Review

Application of Nanotechnology in Enhancing Efficacy of African Herbal Medicines-A review

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Application of Nanotechnology in Enhancing Efficacy of African Herbal Medicines-A Review

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Abstract: African herbal medicine has been used for centuries as a means of treating various ailments. However, limitations in the effectiveness and delivery of these herbal remedies have necessitated exploration of alternative approaches to enhance their efficacy. Nanotechnology offers promising solutions by providing novel methods for delivery, targeting, and controlled release of bioactive compounds from the herbal medicines. This paper reviews application of nanotechnology in improving the efficacy of African herbal medicine. The use of nanocarriers, such as liposomes, solid lipid nanoparticles, polymeric nanoparticles, and nano emulsions, to encapsulate and deliver bioactive compounds have been discussed. Additionally, various nanotechnology-based strategies, including surface modification, targeted drug delivery, and stimuli-responsive systems have also been explored. Finally, the review has explored future perspective of African herbal medicine by looking at their safety considerations, regulatory aspects, and commercialization potential. The integration of nanotechnology applications with African herbal medicine has the potential to revolutionize traditional healthcare practices in Africa, by providing cheaper and effective therapeutic options to conventional medicines.

Keywords: African herbal medicine; nanocarriers; nanotechnology; bioactive compounds; efficacy; drug delivery

1. Introduction

Traditional herbal medicine is a sum of knowledge, skills, and practices based on theories, beliefs, and experiences of different indigenous cultures used in prevention, diagnosis, and treatment of illnesses. WHO refers herbal medicine as herbs, herbal materials, herbal preparations, and finished herbal products that contain whole plants, parts of plants, or other plant materials, including leaves, bark, berries, flowers, and roots or their extracts, as active ingredients intended for human therapeutic use or for other benefits in humans and animals. However, according to WHO, at least 80% of people in Africa still rely on medicinal plants for their health care [1]. Major obstacles to the use of African medicinal plants are their poor-quality control, efficacy and safety [2]. The future of African traditional medicine is bright if viewed in the context of its enhanced efficacy and safety through application of nanotechnology. Formal recognition and integration of traditional medicine into conventional medicine has much promise in the future if this will involve its proper identification, documentation, conservation, and utilization. Moreover, much of ethnomedicinal information is largely not validated by scientific evidence, to provide information on its scientific and clinical merit, which is drawn from *in vitro* and *in vivo* studies/bioassays on crude extracts from various plants [3]. The efficacy of extracts from a herbal plant is due to its complex chemical nature that provides certain therapeutic effects from its different parts. Chemical components or phytochemicals are found in plants, and they are responsible for various therapeutic effects of medicinal plants. These phytochemicals include alkaloids, glycosides, tannins, acids, coumarins, sterols, phenols, etc. Many modern pharmaceuticals have been modeled or are known to be originally derived from these

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chemicals, for example, aspirin is synthesized from salicylic acid derived from the bark of *Salix alba* and the meadowsweet plant, *Filipendula ulmaria*. Quinine from *Cinchona pubescens* bark and artemisinin from *Artemisia annua* plant are antimalarial drugs. Moreover, Vincristine and Vinblastine are anticancer drugs known to be derived from Madagascar periwinkle (*Catharanthus roseus*), used for treating leukemia. Morphine and codeine are derived from the opium poppy (*Papaver somniferum)*, used in the treatment of diarrhea and pain relief, while digitoxin is a cardiac glycoside derived from foxglove plant (*Digitalis purpurea*). Some medicinal plants are also important materials in the cosmetic industries [4].

2. African Herbal Medicine and Their Challenges

African herbal medicine has been practiced for centuries across the continent, with diverse indigenous knowledge systems reflecting the rich cultural and ecological diversity of Africa. Traditionally, herbal remedies have been central to healthcare in many African communities, often serving as the first line of treatment for various ailments. These herbal practices are based on the use of plants, plant-derived substances, and other natural resources to promote healing. However, despite their long history and widespread use, African herbal medicines face several challenges in terms of scientific validation, commercialization, and integration into modern healthcare systems [5].

2.1. Scientific Basis and Benefits of African Herbal Medicine

African herbal medicine relies on a wide array of plant species, many of which are used for treating infections, inflammation, pain, digestive disorders, and chronic conditions such as diabetes, hypertension, and cancer. The pharmacological properties of these plants are attributed to bioactive compounds like alkaloids, flavonoids, terpenoids, and tannins, which have demonstrated various therapeutic effects [6]. For example, *Prunus africana* is well-known for its efficacy in treating benign prostatic hyperplasia, while *Rauwolfia vomitoria* is used in the management of hypertension due to its reserpine content. Moreover, *Moringa oleifera*, which is often referred to as the "*drumstick tree*," is praised for its antioxidant and anti-inflammatory properties, making it a popular remedy for conditions like arthritis and malnutrition [7]. Several studies have shown that, African herbal medicines can exhibit antimicrobial, antiviral, and anti-inflammatory activities, contributing to their therapeutic potential. However, the full extent of these plants' medicinal properties requires further scientific investigation, particularly through controlled clinical trials and phytochemical analysis [8].

2.2. Challenges Facing African Herbal Medicine

One of the primary challenges in African herbal medicine is the absence of standardized production methods. Without rigorous quality control measures, the potency, purity, and safety of herbal products cannot be guaranteed. Variability in plant species, collection methods, and preparation techniques can lead to inconsistent outcomes and potential safety risks [9]. The rich knowledge of traditional herbal practices is often passed down orally, leading to the risk of losing valuable medicinal knowledge due to cultural erosion and decline of indigenous languages. Additionally, younger generations may not be as interested in learning or preserving these traditions, exacerbating the loss of indigenous knowledge on African traditional medicine [10]. While there is growing interest in African herbal medicines, scientific research and clinical trials are limited compared to other regions like Asia or Europe. Many herbs used in traditional African medicine have not undergone the required rigorous preclinical and clinical testing necessary to confirm their efficacy, safety, and optimal dosages. Without such validation, these medicines remain largely anecdotal in their use, hindering their acceptance in mainstream healthcare systems [11]. Moreover, in many African countries, the regulatory frameworks for herbal medicine are either underdeveloped or poorly enforced. This lack of regulation leads to proliferation of substandard products on the market, which can pose health risks. Moreover, there is often insufficient collaboration between governments, researchers, and traditional healers in establishing policies that would ensure safe and effective use

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of herbal medicines [12]. African herbal medicines are also often at risk of biopiracy, where pharmaceutical companies or foreign entities patent traditional knowledge and plant-based formulations without fair compensation to the indigenous communities who have long utilized these resources. This has raised ethical concerns about intellectual property rights and equitable access to the benefits of herbal medicine commercialization in Africa [13].

African herbal medicine offers a potential for addressing both common and complex health challenges across the continent. However, realizing this potential requires overcoming significant obstacles, including standardization, scientific validation, regulatory oversight, and protection of indigenous knowledge. Efforts to bridge the gap between traditional knowledge and modern scientific clinical practices are essential for the future integration of African herbal medicines into African healthcare systems. As research, policy development, and community engagement progress, African herbal medicines could play a critical role in the health and well-being of millions, not only in Africa but around the world, as has been the case with anti-malarial drugs like *Artemether* and *Quinine*.

3. Nanotechnology Application for Enhancing African Herbal Medicine Efficacy

3.1. Adverse Effects

An adverse drug reaction is a harmful reaction due to use of a medicinal substance, which requires prevention or change of dose and/or method of administration, or withdrawal of the medical substance. Any medicinal substance with therapeutic effect can generate unwanted or adverse side effects. The quality, efficacy, and safety of medicinal plants must also be assured just as it is with synthetic drugs. Despite the widespread use of herbal medicines globally, and their reported benefits, they are also not completely harmless. These concerns have been the focus of many medicinal plants research programs. The main toxic constituents from medicinal plants include; neurotoxins, cytotoxins, and metabolic toxins, which can cause harm to major human body systems, such as cardiovascular system, digestive system, endocrine system, urinary system, immune system, muscular system, nervous system, reproductive system, respiratory system, etc [14]. Moreover, several herbal medicines have been reported to have toxic effects and mechanisms for tracking these adverse effects are inadequate, because very few adverse reactions have been reported for herbal medicines, especially when used concurrently with conventional medicines [15,16]. Assessment of herbal toxicity can be difficult, and even when herbal-related toxicity is suspected, a definitive diagnosis is difficult to establish without conducting proper analysis of the plant material.

Toxicity may also arise as a result of herb-drug interaction in situations where there is co-administration of herbal medicines with some conventional drugs or supplements [17]. Incorrect identification and misuse of plants may also lead to toxicity. It is therefore pertinent at this time to have research protocols that will improve therapeutic value of herbal drugs by diagnosing occurrence of their adverse reactions and removing their toxicity [18]. Such information on improved efficacy and reduced toxicity can be invaluable in facilitating decisions for their future use.

3.2. Poor Bioavailability

Effectiveness of medicinal plants depends on supply of their bioactive compounds to target cells or tissues. Most of biologically active constituents of extracts, such as flavonoids, tannins, terpenoids, etc., are highly soluble in water, hence have low absorption because they are unable to cross the lipid membranes of the cells, and they also have excessively high molecular size, resulting in loss of their bioavailability and efficacy [19]. The chemical complexity of extracts is an extremely important consideration for the success of a formulation, because the formulation must also release the active ingredient. Nanotechnology applications can therefore be used to improve the solubility and stability of active herbal constituents, including extending formulation's action and successfully combining active substances with different degrees of cellular/tissue hydrophilicity/lipophilicity [20]. Nanostructured systems can therefore potentiate action of plant extracts, promote sustained release

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of their active constituents, reduce the required dose, decrease side effects, and improve their *in vivo* activity [21,22]. For example, Bhattacharya and Ghosh used lipid-based systems incorporating green tea and ginseng (*Araliaceae*) extracts in various formulations to increase the absorption of active components [23]. Moreover, Su et al developed nanoparticles using *Radix salvia miltiorrhiza* and improved bioavailability of the extract [24]. Some herbal components are highly sensitive to acidic pH of the stomach, which then promotes their destruction and loss of their desired effect after ingestion. Application of different drug delivery systems based on nanotechnology is therefore an interesting approach to improve most desirable properties of traditional medicine formulations [25].

4. Application of Nanotechnology in Herbal Drugs Encapsulation and Delivery

Herbal drugs need a novel scientific approach to deliver their components to targeted body sites in a sustained manner, to increase their therapeutic value by reducing toxicity and increasing their bioavailability. The novel drug delivery approach can be achieved by designing novel drug delivery systems (NDDS) for herbal drugs using nanotechnology, for enhancing their activity and overcoming associated challenges. Integration of a NDDS in the traditional medicine system is therefore essential in managing chronic diseases, such as asthma, diabetes, cancer, HIV/AIDS, TB, etc. [26]. Nanotechnology is a field of applied science which deals with manipulation of matter on a near-atomic scale to produce new structures, materials and devices at a 1 to 100 nm range. The application of nanotechnology in treatment, diagnosis, monitoring, and control of biological systems is referred to as nanomedicine, which includes chemotherapeutic agents, biological agents, immunotherapeutic agents, vaccines, etc. The NDDS can be made of safe materials, including synthetic biodegradable polymers, lipids, polysaccharides, nanoparticles, etc. [27].

The activity of herbal medicines depends on overall function of a variety of their active components, all of which provide synergistic action and thus enhance the therapeutic value of herbal drugs. However, most of the herbal drugs are insoluble in nature, which leads to their lower bioavailability and increased systemic clearance after ingestion, thereafter requiring repeated administration or higher dose, which makes them poor candidates for future therapeutic use. The chemical complexity of herbal extracts is an extremely important consideration for the success of a formulation, because it must also release the active ingredient. Vehicles of these drugs must therefore concurrently improve the solubility of the drug, minimize its degradation process, reduce any toxicity, and mask any bad taste, while controlling the active absorption and biological response [28,29]. The ability to improve new substances, such as by increasing selectivity and efficacy, protecting against thermal- or photo-degradation, reducing side effects, and controlling the release of their active constituents before they are used therapeutically, makes this approach even more attractive [30,31]. However, use of large sized materials in drug delivery poses major challenges, including *in vivo* instability, poor bioavailability, solubility, and absorption in the body, issues with target-specific delivery, and possible adverse effects from toxicity. The Use of new NDDS for targeting drugs to specific body parts can therefore be an option that might solve all these highlighted challenges, hence a need for understanding nanotechnology [32,33].

Research on nanomaterials has gathered significant attention in recent years due to their unique physicochemical properties, largely derived from their nanoscale dimensions. These properties make nanomaterials particularly attractive for a range of applications, especially in the fields of drug delivery, diagnostics, and bioimaging [34]. Below is a detailed literature review on five key types of nanomaterials, namely: liposomes, solid lipid nanoparticles (SLNs), polymeric nanoparticles, nano emulsions, and phytosomes.

4.1. Liposomes

Liposomes are spherical vesicles composed of one or more phospholipid bilayers, capable of encapsulating both hydrophilic and lipophilic substances. They mimic biological membranes, making them excellent candidates for drug delivery applications. Liposomes are made of lipids, which can be phospholipids (such as phosphatidylcholine) or other lipid molecules. The lipid bilayer

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can be single bilayer or multiple bilayers. Hydrophilic drugs can be encapsulated in the aqueous core, while hydrophobic drugs are incorporated into the lipid bilayer [35]. Liposomes are widely used for drug delivery to enhance solubility, stability, and bioavailability of poorly water-soluble drugs. Liposomes can deliver genetic material like plasmids to target cells, acting as non-viral vectors. Liposomal formulations can also serve as adjuvants in vaccines to enhance the immune response. The formulations can be used in topical formulations for delivery of active ingredients like vitamins and antioxidants to the skin [36,37].

Liposomes have many advantages such as biocompatibility and biodegradability, ability to deliver both hydrophilic and hydrophobic drugs, controlled release of encapsulated substances, and also, they have ability to enhance drug stability and reduce toxicity. Liposomes' challenges include; their large-scale production can be costly and complex, and they also have stability issues, such as they can undergo fusion, leakage, or aggregation over time. They also may have toxicity issues depending on their composition, where they may cause adverse reactions in some cases [38]. There are recent advancements on liposomes, for example, PEGylating, which is coating liposomes with polyethylene glycol, is used to extend circulation time in the bloodstream and prevent premature clearance by the immune system. Targeted liposomes resulting from surface modification with ligands can target specific receptors on diseased cells, e.g., cancer cells, thereby improving drug targeting [39].

4.2. Solid Lipid Nanoparticles

Solid lipid nanoparticles (SLNs) are colloidal carriers made from solid lipids which have been stabilized by surfactants. They are typically in the nanometer size range (10-1000 nm) and can encapsulate both hydrophilic and hydrophobic drugs [40]. SLNs are composed of a solid lipid core, which is often a triglyceride, fatty acid, or wax, surrounded by a stabilizing surfactant layer. The lipids are solid at body temperature, ensuring controlled drug release and protection of the encapsulated drug. Some applications of SLNs include; drug delivery, where they improve stability and bioavailability of drugs, particularly for lipophilic compounds. SLNs are used to deliver active ingredients such as vitamins or sunscreens. They can also encapsulate phytochemicals or other bioactive compounds for various therapeutic applications [41]. Some advantages of SLNs include; high stability due to solid lipid core, biocompatibility and biodegradability, controlled and sustained drug release. As regards to challenges, the SLNs have limited capacity for hydrophilic drugs, and formation of crystalline structures within SLNs can lead to instability and release problems [42]. Recent advancements on SLNs have come out with nanostructured lipid carriers (NLCs), which are a newer generation of SLNs that combine solid lipids with liquid lipids to overcome crystallization issues and improve drug loading [43].

4.3. Polymeric Nanoparticles

Polymeric nanoparticles are solid, submicron-sized particles made from biocompatible and biodegradable polymers. They can be classified into two main types: nanospheres (matrix systems) and nano capsules (core-shell systems). These nanoparticles are composed of natural or synthetic polymers like poly-lactic-co-glycolic acid (PLGA), chitosan, polycaprolactone (PCL), or poly-lactic acid (PLA). The drug can either be encapsulated within the polymer matrix (nanospheres) or dissolved in the core surrounded by a polymer shell (nano capsules) [44]. Polymeric nanoparticles provide controlled drug delivery, sustained release of encapsulated drugs, reducing side effects and improving therapeutic efficacy. By surface-modifying these nanoparticles with targeting ligands, drugs can be specifically delivered to cancer cells. The polymeric nanoparticles can also be employed for non-viral gene delivery [45]. The polymeric nanoparticles can be functionalized for customizable release profiles due to their versatile polymer composition, biocompatibility and Biodegradability. They also have the ability to target specific cells via surface modifications, for example antibody conjugation [46]. Degradation of some polymers may result in premature drug release or toxicity. The polymers may also require specific preparation methods, making their large-scale manufacturing

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difficult. These particles can release drugs in response to environmental stimuli, such as changes in pH, temperature, or enzyme activity, and by attaching targeting ligands or stealth agents like PEG, the polymeric nanoparticles can improve drug delivery specificity and reduce immune systemic clearance [47].

4.4. Nano Emulsions

Nano-emulsions are thermodynamically stable mixtures of oil and water, stabilized by surfactants, with droplet sizes typically between 20-200 nm. These droplets can encapsulate hydrophobic drugs and act as carriers for them. Nano-emulsions consist of an oil phase, an aqueous phase, and surfactants or co-surfactants to reduce surface tension and stabilize the droplets. The oil phase is typically composed of vegetable oils, medium-chain triglycerides, or other lipid compounds [48]. Nano emulsions are effective in delivering lipophilic drugs or poorly water-soluble compounds. Cosmetic and pharmaceutical formulations are used for encapsulating active ingredients like vitamins and essential oils for better skin absorption. Nano emulsions are suitable for both oral and intravenous administration due to their small size and stability [49]. They are particularly useful for drugs with poor water solubility, ease of fabrication and scalability. They are also stable over time, especially compared to conventional emulsions [50]. Despite being thermodynamically stable, nano emulsions can still be susceptible to phase separation under certain conditions. The choice of surfactant and co-surfactant is critical, as some may be toxic at higher concentrations. By incorporating targeting ligands on the surface of nano-emulsions, it is possible to direct them to specific sites in the body, such as tumor tissues [51].

4.5. Phytosomes

Phytosomes are complexes formed by binding plant-derived active ingredients, for example flavonoids and alkaloids, to phospholipids, creating a lipid-bilayer structure that facilitates better absorption of these bioactive compounds. Phytosomes consist of natural plant extracts complexed with phospholipids such as phosphatidylcholine. The plant molecules are encapsulated into the bilayer structure of the phytosome, enhancing solubility and bioavailability of poorly soluble bioactive compounds. [52,53]. The phytosomes are used to deliver herbal medicines like *Ginkgo biloba*, *Curcumin*, and others, with improved bioavailability [54]. They enhance the absorption of plant-based supplements, vitamins, and antioxidants. Phytosomes are also used in skincare formulations to improve penetration and effectiveness of plant-based active ingredients. By forming complexes with phospholipids, they enhance absorption and therapeutic effect of herbal extracts. The lipid-based structure of phytosomes improves the targeting of bioactive compounds to specific tissues [55]. Preparation of phytosomes requires the use of specific techniques, which can be resource-intensive. Similar to other lipid-based formulations, the phytosomes can be susceptible to degradation or oxidation. New advancements in the preparation of phytosomes include the use of more stable phospholipids, which enhance their shelf-life and effectiveness in topical and oral formulations. Phytosomes are being studied in combination with other therapeutic agents, such as in cancer therapy or metabolic disorders, to enhance therapeutic outcomes [56]. Each of the above liposomes, SLNs, polymeric nanoparticles, nano emulsions, and phytosomes offers distinct advantages in terms of drug delivery, bioavailability, and controlled release. However, their challenges remain as regards to stability, scalability and potential toxicity. Ongoing advancements in the formulation and targeting strategies, as well as new techniques like surface functionalization and nanostructured carriers, hold great promise in overcoming these challenges and expanding their therapeutic applications.

5. Strategies for Improving Efficacy of African Herbal Medicines

Herbal medicines have gained significant attention due to their therapeutic potential, but their full efficacy is often limited by challenges such as poor bioavailability, low solubility, and suboptimal absorption [57]. To address these limitations, several advanced drug delivery strategies have been

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developed to enhance the efficacy of herbal medicines**.** These strategies include; surface modification, targeted drug delivery, stimuli-responsive systems, and combination therapies.

5.1. Surface Modification

Surface modification of herbal drug delivery systems is a technique used to improve pharmacokinetics and therapeutic efficacy of herbal active compounds. Modifying the surface properties of nanoparticles, liposomes, or other delivery carriers can enhance their solubility, stability, and bioavailability. For example, coating of herbal extract-loaded nanoparticles with polyethylene glycol (PEG) or chitosan can help reduce drug degradation, improve absorption, and prolonged circulation time in the body [58]. Studies have demonstrated that, surface-modified nanoparticles can facilitate the controlled release of bioactive compounds and target specific tissues, thereby improving their efficacy in treating diseases like cancer and diabetes [59]. Moreover, the addition of surface-active agents or targeting ligands to drug carriers can enable site-specific delivery. For example, the conjugation of antibodies or peptides to nanoparticles allows for targeted drug delivery to specific cells or tissues, reducing off-target effects and increasing the therapeutic index. Surface modification has thus emerged as a powerful tool in improving the overall performance of herbal medicines by enhancing their stability, solubility, and targeting precision [60].

5.2. Targeted Drug Delivery

Targeted drug delivery is an approach that directs the active compounds in herbal medicines to specific cells or tissues, increasing the local concentration at the site of action and minimizing side effects. This strategy utilizes biological markers or surface receptors to guide the herbal active compounds to the intended targets, such as cancer cells, inflamed tissues, or specific organs [61]. Recent studies have shown that, nanoparticles, micelles, and dendrimers can encapsulate herbal extracts when functionalized with ligands that specifically bind to receptors overexpressed in diseased tissues. For example, the use of folic acid-conjugated nanoparticles to deliver *Curcuma longa* (turmeric) extracts to cancer cells has been shown to improve anti-cancer effects by increasing the accumulation of curcumin at the tumour site while minimizing systemic toxicity [62]. Similarly, targeting of vascular endothelial growth factor (VEGF) receptors has been explored to deliver anti-inflammatory herbal compounds to sites of chronic inflammation, such as in rheumatoid arthritis [63,64]. Targeted drug delivery enhances the therapeutic efficacy of herbal medicines by ensuring that, their bioactive compounds reach the right cells at the right time, thus enhancing their bioavailability and reducing the potential for adverse effects [65]

5.3. Stimuli-Responsive Systems

Stimuli-responsive drug delivery systems, also known as "smart" drug delivery systems, are designed to release active compounds in response to specific physiological or environmental conditions, such as changes in pH, temperature, or the presence of enzymes or other biomolecules. These systems provide controlled and localized release of herbal bioactive compounds, improving their therapeutic outcomes [66,67]. For example, pH-sensitive nanocarriers have been developed to encapsulate herbal medicines like *Ginkgo biloba* extract or *Panax ginseng* and release them in response to the acidic environment of tumors or inflamed tissues. The use of such systems can increase concentration of bioactive compounds at the target site while minimizing systemic exposure [68]. Thermo-responsive systems that release their contents upon exposure to body temperature are also promising for enhancing the delivery of herbal compounds in a controlled manner [69]. Moreover, enzyme-sensitive systems have been explored to release herbal bioactive compounds at sites where certain enzymes are overexpressed, such as in tumors or inflammatory areas [70,71]. The application of these stimuli-responsive systems to herbal medicines can improve the therapeutic index by allowing for site-specific, controlled release in response to the pathophysiological conditions of the disease, thus optimizing efficacy [72].

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5.4. Combination Therapies

Combination therapy involves the use of multiple therapeutic agents to enhance efficacy. The synergistic effects of combining herbal extracts with conventional drugs or with other herbal compounds can amplify therapeutic effects, reduce resistance, and minimize side effects from conventional drugs [73,74]. One promising approach is combining herbal medicines with chemotherapy agents or anti-inflammatory drugs. For example, combining curcumin, which is a bioactive compound from *Curcuma longa*, with standard chemotherapy agents has been shown to increase the sensitivity of cancer cells to treatment while reducing the toxic side effects of chemotherapy [75,76]. Similarly, combining anti-diabetic herbal extracts like *Momordica charantia* (bitter melon) with insulin therapy has demonstrated improved blood glucose control in diabetic patients [77,78]. Moreover, herbal medicines can be combined with other herbal extracts to exploit their synergistic properties. For example, the combination of *Andrographis paniculata* and *Withania somnifera* has been found to enhance the anti-inflammatory effects and improve immunity, offering a more potent alternative to single herbal treatments [79,80]. Combination therapies therefore represent a multifaceted approach by optimizing the efficacy of herbal medicines, with the potential for enhancing therapeutic outcomes across various disease conditions [81]. The strategies outlined above, that is surface modification, targeted drug delivery, stimuli-responsive systems, and combination therapies, hold great promise for enhancing the efficacy of African herbal medicines [82]. By addressing key challenges facing African herbal medicines, such as poor bioavailability, inadequate solubility, and nonspecific targeting, these strategies can improve the therapeutic outcomes of African herbal formulations [83]. However, further research, including preclinical and clinical trials, is needed to optimize these strategies and fully realize the potential of African herbal medicines in modern therapeutic applications [84]. As these innovative approaches continue to evolve, they offer exciting prospects for the integration of herbal medicines into evidence-based clinical healthcare in Africa [85,86].

6. Future Perspective for African Herbal Medicine

The increasing global interest in herbal medicine has propelled African traditional medicine to the forefront of drug discovery and development research, presenting significant potential for both healthcare and economic development. However, several key areas must be addressed to effectively harness this potential [87]. This final part of this review explores the safety considerations, regulatory aspects, and commercialization potential of African herbal medicine, drawing insights from current literature.

6.1. Safety Considerations

Safety remains a critical concern for African herbal medicine due to the variety of traditional preparations, presence of bioactive compounds with potential toxicity, and lack of standardized dosages and formulations [88]. Studies have highlighted that, some traditional herbs used in African traditional medicine contain toxic alkaloids, glycosides, or heavy metals which, without proper handling, may lead to adverse health effects [89,90]. For example, *Aristolochia species* used traditionally in parts of Africa contain aristolochic acid, known for nephrotoxic and carcinogenic properties [91]. Moreover, there are challenges related to contamination, such as microbial contamination and adulteration. Research suggests that, a significant number of herbal preparations are often not well documented for safety due to informal and unstandardized preparation practices [92]. This literature review thus underscores the need for conducting rigorous toxicological assessments, safety monitoring systems, and standardized dosage of African traditional medicines to mitigate their possible risks [93,94].

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6.2. Regulatory Aspects

The regulation of herbal medicine in Africa is a complex issue, influenced by a blend of traditional knowledge systems and modern health regulations. In many African countries, herbal medicine operates outside formal health systems, leading to unregulated use [95,96]. Regulatory agencies such as the World Health Organization (WHO) and the African Union are working on frameworks to establish guidelines for herbal medicine regulation across the continent. For example, the WHO Traditional Medicine Strategy (2014–2023) encourages member states to integrate traditional medicine into national health policies, which has led to progress in some regions [97,98,99]. However, only a few African countries have formal regulatory frameworks to oversee the quality, safety, and efficacy of herbal products. Countries such as Nigeria and South Africa have made significant progress in this regard, with agencies like National Agency for Food and Drug Administration and Control (NAFDAC) setting standards for herbal medicine. Yet, the implementation remains inconsistent across the continent, highlighting the need for harmonized regulatory policies, standardized testing, and robust enforcements [100].

6.3. Commercialization Potential

African herbal medicine has a high commercialization potential, offering opportunities for both local and international markets. Africa is home to thousands of unique plant species with medicinal properties, many of which are in demand worldwide for their therapeutic benefits. For example, medicinal plants such as *Harpagophytum spp* and *Aloe ferox* (Devil's claw) and *Siphonochilus aethiopicus* (African ginger) have shown promise in treating various ailments and are already used in nutraceutical and cosmetic industries [101]. The development of African herbal medicine market, however, faces challenges in intellectual property rights, benefit-sharing agreements, and market access. A lack of robust intellectual property protection for African traditional knowledge can lead to biopiracy, where foreign companies exploit African medicinal plants without benefit-sharing [102]. Collaborations between African governments, research institutions, and pharmaceutical companies can therefore address these challenges by investing in cultivation, sustainable harvesting, and product development, thus enhancing local economies and supporting biodiversity conservation [103,104].

7. Conclusion

While African herbal medicine holds substantial promise, its future depends on addressing efficacy, safety, regulation, and commercialization aspects as highlighted in this review. The safety challenges can be mitigated through scientific validation and toxicological studies, while regulatory frameworks can ensure quality and efficacy. Finally, commercialization, when managed sustainably and equitably, will offer a pathway for economic growth and global recognition of indigenous African traditional knowledge [105,106].

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