumorigenesis.

1. Inhibition of Pro-Inflammatory Pathways

The plant *M. oleifera* contains elevated polyphenols and flavonoids that function to stop the action of inflammatory enzymes, such as cyclooxygenase and lipoxygenase. Studied compounds demonstrate their ability to control NF-κB signaling pathways, which helps decrease secretion of cytokines including TNF-α and IL-1β (Chis *et al.*, 2024). *M. oleifera* reduces chronic inflammation to establish an unfavorable condition for cancer cell growth and proliferation.

2. Enhancement of Immune Surveillance

M. oleifera enhances immune function in addition to its anti-inflammatory qualities by supplying micronutrients that both boost natural and acquired immunity systems. Toxins and cancer cells may show better elimination by the immune system due to the combination of bioactive peptides and essential vitamins and minerals in gelatin. Physicians find immunomodulatory characteristics of cellulose sodium nanoparticles particularly useful for cancer treatment because they help decrease adverse effects from standard therapies while enhancing patient results.

Multiple anti-inflammatory bioactive compounds found in *M. oleifera* demonstrate strong potential to control cancer development.

Molecular Mechanisms Underlying Anticancer Effects

1. Modulation of Cell Signaling Pathways

Anticancer activities of *M. oleifera* stem from its capability to control essential cell signal pathways:

• *JAK2/STAT3 Pathway*: Alkaloid extracts obtained from *M. oleifera* prevent the JAK2/STAT3 signaling pathway in NSCLC human cells. The inhibitory effect reduces cell survival gene transcription and affects cell proliferation genes, leading to programmed cell death (apoptosis) (Xie *et al.*, 2021). The modification of this signaling pathway matters most due to its vital position in various cancers.

• *Down-Regulation of Oncogenes*: Several studies indicate that *M. oleifera* extracts suppress the activity of oncogenes, including c-myc, BRCA1, mta-1 and p53 mutated forms. Gene suppression has two effects on cells: it disrupts normal cellular cycles and blocks cancer cell proliferative signals to prevent tumor growth (Pappas *et al.*, 2021).

• *Cell Cycle Arrest*: Specific compounds found in *M. oleifera* cause cells to arrest at checkpoints such as G0/G1 or G2/M phases of the cell cycle. The arrest created by this method stops cancer cell multiplication before it becomes out of control, thus creating an opportunity to start the apoptotic pathway.

2. Induction of Apoptosis

Anticancer agents kill cancer cells through apoptosis induction as a fundamental mechanism of their action. Scientific studies have demonstrated *M. oleifera* extracts initiate apoptotic cell death in multiple cancer test models. Siddiqui *et al.* (2021) demonstrated that compounds extracted from *M. oleifera* fruits triggered human liver cancer cells toward apoptosis using caspase-3 enzymatic activity, which is important for the apoptotic cascade. Bhadresha *et al.* (2022) found evidence supporting the apoptotic effect of *M. oleifera* leaf extract against lung cancer cell lines, thus adding to its demonstrated cytotoxic effect.

Inner cell processes linked to apoptosis initiation depend on intrinsic and extrinsic signaling pathways. Oxidative stress and DNA damage usually initiate the apoptotic process, which acts through mitochondria in the intrinsic pathway. The strong antioxidant capabilities of *M. oleifera* cause scientists to believe its phytochemicals defend cells against oxidative stress yet activate mitochondrial dysfunction to initiate caspase activation in cancer cells. The extrinsic

pathway, along with death receptor signaling, serves as a second mechanism for *M. oleifera* compound actions in apoptotic cell death processes, according to recent research evidence.

3. Inhibition of Cell Proliferation and Metastasis

Among its effects, *M. oleifera* demonstrates the ability to slow down cell multiplication in addition to blocking metastatic processes. The research conducted by Balogun *et al.* (2021) shows *M. oleifera* extracts can potentially modify the expression of the BRCA-1 gene through system biology evaluation. This gene oversees DNA repair pathways alongside cell cycle regulation. *M. oleifera* regulates both BRCA-1 expressions along with associated oncogenes which suppresses cancer cell proliferation and obstructs metastatic scattering.

Research shows that *M. oleifera* activates gene expression control, which results in c-myc oncogene suppression to stop cell cycle progression in malignant cells (Pappas *et al.*, 2021). The antitumor response from *M. oleifera* results from the dual action of cell cycle arrest and apoptosis induction, so it shows potential in anticancer drug development.

4. Antioxidant Activity and DNA Protection

M. oleifera demonstrates a protective dual mechanism against cancer formation because of its antioxidant functions. *M. oleifera* functions as an antioxidant defense that protects normal genetic material from DNA damage to prevent cancer development. Modifying redox balance inside cancer cells leads to excessive oxidative stress that exceeds the tolerance threshold of these cells, which results in their death. *M. oleifera* contains high amounts of vitamins and polyphenols, resulting in antioxidant activity that serves as the basis for its chemopreventive properties (Srivastava *et al.*, 2023).

The anticancer properties of *M. oleifera* function through multiple molecular pathways, which include both signaling pathway disruption and apoptotic cell death regulation and cell proliferation control while affecting inflammatory markers and antioxidants. The therapeutic potential of *M. oleifera* extract emerges from its complex bioactivity capabilities because of its abundant phytochemical content. Recent scientific studies validate the effectiveness of *Moringa oleifera* bioactive compounds which target the PI3K/AKT/mTOR signaling pathway to induce apoptosis and halt ovarian cancer cell growth for possible integration into oncologic care (Mutthuraj *et al.*, 2024). Preclinical research on different cancer models has validated the mechanistic findings by showing an effective antitumor effect.

Preclinical Evidence across Cancer Models

As illustrated in table 1, several preclinical studies have demonstrated that *Moringa oleifera* exhibits potent anticancer effects through various mechanisms.

Table 1: Preclinical evidence on the anticancer effects of Moringa oleifera

Type of Cancer	*M. oleifera* Extract/ Formulation	Mechanism/ Action	Outcomes	References
Lung Cancer (NSCLC)	*M. oleifera* alkaloid extracts	Modulation of the JAK2/STAT3 pathway; downregulation of survival genes	Reduced cell growth and induced apoptosis	Xie *et al*. (2021)
Colon Cancer	Silver nanoparticle formulations from M. oleifera leaf extract	Enhanced delivery via nanoparticle formulation improving bioavailability	Tumor reduction in a chemically induced rat model	Aboulthana *et al*. (2021)
Breast Cancer	M. *oleifera* bioactive compounds/extract	Targeting HIF-1α; anti-proliferative effects and promotion of apoptosis	Inhibition of cell growth and metastasis formation	Masarkar *et al*. (2023); Moremane *et al*. (2023)
Liver Cancer	*M. oleifera* fruit components; seed oil and leaves powder	Induction of apoptosis via caspase-3 activation; binding to TGF β1 for hepatoprotection	Cytotoxic effects on liver cancer cells and hepatoprotection	Siddiqui *et al*. (2021); Susanto *et al*. (2023)
Oral & Colorectal Cancer	Nanoparticle-based *M. oleifera* leaf extract formulations	Modulation of inflammatory proteins (e.g., TNFα, IL10, HSP27); induction of apoptosis	Inhibition of proliferation and tumor protein modulation	Budhy *et al*. (2023); Al-Shalabi *et al*. (2023)

1. Lung Cancer Models

NSCLC serves as one of the principal killers among cancer-related deaths throughout the international community. Xie *et al.* (2021) investigated *M. oleifera* alkaloid extracts through an important study which showed meaningful antitumor effects in NSCLC cell lines. The research established that the extract affected the JAK2/STAT3 signaling pathway which decreased cell growth and promoted cell death. The test results present reliable evidence to support further research on compounds derived from *M. oleifera* for lung cancer treatment approaches.

2. Colon Cancer Studies

The research on *M. oleifera* extends to investigating its effects on colon cancer. Scientists evaluated silver

nanoparticle formulations synthesized from *M. oleifera* leaf nano-extracts through their effect against chemically induced colon cancer in a rat model, according to Aboulthana *et al.* (2021). Scientists discovered that assessing *M. oleifera* compounds in nanoparticles when dispersed resulted in better tumor reduction and histopathological results in the case of treated animals. Laboratory experiments in test tubes confirm previous findings that plant extracts prevent colon cancer cell multiplication and demonstrate that this occurs through mechanisms that include cell cycle pauses and programmed cell death.

3. Breast Cancer Research

Treatments for breast cancer are complex because the disease features multiple subtypes and complex origins. Current scientific research demonstrates that *M. oleifera* extracts successfully inhibit the growth of breast cancer cells. The research by Masarkar *et al.* (2023) showed how *M. oleifera* bioactive compounds specifically act on hypoxia-inducible factor-1 alpha (HIF-1α), which enables tumors to thrive in hypoxic environments. The research by Moremane *et al.* (2023) investigated *M. oleifera* extracts to determine their anti-proliferative impact on breast cancer cells by causing cell death and blocking metastasis formation. The studies suggest *M. oleifera* shows promise as an extra therapy for breast cancer treatment by targeting hypoxic pathways.

4. Liver Cancer Models

Research shows that *M. oleifera* has demonstrated strong potential in treating liver cancer. The research by Siddiqui *et al.* (2021) investigated the toxic properties of *M. oleifera* fruit components against human liver cancer cells. The bioactive components demonstrated their ability to attach to caspase-3 through experimental cytotoxicity tests along with molecular docking evaluation of this essential apoptosis enforcement mechanism. The combined methodology indicated *M. oleifera* compounds hold great promise for killing hepatocellular carcinoma cells thus, enabling more research into preclinical and clinical development. According to Susanto *et al.* (2023), *Moringa oleifera* seed oil (MOSEIL) and leaves powder (MOLP) show strong hepatoprotective and anti-fibrotic abilities because they bind tightly to TGF β1, a crucial protein involved in liver disease progression.

5. Oral and Colorectal Cancer

Recent scientific evidence shows that *M. oleifera* exhibits potential benefits in controlling oral cavity cancers together with colorectal cancers. According to Budhy *et al.* (2023), the nanoparticle-based *M. oleifera* leaf extract formulations successfully controlled the protein expression profile including TNFα and IL10 and HSP27 in oral cavity cancer sample models. According to Al-Shalabi *et al.* (2023), the extracts from *M. oleifera* demonstrated two key actions that led to cellular proliferation inhibition and cancer cell death through the induction of programmed cell death. Multiple experiments indicate that *M. oleifera* has potential as a unique treatment for cancer through bioinformatics research findings.

6. Comparative Efficacy and Synergistic Effects

Multiple studies have shown that *M. oleifera* extracts have direct harmful effects on cancer cells while also making standard chemotherapeutic treatments work better. Multiple signaling pathways receive modulation and the phytochemical compounds demonstrate combined antioxidant and anti-inflammatory and immunomodulatory actions which create this synergistic effect. Research findings documenting the decrease of oncogenes in multiple investigations (Pappas *et al.*, 2021) show *M. oleifera* disrupts pathways responsible for cancer cell advancement while making cells more receptive to typical cancer treatments.

The anticancer potential of *M. oleifera* is demonstrated through solid experimental data from various cancer cell models. Scientific research has demonstrated *M. oleifera*'s effective cancer-fighting properties, which extend throughout the cancer types of lungs, colon, breast, liver and oral cancer making it essential to study its clinical applications in depth.

7. Herbal Syrup Formulation and Chemopreventive Efficacy

Laude *et al.* (2022) obtained important glucosinolate derivatives such as niazirin, niazinin, niazimicin, and niaziminin from *Moringa oleifera* seed ethanolic extract. Research findings showed that these compounds display strong antiproliferative along with apoptotic and antimigratory and antiangiogenic effects within different types of human cancer cells. The research team created a leaf extract-based herbal syrup formulation which served to activate antioxidant response elements (ARE) and specifically reduce SKOV-3 ovarian cancer cell multiplication while reinforcing the cancer-prevention properties of *M. oleifera*.

Although preclinical studies have validated anticancer potential of the *Moringa oleifera*, bioavailability constraints have kept investigators to search for alternate advanced methods such as nanotechnology and molecular docking, to improve therapeutic delivery.

Nanotechnology and Molecular Docking Approaches

1. Enhancing Bioavailability through Nanoparticle Formulations

Plant-based compounds encounter difficulty in becoming available for therapeutic use because their distribution in the human body remains insufficient. Through nanotechnology research, scientists have discovered effective solutions to handle these present obstacles. In recent times, investigations have focused on nanoparticle creation through *M. oleifera* extract to boost the delivery capabilities and therapeutic effects of its bioactive compounds. The anticancer properties in colon cancer models improved when researchers combined silver nanoparticles with *M. oleifera* leaf extract, according to Aboulthana *et al.* (2021). Furthermore, nanoparticles enabled better cell absorption together with sustained drug delivery of active agents, which generated superior therapeutic results.

The delivery of *M. oleifera* extracts through nanoparticles resulted in modified inflammatory cytokine and stress protein expressions, according to Budhy *et al.* (2023) in oral cancer studies, which demonstrate how nanotechnology strengthens the cancer-fighting properties of this plant material. The use of nanotechnology represents a possible

solution for creating targeted drug delivery systems that improve performance and reduce unintended side effects in the body.

2. Molecular Docking and in-Silico Studies

Modern pharmaceutical research significantly depends on molecular docking studies because of their critical nature for drug development. They offer insights into binding affinities and potential mechanisms of action of bioactive compounds. Studies have used molecular docking approaches to study *M. oleifera* chemical compounds binding with cancer-associated molecular targets.

Aja *et al*. (2021) performed extensive research that combined *M. oleifera* phytochemical-derived test compound synthesis with molecular docking and ADMET analyses. Several oncogenic targets that control cell proliferation and survival pathways were found to have effective binding capabilities with these compounds. The research of Saputri *et al.* (2022) utilized molecular docking to study *M. oleifera* leaf compounds as possible anticancer agents for colon cancer treatment.

The research conducted by Frengki *et al.* (2023) showed that *M. oleifera* leaf metabolites made cancer cells more responsive to doxorubicin drug treatment by incorporating computational models. The molecular docking analyses provide both *in vitro* and *in vivo* anticancer activity explanations and validate the potential of *M. oleifera* as an agent to develop new anticancer drugs.

Naw *et al.* (2023) carried out an investigation through in-silico methods to identify preliminary bioactive properties of *M. oleifera*. The approach involved obtaining compounds from standard databases while predicting their antioxidative and anticancer potentials followed by visualizing three-dimensional biochemical structures containing desirable bioactivity properties. The bioactivity assays revealed that Rutin a main flavonoid derivative of *M. oleifera* showed considerable antioxidant properties together with cancer-fighting abilities (Naw *et al.*, 2023). Research results show *M. oleifera*'s potential to become an alternative medicinal agent which justifies developing standardized drug products from it.

3. Integrating in-Silico and Experimental Approaches

Molecular docking working together with experimental research creates a strong approach to finding new effective anticancer drugs. Virtual predictions function first as a screening method to identify potential compounds before further testing in lab and animal experiments. The combined approach delivers two essential advantages to the process: (i) immediate drug discovery operations become more efficient with the utilization of this method; (ii) bioactive compound interactions with target molecules become clearer to scientists due to this method.

Scientific investigation of *M. oleifera* applying nanoparticle technology and molecular docking methods has already produced beneficial outcomes that demonstrate better bioavailability along with cancer cell-specific toxicity in different cancer test models. The development of clinically useful therapies needs integration approaches to transform preclinical research results.

4. Integrating Computational and Experimental Methodologies

Researchers use molecular docking together with experimental studies as a solid framework within anticancer drug discovery research. Through virtual modeling *M. oleifera* bioactive compounds were identified leading to their analytical verification using cytotoxicity tests and animal experimentations. A holistic method speeds up the development of new cancer medications while it helps researchers understand better the chemical processes that control efficacy.

Integration of *Moringa oleifera* in Cancer Prevention and Therapy

1. Nutritional Supplementation and Functional Foods

In addition to its anticancer properties, *M. oleifera* provides significant nutritional value, which helps strengthen body systems to fight cancer. Through its high content of vitamins, minerals and antioxidants the plant stands as an important element in DNA protection against oxidative damage and reinforces immune strength at equal significance to cancer risk reduction (Arora and Arora, 2021; Bibi *et al.*, 2023). The medical community uses *M. oleifera* to create food supplements and functional foods that help prevent cancer development.

M. oleifera proves suitable for integrative oncology management because it provides nutritional benefits along with bioactive compounds for cancer treatment. The supportive nutrition in *M. oleifera* benefits chemotherapy patients because it may reduce chemotherapy side effects and enhance their quality of life.

2. Synergistic Use with Conventional Therapies

M. oleifera stands as a suitable choice in integrative oncology management since it combines nutritional advantages with therapeutic bioactive compounds for cancer therapy. Chemotherapy patients gain supportive nutritional benefits from *M. oleifera* that help decrease adverse reactions to their treatment while improving their lifestyle quality. Use of *M. oleifera* metabolites enhances breast cancer cell sensitivity to doxorubicin in laboratory tests (Frengki *et al.,* 2023), demonstrating how this effect could have practical clinical applications.

The combination of natural ingredients with standard therapies presents new possibilities to lower the development of drug resistance, which represents a major challenge in cancer treatment. The multiple cellular pathways targeting property of *M. oleifera* allows the potential to bypass resistance barriers, which reduce single-agent treatment effectiveness.

3. Radioprotection and Mitigation of Treatment Side Effects

Studies show *M. oleifera* possesses benefits that protect individuals from radiation damage. Adopting antioxidant properties enables *M. oleifera* to conserve healthy tissues from radiation therapy side effects by removing free radicals

produced during treatment. The study of *M. oleifera* supplements during radiation therapy through clinical investigations would generate crucial information about their ability to decrease treatment-related toxicity.

4. Regulatory and Safety Considerations

Multiple regulatory tests and safety assessments will help *M. oleifera* advance from laboratory testing to human clinical applications. Dietary supplements derived from *M. oleifera* receive safe status at present, yet concentrated extracts or single compounds intended for treatment purposes need thorough toxicity examinations. Standardized extraction methods with quality control procedures must exist to guarantee reliable and safe procedures. Upcoming clinical research needs to focus on defining optimal drug doses while collecting information about how the body processes the medication and performing extended-term safety tests in different patient groups.

5. Clinical Translation: Current Status and Future Prospects

The research demonstrating *M. oleifera*'s anticancer effects exists in abundance, but its clinical application development is currently in its initial stages. Extensive clinical trials must happen to confirm the safety and find the best dose levels and effective performance of *M. oleifera*-derived formulations when used by human subjects. *M. oleifera* needs additional research on extract composition consistency along with bioavailability testing so that healthcare professionals can use it as an established cancer therapy protocol.

The aggregate evidence from various *M. oleifera* studies at the molecular and cellular and animal levels justifies its clinical assessment. Future medical studies need to develop pharmacokinetic profiles as well as therapeutic window determination and extended outcome evaluation of cancer patients. *M. oleifera* shows potential as a safe adjunct therapy to potentially boost the effectiveness of current cancer treatments because of its favorable toxicological profile.

Nanotechnology and *in silico* studies gained from these insight allow for optimization of the delivery of *Moringa oleifera* compounds and the integration with conventional cancer therapies.

Integration into Conventional and Complementary Cancer Therapies

M. oleifera presents itself as an appealing therapeutic candidate because it uses multiple mechanisms to address cancer treatment such as:

1. Nutritional Supplementation and Functional Foods

The remarkable nutritional composition of *M. oleifera* qualifies it to function as a food with added health benefits. Strengthening such products through added *M. oleifera* extracts has resulted in both better nutritional values and enhanced antioxidant characteristics within fortified yogurts, beverages and dietary supplements. Objects categorized as functional food serve multiple health functions, including cancer-related benefits through their ability to cut down oxidative stress and reduce inflammation.

2. Synergistic Use with Chemotherapy and Radiotherapy

The scientific literature indicates that *M. oleifera* extracts work together with standard chemotherapy drugs to produce stronger cell-killing effects and minimize drug immunity. It contains antioxidant characteristics that provide protection against radiation damage when protecting normal tissues. This combination strategy to use this extract could reduce the required doses of toxic drugs used during chemotherapy or radiotherapy and also improve patient tolerance to this type of treatment.

3. Targeted Therapies and Personalized Medicine

Molecular tests and personalized medicine help doctors create treatment plans that match each patient's unique disease pattern when using *M. oleifera*. Treatments which use *M. oleifera* extracts may produce optimal results among patients whose tumors exhibit activity patterns in the PI3K/AKT/mTOR pathway or CDK dysregulation. The identification of receptive patient groups through clinical research together with biomarker examination remains essential to determine which patients would benefit from integrative treatment approaches.

4. Clinical Applications and Pharmacological Insights

The study by Darekar *et al.* (2023) presents an extensive review concerning pharmacological aspects and therapeutic usages of *Moringa oleifera*. The research establishes that the plant displays potent antioxidant properties together with anti-inflammatory and anticancer functions through its bioactive compounds. The researchers examined the problems associated with *M. oleifera* extract standardization along with its opportunities for creating pharmaceutical products for clinical use. Additional clinical studies must be conducted to optimize *M. oleifera* safety performance because existing evidence demonstrates its potential for therapeutic integration.

However, significant challenges including standardization, bioavailability concerns and long-term safety considerations remain to be overcome regarding *Moringa oleifera* integration with conventional treatments.

Challenges, Limitations and Future Perspectives

1. Standardization and Quality Control

Extract standardization from *M. oleifera* represents a significant therapeutic limitation to its therapeutic potential. Different production conditions during cultivation along with extraction methods and time of harvesting result in substantial phytochemical variations among *M. oleifera* products. The challenges for regulatory approval become more difficult due to the inconsistent preclinical research findings. Future researchers need to create standardized extraction methods together with quality assurance systems for obtaining consistent therapeutic benefits.

2. Bioavailability and Pharmacokinetics

The low bioavailability of *M. oleifera* phytochemicals reduces their effectiveness in human body systems. The therapeutic outcomes of these compounds suffer from their insufficient solubility along with speedy metabolism in the

body. The application of nanotechnology as a bioavailability enhancement method needs additional investigation to optimize delivery systems along with complete knowledge about the *in vivo* pharmacokinetics of *M. oleifera*-derived compounds.

3. Safety and Toxicity Concerns

The safety aspects of Molucca root consumption as a dietary ingredient are clear, whereas the safety assessments for extracted compounds or bioactive fractions remain under evaluation. Preclinical tests suggest low toxicity levels, but human beings need thorough toxicological assessments before final approval. Research focused on extended periods helps determine any unwanted side effects that might occur from long-term medication use, especially among cancer patients receiving ongoing treatment.

4. Integration into Multimodal Cancer Therapy

Fully implementing *M. oleifera* in cancer treatment requires combined efforts among traditional medical practitioners, pharmacological experts and clinical oncology specialists. Researchers need to examine how *M. oleifera* extracts would work with traditional chemotherapeutic medications and targeted therapy for a combined therapeutic effect. Combination therapy that targets tumors and their associated microenvironments has the potential to create the most beneficial therapeutic effects.

5. Economic and Accessibility Considerations

As a major benefit, *M. oleifera* exists at affordable prices throughout developing countries and around the world. The technical obstacles to pharmaceutical-grade scale-up production combined with quality control standards and advanced formulation technologies create post-economic obstacles. Global implementation of *M. oleifera* therapies requires resolving the mentioned key issues to succeed in low-resource regions.

Conclusion

The examined evidence indicates that *Moringa oleifera* presents extensive anticancer properties as a multifunctioning therapeutic agent. *Moringa oleifera* demonstrates its anticancer effects through its bioactive compounds that affect fundamental signaling pathways and trigger cellular apoptosis and kill cancer cells and combat chronic inflammation. Multiple preclinical studies show that both *Moringa oleifera* extracts and nanoparticles based on its formulations exhibit potent antitumor efficacy in various cancer models of lung, colon, breast, liver and oral types.

The experimental findings of *M. oleifera* receive additional support from molecular docking analysis as well as the benefits of incorporating *M. oleifera* into nutritional programs. None of the successful trial results addresses the continued challenges regarding standardization, bioavailability issues, and clinical translation needs. Next-generation scientific investigations need to solve these matters through proper clinical testing protocols along with state-of-the-art dosage technology and combined treatment methods.

The plant species *Moringa oleifera* brings great potential towards combating cancer as a natural resource. This plant could become an effective and low-risk element or supportive option in multimodal oncology management systems because it offers affordable treatments with minimal toxicity that enhance both patient outcomes and quality of life. The advancement of research projects shows potential for *M. oleifera* to change from traditional usage to foundational status in contemporary integrative oncology practices.

Future Research Directions

Additional research needs to focus on multiple important aspects:

✓ *Clinical Trials*: The medical community requires well-structured clinical research studies to determine *M. oleifera*'s effectiveness and security profile when treating cancer patients.

✓ *Mechanistic Studies*: The execution of modern molecular and systems biology techniques needs to happen to decode the intricate relations that exist between *M. oleifera* phytochemicals and cancer pathways.

✓ *Formulation Development*: The clinical benefit of *M. oleifera* extracts might increase through ongoing nanotechnology research and advancement of new drug delivery methods.

✓ *Biomarker Discovery*: The identification of predictive biomarkers for *M. oleifera* therapies would serve both to choose patients and develop individualized therapeutic approaches.

✓ *Integration Strategies*: The clinical success of *M. oleifera* depends on how researchers discover its most effective integration with current therapy treatments, including chemotherapy and immunotherapy and radiotherapy.

Preclinical research findings need transformation into clinical therapeutic methods, which will require solutions to these important implementation obstacles.

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