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Review

Sustainable synthesis of bionanomaterials using non-native plant extracts for maintaining ecological balance: A computational bibliography analysis

Jaison Jeevanandam, João Rodrigues [*]

CQM - Centro de Química da Madeira, MMRG, Universidade da Madeira, Campus da Penteada, 9020-105, Funchal, Portugal

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ABSTRACT

Biological approaches via biomolecular extracts of bacteria, fungi, or plants have recently been introduced as an alternative approach to synthesizing less or nontoxic nanomaterials, compared to conventional physical and chemical approaches. Among these biological methods, plant-mediated approaches (phytosynthesis) are reported to be highly beneficial for large-scale, nontoxic nanomaterial synthesis. However, plant-mediated synthesis of nanomaterials using native plant extract can lead to bioprospecting issues and deforestation challenges. On the other hand, non-native or invasive plants are non-indigenous to a particular geographic location that can grow and spread rapidly, ultimately disrupting the local and endogenous plant communities or ecosystems. Thus, controlling or eradicating these non-native plants before they damage the ecosystem is necessary. Even though mechanical, chemical, and biological approaches are available to control non-native plants, all these methods possess certain limitations, such as environmental toxicity, disturbance in the nutrient cycle, and loss of genetic integrity. Therefore, non-native plants were recently proposed as a novel sustainable source of phytochemicals for preparing nanomaterials via green chemistry, mainly metallic nanoparticles, as an alternative to native, agriculture-based, or medicinal plants. This work aims to cover a literature gap on plant-mediated bio-nanomaterial synthesis with an overview and bibliography analysis of non-native plants via novel data mining and advanced visualization tools. In addition, the potential of non-native plants as a sustainable, green chemistry-based alternative for bionanomaterial preparation for maintaining ecological balance, the mechanism of formation via phytochemicals, and their possible applications to promote their control and spread were also discussed. The bibliography analysis revealed that only an average of 4 articles have been published in the last 10 years (2013–2023) on non-native/invasive plants for nanomaterial synthesis, which shows the significance of this article.

1. Introduction

The global market value of nanomaterials in 2016 was $7.3 billion United States Dollars (USD), which is expected to reach a market growth at a compounded annual growth rate (CAGR) of 13.1% from 2020 to 2027 (Inshakova et al., 2020). Various synthesis methods are available to produce nanomaterials on a large scale to meet the global nanomaterials market, with a particular focus on reducing production costs and gaining high profits. Hence, the selection of synthesis methods plays a major role in the industrial production of nanomaterials. Physical and chemical approaches are the conventional methods for nanomaterial preparation (Gour and Jain, 2019). These synthesis approaches are highly beneficial in yielding significantly stable nanomaterials with the possibility to alter their properties specific to desired applications (Jamkhande et al., 2019). However, the involvement of costly sophisticated equipment and energy sources for physical synthesis (Shnoudeh et al., 2019) and the utilization of hazardous chemicals as reducing and stabilizing agents for chemical synthesis are the limitations of conventional nanomaterial preparation approaches (Kaabipour and Hemmati, 2021; Mohamad et al., 2018). Further, these conventional methods will lead to high production costs, which may affect the overall profit of nanomaterial production industries (Albalawi et al., 2021). Hence, biosynthesis approaches are introduced as an alternative to conventional nanomaterial synthesis as they involve natural biochemicals as reducing and stabilizing agents for the formation of nanosized particles (Lade and Shanware, 2020). Microbes and plants are the two major sources of biochemicals that can be utilized to fabricate nanomaterials (Bala and Rani, 2020; Saravanan et al., 2020). Recently, the

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[*] Corresponding author.
E-mail addresses: joaor@uma.pt, joaoc@staff.uma.pt (J. Rodrigues).

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biochemicals from microbes, such as bacteria, fungi, and algae, have been used for nanomaterial formation, that are foreseen to reduce the production cost (Lahiri et al., 2021). Microbial synthesis approaches have been identified to yield nanomaterials with less or no toxicity, high bioavailability, biocompatibility, and bioreactivity. However, the main limitations of this method are more time-consuming to yield the final product, difficulties in controlling the size, morphology, and crystallinity of nanomaterials, and difficulties in downstream processes (Jeevanandam et al., 2016). Thus, phytochemicals extracted from plants, known as the phytosynthesis approach, are used as a potential alternative for microbe-mediated nanomaterial production (Jeevanandam et al., 2020a). The ability of phytosynthesis to form nanosized particles with low toxicity and enhanced biological properties is beneficial for biomedical and environmental applications (Capanoglu et al., 2022; Jadoun et al., 2021). However, the resultant nanomaterials from phytosynthesis lack stability compared to microbe-mediated and conventional synthesis (Govekar et al., 2021; Patil and Chandrasekaran, 2020). Further, the utilization of agricultural plants and medicinal herbs to produce nanomaterials for commercial purposes can lead to bioprospecting and biopiracy challenges, which is another major limitation of the plant extract-mediated approach (Barhoum et al., 2020; Dixit et al., 2021).

According to the Natural Resources Conservation Service Connecticut (NECSC) of the United States Department of Agriculture (USDA), a non-native or invasive plant is defined as an alien, non-indigenous to a specific ecosystem. Its introduction in a region will lead to disruption in the local plant population and a decline in soil quality, eventually affecting the ecosystem's economy, environment, and human health (Young et al., 2020). It was reported by the Food and Agriculture Organization of the United Nations (UNFAO) in 2003 that forests on a global scale possess 39% of native and non-native plants, with 15% of exotic, non-native plants and 7% of non-native exotic plants. The report also emphasized that the number of non-native plants is higher in Africa (219 species), followed by Asia (181 species), South America (178 species), North America (155 species), Australia (120 species), and Europe (95 species) (Haysom and Murphy, 2004). There are no reports of a specific non-native plant that has been spread globally, although their number can increase due to increasing global deforestation and climate change (Gudiel, 2013; Hou et al., 2014; Vicente et al., 2013). There are several reasons for the successful spread of non-native plants, such as a large number of seeds produced, deep root systems that make them resistant to fire, ability to proliferate, utilizing most of the soil nutrients, and limiting the growth of native plants in a specific geographic location, eventually affecting the balance in the ecosystem (Nguyen et al., 2022; Oduor et al., 2016). The ecological imbalance will later affect the food chain, agriculture, and economy, leading to drastic long-term climate change in a specific ecosystem (Conway et al., 2019; McCary et al., 2016; Radosevich et al., 2007; Rai and Singh, 2020). Thus, it is necessary to control these non-native plants before they damage the ecosystem. Even though mechanical, chemical, and biological approaches are available to control non-native plants (Caplat et al., 2012; Feng et al., 2021), all these methods possess certain limitations, such as costs, environmental toxicity, disturbance in the nutrient cycle, and loss of genetic integrity (Kettenring and Adams, 2011b; Sindel et al., 2018). Recently, non-native plants have been identified to be helpful as a source for nanomaterial preparation (Nguyen et al., 2023c). For instance, nanocellulose has been recently proposed as a novel alternative phytochemical source for the preparation of nanomaterials/bionanomaterials instead of conventional agriculture-based, native, or medicinal plants (Almeida et al., 2021; Evdokimova et al., 2021; Nguyen et al., 2023b; Phukan et al., 2018). However, there is limited literature to attract researchers to utilize non-native plants as a potential alternative for native plants to prepare less/non-toxic nanomaterials, which is a major research gap in this field. Further, there are no clear guidelines on the utilization of non-native plants in biomedical applications to reduce their population and avoid the potential damage they cause to the ecosystem. Hence, this article offers a comprehensive overview and computational bibliography analysis for the first time on the use of these plants for sustainable nanomaterial synthesis as an alternative to traditional methods using native plants. In addition, the types of sustainable nanomaterials that can be synthesized via non-native plant extracts, the bionanomaterial formation mechanism via phytochemicals from non-native plants, and their possible applications, especially in the biomedical and environmental fields were also discussed.

2. Global overview of non-native or invasive plants

In general, non-native plants must be avoided in agricultural fields as they will affect the growth and yield of cash crops (Oduor, 2013; Radosevich et al., 2007). It can be noted that the non-native plants in an archipelago or island ecosystem will lead to more adverse effects due to a lack of competition and ecological niche compared to a forest ecosystem (Sindel et al., 2018; Smith-Ramirez et al., 2013). Paini et al. reported the effect of almost 1300 non-native plants in agricultural fields from 124 countries worldwide in 2016 (Paini et al., 2016). The study showed that China ($117,290), the United States of America ($70,381), Brazil ($33,760), India ($33,065), Japan ($23,490), Republic of Korea ($14,349), Turkey ($13,267), Argentina ($13,204), France ($12,532) and Mexico ($11,277) are the top ten countries, that spends a portion of their national budget in millions for eliminating non-native plants as shown in Fig. 1. Currently, the annual budget of these countries reaches several billion for the elimination of non-native plants (Bodey et al., 2023; Marchante et al., 2023; Tateosian et al., 2023; Weidlich et al., 2020). This demonstrates the widespread of non-native plants and the need to consider reusing them instead of simply eliminating them.

Africa is one of the continents with several non-native plant species affecting the natural and agricultural ecosystems. In Africa, exotic weeds act as non-native plants, disrupting 80–90% of agriculture in countries such as Zambia, Angola, Ethiopia, Malawi, Sudan, Uganda, and Mozambique (Webb and Conroy, 1995). Apart from agriculture, non-native plants in Africa also affect natural pasture lands, especially in countries like Senegal, Sudan, Kenya, and Niger, which eventually affect the livestock sector (Aklilu and Wekesa, 2002). *Parthenium hysterophorus*, *Prosopis* species, *Chromolaena odorata*, and *Lantana camara* are the most common non-native plant species in the African continent (Witt, 2010). Further, non-native plants are widely present in Asian countries, such as India, China, Malaysia, Philippines, Singapore, Indonesia, Cambodia, and Vietnam (Peh, 2010). Among these Asian countries, India and China are the sources of non-native plant species that eventually spread to other Asian countries. There are thirteen common plant species, which include *Eichhornia crassipes*, *Pistia stratiotes*, *Lantana camara*, *Panicum maximum*, *Opuntia stricta*, *Spathodea campanulata*, *Swietenia macrophylla*, *Eupatorium adenophorous*, *Limnocharis flava, Epipremnum aureum*, *Myroxylon balsamum*, *Saritaea magnifica*, and *Clusia rosea*, that are considered as widely spreading non-native species in Asian countries (Von Rintelen et al., 2017; Witt, 2017).

Australia is a unique archipelago continent where it is difficult for a non-local plant to invade due to restricted pest control in the borders. However, once invaded, they can swiftly spread and replace the local plant species (Harvey et al., 2012). A latest known publication has accounted for about 2700 non-native plants in Australia, where 20 new species are added every year, which shows the increasing number of non-local (invasive) plants (Low, 2002) and their potential negative environmental impact. According to the Australian Weeds Committee, *Acacia farnesiana*, *Andropogon virginicus*, *Arundo donax*, *Annona glabra*, *Alternanthera philoxeroides*, *Solanum mauritianum*, *Cryptostegia grandiflora*, different *Opuntia* species, *Brassica tournefortii*, and *Asparagus aethiopicus* are the most common non-native plants in Australia (Martin et al., 2006). IUCN has reported that non-native alien species, including non-native plants, have led to annual damage of 12 billion euros in the European Union (EU) due to their effect on damaged infrastructure

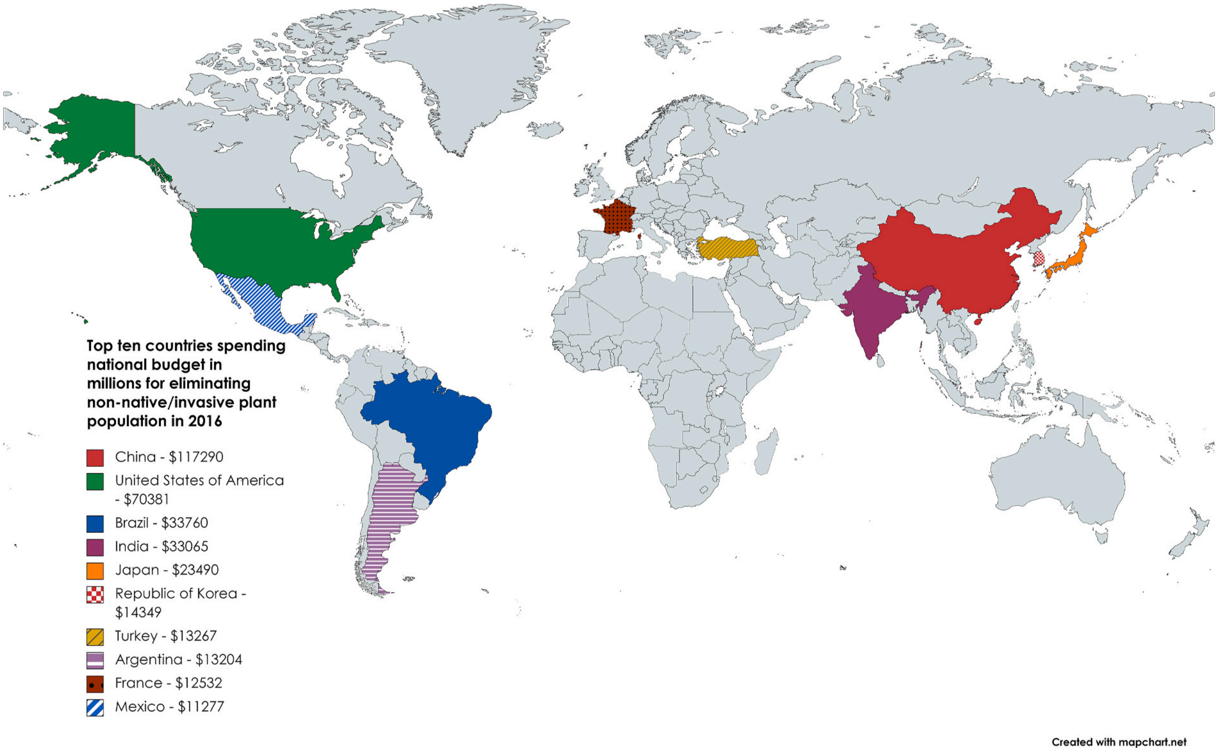

Fig. 1. National budget spent by top ten countries in millions to control non-native plant populations. Data from Paini et al. (Paini et al., 2016) (Map created with mapchart.net and licensed under a Creative Commons Attribution-ShareAlike 4.0 International License).

(Keller et al., 2011), human health (Rai and Singh, 2020), and agricultural losses (Milanović et al., 2020). In 2015, there were about 354 threatened species, 124 of which were threatened plants, and 19% were non-native species in Europe (Genovesi, 2005). In the list by European and Mediterranean Plant Protection Organization (EPPO) from 2006 to 2021, there are four A1 non-native plant species, such as *Triadica sabifera*, *Lygodium japonicum*, *Lespedeza cuneata*, and *Cortaderia jubata*, and 29 A2 non-native plant species in EU countries, including *Amaranthus* (*A. palmeri* and *A. tuberculatus*) species and *Celastrus orbiculatus* added in 2020 and 2021, respectively.

Moreover, North and South American countries also possess various non-native plants, similar to other continents (Brooks et al., 2001; Chen, 2019; Kaufman and Kaufman, 2013). Most non-native plants in North America are present in the United States due to excess and lenient trade and transport policies with the inter- and intra-continental countries (Henderson et al., 2006). Furthermore, five non-native plants from South America, such as *Egeria densa*, *Pistia stratiotes*, *Eichhornia crassipes*, *Salvinia molesta*, and *Myriophyllum aquaticum,* have been spread as non-native plants to several countries in other continents due to suitable climatic conditions (Lozano, 2021). South America, Brazil, Chile, and Argentina have almost 300 non-native species (UFZ, 2011; Zenni and Ziller, 2011). All these studies emphasized that non-native plants impose a crucial challenge to the environment and agriculture.

3. Invasion pathways of non-native plants and their control measures

Invasion pathways of non-native plants in a new specific site can be extensively spread via natural and man-made approaches, while the man-made method is sub-classified into intentional and unintentional processes, as shown in Fig. 2 (A) (Turbelin et al., 2017). Transportation, live plants, ecological disturbance, and natural spread are common pathways for widespread non-native plants in a specific site (Pyšek et al., 2011; Visser et al., 2017). It is evident from the literature that the synergistic effect of natural and man-made pathway modes can lead to extensive growth of the non-native plant in a new location (Wang et al., 2015; Xia et al., 2020).

The growth, spread, and development of non-native plants can be controlled by mechanical, chemical, and biological measures, as shown in Fig. 2 (B). The physical method to eliminate non-native plants is defined as the mechanical method. Elimination of non-native plants, including their root system, from the place of their growth is the primary aim of the physico-mechanical method. Hand pulling, hoeing, mowing, and cultivators are significant mechanical methods for controlling non-native plants (van Wilgen et al., 2001). However, the requirement of heavy equipment, labor costs (Miller et al., 2013), low productivity in agriculture, demand of physical force (Das et al., 2021), alterations in vegetation change via hydrological factor modification (Kołos and Banaszuk, 2018), pre-plant operation cost, dryness of strips, and timeliness in wet falls are the limitations of mechanical methods (Thomas et al., 2006). In some instances, the prescribed burning of non-native plants is also considered a mechanical method. The main advantage of this method is that the burned plant can offer nutrients to the soil. However, burning can lead to erosion, vegetation damage, and the production of smoke and ashes, which is hazardous to humans and other animals (Carson et al., 2018; Richburg and Patterson Iii, 2003) and is not a guarantee of eradication of non-native species.

The chemical methods using herbicides have been introduced as a potential alternative to eliminate non-native agriculture plants. The most common herbicides used to control and inhibit the growth of non-native plants are triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid) and glyphosate (N-(phosphonomethyl)glycine) (Harrington and Miller, 2005). Notably, the type of herbicide application, such as foliar spraying and treatment of stump cuts, also decides their efficacy in controlling the growth and development of non-native plants (Love and Anderson, 2009). Even though chemical methods are beneficial in preventing non-native plants with high efficacy, they can also lead to toxic effects towards native plants, beneficial soil microbes, and reduced soil fertility (Gupta, 2018). Thus, biological approaches, either plant or microbe-based herbicides or a mixture of natural and synthetic

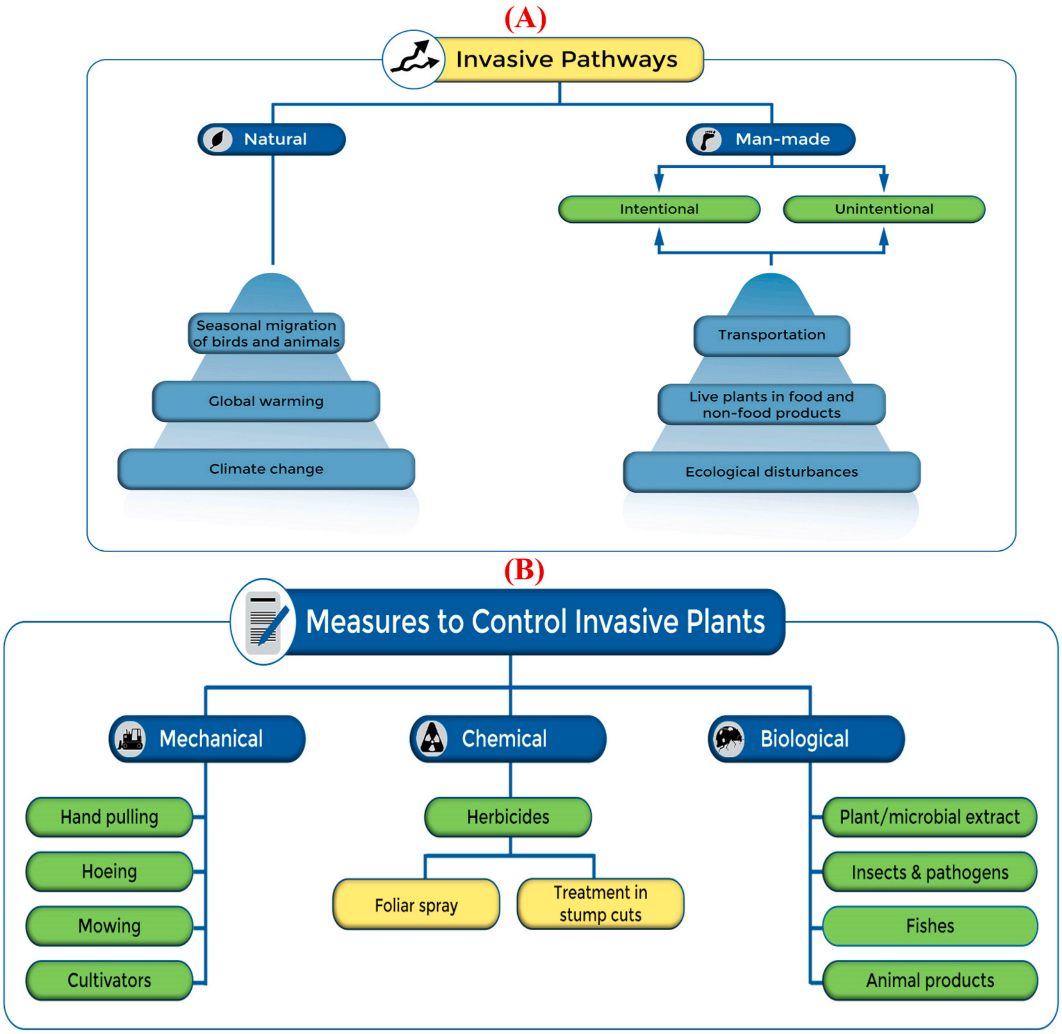

Fig. 2. (a) Identification of pathways that facilitate the spread of non-native plants; (b) Classification of measures to control non-native/invasive plants.

herbicides, have been introduced recently as an alternative to chemical-based non-native plant control measures.

Biological methods generally include extracts from plants (Lim et al., 2017) or microbes (Ge et al., 2018; Gribben et al., 2017; Li et al., 2015), insects (Marchante et al., 2017), fishes (Martin et al., 2010), pathogens (Abgrall et al., 2019; Sarà et al., 2021), and animal products (Culliney, 2005). In addition, genetically modified biological organisms have also recently been proposed to reduce the spread of non-native plants via targeted inhibition without affecting native plants (Teem et al., 2020). Even though biological approaches are environment-friendly in reducing non-native plants, they are time-consuming, affect native plants, and are less efficient than chemical methods (Fletcher et al., 2019; Reeves, 2017). Thus, an alternative method is required to control the spread of non-native plants and utilize them for desired applications. A comparative analysis of control measures to reduce non-native plants with their advantages and limitations was summarized in Table 1.

4. Computational literature review of non-native plants as phytochemical sources for nanomaterial synthesis

Smaller-sized particles with one or more external dimensions in the range of 1–100 nm (1–1000 nm in some instances) are termed nanoparticles or nanomaterials. These nanomaterials are under extensive research to be beneficial in various desired applications (Yonezawa, 2018). Further, nanomaterials are synthesized via chemical, physical, and biological methods. The physical and chemical methods are helpful in yielding stable, smaller-sized nanomaterials, compared to biosynthesized nanomaterials with the ability to transform their morphology, depending on the desired applications (Jeevanandam et al., 2022). However, the resultant nanomaterials are mostly toxic to humans and the environment (Jeevanandam et al., 2016). Contrarily, the biological method utilizes biomolecules from microbes, and there has been no bibliography analysis of invasive plants in the past decade, which is that these biosynthesized nanomaterials or bionanomaterials are polydisperse and less/unstable compared to nanomaterials synthesized via physical and chemical approaches (Andra et al., 2019). Among biological organisms, plants, especially traditional plants, are the most common source of biomolecules that are beneficial in acting as reducing and stabilizing agents for bionanomaterial formation (Jadoun et al., 2021). The collection of biomolecules from a commonly available or medicinal plant for the large-scale production of nanomaterials may lead to deforestation or bioprospecting challenges (Ghosh et al., 2022). Hence, an alternative approach must be identified to replace the traditional plant's use as a source of biomolecules to synthesize less/non-toxic nanomaterials. The primary and secondary metabolism products named phytochemicals present in the plants as biomolecules, such as flavonoids, phenols, terpenoids, carotenoids, catechins, and anthocyanidins, along with vitamins and proteins, are beneficial in nanomaterial formation (Aboyewa et al., 2021; Park et al., 2011). All these phytochemicals are present in non-native plants, which will be beneficial for less/non-toxic nanomaterial synthesis, especially for biomedical applications, and to control their growth in competition with

Table 1
Advantages and limitations of conventional measures to control non-native plants.

Measures to control non-native plants	Advantages	Limitations
Hand pulling	Less/no cost for equipment, labor-saving, and livelihood resilience strengthening ability (Rueda-Ayala et al., 2010)	High cost, skills, infrastructure, and risk (Manning and Miller, 2011).
Hoeing	A practical method to eliminate all types of weeds, replace chemical pesticides, contribute to water management, provide more air in the soil with low maintenance and purchase costs, and not pollute ground and surface water (Lötjönen and Mikkola, 2000).	This method leads to permanent lower back pain to farmworkers (Machleb et al., 2018).
Mowing	This method can reduce weed vigor, survival, and growth and reduce/prevent seed production (Abu-Dieyeh and Watson, 2005).	The method is ineffective in eliminating vegetative structures, such as rhizomes, stolons, corms, bulbs, and tubers (Manning and Miller, 2011).
Cultivators	This method helps to decrease competition among weeds for resources, such as nutrients, water, and sunlight, to allow effective crop growth (Lati et al., 2016).	Method considered as less effective among heavy or compacted soil types (Cloutier et al., 2007).
Foliar spray of herbicides	This method eliminates non-native plants rapidly and economically (Kudsk, 2008).	Spray drift and off-target damage are the limitations (Green and Owen, 2011).
Herbicide treatment in stump cuts	This method is suitable for grasses, shrubs, and dense vines less than 6 m tall (Kochenderfer et al., 2013).	Stump cuts open areas to light and triggers weed growth instead of reducing them via herbicides (Marrs, 1985).
Plant/microbial extract	This method is environment-friendly and does not adversely affect the soil and water bodies (Arafat et al., 2015).	Large quantities of plants/microbes are required to extract a decent quantity of extracts. Microbial extraction of biomolecules is a highly time-consuming process (Harding and Raizada, 2015; Hasan et al., 2021).
Insects and pathogens	This method turns non-native plants into feed for insects and pathogens, making soil nutrients, sunlight, and water available for native plants (McEvoy, 2002).	Introducing a new insect or pathogen, either natural or genetically engineered, will lead to an increment in their population, which will eventually make them an alien species (Capinera, 2005).
Fishes	This method improves the native fish population and reduces non-native plants. It is considered an effective, inexpensive, and long-term approach (Geletu, 2023).	This method can only be used to eliminate/reduce non-native aquatic plants (Chisholm, 2006).
Animal products	This method helps the growth of herbivorous animals/cattle that can feed on non-native plants, which will eventually help in the development of carnivorous animals and agriculture (Monteiro and Santos, 2022).	This approach may lead to an imbalance in the herbivorous and carnivorous animals in an ecosystem. In addition, once all the non-native plants have been eliminated from the environment, the population of herbivorous animals that feed on them may face a decline (Gonçalves et al., 2021).
Nanomaterial synthesis from phytochemicals extracted via non-native plants (proposed in the present study)	This approach helps to reuse non-native plants, unlike just eliminating them from the environment. Reusing non-native plants will help reduce their use and reduce/block the use of native plants in nanomaterial synthesis.	This approach requires pre- and post-processing of non-native plants and intense extraction and purification of phytochemicals, which involves high initiation, downstream, and maintenance costs.

native plants in a specific ecosystem (Phukan et al., 2018). Hence, non-native plants have been utilized as an alternative to common native plants in recent times to synthesize metal, metal oxide, and other novel nanomaterials. Nevertheless, despite the reported advantages, non-native species have been scarcely used to prepare nanomaterials and have never been used for large-scale synthesis of nanomaterials.

4.1. Data collection and analyses

In this present study, the keyword terms "Invasive plants", "Plant synthesized nanomaterials", or "Plant synthesized nanoparticles" and "Invasive plants, plant synthesized nanomaterials, and plant synthesized nanoparticles" were separately searched for the last years (2013–2023) in common research article search engines, such as Web of Science™ (WoS), PubMed®, and Scopus® (ScienceDirect®), following the method used by Khan and colleagues (Khan et al., 2016), as shown in Fig. 3. The publication survey included all the articles with the keyword "Invasive plants", "Plant synthesized nanomaterials" and excluded articles with keywords "Alien plants", "Foreign plants", "Non-indigenous plants", "Phytosynthesized nanomaterials" and "Biosynthesized nanomaterials". The selection of keywords in the present work is based on the highest number of publications with specific terms representing "Non-native/invasive plants" and "Plant synthesized nanomaterials". The publication survey showed that the number of publications for the keyword "Invasive plants" is higher compared to other keywords. When the keyword "Invasive plants, plant synthesized nanomaterials, and plant synthesized nanoparticles" is searched, only a few articles are available (maximum of 16 articles in WoS), which emphasizes that there is less focus on using these invasive plants as a potential alternative for phytochemical source to synthesize nanoparticles. The publications with invasive plants to synthesize nanoparticles started after the year 2013, which increased after 2019, after the recommendation by the Council of Europe in the Convention on the Conservation of European Wildlife and Natural Habitats [Recommendation no. 203 (2019)] to control invasive alien species and reuse them for other applications (Brundu et al., 2020). Hence, these aspects indicate the high necessity to focus on non-native plants as a green chemistry-based alternative for nanoparticle preparation.

Later, VOSviewer version 1.6.19 (from Centre for Science and Technology Studies, Leiden University, The Netherlands) was used to analyze and visualize the publications following the methodology by Bukar and colleagues (Bukar et al., 2023) with specific terms, such as "Invasive plants", "Plant synthesized nanoparticles" or "Plant synthesized nanomaterials" and "Invasive plants, plant synthesized

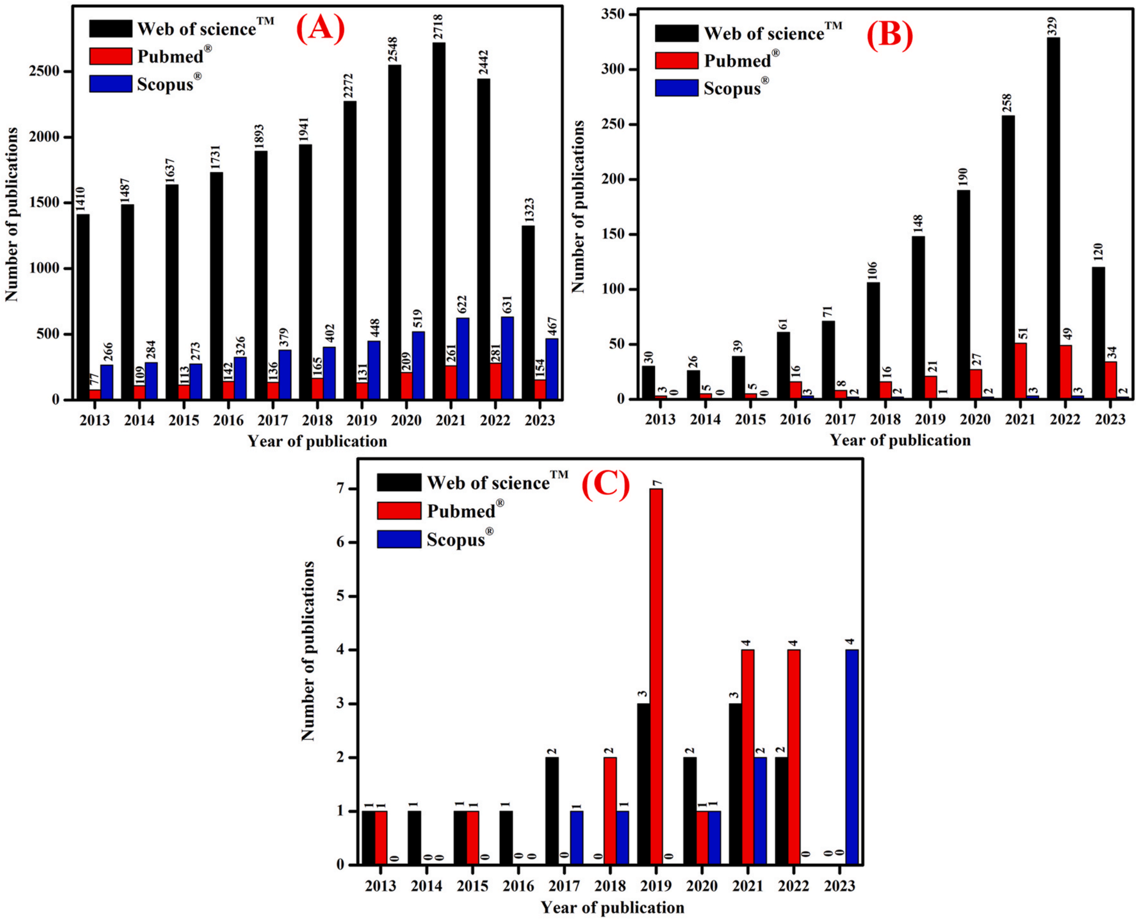

Fig. 3. Number of publications for the past ten years for the terms: (A) Invasive plants; (B) Plant synthesized nanoparticles or Plant synthesized nanomaterials; and (C) Invasive plants, plant synthesized nanoparticles, and plant synthesized nanomaterials.

nanoparticles, and plant synthesized nanomaterials". The bibliographic database file was collected from the search engines and uploaded into the software separately, where the maps were created based on bibliographic data. A complete counting method was used for the analysis, where "co-occurrence'" of the term is utilized as the analysis type with "all keywords" as the unit of analysis. The term "Invasive plants" was initially analyzed to plot their network and density visualization maps (showing the concentration of each term that is in connection with the main terms) from Web of Science™/PubMed®/Scopus®/ScienceDirect search engines as shown in Fig. 4 and Figure S1 (supplementary information file). The inference from the complete counting method, comparing the network and density visualization maps, reveals that the keyword for the main analysis (Invasive species) is highly concentrated with a large number of publications (1213 total keywords as items interlinked with each other). Further, the term "Invasive species" is identified as the common term, which connects other specific terms, such as "Alien plants", "Invasive plants", and "biological invasion", as shown in supplementary information Table S1. A study by Kettenring and Adams in 2011 evaluated invasive plant control experiments, which focused on the cost and revegetation ability of native plants after implementing control measures (Kettenring and Adams, 2011a). Thus, there has been no bibliography analysis of invasive plants in the past decade, which is a significant novelty of the current study. Moreover, Table S1 also shows that publications related to invasive plants exist mainly in Europe, Australia, and Africa, according to all the databases, with few publications from North America (WoS). This reveals that invasive plants exist in most of the continents, and there is a need on these continents to eliminate, reduce, and reuse them for potential applications. It can be noted that the publication analysis via PubMed® (Fig. 4 B and Figure S1 B) has connections with the keywords, such as "Invasive species", "Invasion", "Phytochemicals", and "Nanoparticles", where it is evident that the nanoparticles can be synthesized via phytochemicals extracted from invasive species (plants). Furthermore, it is clear from the density visualization map that the publication focus is high on the term "Invasive species" (Web of Science™ and Scopus®), whereas"Invasive species" and "Phytochemicals" (PubMed®) are focused. Apart from these connections, there is no connection between the terms "Invasive plants" and "Plant synthesized nanoparticles". However, there is no direct connection between these keywords, which shows the need for a focus among researchers to utilize invasive plants for nanoparticle synthesis.

The computational analysis of the publications with the term "Plant synthesized nanoparticles" or "Plant synthesized nanomaterials" was examined to plot their network, overlay, and density visualization maps from Web of Science™/PubMed®/Scopus®/ScienceDirect search engines were displayed in Fig. 5, and Figure S2 (supplementary information). The publication analysis showed that the terms "Green synthesis" and "Biosynthesis" are the common terms (highly concentrated with several interlinks) in WoS, PubMed®, and Scopus®, respectively, which connects other specific terms (185 of total keywords as items interlinked with each other), such as plant extracts, nanomaterials, and nanoparticles as shown in supplementary information Table S1. It can be noted via the publication analysis showed that there is no connection with the term "Invasive species" or "Invasive plants". Further, it is evident from the density visualization maps (Figure S2 A, B, and C) that the 'green synthesis' is the primary focus of all the bibliography searches via WoS. In contrast, the bibliography data is dissipated in PubMed® and Scopus® databases. In particular, the Scopus® search showed that

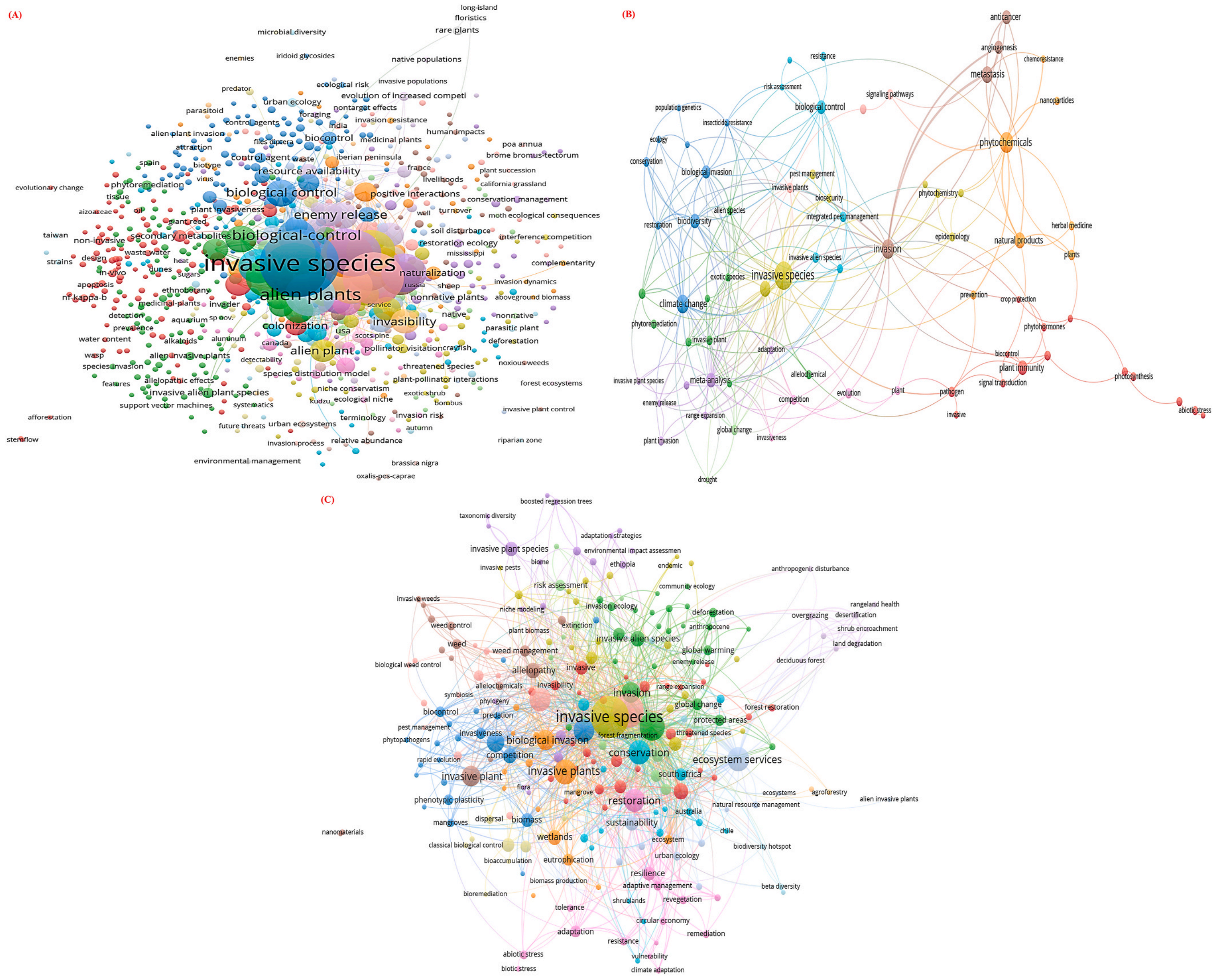

Fig. 4. Network visualization maps of publication analysis using (A) Web of Science™, (B) PubMed® and (C) Scopus®/ScienceDirect search engines for the keywords "Invasive plants". Note: The images are of high quality and zoomed in (250%) to view the networks, links, and terms.

the terms "Biosynthesis" and "Nanoparticles" are the connecting factors, where "Biosynthesis" term is interconnected with the terms "Biomedical applications", "agnps" (silver nanoparticles), and "Diagnosis and imaging", and the term "Nanoparticles" is interconnected with "Plants extract", "Nanotechnology" and "Biogenic nanoparticles'. Thus, it is apparent that silver nanoparticles are widely prepared via plant extracts and are extensively utilized for biomedical applications, such as diagnosis and imaging applications. Moreover, recent systematic studies used bibliographic analysis of plant synthesized nanomaterials that are specific to biomedical applications, such as anticancer agents (Andleeb et al., 2021) and plant-mediated metallic nanoparticle synthesis with biological properties (Hanan et al., 2018; Vijayaraghavan and Ashokkumar, 2017). Hence, it is evident that there is no extensive bibliography analysis on plant synthesized nanomaterials that have not been specific to a particular nanomaterial or application for a decade, as presented in this study.

The computational analysis of the publications with the terms "Invasive plants", "Plant synthesized nanoparticles" AND "Plant synthesized nanomaterials" was examined to plot their network, overlay, and density visualization maps from Web of Science™/PubMed®/Scopus®/ScienceDirect search engines were displayed in Fig. 6, supplementary information Figure S3 and Table S1 (44 of total keywords as items interlinked with each other). It is evident from the bibliography analysis via WoS (Fig. 6 A and supplementary information Figure S3. A) that none of the terms were linked, where the term "Agrochemicals" is in the central focus with high concentrations. Further, the bibliography analysis via PubMed® (Fig. 6 B and supplementary information Figure S3. B) shows that the term "Silver nanoparticles" is in the central focus with a high concentration of publication, which is interlinked with the terms, such as "Invasion" and "Plant extract" (with comparatively lesser concentration). Furthermore, the bibliography analysis via Scopus® revealed that the term "Nanomaterials" is in the central focus with high concentration, which is interlinked with the terms "Invasive plant", "Biosurfactants", "Agriculture wastes", "Phytochemicals", "Prognosis" and "Diagnosis". It is worth noting that the density visualization map of Scopus® database analysis (supplementary information Figure S3. C) of the term "Nanomaterials" are interconnected via the terms "Invasive plant", "Biosurfactant", and "Agriculture wastes". However, the density visualization analysis revealed that there is no/lesser connection with the main and subsequent keywords. The lesser publication volume and concentration of main keywords (compared to other keywords, "Invasive species" and "Plant synthesized nanomaterials/nanoparticles" shows that there is very little publication and research focus on utilizing phytochemicals extracted from invasive plants for nanoparticle

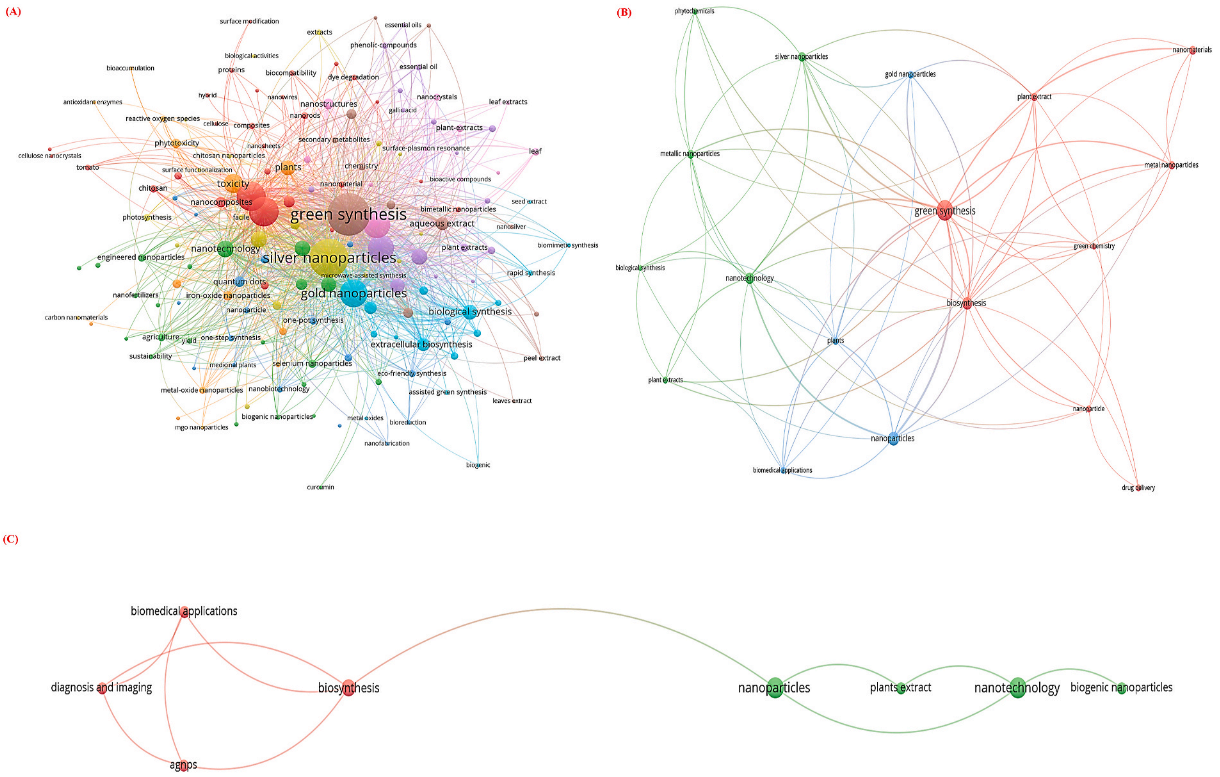

Fig. 5. Network visualization maps of publication analysis using (A) Web of Science™, (B) PubMed®, and (C) Scopus®/ScienceDirect search engines for the keywords "Plant synthesized nanomaterials or Plant synthesized nanoparticles". Note: The images are high quality and zoomed in (250%) to view the networks, links, and terms.

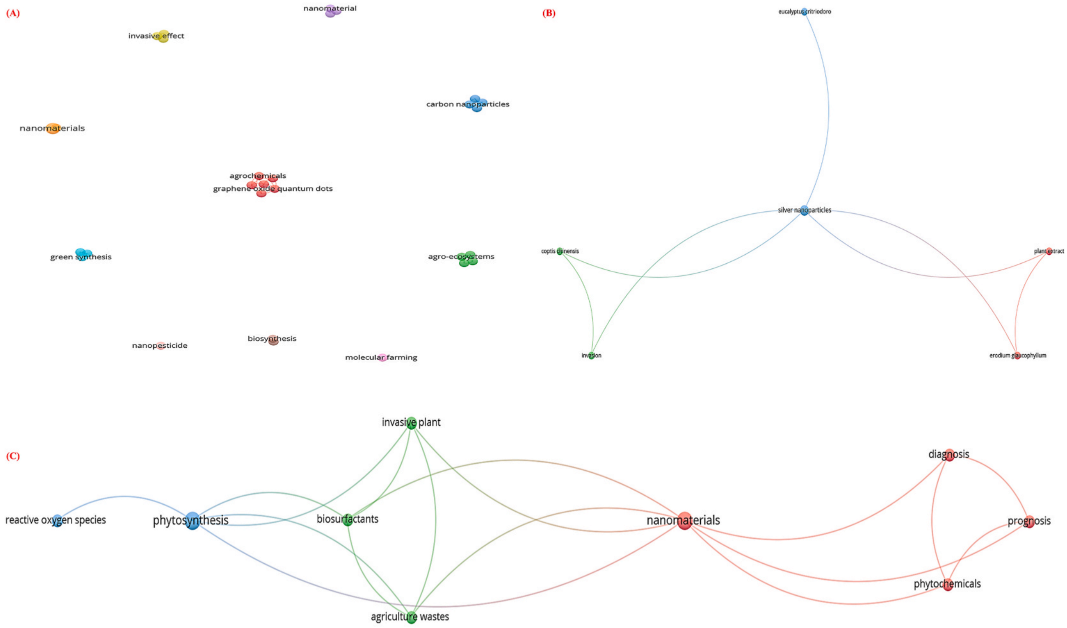

Fig. 6. Network visualization maps of publication analysis using (A) Web of Science™, (B) PubMed®, and (C) Scopus®/ScienceDirect search engines for the keywords "Invasive plants" AND "Plant synthesized nanomaterials or Plant synthesized nanoparticles". Note: the images are high quality and zoomed in (250%) to view the networks, links, and terms.

synthesis.

It is evident from the computational bibliography analysis (as in Figs. 3–6, Figure S1-3, and Table S1) that there are numerous research articles on invasive (non-native) plants and their related keywords. There is no comparative keyword analysis of "Invasive plants", "Plant synthesized nanomaterials", and "Invasive plant synthesized nanomaterials" in any of the previous studies, which makes the current analysis pioneering research in the field of the non-native plant (elimination and reuse) and nanomaterials (alternate synthesis approach). Additionally, there are only a few research articles on non-native plant synthesized nanoparticles compared to plant synthesized nanoparticles. Thus, non-native plants can be a novel alternative source of phytochemicals for the synthesis of nanoparticles.

5. Non-native plants as a sustainable phytochemical source for nanomaterials synthesis

Recently, several nanomaterials, such as metal, metal oxide, carbon, and other nanomaterials, were synthesized using phytochemical extracts from non-native plants. The most common experimental method for the formation of nanomaterials is to either dry or directly boil the plant parts, filter them to extract crude phytocompounds, and mix them with an optimized proportion of aqueous or alcohol dissolved precursor chemicals (de Jesus et al., 2024). In recent attempts, phytochemical extraction methods, such as Soxhlet, superficial, decoction, or digestion, were utilized to isolate separate phytochemicals and mix them with precursors to form nanomaterials (Ikhuoria et al., 2024). In these methods, constant stirring, heating (heating plate, microwave), and ultraviolet or infrared lights were used as catalysts for the rapid formation of nanomaterials (Bokov et al., 2021; Schwenke et al., 2015).

5.1. Metal nanomaterials

Gold and silver are significant metal nanomaterials that are widely utilized and are under extensive research for biomedical applications. Phukan et al. (2018) used a wild-growing, non-native plant named *Lantana camara* in India (Arunachal Pradesh) for the synthesis of gold nanomaterials. In this study, gold nanomaterials were synthesized using the phytochemicals present in the flower extract of the plant. The results showed that the flower extract has led to the formation of spherical-shaped, 10 nm-sized gold nanomaterials. In addition, the study also emphasized that the morphology of the resultant nanomaterial can be altered from polygonal to deformed spheres by changing the concentration of the flower extract (Phukan et al., 2018). Likewise, Anuradha et al. demonstrated the synthesis of gold nanomaterials using the phytochemical extract of *Pistia stratiotes* L. (worthless weed pistia). The aerial and submerged plant portion was used for the synthesis, which was identified to contain protein polypeptides, which can act as a capping or stabilizing agent to reduce gold ions and form gold nanomaterials. The study showed that the phytochemical extract of the non-native plant could lead to the formation of the monodispersed sphere and anisotropic hexagon, truncated triangles, hexagon, triangle, and pentagon with sizes in the range of 20–155 nm, depending on the extract and gold precursor concentration (Anuradha et al., 2015). Similarly, Ganaie et al. synthesized gold nanomaterials using the terrestrial non-native *Antigonon leptopus* plant leaf extract. In this study, the aqueous leaf extract of the non-native plant, which contains proteins, amino acids, flavones, polysaccharides, and terpenoids, has been utilized as the reducing or stabilizing agent for gold nanomaterial formation. The results showed that 25-55 nm-sized gold nanomaterials could be prepared via aqueous plant extract with distinct shapes, such as spherical, tetrahedral, triangle, pentagon, and irregular shapes, depending on the reaction time and pH of the reaction mixture (extract and gold precursor) (Ganaie et al., 2016b). Moreover, Abbasi et al. prepared 3-100 nm-sized, monodispersed spherical and polydispersed polygon, rod, hexagon, triangle, and truncated triangle-shaped gold nanomaterials using non-native *Ipomoea carnea* plant. The study showed that proteins and polysaccharides are responsible for gold nanomaterial formation (Abbasi et al., 2015). In 2023, Leyu et al. prepared monodispersed, stable, spherical shaped, and 3.41–14.5 nm sized gold nanoparticles via invasive alien plant species named *Parthenium hysterophorus*. The results showed that the existence of triterpenoids, flavonoids, proteins, pigments, and polyphenols is responsible for the formation of nanoparticles (Leyu et al., 2023).

Apart from gold, silver nanomaterials are widely synthesized using non-native plants. Recently, total phenol and flavonoid-rich phytochemical extracts of non-native plants, such as flowers of goldenrod, the rhizome of Japanese knotweed, and the fruit of staghorn sumac, were used to prepare silver nanomaterials on the surface of cotton fabric. The results showed that the Japanese knotweed, staghorn sumac, and goldenrod extracts have led to the formation of spherical 109–176, 112–218, and 90-113 nm-sized silver nanomaterials, respectively, due to the synergistic effect of biomolecules, such as chlorogenic acid, caffeic acid, catechin, rutin, and gallic acid (Čuk et al., 2021). Further, Malini et al., in 2020 synthesized spherical-shaped, smooth--surfaced silver nanomaterials in the form of capsules with chitosan and a crystallite size of 30 nm using a non-native plant named *Prosopis juliflora*. The study identified that the existence of novel alkaloids called julifloravizole and flavonoids served as potential reducing and stabilizing agents for the nanosized silver particle formation (Malini et al., 2020). Furthermore, Abeska and Cavas in 2021 fabricated spherical silver nanomaterials with 22 nm crystallite size via non-native *Caulerpa cylindracea* seaweed powder. The results showed that secondary metabolites and peptides are involved in forming silver nanomaterials (Abeska and Cavas, 2021). In the same year, Le et al. also synthesized 22 nm-sized, spherical, and smooth-surfaced silver nanomaterials using the non-native *Tradescantia spathacea* plant leaf extract. The study showed that the organic acids and phenolics acting as reducing and stabilizing agents are responsible for silver nanomaterial synthesis (Le et al., 2021). More recently (2023), invasive plants, such as *Ageratum conyzoides* (Paramasivam et al., 2023) and *Ageratina Adenophora* (Latha et al., 2023), were utilized for the synthesis of silver nanoparticles. Other metal nanomaterials, such as platinum using *Antigonan leptopus* (Ganaie et al., 2018) and water hyacinth (Leo and Oluwafemi, 2017), copper using *Parthenium hysterophorus* (Rai and Lall, 2021), and palladium using *A. leptopus* (Ganaie et al., 2016a) were also synthesized using non-native plants.

5.2. Metal oxide nanomaterials

Besides metal nanomaterials, metal oxide nanomaterials have recently been extensively synthesized using non-native plants. In 2018, Sadasivam et al. demonstrated the synthesis of zinc oxide (ZnO) nanomaterials using the phytochemicals extracted from the non-native *Lantana aculeata* plant, which is a native plant in the Caribbean islands, Central and South America (Sadasivam et al., 2018). The results showed that the phytochemicals in the plant, such as camaric, ursolic, pomolic, betulonic, betulinic, lantadene, lantic acid, and the iridoid glucosides theveside and theviridoside have led to the formation of 12–25 nm-sized spherical-shaped ZnO nanomaterials (Imran and Ravi, 2020). Similarly, non-native plants, such as *Parthenium hysterophorus* L. (Rajiv et al., 2013), *Celosia argentea* (Vaishnav et al., 2017), *Thryallis glauca* (Cav.) Kuntze (Dey and Somaiah, 2022), *Eupatorium adenophorum* (Maheo et al., 2022), and *Eichhornia crassipes* (Rajiv et al., 2018) were used for the extracts of phytochemicals to be beneficial as reducing and stabilizing agents for ZnO nanomaterial formation. Likewise, copper oxide (CuO) nanomaterials were fabricated using a tropical *Sida acuta* weed leaf extract. The resultant nanomaterials were identified to be 50 nm of average size (width) of CuO nanomaterials with nanorod morphology due to nitro compounds, alkynes, alkane, and alkyl halides aromatic phytochemicals in the extract (Sathiyavimal et al., 2018). In addition, non-native plants, including *Eichhornia crassipes* (Vanathi et al., 2016), *Gomphrena globosa*, and *Gomphrena serrata* (Chandrasekar et al., 2021), were used for the synthesis of CuO nanomaterials. Moreover, the leaf extract of *Chromolaena odorata* has been identified as beneficial for synthesizing magnesium oxide (MgO) nanomaterials. The results showed the formation of 12.3 nm-sized, cubic MgO nanomaterials due to alkyne presence, especially 1-heptadec-1-yuyl-cyclopentanol in the leaf extract (Essien et al., 2020). Similarly, *Chromolaena odorata* root extract has been utilized to synthesize iron oxide (Fe_3O_4) nanomaterials. In this study, the resultant nanomaterials were identified to be in 5.6–16.8 nm with an agglomerated spherical shape due to the presence of aromatic compounds in the root extract (Nnadozie and Ajibade, 2020). Additionally, nanomaterials, such as magnesium oxide using *Eichhornia crassipes* (Jayanthi and Muthukrishnan, 2023), iron oxide using *Centaurea solstitialis* (Isik et al., 2023), nickel oxide using *Eichhornia crassipes* (the well-known and troublesome water hyacinth) (Zhang et al., 2021), titanium dioxide using *Cannabis sativa* (Hafeez et al., 2021), and mesoporous silicon dioxide using *Pennisetum purpureum* (Akpotu and Moodley, 2018) were also prepared using non-native plants.

5.3. Other novel nanomaterials

Several novel nanomaterials, such as alloys, composites, and natural polymers, were recently prepared using non-native plants. Chowdhury et al. fabricated novel gold-palladium alloy nanomaterials using flower extract from the non-native *Lantana camara* plant. The study revealed that the flower extract possesses phenolic compounds, which led to the formation of 10–40 nm particles with morphologies, such as pentagon, sphere, triangle, and hexagon (Chowdhury et al., 2018). Further, cellulose nanofibrils were synthesized using the already cited water hyacinth (*Eichhornia crassipes*) as natural nanofibers. In this study, cellulose was extracted from the non-native plant's stem and transformed into a 10–35 nm nanofibril with a mean fibril width of 19.2 ± 4.3 nm (Sun et al., 2020). Furthermore, Marinas et al. engineered novel cellulose microfibers using the pods of a non-native *Gleditsia triacanthos*, which affects agriculture in Eastern Europe (Marinas et al., 2021). The study

Table 2
Non-native plants utilized for the synthesis of metallic nanomaterials.

Non-native plant	Geographical location	Nanomaterials	Size/Morphology	Proposed applications	References
Metal nanomaterials					
Borassus flabellifer	India (Chennai)	Silver and gold	~7–9 nm and ~5–7 nm, spherical	Breast cancer treatment	Vandarkuzhali et al. (2021)
Parthenium hysterophorus	Ethiopia	Gold	3.41–14.5 nm, spherical	Antimicrobial applications	Leyu et al. (2023)
Parthenium hysterophorus	India (Salem)	Silver	10.3 ± 1.7 nm, spherical	Liver cancer treatment	Sivakumar et al. (2021)
Taraxacum officinale	South Korea	Silver	~15 nm, spherical	Liver cancer treatment	Saratale et al. (2018)
Parthenium hysterophorus	India (Allahabad)	Copper	1–100 nm, spherical	Antimicrobial (antioxidant)	Rai and Lall (2021)
Prosopis juliflora	India (Coimbatore)	Silver	30 nm crystallite size, spherical	Antibacterial (photocatalytic)	Malini et al. (2020)
Rhus typhina, Fallopia japonica, Solidago canadensis	Slovenia	Silver	90–200 nm, spherical in cotton fabric	Antibacterial (UV-protective cotton fabrics)	Čuk et al. (2021)
Tradescantia spathacea	Vietnam	Silver	22.4 nm, spherical	Antifungal activity	Le et al. (2021)
Ageratum conyzoides	India	Silver	30–90 nm, irregular spherical and triangular	Antiplasmodial application	Paramasivam et al. (2023)
Ageratina adenophora	India	Silver	84 nm, face-centred cube	Antibacterial application	Latha et al. (2023)
Metal oxide nanomaterials					
Lantana aculeata	India (Coimbatore)	ZnO	12–25 nm, spherical	Cervical cancer treatment	Sadasivam et al. (2018)
Boerhavia diffusa linn	Pakistan	ZnO	23–32 nm, hexagonal	Liver cancer treatment	Ashraf et al. (2022)
***Thryallis glauca* (Cav.) Kuntze**	India (Pondicherry)	ZnO	50 nm, crystalline hexagonal wurtzite structure	Antibacterial application	Dey and Somaiah (2022)
Eupatorium adenophorum	India (Tamil Nadu)	ZnO	42.60 nm, spherical and hexagonal morphology	Antidiabetic application	Maheo et al. (2022)
Cannabis sativa	Pakistan	TiO_2	11–48 nm, spherical and irregular flakes and grains	Antimicrobial agent	Hafeez et al. (2021)
Chromolaena odorata	Nigeria	MgO	12.3 nm, cube	Antimicrobial agent (catalytic)	Essien et al. (2020)
Eichhornia crassipes	India (Chennai)	MgO	~30 nm, spherical morphology	Antibacterial application	Jayanthi and Muthukrishnan (2023)
Sida acuta	India (Chennai)	CuO	50 nm (width), rod	Antibacterial applications	Sathiyavimal et al. (2018)
Parthenium hysterophorus	India (Coimbatore)	ZnO	27 nm, hexagon, and 84 nm, spherical	Antifungal application	Rajiv et al. (2013)
E. crassipes	India (Coimbatore)	CuO	28 nm (diameter), spherical	Antifungal activity against plant pathogens	Vanathi et al. (2016)
Gomphrena globosa* and *G. Serrata	India (Chennai)	CuO	20–80 nm, irregular, rod and hexagon	Non/less toxic biomedical application	Chandrasekar et al. (2021)
Centaurea solstitialis	Turkey and India	Iron oxide	Less than 100 nm, homogenous spherical morphology	Antimicrobial photodynamic therapy	Isik et al. (2023)
Novel nanomaterials					
Gleditsia triacanthos	Romania	Cellulose microfibers	Thickness: 40–120 nm; Length: 0.2–1 μm	Antimicrobial wound dressing application	Marinas et al. (2021)
Eichhornia crassipes	Thailand	Carbon nanohorn	39 nm	Reutilization of the non-native plant as potential biomass	Vanavanichkul et al. (2021)
Eichhornia crassipes	Malaysia	Cellulose nanofibrils	10–35 nm	Sustainable packaging application	Sun et al. (2020)
Eichhornia crassipes	Ethiopia	Copper-silver bimetallic oxide nanocomposite	13.38–13.56 nm, irregular spherical morphology	Antibacterial application	Belay et al. (2023)
Solidago canadensis	China	Biochar-supported nano-sized lanthanum composite	10–20 nm of diameter, 60–100 nm of length, nanorod or needle-like structure	Phosphate removal from water application	Zong et al. (2023)
Opuntia stricta	Malaysia	Zinc ferrite-loaded activated carbon nanocomposites	Honeycomb irregular porous structure	Adsorbent application	Nguyen et al. (2023a)

emphasized that the excessive presence of vanillic acid, 4-hydroxy benzoic acid, and ferulic acid has led to the formation of cellulose microfibers with a length of 0.2–1 μm and thickness of 40–120 nm. Moreover, Amiri et al. prepared a novel cobalt ferrite silica magnetic nanocomposite using *Salix alba* bark extract, which is a native plant in Europe and non-native in the United States. The study showed that the plant extract has led to the formation of a ~15 nm-sized, spherical nanocomposite due to the presence of Salicin ((2*R*,3*S*,4*S*,5*R*,6*S*)-2-(Hydroxymethyl)-6-[2-(hydroxymethyl)phenoxy]oxane-3,4,5-triol) as the core biomolecule (Amiri et al., 2017). Recently, copper-silver bimetallic oxide using *E. crassipes* (Belay et al., 2023), biochar-supported nano-sized lanthanum composite using *Solidago canadensis* (Zong et al., 2023), and porous carbon using *Opuntia stricta* (Nguyen et al., 2023a) were utilized for the formation of nanocomposites. In general, native plants, including certain medicinal plants, are conventionally used for the synthesis of nanoparticles, especially for biomedical applications. If these plants have been channelized for large/commercial scale phytochemical-based nanoparticle production, there will be a high risk of deforestation, bioprospecting, and ecological imbalance (Jeevanandam et al., 2022). Hence, all these studies mentioned in this section demonstrate that the utilization of non-native plants can lead to the formation of nanomaterials, which can be employed for large-scale nanoparticle production and thereby be beneficial in controlling them. Table 2 lists various non-native plant types used to synthesize nanomaterials, their place of origin, size, and morphology of the resultant particles, and their proposed benefits in diverse applications. It has been emphasized in Table 2 that non-native plants are beneficial in synthesizing distinct, less/nontoxic, biocompatible types of nanomaterials, especially for recycling non-native plants to be utilized in biomedical and environmental applications. Moreover, most of the non-native plant synthesized nanomaterials are identified to be potentially used for cancer (treatment) and microbial cell inhibition (antimicrobial agents), as the resultant nanomaterials are determined to be less toxic to the host or normal cells (compared to chemically synthesized nanomaterials) with the ability to control non-native plants in the local ecology and reuse them in biomedical applications. However, it can be noted that the lack of reproducibility, standard procedure, and low stability compared to conventional methods are the limitations of the non-native plant-mediated nanomaterial synthesis approach (Jeevanandam et al., 2022).

6. Mechanism of sustainable nanomaterial formation

The exact mechanism for the formation of nanomaterials via plant-based biomolecules has not yet been identified, as several factors determine their reduction, nucleation, and stabilization (Abbasi et al., 2015). However, various studies have proposed that the synergistic effect of phytochemicals present in plants is responsible for bionanomaterial formation (Alves et al., 2019; Jeevanandam et al., 2020b; Król et al., 2019). It is also noteworthy that a plant can be considered non-native in a specific region, which would have been categorized as a native and common plant in another geographic region (Majewska et al., 2018; Trammell et al., 2020). Thus, as expected, the mechanism proposed for bionanomaterial formation via plant-based biomolecule will also be suitable for non-native plants, as shown in Fig. 7. Generally, phytochemicals, such as phenols, flavonoids, terpenoids, polysaccharides, vitamins, and proteins extracted from plants, act as reducing and stabilizing agents for bionanomaterial formation (Aslam et al., 2021). These phytochemicals and precursors are initially triggered via heat or electromagnetic radiation (visible/ultraviolet/infrared light or microwave) to transform their complex into a simplified structure (Ishak et al., 2019). Later, the reaction time determines the binding of the triggered or activated phytochemicals with the precursor molecule to reduce the ions to atom clusters (nucleation) and stabilize them to form nanosized particles (Bala and Rani, 2020). A more detailed mechanism has been discussed in previous works by the authors (Jeevanandam et al., 2016, 2017). However, a non-native plant in a region will proliferate by utilizing the nutrients from the soil due to competitive growth as well as natural selection (survival), making it unavailable for native plants, leading to ecological imbalances (Parepa et al., 2019). Hence, the extracts from such non-native plants will have a higher concentration of phytochemicals and other biomolecules than their native variants and other native plants in the area (Skubel et al., 2020) due to the uptake of high nutrient levels (Gabriel et al., 2018). Thus, non-native plants will be more beneficial for synthesizing nanomaterials than native plants to eliminate their presence, reutilize them, and yield better (smaller sized) and environment-friendly (less/nontoxic) nanomaterials. In addition, other types of non-native plants in each location could generate different types of nanomaterials without resorting to endogenous species or using the traditional chemical synthesis of nanomaterials. However, it must be considered that issues such as soil,

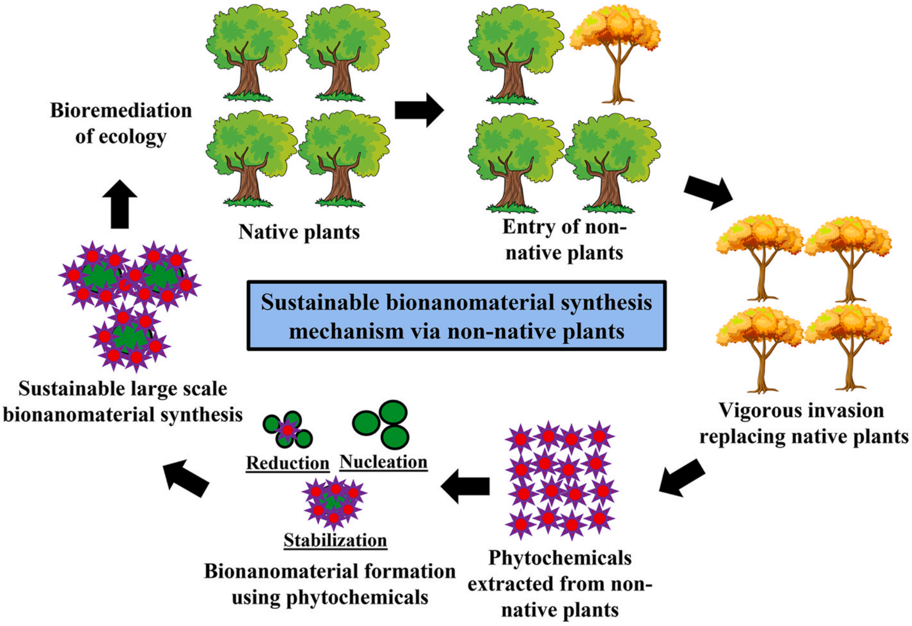

Fig. 7. Sustainable nanomaterial synthesis mechanism via non-native plants for bioremediation process.

sun exposure, and altitude can affect the phytochemical composition of plant extracts used in the synthesis of nanomaterials, which can result in nanomaterials with different sizes and/or morphologies depending on the geographic location of the same non-native species. Nevertheless, it has been identified that process optimization, e.g., using artificial intelligence (AI), machine learning (ML), and data mining, can be applied to the preparation of nanomaterials with controllable size and shape via non-native plants at commercial prices (Jami and Jabbarzadeh, 2021; Jin et al., 2023; Tao et al., 2021).

7. Futuristic application of non-native plant-synthesized bionanomaterials

The nanomaterials synthesized via non-native plants will have biomolecules with functional groups, eventually reducing their toxicity compared to physical or chemical synthesized nanomaterials (Rajeshkumar and Bharath, 2017). Moreover, the high concentration of phytochemicals present in non-native plants (as mentioned in section 5) (Skubel et al., 2020) will lead to the formation of nanomaterials with desired morphology (Ovais et al., 2018). These novel phytosynthesized nanomaterials are proposed to benefit various biomedical and pharmaceutical applications (Jan et al., 2021). Even though several studies (refer to section 5) showed that phytosynthesized nanomaterials using non-native plants are identified as an alternative to conventional synthesis methods, there are certain limitations, such as lack of reproducibility and standard synthesis procedure (Saleh and Yousaf, 2018; Silva et al., 2015). The location of plants, their geography, soil content, and other external factors play a major role in the quantity and purity of phytochemical extracts, which eventually influences the resultant nanomaterial's morphology (Barhoum et al., 2020; Shaikh et al., 2021). Further, there is no standard plant synthesis procedure (as in sol-gel or chemical vapor deposition) for nanomaterial synthesis (Vaseghi and Nematollahzadeh, 2020). This limitation can be solved in the future by isolating specific (instead of crude) phytochemicals responsible for nanomaterial formation, elucidating the formation mechanism, and utilizing them for their fabrication (Peralta-Videa et al., 2016). Recently, bioplastics have gained significant attention among researchers as conventional plastics are toxic to the environment and humans (Narancic et al., 2020). Cellulose, chitosan, chitin, and other natural polysaccharides have been extracted from plants and transformed into nanomaterials via novel green chemistry processes to form bioplastics with enhanced physicochemical properties (Aguilar et al., 2019). Thus, bioplastics from natural polymer-based nanomaterials extracted and synthesized using non-native plants can benefit specific biomedical applications (Anantachaisilp et al., 2021), such as drug delivery, orthopedic devices, and the preparation of tissue engineering fibrous scaffolds (Bano et al., 2018). Likewise, cellulose extracted from non-native plants can be fabricated into standalone nanomaterials or combined with other nanomaterials as composites, for instance, to be used in antimicrobial textile applications (Čuk et al., 2021). Further, the nanomaterials and nanocomposites synthesized via non-native plant extracts can be beneficial for bioimaging (Prabha et al., 2020), biosensors (Noah and Ndangili, 2022), drug as well as gene delivery (Augustine and Hasan, 2020; Gul et al., 2021), the production of wound plasters (Marinas et al., 2021) and environmental remediation (Bolade et al., 2020), as the resultant nanomaterials will be less/nontoxic due to the existence of biomolecules as their surface functional group (Chowdhury et al., 2020). Likewise, phytosynthesis methods via non-native plants using novel catalysts (Tripathi et al., 2017), hybrid approaches (biogenic and chemical methods) (Kumar Das et al., 2014), and agriculture wastes (Sangeetha et al., 2017) can also be explored in the future. Moreover, the latest computational methods, such as machine learning, deep learning, and molecular simulation approaches, will help in identifying specific phytochemicals from non-native plants that can be beneficial in the formation of nanomaterials (Jami and Jabbarzadeh, 2021; Jin et al., 2023; Tao et al., 2021).

Furthermore, non-native plant-synthesized nanomaterials that are less or nontoxic can be used for zero-dimensional carbon nanomaterial (e.g., carbon quantum dots) synthesis as the non-native plants contain various carbonaceous biomolecules. Such nanomaterials can benefit magnetic resonance imaging and dual bioimaging applications without or with minimal toxicity toward the host in the future (Wang et al., 2021). Even though these nanomaterials synthesized via non-native plant extract are beneficial in medical applications, the purity of these nanomaterials must be improved via the purification process for valorization and commercial applications in the future (Krishnani et al., 2022).

8. Conclusions

Non-native plants are not beneficial for the environment and possess a high potential to cause critical ecological imbalance and food chain in an ecosystem, eventually affecting all other living organisms, including native plants, microbes, animals, and humans. Thus, several bioremediation methods have been proposed and implemented recently to eradicate non-native plants and safeguard native plants. However, conventional methods have been reported to cause various environmental side-effects, adding to the emerging climate change and global warming challenges. On the other hand, the bibliography and previous experimental analysis in the present work reveal that phytochemicals from non-native plants can be an alternative source of biomolecules for nanomaterial synthesis. Hence, the utilization of non-native plants for sustainable bionanomaterial synthesis can be a novel approach to control their growth and use them for beneficial applications, compared to native plants, as large-scale bionanomaterial production can lead to bioprospecting and deforestation challenges. The approach proposed in this work to utilize non-native plants as a phytochemical source for nanomaterial preparation can be highly beneficial as a critical aspect in following the sustainable bioprospecting policy recommended by the United Nations and European Union (General Assembly Resolution 69/293 in 2015 and regulation law of invasive alien species [EU IAS 1143/2014]). Further, the environmental consequences of non-native plants can be reduced by utilizing them as a potential source for nanomaterial production in the future. Additionally, non-native plant-based phytochemical extracts for sustainable bionanomaterial synthesis and production (only 44 publications without any interlinks with the keyword "Invasive plants") are relatively new compared to the traditional phytosynthesis approach via native plants (185 publications specific to plant synthesis nanomaterials). However, extensive research is needed in the future to validate the benefits and limitations of this new approach of utilizing non-native plant-extracted phytochemicals in potentially reducing the costs of eradicating alien plants and their importance in synthesizing sustainable, less toxic, and more biocompatible nanomaterials.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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