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Harnessing the Power of Seabuckthorn in Green Synthesis of Nanoparticles: Opportunities and Challenges

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ABSTRACT

Nanoparticles (NPs) have extended substantial popularity in everyday care products owing to their unique physicochemical features. However, traditional synthesis routes typically involve dangerous chemicals and high-energy processes that are a threat to the environment and safety. Green synthesis is a sustainable strategy for nanoparticle (NP) synthesis that takes advantage of plant-based reducing agents as substitutes for harsh chemicals. Seabuckthorn (*Hippophae rhamnoides*) extract is a prime candidate with an excellent list of bioactive compound profile that includes flavonoids, phenolics, and vitamins. Such natural components provide the possibility of using a cleaner, greener, and sustainable route for the formation of nanoparticles. This review paper explores the potential role of Seabuckthorn extract in the green synthesis protocols of NPs (NPs) based on its exceptional antioxidant, anti-inflammatory, and antimicrobial activities. A critical analysis of the synthesis procedure highlights the benefits of using Seabuckthorn extract over conventional approaches in terms of increased biocompatibility and eco compatibility. In addition, this review discusses the variety of nanoparticles that may be synthesised with Seabuckthorn extract. In addition, we critically evaluate the current research scenario, competition in scaling up the synthesis process, and the directions for enhancing the use of Seabuckthorn extract-mediated nanoparticles in diverse applications. The results highlight the significance of sustainable methods in nanotechnology, opening the door for eco-friendly innovations in personal care products.

Keywords: Nanoparticles; Green synthesis; Seabuckthorn; Bioactive compounds; Antioxidants; Antimicrobials

NOMENCLATURE

NPs : Nanoparticles
AgNPs : Silver NPs
CuNPs : Copper NPs
ZnO-NFs : Zinc oxide nanoflakes
UV : Ultraviolet
Ω : Omega (used to denote omega fatty acids: ω-3, ω-6, ω-7, ω-9)
Ie : *id est* (that is)
Fig. : Figure (e.g., Fig.1, Fig.2)
Etc. : Et cetera
AuNPs : Gold NPs
MONPs : Metal Oxide NPs
SPR : Surface plasmon resonance
DLS : Dynamic light scattering
FTIR : Fourier transform infrared spectroscopy
XRD : X-ray diffraction
EDX : Energy dispersive X-ray spectroscopy
FESEM : Field emission scanning electron microscopy
FETEM : Field emission transmission electron microscopy
TEM : Transmission electron microscopy
ABTS : 2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
GSH : Glutathione
$AgNO_3$: Silver nitrate
$PdCl_2$: Palladium(II) chloride

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1. INTRODUCTION

Nanotechnology has changed different fields of science, changing the way we conduct research, development, and innovation. One of the significant advancements in nano sciences is development of nanoparticles (NPs) as a valuable material due to their exceptional physicochemical characteristics[1]. These small particles with dimensions between 1-100 nanometer demonstrate outstanding biocompatibility, stability, and low toxicity, rendering them an appealing candidate for different applications[2]. The capability of NPs to interact on the molecular scale has seen their widespread application (Fig.1). in pharmaceuticals, cosmetics, environmental clean-up, and biomedical sciences[3]. Traditional skincare interventions, though pervasive, are in most cases riddled with setbacks such as reduced penetration, lack of stability, and side effects. NPs, by comparison, represent a new technology in skincare, allowing for the effective delivery of bioactive materials, improving efficacy of treatment, and allowing controlled release.

This focused method allows NPs to communicate with skin cells, minimizing the potential for side effects and enhancing general skin well-being[4-5]. In recent years, there has been a notable move towards green synthesis techniques for generating NPs using plant and microbial extracts to prevent the harmful effects of traditional chemical synthesis[6-7].

Green synthesis methods entail phytochemicals, proteins, as well as enzymes as stabilising and reducing agents, and hence are environmentally friendly and biocompatible options. This method not only decreases ecological influence of nanoparticle synthesis protocol but also increases the stability and biocompatibility associated with the produced NPs[6] Silver[8], zinc oxide[9], and copper NPs[10] have shown noteworthy latency in dermatology, possessing antioxidant, antimicrobial as well as anti-inflammatory, along with UV-protective capabilities. The NPs have proved efficient in hindering bacterial strains, modulating oxidative stress, and inducing skin regeneration. For example, silver NPs have been proven to prevent the growth of *Escherichia coli* and *Bacillus subtilis*, making them suitable ingredients for antimicrobial skincare products[8]. The creation of biologically synthesised NPs has opened doors to their application in advanced skincare and biomedical technologies. In addition, the employment of green synthesis techniques allows for the mass production of NPs, making them a suitable candidate for commercial skincare products. The union of nanotechnology and green chemistry has great potential to transform skin health and open doors to safer, more effective skincare treatments. As this field keeps evolving, we are bound to witness the creation of new nanoparticle-based cosmetics that not only enhance skin health but also ensure sustainability and ecocompatibility[11]. Why then not adopt a plant extract that already qualifies as a cosmetic agent and has medicinal as well as nutraceutical significance.

Seabuckthorn (*Hippophae spp.*) is a medicinally valuable plant species well known for its rich nutrient profile and diverse pharmacological properties. The versatile plant encompasses an assortment of bioactive compounds, which make it one of the most respected medicinal herbs with unmatched therapeutic and nutritional value[12]. The green synthesis of metallic NPs using *Hippophae* species has proven to be effective and environmentally friendly, harboring immense biomedical and environmental applications[13]. Importantly, silver NPs (AgNPs) from *Hippophae* salicifolia berries and leaves were rich in antioxidant and antibacterial activities with variation in size depending on the solvent used for extraction[14]. Likewise, copper NPs (CuNPs) obtained from *Hippophae rhamnoides* stem extract displayed strong anticancer activity against HeLa cells. These results highlight the therapeutic potential of phyto-mediated NPs, and these present an encouraging alternative to chemically produced analogues[15]. Furthermore, NPs from *Hippophae* have the potential in environmental remediation, especially wastewater treatment. ZnO-NFs derived from *Hippophae* fruit displayed impressive photocatalytic performance, being capable of photodegrading industrial dyes when irradiated by ultraviolet light[16]. The non-toxicity, low cost, and reusability of the nanomaterials indicate them as an approaching candidate for use in the environment. The capability of synthesizing diverse metallic NPs from

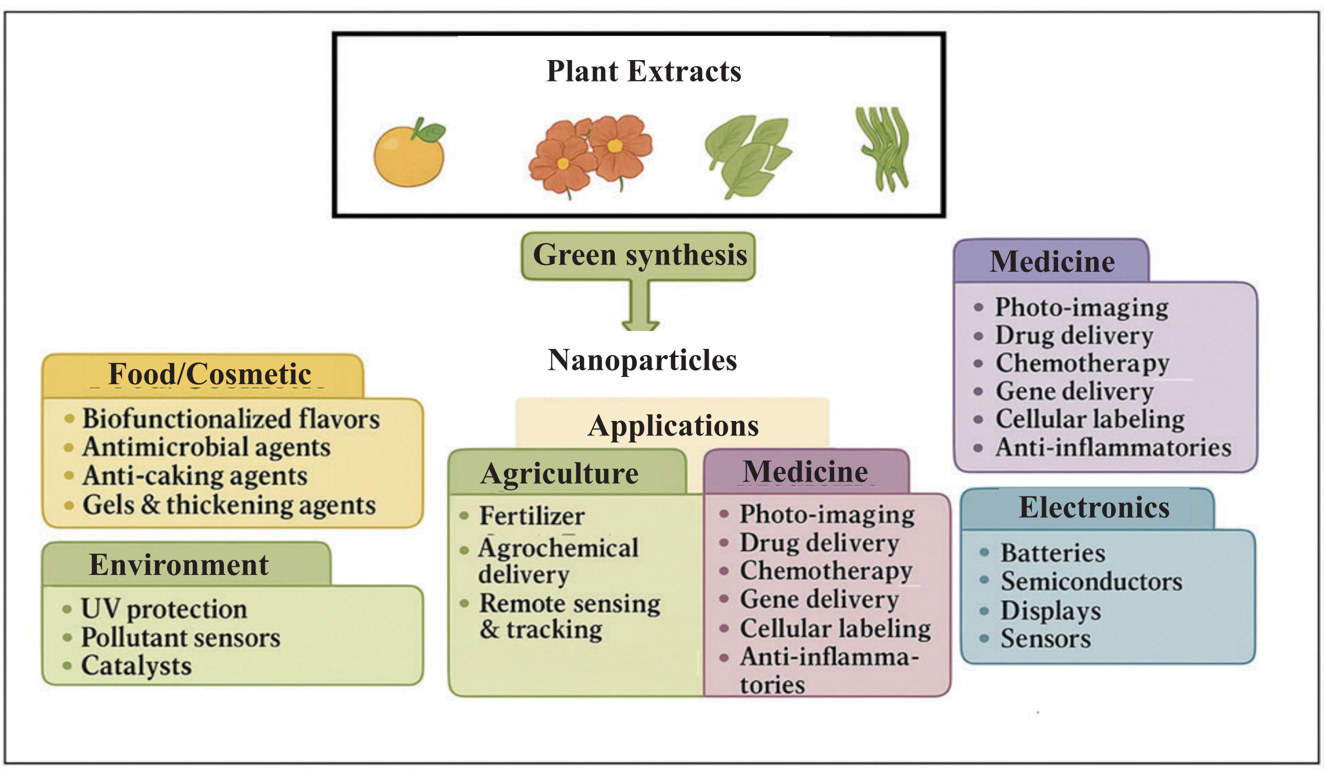

Figure 1. Green synthesis of NPs using plant extract and their utility in diverse applications.

Hippophae extracts based on a green strategy emphasizes the significance of plant-based nanotechnology in combating environmental issues. Exploring further and optimising these NPs could open doors to new, environmentally friendly technological innovations in medicine, agriculture, and sustainable development. This review seeks to give an extensive summary of the synthesis, characterisation, and uses of green-synthesised NPs in skin protection. Through the evaluation of recent progress and modern approaches, we aspire to give insight into the viability of plant- and microorganism-mediated nanoparticle synthesis as a green approach to skincare innovation. In addition, we elaborate on the future and challenges of incorporating NPs into dermatological products, with a view to increasing biocompatibility, stability, and mass production.

2. SEABUCKTHORN: A BIOACTIVE POWER HOUSE

2.1 Botanical Description and Distribution

Seabuckthorn (*H. rhamnoides*) is a perennial shrub of the Elaeagnaceae group and it is highly regarded medicinal plant known for its unmatched therapeutic as well as nutritional merits[17]. The extensive root structure of this plant aids to resists soil erosion and permits the plant to survive in nutrient lacking soils. Seabuckthorn comes under category of dioecious plant, i.e., cross-pollination is needed between male and female whorls of flower for fruit production. The shrub is called to bear orange-yellow fruits, which is rich in Ascorbic acid, organic acids and pomello-like flavor[18]. Owing to their exceptionally high nutritional profile and citrus flavor, these berries are highly cherished. They contain many important fatty acids, like ω-3, 6, 9, and 7 along with 4 and make them sought after in both the industrial pharmaceutical as well as the nutraceutical sectors[18-20].

The temperate and cold areas of Asia and Europe are the primary regions where Seabuckthorn is extensively grown. The plant flourishes well in drained environments available in riverbanks, coastal areas and even at the slopes of mountains[21]. Furthermore, its remarkable adaptability allows the plant to thrive in progressively harsher environment, including low temperature, drought, and infertility of soil. In Asia, this plant is grown in bulk in China, India and Russia and other neighbours. China claims the principal natural and cultivated population of Seabuckthorn, employing the plant for both conservation as well as commercial purposes[22]. In India, Seabuckthorn serves as a defensive agent for delicate mountain ecosystems predominantly located at higher altitudes, which includes places like Ladakh, Himachal Pradesh, etc[23] For agricultural expansion and soil restoration, some varieties of Seabuckthorn have been introduced to foreign countries for agricultural and ecological purposes. Because of its remarkable flexibility and strength, Seabuckthorn is progressively being cultivated for its many latent uses[24].

2.2 Chemical Composition and Bioactive Compounds

Seabuckthorn (*Hippophae rhamnoides*) exhibits extensive nutritional as well as pharmacological significance and is quite rich in ample variety of bioactive compounds. Its complex composition profile primarily includes an array of vitamins and minerals Fig.2. with some other biomolecules such as monocarotenoids and polycarotenoids, phenolic compounds, flavonoids, long chain fatty acids as well as some essential elements, rendering it a highly valuable reserve for diverse fields like cosmetics, nutraceuticals, and medicine. The bioactive compounds of this plant are mainly found in its bark, leaves, seeds, and berries, which remarkably contrast in their chemical composition[25]. The below mentioned is the bioactive compound profile in Seabuckthorn and is also summarised in Table 1.

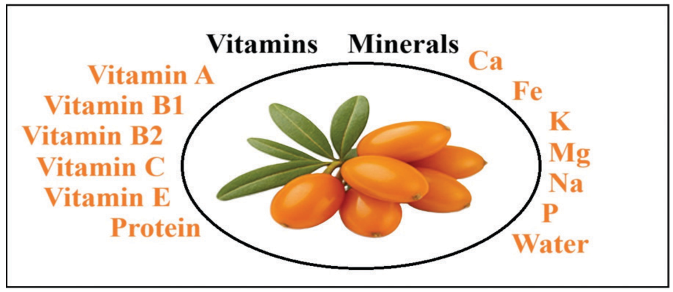

Figure 2. Nutrient profile of Seabuckthorn dry berry.

2.3 Vitamins and Minerals

Seabuckthorn differentiates its aura owing to enormous content of Ascorbic Acid (vitamin C) that varies in the range of 2 to 25 mg/g of fresh berries, which is quite higher than that of mainly most citrus fruits. In addition, Seabuckthorn berries possess considerable amounts of essential vitamins that contribute to their strong antioxidant and anti-inflammatory potential. They contain vitamin A (retinol) in the range of approximately 80–100 mg/kg, which supports skin regeneration and immune defense. The berries are particularly rich in vitamin E (tocopherols and tocotrienols), with concentrations ranging from 160 to 250 mg/kg, known to protect against oxidative damage. Vitamin K is also present in notable amounts (about 110–150 µg/kg), aiding in wound healing and reducing inflammation. Furthermore, Seabuckthorn provides a spectrum of B-complex vitamins, including B1 (thiamine) at 2-4 mg/kg, B2 (riboflavin) at 3-5 mg/kg, B6 (pyridoxine) at 4-6 mg/kg, and B12 (cobalamin) at 0.1–0.2 mg/kg. These nutritional attributes reinforce the suitability of Seabuckthorn as a potent and sustainable candidate for green nanoparticle synthesis in cosmetic applications[26].

2.3.1 Flavonoids and Polyphenols

The Seabuckthorn plant contains a high content of flavonoids like kaempferol, quercetin, and isorhamnetin. These bioactive compounds are known to have potent antioxidant, anti-inflammatory, and even antimicrobial characteristics which in turn aids to mitigate risks of chronic diseases and cancer. Furthermore, some polyphenols namely catechins and proanthocyanidins assist the plant cells in capturing free radicals and alleviating oxidative stress[27].

2.3.2 Carotenoids and Pigments

Also, Seabuckthorn is well known to have abundant reserve of carotenoids, which tends to endow the brightly coloured orange hue of its berries. The major carotenoids present are β-carotene, zeaxanthin, astaxanthin, and lycopene. All these bioactive compounds are vital in the upkeep of immunity, vision, dermal UV-protection, etc. As a precursor of Vitamin A, β-carotene is vital for healthy eyesight and cellular growth[28].

2.3.3 Essential Fatty acids

Seabuckthorn plant berry's heightened concentration of ω fatty acids, majorly including ω-6, ω-3, ω-7, and ω-9, counts one of its unique physiognomies. Palmitoleic acid, an uncommon fatty acid which is a plant derivative, is present in the seed and pulp oil of the fruit and exhibits notable anti-inflammatory properties along with skin-regenerating characteristics. These fatty acids upkeep general metabolism, augmenting skin hydration processes, and promoting cardiac health[29].

2.3.4 Essential Minerals and Trace Elements

Being tremendous source of all the essential minerals, such as potassium, calcium, iron, magnesium, and zinc, Seabuckthorn promote and enhance ample physiological processes, that includes enzymatic activity, bone health and immune support, that have dependence on these minerals. Moreover, trace elements such as selenium and copper improve the antioxidant potential of the plant and support cellular repair mechanisms[30].

2.3.5 Organic Acid and Sterols

Seabuckthorn berries display a tangy flavour on account of its good content of organic acids like citric, malic, and ascorbic acids. These acidic constituents act as natural preservatives, aiding in better digestion, and improving nutrient absorption and uptake. Likewise, β-sitosterol, etc, upkeep cardiovascular health as well as cholesterol regulation. The chemical composition of Seabuckthorn having high content of bioactive compounds, renders it a dominant natural reservoir with broad applications in cosmetics, health care and functional foods. The diverse profile of its bioactive compounds, viz-flavonoids, vitamins, carotenoids, and fatty acids, offer robust antioxidant, anti-inflammatory, and antimicrobial benefits. Ongoing research stays to discover the complete healing potential of Seabuckthorn, further solidifying its part in natural medicine and sustainable product development[31].

Table 1. Bioactive composition of Seabuckthorn fruit berries

Category	Bioactive compounds	Properties and benefits	Reference
Vitamins and antioxidants	➢ vitamin C (Ascorbic acid): 2–25 mg/g fresh berries ➢ Vitamın A (Retinol) ➢ Vitamin E (Tocopherols, Tocotrienols) ➢ Vitamin K ➢ Vitamin B complex (B1, B2, B6, B12)	Antioxidant, anti-inflammatory, protects against oxidative damage, enhances immunity	Dobre[32], *et al*
Flavonoids and polyphenols	➢ Kaempferol ➢ Quercetin ➢ Isorhamnetin ➢ Catechins ➢ Proanthocyanidins	Antioxidant, anti-inflammatory, antimicrobial, reduces risk of chronic diseases and cancer, scavenges free radicals	Yang[33], *et al*
Carotenoids and pigments	➢ β-carotene ➢ Zeaxanthin ➢ Astaxanthin ➢ Lycopene	Supports immunity, vision, skin UV protection; β-carotene is a precursor to vitamin A	Visan[34], *et al*
Essential fatty acids	➢ ω -3 ➢ ω -6 ➢ ω -7 (Palmitoleic acid) ➢ ω -9	Anti-inflammatory, supports skin regeneration, metabolism, hydration, and cardiovascular health	Cakir[35], *et al*
Essential minerals and trace elements	➢ Potassium ➢ Calcium ➢ Iron ➢ Magnesium ➢ Zinc ➢ Selenium ➢ Copper	Enhances enzymatic activity, bone health, immune support; selenium and copper boost antioxidant activity and cellular repair	Yu[36], *et al*
Organic acids and sterols	➢ Citric acid ➢ Malic acid ➢ Ascorbic acid ➢ β-sitosterol	Aid digestion, nutrient absorption, act as preservatives; β-sitosterol supports cardiovascular health and cholesterol regulation	Lee[37], *et al*

3. GREEN SYNTHESIS OF NANOPARTICLES

3.1 Mechanism of nanoparticle synthesis

An eco-friendly practical method which exploits the plant's abundant bioactive compounds is the green synthesis of NPs using Seabuckthorn (*H. rhamnoides*). In general, the mechanism involves reduction by reducing agent followed by capping by the stabilising agent. Flavonoids, polyphenols, ascorbic acid, and other biomolecules found in Seabuckthorn function as natural reducing agents, converting metal ions into their nanoscale equivalents. Seabuckthorn extract exhibit the potential to reduce metal ions (e.g., Ag^+ to Ag^0) by donating electrons to a metal salt solution such as silver nitrate ($AgNO_3$) or auric chloride ($AuCl_3$)[38-39]. This reduction sets the point for the synthesis of NPs by initiating the nucleation phase, in which minute metallic clusters start to form. The particles need to go through a growth phase post nucleation, where more metal atoms summate onto the nuclei that already exist. Temperature, pH, and the concentration of plant extract along with metal ions all have an impact on this process. Seabuckthorn's biomolecules also acts as stabilising and capping agents, limiting disproportionate aggregation and guaranteeing a dependable distribution of particle diameters. Flavonoids and tannins has functional groups moieties such as carbonyl (-C=O) and hydroxyl (-OH) that interact sturdily with the particle surface to set them stable. The outcome is the creation of biocompatible, extensively distributed NPs with superior physicochemical characteristics apposite for a range of environmental and biomedical uses[40].

On comparison with traditional methods, the Seabuckthorn green approach of nanoparticle synthesis has several advantages. Since toxic reducing agents are no longer needed, the protocol is benign and more environmentally friendly. Additionally, the existence of natural phytochemical moeties in the biologically capped NPs fallouts in enhanced antioxidant, antimicrobial, as well as catalytic properties. Applications pertaining to these NPs in drug delivery, wound healing, biosensors, and environmental remediation are amazingly promising. Seabuckthorn-mediated synthesis of NPs may be a viable and affordable way to generate nanomaterials with significant biomedical applications along with additional refinement.

3.2 Role of Bioactive Compounds in Nanoparticle Synthesis

Seabuckthorn (*H. rhamnoides*) is a fine cradle of bioactive compounds that bears a crucial role in green synthesis of NPs. These compounds, that majorly includes flavonoids, terpenoids, polyphenols, tannins, and polysaccharides, serve as reducing, capping, and stabilising agents during the process of nanoparticle formation. When an ionic salt solution such as that of Zinc Nitrate or Silver nitrate is made to react with this plant extract, these biomolecular entities expedite the reducing process of metallic ions to their corresponding elemental counterparts by electrons donation. Let say, flavonoids are potent antioxidants that proficiently reduce Ag^+ to Ag^0 or Au^{3+} to Au^0, initiating formation of NPs[25,38-39].

Besides reduction of metal ions, bioactive compounds present in this plant also influence growth and stability of NPs. Polyphenols and flavonoids possess functional groups viz- hydroxyl (-OH) and carbonyl (-C=O) etc, which show interaction with the particle surface to avoid hysterical aggregation. This capping action ensures that the NPs are well-dispersed hence stable over a long period of time[42]. In addition, the presence of proteins and polysaccharides in the extract improves colloidal stability by creation of a protective layer around NPs and halting

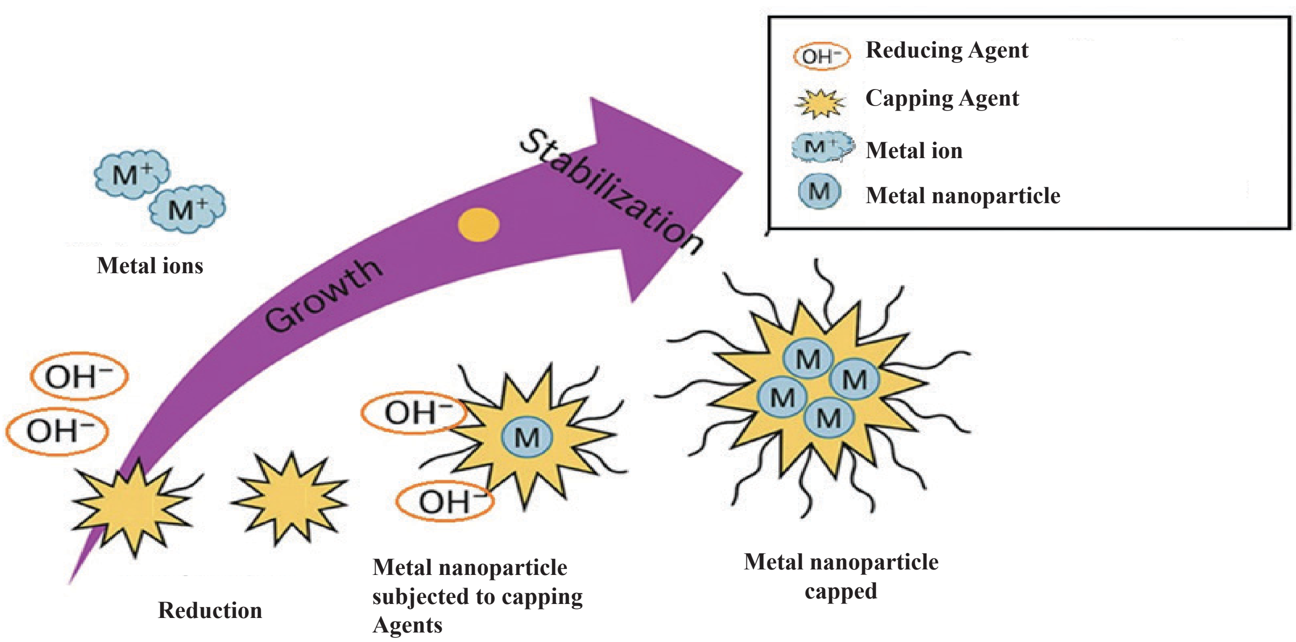

Figure 3. Schematic diagram of mechanism of metal nanoparticle formation and its capping.

agglomeration. These molecules also impose control on nanoparticle diameter and geometry, which can be adjusted by optimising Seabuckthorn extract concentration and reaction conditions like pH and temperature[43] as explained in 3.3. The bioactive constituent's profile of Seabuckthorn not only facilitates nanoparticle synthesis but also enhance their biological characteristics. The phytochemical-coated NPs show enhanced antimicrobial, antioxidant, and catalytic activities, rendering them appropriate for Applications in biomedical field including wound healing, drug targeting and biosensing[44]. The presence of tannins and flavonoids imparts further therapeutic promise, since these moeities possess anti-inflammatory as well as antimicrobial activity[45]. By utilising these biocompatible biomolecules in nature, Seabuckthorn-assisted green synthesis of NPs opens up an avenue for inexpensive, environmentally friendly, and biocompatible alternatives to traditional chemical protocols, setting the stage for eco-friendly nanoscience applications.

3.3 Factors Affecting Synthesis Efficiency

The efficiency of nanoparticle synthesis using Seabuckthorn (*Hippophae rhamnoides*) is significantly inclined by many factors namely pH of solvent, temperature of synthesising chamber, and concentration of both the metal salt and plant extract etc. These parameters have a critical role in determining the size, shape, stability, and yield of the synthesised NPs. Optimising these factors warrants controlled synthesis, preventing excessive aggregation or incomplete reduction.

3.3.1 Effect of pH

The prudent control of multiple parameter values is critical for the eco-friendly green synthesis of NPs based on Seabuckthorn extract, particularly pH, as it directly standardizes the ionization state of bioactive compounds existing in the extract sourced from various parts of plant. Bioactive molecules such as flavonoids and polyphenols has natural reducing and stabilising properties, with their efficacy greatly inclined by the pH of the surrounding medium[46]. Under alkaline conditions (pH 8–10), the reduction of metal ions befalls speedily due to rapid electron donation by deprotonated bioactive molecules, leading to formation of NPs with uniform and stable dispersions. Conversely, at low pH values (acidic conditions, pH 3–5), the reduction process is slower, leading to larger and polydisperse NPs due to incomplete or uncontrolled nucleation[47]. Acidic conditions may also degrade certain bioactive compounds, reducing their ability to form NPs effectively[48-49].

In a study, Ag NPs (silver nanostructures) were synthesised from methyl alcohol and corresponding aqueous extract juice of the underutilised Northern Indian-grown *H. salicifolia* leaves as well as fruit berries. Various synthesis constraint including concentration of extract, concentration of $AgNO_3$ (precursor), pH of the reaction chamber and its temperature, as well as reaction time, were optimised to accomplish a greater yield of silver nanoparticles, with pH being utmost important aspect in regulating nanoparticle diameter and yield amount. Ag NPs synthesised under optimal conditions were characterised using UV–vis spectroscopy, XRD, DLS, EDX, FTIR, FESEM, and FETEM. TEM outputs discovered that Seabuckthorn leaf and berry extract-mediated synthesised Ag NPs were monodispersed spheroids, with particle sizes ranging from 7.88 ± 2.8 nm to 13.86 ± 6 nm, with aqueous extract-derived Ag nanoparticles being smaller than those obtained from methyl alcohol extracts. The synthesised yields were further assessed for their antioxidant as well as antibacterial characteristics, where those produced from methanol leaf extracts exhibited

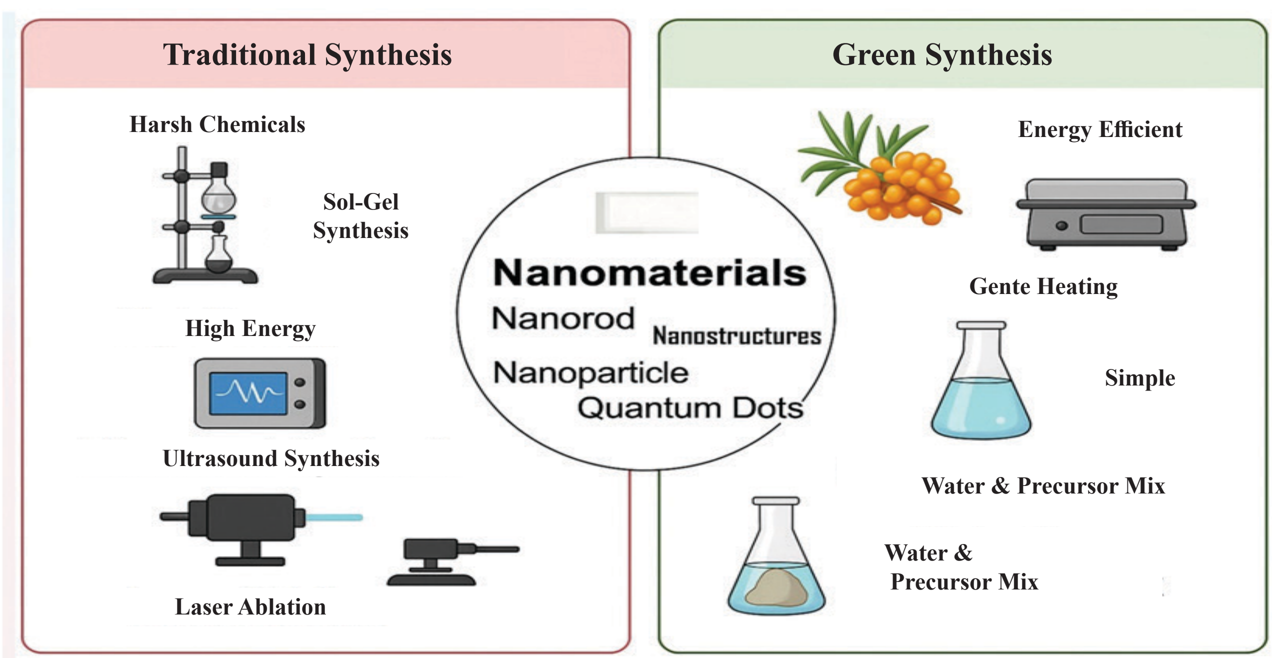

Figure 4. A diagrammatic contrast between traditional methods vs green synthesis.

the highest antioxidant and good antibacterial potential. Notably, Ag NPs synthesised from leaf extracts demonstrated superior antioxidant activity compared to pure vitamin C in the ABTS assay[50]. These findings above indicate that Ag NPs synthesised from *H. salicifolia* leaves and berries extract possess momentous antioxidant as well as antibacterial latency, making them promising candidates for controlling and preventing bacterial infections.

3.3.2 Effect of Temperature

Temperature has a central role in the reaction kinetics and performance of nanoparticle synthesis too, affecting reduction of metal ions and the stability of the NPs[51]. Higher temperatures with a range of 40–80°C enhance reduction of metallic ions to NPs, supporting fast nucleation and growth[52]. Still, extremely high temperatures cause uncontrolled growth of particles, which leads to aggregation or empty space formation. On the other hand, reduced range of temperatures i.e., below 30 °C slows down the reaction, resulting in incomplete reduction and low nanoparticle yield[53.] Optimal temperature range should be maintained to achieve the balance of nucleation and growth and obtain well-dispersed and stable dispersion of NPs.

Experiments have proven that no silver NPs (AgNPs) were synthesised at temperatures below 37 °C[54]. In another criticism with the use of grape seed extract, maximum absorbance was observed at 20 °C among various reaction temperatures tested between 20 and 100 °C, showing that 20 °C was best temperature for Ag NP synthesis[55]. Moreover, the influence of temperature on Ag^+ ion reduction and AgNP synthesis was studied employing Vitex agnus-castus leaf extract. The outcomes indicated that reduction of these ions was very fast even at 40 °C, but synthesis was successful at higher temperatures ranging from 60 to 80 °C. This indicates that Vitex agnus-castus extract is endowed with both powerful reducing agents responsible for rapid silver ion reduction and efficient stabilizing agents that inhibit excessive particle growth.[56] These findings top highlight the need for meticulous temperature optimisation to produce efficient nanoparticle yield with the desired properties. Temperature optimisation is important in achieving equilibrium between nucleation and growth to produce stable, well-dispersed, and functional NPs[57].

3.3.3 Effect of Concentration

The level of metal salts and plant extracts also has a crucial part in determining the size, shape, and stability of NPs yield after the process[58]. An increase in the level of plant extract increases the availability of bioactive compounds, thus facilitating effective reduction and stabilisation, which leads to yield of small and well-dispersed NPs as seen in hibiscus extract in study[59]. Nevertheless, a high concentration of salts will cause fast aggregation, resulting in large NPs with excessive nucleation, whereas an insufficient concentration of plant extract might cause incomplete reduction, leading to unstable or polydisperse NPs[60]. Thus, obtaining the proper balance between concentrations of metal salt and plant extract is a step of concern in synthesizing good quality, monodisperse NPs.

The concentration's effect of plant extract on nanoparticle formation has been extensively observed in various studies. For instance, gold NPs synthesised using Ginkgo biloba leaf extract showed a slight blue shift in the Surface Plasmon Resonance (SPR) peak of the UV-Visible spectra as the extract concentration increased, indicating size variation[61]. Similarly, an upsurge in *Anogeissus latifolia* gum concentration enhanced the reduction rate of palladium ions, with 1 mmol/L $PdCl_2$ identified as the optimal concentration for synthesising small-sized palladium NPs[62].

In another study, an increase in T. collinus leaf extract concentration resulted in a higher number of secondary metabolites, leading to formation of stable and much smaller sized NPs[63]. The diameter of ZnO NPs yielded after synthesis using Hibiscus sabdariffa extract was also ominously influenced by concentration of plant extract[59]. The concentration of Aloe vera leaf extract affects the shape as well as diameter of gold NPs synthesised, where lower concentrations form larger, triangular-shaped NPs, while higher concentrations ensued in spherical NPs[64]. Likewise, the concentration of Garcinia mangostana peel extract influenced metal nanoparticle production, with higher concentrations leading to bigger harvest[65].

3.3.4 Effect of Reaction Time

The duration of process in synthesis reaction has a crucial concern in nanoparticle formation, as it dictates the degree of nucleation as well as growth[66]. Less reaction time (not more than an hour) can result in incomplete reduction, leading to small but unstable NPs, while prolonged reaction time may induce secondary growth, leading to aggregation and the formation of larger NPs. Typically optimal reaction duration falls within the range of 2–6 hours, ensuring the good yield of stable and well-dispersed NPs[67]. Many studies have underscored the importance of reaction time in nanoparticle synthesis. For instance, Azadirachta indica leaf extract was cast-off to synthesize silver NPs (AgNPs), where enhancing the reaction duration from half to 4 hours led to variations in nanoparticle size, ranging from 10 to 35 nm[68]. Similarly, an increase in reaction time during Berberis vulgaris leaf extract-mediated synthesis enhanced nanoparticle reduction, resulting in increased production. However, prolonged reaction times can also lead to an increase in nanoparticle size due to the accumulation of colloidal silver NPs[69]. Different plant extracts exhibit varying reaction times for optimal nanoparticle synthesis. In case of Punica granatum plant extracts, a reaction time of 2 hours yielded a higher production of copper NPs,[70] while Ficus hispida Linn. leaf extracts unveiled enhenced SPR peak intensity in just one hour of reaction duration[71]. Arabian dates extract accomplished the maximum production of platinum NPs within 10 hours,[72] whereas Cassia auriculata L. flower extracts optimised silver nanoparticle formation within 24 hours[73]. These findings emphasize the significance of optimizing reaction time to ensure the successful synthesis of NPs with desired size, stability, and functionality.

3.3.5 *Effect of Stirring Speed*

Stirring speed too is an important factor considering the efficiency of nanoparticle synthesis, affecting uniformity and stability. Higher values of stirring speeds leads to more mixing, promoting enzymatic nucleation as well as uniform growth. Though, excessive stirring can result in fragmentation and irregular shapes. A critique on formation of silver nanoparticle by glutathione aqueous solution explored the effects of stirring speed and duration on nanoparticle formation and found that higher stirring speeds increased nanoparticle diameter and stability, while longer stirring times results in increased mean nanoparticle size only[74]. Optimising stirring speed and duration is important step for regulating size, stability, and uniformity of forming nanoparticle in green synthesis processes[74-75].

By optimizing these five key factors (pH, temperature, concentration, reaction time, and stirring speed), the efficiency of synthesis of NPs can be significantly enhanced. Like other extracts as well, Seabuckthorn can also works well even with greater benefits as discussed. This ensures the production of high quality nanomaterials for diverse applications in biomedical and environmental sciences.

4. TYPES OF NANOPARTICLES SYNTHESISED USING SEABUCKTHORN EXTRACT

4.1 Metallic NPs

Seabuckthorn has been the focus of great deal of research and investigation, predominantly in the perspective of its potential involvement to eco-friendly and sustainable protocols for the formation of metal NPs. The bioactive compounds that are present in abundance in its leaves, fruits, and bark-including a variety of flavonoids, polyphenols, tannins, ascorbic acid, and terpenoids-play crucial roles as reducing, stabilising, and capping agents during the intricate process of nanoparticle synthesis, thereby significantly facilitating the formation of NPs that possess specifically tailored properties suitable for numerous applications.

A variety of metal NPs, including silver (Ag), gold (Au), and copper (Cu), have been successfully synthesised by utilising the extract of Seabuckthorn, with each of these NPs exhibiting distinct and unique physicochemical and biological properties that make them particularly well-suited for a wide range of practical applications across different fields.

4.1.1 *Silver NPs (AgNPs)*

Silver NPs are highly sought after in the scientific community for their outstanding antimicrobial activity and has been known to be one of the most researched nanomaterials available in terms of antimicrobial activities. The green synthesis protocol of AgNPs using plant extract juice has expanded significant attention for biomedical and engineering applications. However, the utilisation of Seabuckthorn berry extract, a traditional Chinese medicine renowned for its antioxidant, anti-inflammatory, and anticancer properties, remains unexplored. This critique presents an environmentally friendly and simple approach for AgNPs synthesis with Seabuckthorn berry extract under ultrasonic waves at room temperature. The optimised AgNPs, prepared at pH 10.0 with a material ratio of 1:1 for 4 hours, had a face-centered cubic structure, spherical morphology, and an average particle size of 27.3 ± 0.2 nm. The AgNPs synthesised displayed strong anticancer latency against different cancer cell lines, excellent antioxidant latency, but poor antibacterial activity. These findings highlight the latency of Seabuckthorn berry extract as a non-toxic, low-cost, as well as eco-friendly natural resource for AgNP synthesis, with promising applications in biomedical fields.

These advantageous characteristics render silver NPs particularly well-suited for a variety of practical applications, including but not limited to wound healing, protective coatings, and the development of biomedical devices, where their multifunctional properties can significantly enhance performance and effectiveness. Furthermore, the specific size and morphology of these NPs can be meticulously controlled and fine-tuned by varying critical factors such as pH levels, temperature conditions, and the concentration of the Seabuckthorn extract used in the synthesis process, thereby allowing researchers and manufacturers to produce NPs with desired and bespoke properties that meet the demands of various applications.

4.1.2 *Gold NPs (AuNPs)*

Gold NPs are highly biocompatible and have potential applications in targeted drug delivery, biosensing, and cancer therapy[77]. Seabuckthorn extract efficiently catalyzes the reduction of Au^{3+} ions from $HAuCl_4$ to AuNPs[72,78]. The synthesis of metallic NPs using plant extracts which are rich in antioxidants offers numerous benefits. These extracts contain natural reducing and stabilising agents that effectively functionalize gold NPs.

4.1.3 *Copper NPs (CuNPs)*

The environment friendly synthesis of NPs has garnered momentous interest in current years due to their biocompatible and eco-sustainable properties. Plant-based synthesis of metallic NPs has emerged as a promising approach in nanomedicine, particularly for antimicrobial and anticancer applications. In study done by, the use of the stem extract of *Hippophae rhamnoides* L., a Himalayan plant, was explored for the synthesis of copper NPs (CuNPs). Advanced analytical techniques, were employed to characterize the synthesised CuNPs, revealing predominantly spherical NPs with diameters ranging from 38 nm to 94 nm[79].

4.2 Metal Oxide NPs

MONPs too can be synthesised entailing the Seabuckthorn extract as the reducing agent. MONPs occupies a quite wider niche in the field of cosmetics and other personal care products. Therefore, the question of these nano cosmetics being ecofriendly is a matter of concern.

4.2.1 Ferric Oxide NPs

Seabuckthorn (*Hippophae rhamnoides*) has emerged as a promising agent in the green synthesis of ferric oxide NPs (FeO-NPs), leveraging its rich phytochemical profile. The synthesis process typically involves using extracts to reduce metal ions, resulting in NPs with desirable charecteristics for diverse applicability[80]. Seabuckthorn plant extracts can be used to synthesize FeO-NPs through thermal conversion processes, and the synthesis is eco-friendly, avoiding harmful chemicals, and can be performed at room temperature, enhancing its commercial viability.

4.2.2 Zinc Oxide NPs

The green synthesis of zinc oxide NPs (ZnO NPs) using Seabuckthorn (*Hippophae rhamnoides)* fruit and other plants has emerged as a promising method owing to its green approach and effective applications in environmental remediation. This synthesis leverages the natural bioactive compounds present in extracts, which has reducing as well as stabilising properties, facilitating the formation of ZnO NPs with desirable characteristics. The ZnO NPs were synthesised through a co-precipitation method, utilizing Seabuckthorn or others plant's fruit extract as a natural reducing agent[81-82].

The Seabuckthorn-derived ZnO NPs demonstrated exceptional photocatalytic activity, achieving over 99 % degradation of various industrial dyes within 30 minutes under UV light. This method is noted for being inexpensive, non-toxic, and reusable, making it a viable option for wastewater treatment.[83]

4.2.3 Titanium Dioxide NPs

The green synthesis of titanium dioxide (TiO_2) NPs using Seabuckthorn extracts presents a promising eco-friendly approach. This method leverages the phytochemicals in Seabuckthorn, known for their antioxidant and antimicrobial properties, to facilitate the formation of TiO_2 NPs without harsh chemicals. These NPs exhibit noteworthy photocatalytic activity, augmenting degradation rates of pollutants under solar energy, and demonstrate antimicrobial characteristics, exhibiting a dual function as both a photocatalyst and an antibacterial moeity[81,84]. However, challenges such as scalability and consistency in nanoparticle size and properties remain, and further research is needed to optimize these processes for industrial applications. The green synthesis process of MONPs by Seabuckthorn extract has been publicised to be a cost-effective, environmentally friendly, and biocompatible tactic. The bioactive profile of compounds in the extract facilitate the formation of metal oxide NPs (MONPs) with controlled size, shape, and properties.

This approach has the prospective to revolutionize the field of nanoscience, enabling the large-scale production of metal oxide NPs for ample applications in biomedicine, environmental remediation, and energy storage.

Table 2. Seabuckthorn being used in green synthesis of nanomaterials with their practical implication

Nanoparticles	Size	Seabuckthorn extract used	Method	Practical implication	References
Silver NPs	15.8 $\pm$4.8 nm	Leaf Extract	Soxlet Extraction	Calorimetric detection	Kaur[85], *et al*
	27.3 $\pm$0.2 nm	Berry Extract	Ultrasonic Radiation	Potential development of antioxidant and anticancer agent	Wei[38], *et al*
		Aqueous mixed extract	Co-precipitation	Bacteriocidal Applications	Preda[86], *et al*
		Aqueous Leaf extract	Co-recipitation	Biomedical Applications	Ahmed[87], *et al*
Copper NPs	38.94 nm	Stem Extract	Co-precipitation	Nanomedicine owing to their biocompatibility and anticancer activity.	Dadhwal[13], *et al*
Zinc Oxide NPs	200 nm (Nanoflower)	Berry extract	Co-precipitation	Photocatalysis & Dye degradation	Rupa[81], *et al*
Lipid NPs		Berry extract	Shear homogenisation method	Pharmaceuticals, Neutraceuticals & Cosmetics	Manea[88], *et al*
	93nm (Liposomes)	Leaf extract	SCCO2 Method	Encapsulation efficiency & Antioxidant activity	Ghatnur[89], *et al*

5. CHALLENGES AND LIMITATIONS IN GREEN SYNTHESIS USING SEABUCKTHORN

5.1 Variability in Plant Composition

One of the prime challenges in exploring *Hippophae rhamnoides* (Seabuckthorn) for nanoparticle green synthesis is the intrinsic variability in its phytochemical profile. This ascends due to plentiful factors such as geographical source, type of soil, climatic environments, harvesting time, plant age, and method of extraction. Consequently, the concentration of these bioactive entities-such as flavonoids, terpenoids, and phenolics-may vary significantly even within the same species. This discrepancy can affect the reproducibility of nanoparticle green synthesis method, resulting into variations in size, shape, surface charge, and functionality of the forming NPs. Such inconsistencies pose complications in establishing standardised protocols and hamper scalability for industrial, pharmaceutical and other applications.

Furthermore, slight fluctuations in phytochemical contours can impact the biological activity of the synthesised NPs. For example, antioxidant, antimicrobial, or anticancer properties may not remain consistent between batches if the active phytochemical vary. This becomes particularly critical when the NPs are intended for biomedical use, where regulatory standards require high reproducibility and reliability. Therefore, there is a pressing need for robust quality control strategies, including phytochemical fingerprinting and bioactivity profiling, to ensure uniformity and predictability in the green synthesis process.

5.2 Limited Mechanistic Understanding

Despite the growing popularity of plant-mediated nanoparticle synthesis, the precise biochemical mechanisms involved in the reduction and stabilisation of metal ions by *H. rhamnoides* extracts remain largely unclear. Although phenolic acids, flavonoids, and other antioxidants are believed to play key roles, the exact pathways, reaction intermediates, and kinetic parameters are not well defined. This lack of mechanistic understanding limits the ability to optimize the synthesis process or tailor NPs with specific characteristics. Without a clear comprehension of the chemical interactions at the molecular level, controlling variables such as reaction temperature, pH, and metal salt concentration becomes a trial-and-error approach rather than a rational design strategy.

Moreover, this knowledge gap restricts the combination of green synthesis methods with other advanced techniques, for example bioconjugation or surface functionalisation for targeted drug delivery. A profound understanding of the interactions between plant biomolecules and metallic precursors would not only enhance the efficiency of nanoparticle synthesis but also enable fine-tuning of their biological behavior. Addressing this limitation will need interdisciplinary collaboration among botanists, chemists, and materials scientists, as well as the application of modern analytical tools such as Nuclear Magnetic Resonance (NMR), Fourier-Transform Infrared spectroscopy (FTIR), and High-Resolution Mass Spectrometry (HR-MS).

5.3 Scale-up Difficulties

Scaling up the green synthesis of NPs from laboratory to industrial level presents substantial challenges. While small-scale synthesis using *H. rhamnoides* extract is feasible and often efficient, replicating these results on a commercial scale is complicated by the need for large quantities of plant material, stringent quality control, and consistent environmental conditions. The biological components involved in the synthesis are sensitive to slight changes in temperature, pH, and concentration, all of which are more difficult to regulate in large-scale reactors. Consequently, uniformity in nanoparticle characteristics-such as size distribution and surface morphology-becomes increasingly difficult to achieve.

Additionally, large-scale extraction of *H. rhamnoides* phytochemicals demands sustainable and efficient biomass processing techniques. Overharvesting of wild Seabuckthorn plants could lead to ecological imbalances, while cultivation on a commercial scale may involve significant land, water, and resource inputs. The need for efficient biomass management, waste disposal, and eco-friendly processing methods must be addressed before the technology can be scaled up responsibly. Further research is required to design continuous, closed-loop systems that allow for the efficient, automated, and environmentally friendly production of green NPs on an industrial scale.

5.4 Lack of Comprehensive Toxicological Data

Despite the presumed biocompatibility of plant-based NPs, there is a lack of comprehensive toxicological data specifically addressing those synthesised using *H. rhamnoides*. Most existing studies focus on short-term biological assays, such as cytotoxicity or antimicrobial activity, often using in vitro models. These tests may not adequately predict long-term effects, accumulation, metabolism, or clearance of NPs within living organisms. Without detailed in vivo toxicology data-including chronic exposure studies, biodistribution analysis, and immunogenicity assessments-it is difficult to establish the safety profile of these NPs for clinical or environmental use.

Furthermore, the potential environmental risks posed by the release of green synthesised NPs remain largely unexplored. While they are considered more eco-friendly than chemically synthesised counterparts, their interactions with soil, water, and microbial communities are not fully understood. NPs might undergo transformations in the environment that affect their reactivity, mobility, and toxicity. Therefore, rigorous life cycle assessments and environmental impact studies are necessary to ensure that green nanoparticle synthesis does not inadvertently introduce new ecological concerns. Addressing this limitation will be essential for regulatory approval and public acceptance of green nanotechnology in both biomedical and industrial contexts.

6. CONCLUSION

It can be concluded that the principles of green chemistry and environmentally friendly nanotechnology are confirmed by the application of Seabuckthorn (*Hippophae rhamnoides*) for the green synthesis of NPs as a novel and Eco-friendly method. It contains a rich composition of diverse bioactive molecules like flavonoids polyphenols, carotenoids, and vitamins. The NPs synthesis can be facilitated by the naturally reducing and capping molecules provided by Seabuckthorn. The formation of NPs not only gets facilitated by these phytochemicals but also inherit biological characteristics such as antimicrobial, anticancer, and antioxidant which further build them for their remarkable use in biomedical, environmental, and industrial purposes.

Although Seabuckthorn mediated nanoparticle synthesis has these favourable prospects, there are certain limitations in their full potential. The morphology and functionality of the NPs varies due to the phytochemical variability based on plant part, harvesting conditions, and extraction conditions. Additionally, reproducibility and scalability get limited by the absence of standardised protocols and limited mechanistic insight in the process of nanoparticle formation. The in-vitro and in-vivo study of the issues of nanoparticle stability, long-term toxicity, and environmental fate are required extensively and resolved. Lastly, the shift from laboratory scale synthesis to industrial scale production poses logistical and regulatory challenges that must be overcome.

In summary, Seabuckthorn has tremendous potential as a green resource for the synthesis of NPs, but overcoming the scientific attendant, technical, and regulatory hurdles is essential for its practical and safe use. Future research should focus on the standardisation, mechanistic insight, toxicity profiling, and scalable synthesis methodologies to unlock the potential of Seabuckthorn in green nanotechnology.

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