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Review

Impatiens glandulifera Royle: From ecological threat to biotechnological opportunity – A narrative review

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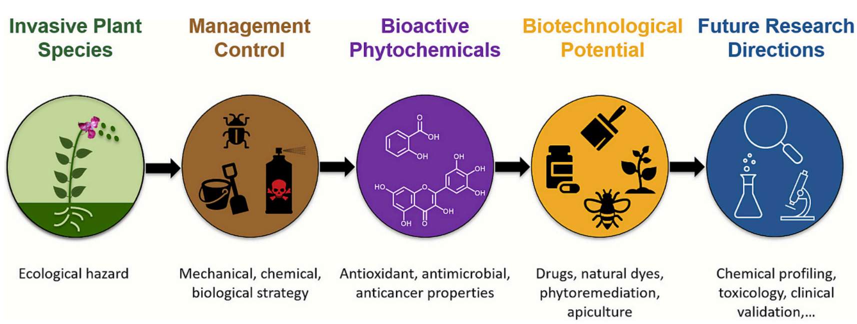
HIGHLIGHTS

- The invasive *Impatiens glandulifera* poses severe threats to biodiversity, ecosystems, and socio-economic stability globally
- Containment and eradication strategies are only marginally effective or expensive
- *I. glandulifera* is rich in diverse bioactive compounds with significant health-promoting properties
- This vigorous plant offers biotechnological and therapeutic potential, turning a problem into a sustainable resource

GRAPHICAL ABSTRACT



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ABSTRACT

Impatiens glandulifera Royle is an invasive alien plant species which poses substantial threat to biodiversity, ecosystems, and socio-economic stability globally. It has successfully colonised a wide range of habitats across Europe, North America, and other temperate regions of the world, facilitated by its aggressive seed dispersal mechanism, high adaptability, and competitive resource acquisition. Despite its ecological threats, *I. glandulifera* contains a wide variety of bioactive chemical constituents, presenting opportunities for novel biotechnological and therapeutic applications. This narrative review synthesises the existing scientific literature on the phytochemical composition, biological activities, ecological impacts, and management strategies associated with *I. glandulifera*. The plant is particularly rich in bioactive compounds, including naphthoquinones, flavonoids, phenolic acids, polysaccharides, essential oils, terpenoids, and steroids, which demonstrate significant antioxidant, antimicrobial, anticancer, anti-inflammatory, antidepressant, and allelopathic properties in preclinical studies. Management approaches have traditionally focused on mechanical eradication, use of chemical herbicides, and experimental biological control measures; however, sustainable solutions involving the valorisation of harvested biomass could substantially mitigate environmental concerns. Based on the available evidence, this review introduces a novel concept positioning *I. glandulifera* as a sustainable source of valuable bioactive compounds with potential applications in the medicinal, cosmetic, food, feed, nutraceutical, and pharmaceutical

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sectors. Nevertheless, significant knowledge gaps persist, particularly concerning comprehensive toxicity assessments, clinical validation of bioactivities, optimized and scalable valorisation strategies, and detailed chemical characterisation across different plant tissues. Addressing these gaps through targeted interdisciplinary research will be essential for realising the commercial potential of *I. glandulifera* and converting its ecological burden into a valuable resource.

1. Introduction

Invasive alien plant species (IAPS) are recognised as one of the main contributors to biodiversity loss with severe impacts on ecosystem services and socio-economic conditions (europa.eu, 2021). IAPS pose a major threat to native plants and animals and can also have negative impacts on human health. The economic damage they cause is high, around 12 billion euros per year, which are spent for eradication and containment of these plants in the EU alone.

Impatiens glandulifera Royle is a native plant to the western Himalayas (Fig. 1), but it is now mainly recognised as one of the most widespread IAPS worldwide (Helsen et al., 2021). In Europe, the plant was designated as an IAPS by the European and Mediterranean Plant Protection Organisation in 2004. It was first introduced as an ornamental plant in the UK in 1839, where it became a distinctive feature of riverbanks with its tall habit and profuse pink flowers (Tanner and Gange, 2020). It then spread quickly across the entire UK while the invasion of continental Europe started 50–100 years later. It is now recognised as one of the most aggressive invasive species in Europe, the Caucasus, Russia, the USA, western and eastern Canada, New Zealand and with rare occurrences in China (Hunan) and Japan (Fig. 1) (Helsen et al., 2021).

I. glandulifera is able to colonise a variety of habitat types (Tanner and Gange, 2020). It can adapt to different soils with varying nutrient availability, sediment type, pH (3.5–7.7), etc., however, it requires very high moisture levels (Beerling and Perrins, 1993). In Europe, it is mainly found in lowland areas and along riverbanks, including moist natural forests, wet meadows, marshes and stream banks. The seeds are highly buoyant in water currents, which strongly influences the spread of the species along rivers (Najberek et al., 2020). Apart from riparian zones, the species can also invade ruderal habitats, transport networks, and highland areas (Kiełtyk and Delimat, 2019). *I. glandulifera* exhibits strong growth under warm, CO_2-enriched conditions (Beerling and Perrins, 1993), suggesting that its distribution is likely to expand under future climate change scenarios. Temperature has been identified as an important determinant of invasion success, implying that ongoing global warming may promote its establishment at higher latitudes and altitudes (Willis and Hulme, 2002). Latitudinal phenological differentiation (Helsen et al., 2020), together with predictive models that project a northward range expansion (Kanmaz et al., 2023), provide further evidence that climate change will facilitate the spread of *I. glandulifera* beyond its current geographic range.

This review provides a comprehensive synthesis of current knowledge on *I. glandulifera*, covering its morphology, invasive traits, and substantial ecological impacts. Since the species is notoriously difficult to control or eradicate, this work advances a novel perspective: repositioning *I. glandulifera* from a problematic invader to a potential sustainable resource. By critically examining both established and prospective chemical constituents—particularly antioxidant and other health-promoting agents—this review underscores the plant's untapped potential for diverse commercial applications. The central contribution lies in the valorisation concept, which reframes *I. glandulifera* not merely as an ecological and economic burden, but as a promising source of bioactive compounds and biomass. In doing so, this narrative review identifies key research gaps, highlights promising scientific avenues, and proposes an integrated pathway that simultaneously mitigates ecological challenges and fosters sustainable utilisation.

2. Methods

A comprehensive literature search was conducted across electronic databases, including Scopus, PubMed, and Web of Science, to identify relevant scientific publications addressing the chemical constituents, biological activities, ecological impacts, and management strategies

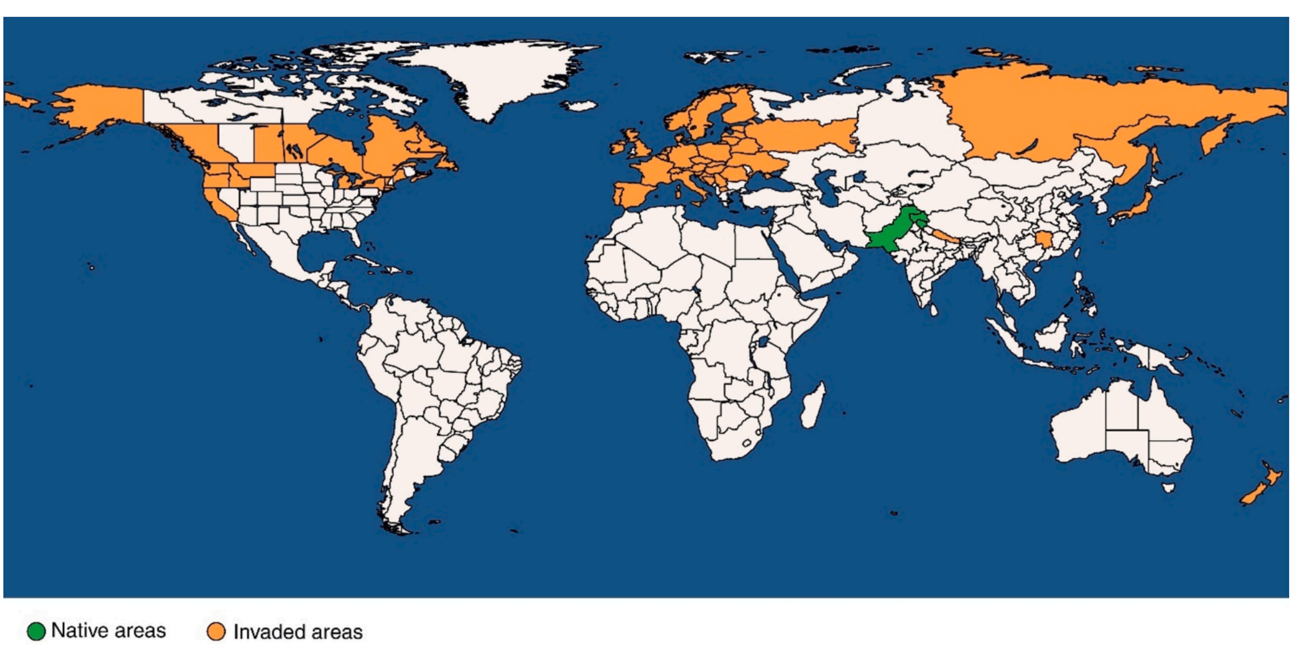

Fig. 1. Current global distribution of *I. glandulifera* (modified from the EPPO Global Database map, SVG format) (EPPO, 2025).

associated with *I. glandulifera*. The search covered all available literature published up to June 2025 without imposing lower date limits, thus ensuring an extensive historical perspective.

The search utilized combinations of relevant keywords and Boolean operators, structured in search queries as presented below. Basic search query was always applied in the search engine. For instance, to explore the literature focusing on plant morphology, we applied *Basic search query* + *Variaton 1* approach; to explore papers on plant's chemical composition, we applied *Variation 2*; to explore papers on plant bioactivity, we applied *Variation 3*; to study plant invasiveness, we applied *Variation 4*; and to study ethnobotanical or traditional use, we applied *Variation 5* search query.

Basic search query: "*Impatiens glandulifera*" OR "Himalayan balsam" OR "*Impatiens glandulifera* Royle" OR "*Impatiens roylei* Walp".

Variation 1: AND ("morphology" OR "plants parts" OR "flowers" OR "leaves" OR "seed pods" OR "stems" OR "roots").

Variation 2: AND ("chemical constituents" OR "phytochemistry" OR "naphthoquinones" OR "flavonoids" OR "phenolic acids" OR "anthocyanins" OR "anthocyanidins" OR "polysaccharides" OR "essential oils" OR "terpenoids" OR "steroids" OR "carotenoids" OR "proanthocyanidins").

Variation 3: AND ("bioactivity" OR "biological activity" OR "pharmacological" OR "antioxidant" OR "antibacterial" OR "antifungal" OR "anticancer" OR "cytotoxic" OR "allelopathy" OR "anti-inflammatory" OR "antidepressant" OR "phytoremediation").

Variation 4: AND ("invasiveness" OR "management" OR "ecology" OR "environmental impact" OR "eradication" OR "containment" OR "seed dispersal" OR "distribution").

Variation 5: AND ("ethnobotanical" OR "traditional" OR "culinary" OR "commercial" OR "natural dye" OR "phytoremediation" OR "pollinators").

Given the breadth of topics addressed, we adopted a descriptive and narrative approach, synthesising findings to highlight major patterns, knowledge gaps, methodological limitations, and areas requiring further research. Studies lacking methodological clarity or presenting ambiguous data were carefully evaluated and, where appropriate, excluded from detailed analysis. Additional exclusion criteria included incomplete reporting of key parameters, irrelevance of reported outcomes to the scope of this review, reliance on outdated or non-standardised methodologies, and inadequate scientific validity (e.g., conference abstracts or non-peer-reviewed reports). To minimise language bias, non-English publications were assessed based on their English abstracts and/or translations generated using online translation tools, with inclusion or exclusion decisions discussed collectively by the authors to reduce subjectivity. These methodological precautions were implemented to ensure transparency, rigor, and contextual relevance in line with best-practice guidance for narrative reviews (e.g., the SANRA scale; (Baethge et al., 2019)), while recognising the interpretative nature of this review format.

3. Plant morphology

I. glandulifera is a large annual plant (therophyte) belonging to the genus *Impatiens* of the Balsaminaceae family (Helsen et al., 2021). It is known by many other names, such as *Impatiens roylei* Walp., Himalayan balsam, Indian balsam, Policeman's helmet, Custodian helmet, Gnome's hatstand, Bobby tops, Kiss-me-on-the-mountain, Touch-me-not, Purple jewelweed, and Ornamental jewelweed. The flowers (Fig. 2A) form inflorescences and vary in colour from pink to purple, occasionally also white (Beerling and Perrins, 1993). The seeds (Fig. 2B and C) are black when ripe and are contained in capsules (Fig. 2D). A single plant can produce between 800 and 2500 seeds on average (Helmisaari, 2010). The lanceolate leaves (Fig. 2E) are arranged opposite or in whorls, usually with three leaves per node. The stems (Fig. 2F) are gnarled-thickened, smooth, hairless, woody and hollow, and can branch out (Beerling and Perrins, 1993). Roots are shallow and fibrous (Fig. 2G).

4. Invasiveness and negative impacts

When an introduction or a spread of an alien plant species causes an imbalance within an ecosystem, the introduced species is termed invasive. The negative effects of IAPS pose a significant threat to ecosystems,

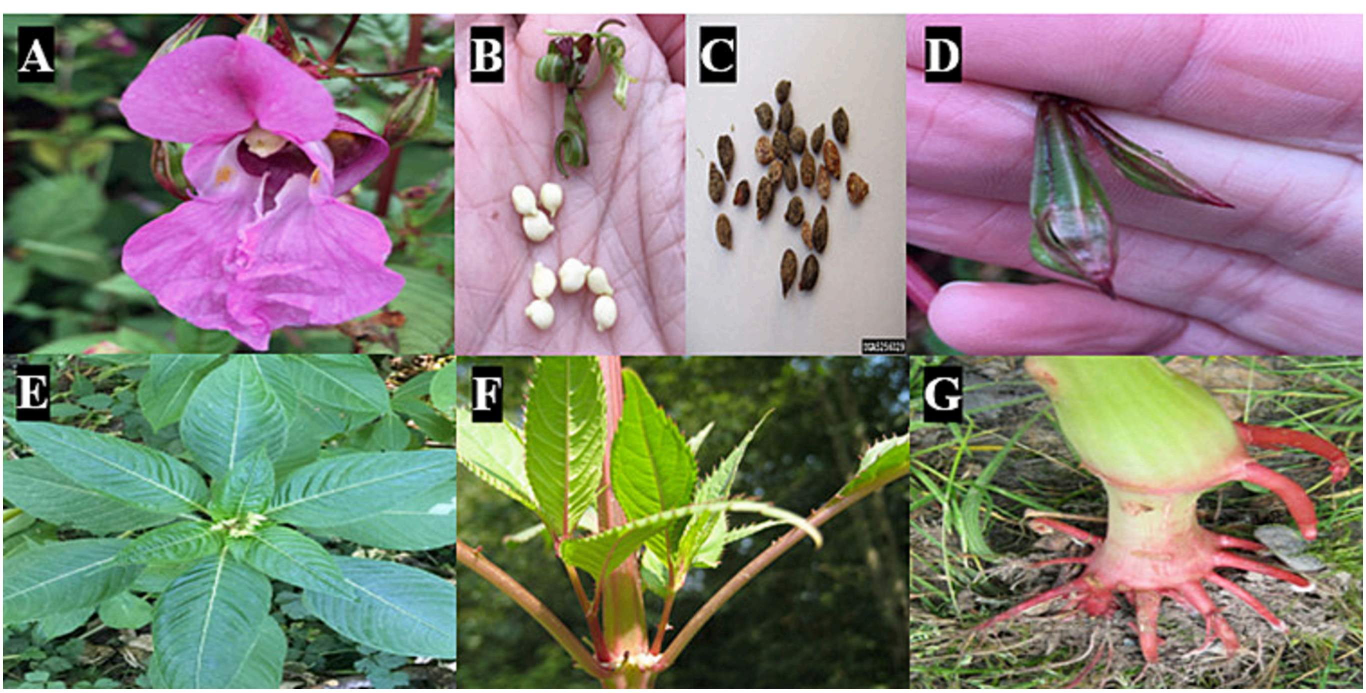

Fig. 2. Constituent parts of *I. glandulifera*: (A) Flower; (B) Dehisced capsule and immature seeds; (C) Mature seeds; (D) Mature, unopened seed capsules; (E) Leaves; (F) Stem with a node; (G) Roots. (Center for Invasive Species and Ecosystem Health (Jan Samanek), 2007); Metro and Invasive Species Council of Metro, 2021) – accessed 26 May 2025.

potentially leading to the extinction of local, autochthonous species. While some studies point to efficient resource utilisation and allelopathy as main contributors to the invasiveness of *I. glandulifera*, the fundamental mechanisms of its spread remain largely unexplored (Mynard and Sánchez, 2023).

4.1. Invasive nature and status of the plant

While initial expansion in the UK was likely unintentional with *I. glandulifera* escaping garden boundaries (Helsen et al., 2021), its subsequent rapid spread (645 km^2/year) has been primarily driven by intentional releases from beekeepers and the public (Rotherham, 2001). The severity of *I. glandulifera* infestation was also recognised by the European Council in 2017 when it added the plant to the consolidated list of invasive alien species of Union concern and strictly prohibited its cultivation, import, trade, planting, transport and deliberate release into the environment (FAO, 2017). In some U.S. states, including Connecticut, Washington, and Oregon (Invasive Plant Atlas of the United States, 2018), it is classified as a noxious weed, with restrictions on its sale, cultivation, and distribution. In the Far Eastern Federal District of Russia, it has an invasiveness status of 1 (Vinogradova et al., 2020). The list continues, but the pattern of these laws and regulations clearly shows the all-round environmental hazard that *I. glandulifera* poses outside its natural habitat.

The rapid rate of spread of *I. glandulifera* could in part be ascribed to its explosive, ballistic seed dispersal mechanism, allowing the mature seeds to reach a speed of up to 4 m/s and a distance of up to 7 m (Deegan, 2012). It is also important to shed light on other seed distribution routes (Fig. 3). Hydrochory (water dispersal of seeds) was likely the decisive mechanism for initial colonisation, particularly in calm or low-lying riverine areas (Greenwood et al., 2020). Anthropochory (dispersal by humans) can also contribute to the long-distance spread, primarily through agricultural machinery and gardening equipment, the transport of garden waste, contaminated topsoil or river gravel (Helsen et al., 2021). The wind and animals are also assumed to contribute to plant's proliferation (Beerling and Perrins, 1993; Helmisaari, 2010). Last, but not least, local dispersal can sometimes interact with long-distance migration processes, further increasing the ease of spread for *I. glandulifera*.

4.2. Management of infected areas and eradication strategies

Many containment strategies have been proposed (Helmisaari, 2010). Preventive measures need to be clear and well organised, while the awareness of the public should be increased (beekeepers and ornamental growers in particular), especially about the plant's rapid spread along waterways (Helmisaari, 2010). Management measures generally aim to prevent seed production and dispersal. In riparian systems, it is advisable to develop appropriate strategies at the river catchment level and work downstream to prevent the re-spread of the invasive species through the influx of new seeds. Such an approach is very complicated, as sites are often inaccessible and land ownership is fragmented. Due to the high regeneration and spreading rate of *I. glandulifera*, eradication is costly and time-consuming, but is in principle achievable either by mechanical, chemical or biological measures.

Mechanical control by hand-pulling and mowing can substantially suppress *I. glandulifera* populations—as shown by a 77 % reduction after a decade of management in the Thayatal–Podyjí National Park (Austria–Czech Republic)—yet residual plants persist, preventing complete eradication and maintaining ecological risk (Schiffleithner and Essl, 2016). After removal, the plant material should be safely disposed of or bagged to prevent re-introduction (Čuda et al., 2020). Disposal by on-site burning is effective, but not preferred, as the plant has a high water content, leading to high energy consumption associated with a significant carbon footprint. Spraying the plant with hot water (Oliver et al., 2020) or steaming the soil at 115 °C was also considered (Bitarafan et al., 2025), but cutting is more time- and cost-effective. When using chemical control, one can choose between selective and non-selective methods. The use of selective chlorinated herbicides (e.g., 2,4-dichlorophenoxyacetic acid and triclopyr) is most effective when *I. glandulifera* grows in grassland areas or together with other monocotyledonous plants. The use of non-selective herbicides, such as glyphosate, necessitates subsequent reseeding of the treated areas to prevent reinvasion. Herbicides should be avoided in riparian regions, as the chemicals can easily spread over larger areas and affect non-target organisms.

In biological control, natural enemies of the plant are used to regulate host populations. A programme, which includes research on classical biological control of *I. glandulifera*, was launched in 2006 (Pollard et al., 2021). In the autochthonous environment of *I. glandulifera*, numerous insects and fungal pathogens have been proposed. The rust fungus *Puccinia komarovii* caused major damage in field experiments, warranting further research. Cross-inoculation studies showed that *P. komarovii* has a sufficiently high host specificity for *I. glandulifera,* and was therefore renamed to *Puccinia komarovii* var. *glanduliferae* (Pollard et al., 2021). Three common endophytes (*Alternaria alternara*, *Cladosporium oxysporum* and *Colletotrichum acutatum*) have shown antagonistic effects against this rust fungus, originally released in the UK in

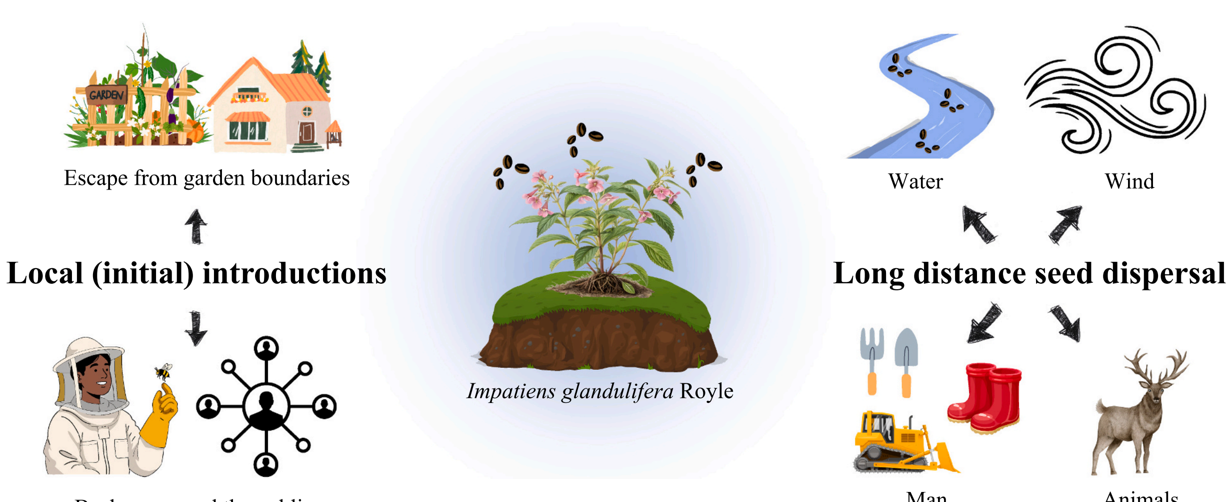

Fig. 3. Schematic overview depicting the introduction and spread of *I. glandulifera*.

2014 (Indian strain) and in 2017 (Pakistani strain) (Currie et al., 2020). However, the impact of the rust on *I. glandulifera* biomass was not as substantial as initially predicted. Currently, the release of the biological agents in the UK is being monitored in the field as the programme is still in development. At EU level, the release of microorganisms as biological control agents is currently not regulated, therefore an appropriate risk assessment should be carried out beforehand. The European herbivore tortricid moth Lepidoptera (*Pristerognatha fuligana*) was also considered as a biological control agent, but showed no significant impact on the vigour of *I. glandulifera* (Burkhart and Nentwig, 2008). To better understand the invasive dynamics of *I. glandulifera* and inform biological control strategies, the chloroplast genome was sequenced to identify genomic variations between contemporary and historical samples (Cafa et al., 2020). This research suggests the chloroplast genome is a reliable genetic marker for population analyses, providing insights into the species' evolutionary pathway and adaptation within invaded regions.

4.3. Allelopathic action

It is a general hypothesis that allelopathic ability of *I. glandulifera* plays a role in its virulent spread and is expressed through different naphthoquinone pigments, such as 2-methoxy-1,4-naphthoquinone (2-MNQ) and 2-hydroxy-1,4-naphthoquinone (lawsone, 2-HNQ), found in different parts of the plant (Kupcinskiene et al., 2025). The highest amounts of naphthoquinones are present in seedlings, but gradually decrease as the plant ages. These secondary metabolites are released into the environment primarily by their secretion from the roots and by leaching from the leaves. Glucosylated steroids glanduliferin A and B and the unstable 1,2,4-trihydroxynaphthalene-1-*O*-glucoside have also been proposed as potential allelopathic compounds (Cimmino et al., 2016). In a series of controlled experiments, the allelopathic effect of aqueous extracts from the shoots of flowering *I. glandulifera* was demonstrated by an apparent reduction in seed germination and seedling development of several other plant species (i.e. *Leucosinapis alba*, *Brassica napus* and *Sinapis alba*) (Csiszár et al., 2013). Similar bioassays carried out on aqueous extracts also demonstrated their strong inhibitory effect on the mycelial growth of ectomycorrhizal fungi (Ruckli et al., 2014). However, by considering both field and greenhouse experiments, it was concluded that allelopathy is unlikely to be the main driver of the spread of *I. glandulifera*, as the effect was comparable to other native plant species found in Europe. It is possible that *I. glandulifera* could have a stronger competitive effect on less resistant coexisting species, but further research is needed to confirm such a hypothesis.

4.4. Plant's environmental and social impacts

The general perception of *I. glandulifera* has shifted from its initial appreciation for floral attractiveness to a primary ecological concern as a result of its detrimental impact on native vegetation and habitats (Tanner and Gange, 2020). For instance, large populations near water bodies can negatively affect ecosystem services by restricting access for recreational activities. In riparian habitats, *I. glandulifera* supplants native vegetation, leading to reduced plant diversity, and hinders forest regeneration through resource depletion and allelopathy (Power and Sánchez, 2020). Furthermore, its attractive flowers, rich in nectar and pollen, may negatively impact the reproduction of native plants and crops by diverting pollinators, ultimately leading to economic losses (Chittka and Schürkens, 2001; Najberek et al., 2024). Beyond its impact on plant communities, *I. glandulifera*'s shallow and minimal root system fails to provide adequate soil stabilisation or protection against high water flows (Metro and Invasive Species Council of Metro, 2021; Tanner and Gange, 2020). As the plant dies in autumn, the soil is left bare and exposed, exacerbating riverbank erosion and sediment loss (Hardwick et al., 2025). The introduction of the dead plant material and eroded sediments into water bodies further degrades aquatic ecosystems by altering the riverbed and reducing water quality, directly affecting biotic interactions (Tanner and Gange, 2020). Adding to these concerns, allelochemicals produced by *I. glandulifera* have been shown to inhibit the growth rate of the green alga *Acutodesmus obliquus* and the planktonic crustacean *Daphnia magna*, thus delaying their maturation by several weeks. The allelochemicals from *I. glandulifera* also affect symbiotic microorganisms, such as mycorrhizal fungi. This disruption can lead to alterations in the soil's microbial composition, consequently reducing soil fertility and slowing the decomposition of organic matter (Diller et al., 2023). Furthermore, the plant generally offers low nutritional value for invertebrates, resulting in reduced diversity and abundance of these animals in invaded areas. The number of aboveground invertebrates increases only after the invasive plant has been removed (Wood et al., 2021). Such inter-ecosystem effects underscore the necessity of incorporating these broader impacts into the risk assessment of invasive species. Given the significant environmental, ecological, and economic burdens associated with *I. glandulifera*, alternative uses for this plant are warranted as a means to help control its spread and mitigate its negative impacts.

5. Chemical constituents of *I. glandulifera* and their biological activities

Although still insufficiently explored, studies on the phytochemical composition of various *Impatiens* species have identified a diverse array of secondary plant metabolites with diverse biological activities. Major classes of researched bioactive compounds include naphthoquinones (Li et al., 2015), phenolic acids (Szewczyk et al., 2016b), flavonoids (Vieira et al., 2016), anthocyanins (Tatsuzawa et al., 2009), coumarins (Panjchayupakaranant et al., 1995), triterpenoid saponins (Zhou et al., 2007), phytosteroids (Cimmino et al., 2016), essential oils (Szewczyk et al., 2016a) and peptides (Table 1) (Yang et al., 2001). Therefore, with its uncontrolled spread and a biomass yield of 5.8 tons of dry matter per hectare, *I. glandulifera* potentially represents a virtually inexhaustible and renewable natural source of health-promoting compounds (Van Meerbeek et al., 2015). Many are of great academic as well as industrial interest and are reviewed in more detail below.

5.1. Naphthoquinones

Naphthoquinones (NQs) constitute a structurally diverse class of aromatic polyketides characterised by a quinonoid core. These compounds are biosynthesised via the polyketide pathway in many plants (e.g. taxa plant) and microorganisms, and have different biological activities (Aminin and Polonik, 2020). For example, 2-HNQ and 2-MNQ have antiviral, antibacterial, antifungal, antitumor and antianaphylactic properties (López López et al., 2014). These pharmacological effects show their potential for further pharmaceutical development of new therapeutics, especially in the context of antimicrobial resistance and cancer chemotherapy (Meyer et al., 2021). In 1974, Chapelle first isolated the bioactive compound 2-MNQ from dried leaves of *I. glandulifera*,

Table 1
Major secondary metabolites found in different parts of *I. glandulifera*.

Metabolite class	Plant part	Reference
Naphthoquinones	flowers, seed pods, leaves, roots	(Cimmino et al., 2016; Ortin and Evans, 2013)
Phenolic acids	flowers, leaves, roots	(Szewczyk and Olech, 2017)
Flavonoids	aerial parts	(Szewczyk et al., 2019; Vieira et al., 2016)
Phytosterols, triterpenoids and fatty acids	seeds, leaves, roots	(Szewczyk et al., 2018a)
Polysaccharides	aerial parts, roots	(Szewczyk et al., 2018b)
Coumarins	roots	(Tříska et al., 2013)
Essential oils	aerial parts, roots	(Szewczyk et al., 2016a)

but subsequent studies confirmed its presence also in seed pods, flowers, and roots (Cimmino et al., 2016). In addition to 2-MNQ, other 1,4-NQs, such as lawsone and juglone derivatives, have also been detected in both aerial and subterranean parts of the plant (Block et al., 2019). However, their reported quantities vary, depending on the plant part analysed and the methodological approach employed.

The functional significance of these compounds has also been investigated. While high concentrations of NQs in *I. glandulifera* flowers have been documented, their specific role within floral tissues remains unclear. Nevertheless, Block et al. associated elevated levels of 2-HNQ and 2-MNQ with a reduced incidence of fungal pathogens (*Metschnikowia reukaufii* and *Aureobasidium pullulans*), which are frequently introduced by pollinators (Block et al., 2019). Previous studies involving *I. glandulifera* collected in France and the Czech Republic confirm the presence of both 2-HNQ and 2-MNQ in the aerial parts of the plant and further show that the year of collection, the method of drying, the extraction solvent, and the storage conditions do not significantly impact the recovery of NQs (Tříska et al., 2013). However, the seasonal dynamics of NQs accumulation has been demonstrated. At the onset of flowering, NQs are most abundant in the leaves, but during flowering they are particularly abundant in the flowers (Lobstein et al., 2001). Towards the end of the growing season, the concentration of NQs decreases significantly.

Tříska et al.'s analysis of *I. glandulifera* root extract revealed a highly fluorescent but unstable compound, 1,2,4-trihydroxynaphthalene-1-*O*-glucoside (THNG), also present in trace amounts in flowers and stems (Tříska et al., 2013). The instability of THNG originates from its susceptibility to hydrolysis by β-glucosidases, which converts it into the unstable 1,2,4-trihydroxynaphthalene (THN) that readily oxidizes to the more stable 2-HNQ. These findings emphasize the critical role of precise extraction and drying methods for accurately profiling the labile compounds (such as THNG) in phytochemical studies.

5.2. Phenolic compounds

Phenolic compounds represent a large and diverse group of plant secondary metabolites. Among these, phenolic acids form a major and ubiquitous subgroup, with particularly high concentrations observed in *I. glandulifera* (Tomás-Barberán and Espín, 2001). Functionally, these compounds are normally released as a part of a plant's defence mechanism against mechanical damage, pathogen invasion, and various environmental stresses. These secondary metabolites have antibacterial and antioxidant properties and are recognised for their broad range of pharmacological activities, including anti-inflammatory, antitumor, anticarcinogenic and antimutagenic effects (Farhoosh et al., 2016).

Recent pharmacological studies have highlighted the neuroprotective activity of specific polyphenols from *I. glandulifera*. Notably, acute ingestion of hyperoside and protocatechuic acid have demonstrated antidepressant-like and anxiolytic effects in murine models. These effects are mediated through the upregulation of brain monoaminergic systems — elevating serotonin, noradrenaline, and dopamine levels — and increasing brain-derived neurotrophic factor (BDNF) expression. Behavioural tests such as forced swimming and tail suspension have corroborated these findings, suggesting the potential of these compounds for managing mood disorders and enhancing cognitive functions (Orzelska-Górka et al., 2019). Importantly, further studies on hyperoside and protocatechuic acid confirmed their procognitive and mood-regulating effects after long-term administration in mice. Chronic use elevated serotonin levels and enhanced memory, reinforcing their value as neuroactive agents derived from *I. glandulifera* (Orzelska-Górka et al., 2023).

Moreover, antimicrobial screening of polyphenol extracts from the aerial parts of *Impatiens* species have shown selective efficacy predominantly against Gram-positive bacteria and *Candida* species, with minimal inhibitory concentration (MIC) values ranging from 125 to 1000 μg/mL, indicating inhibitory effects of a low to moderate degree. However, no significant antibacterial activity was observed against Gram-negative bacteria, likely owing to their outer membrane barriers (Szewczyk et al., 2016b). Additionally, antinociceptive and anti-inflammatory effects of hydroethanolic extracts containing polyphenols from flowers and roots of *I. glandulifera* were shown in mice. These extracts increased thermal pain threshold and reduced chemically induced writhing. While direct inhibition of NF-κB or MAPK pathways was not confirmed, the phenolic profile and behavioural outcomes strongly suggest involvement of these signalling pathways (Szewczyk et al., 2018c).

Bioactive phenolic acids were qualitatively and quantitatively determined from the roots, flowers, and leaves of *I. glandulifera* (Szewczyk and Olech, 2017). Seventeen phenolic acids were found, namely syringic acid, gentisic acid, gallic acid, protocatechuic acid, 4-hydroxybenzoic acid, 3-hydroxybenzoic acid, vanillic acid, *trans*-caffeic acid, *cis*-caffeic acid, *trans*-*p*-coumaric acid, *cis*-*p*-coumaric acid, *trans*-ferulic acid, veratric acid, salicylic acid, 3-hydroxycinnamic acid, *cis*-ferulic acid and *trans*-synaptic acid. Phenolic acids were most abundant in the flower extract where protocatechuic acid was found as the main component at 0.01 % (*w*/*w*). The isolation of protocatechuic acid and *p*-hydroxybenzoic acid from the above-ground parts of *I. glandulifera* has been reported, with the latter exhibiting superior antioxidant capacity in in vitro chemical assays (Szewczyk et al., 2019). In addition to the phenolic acids mentioned above, *p*-coumaric acid hexoside was tentatively identified in alcoholic and aqueous extracts of *I. glandulifera* shoots, including flowers, leaves and fruits (Mikulic-Petkovsek et al., 2024).

Anatomical characteristics of the individual plant part (e.g. certain predominant tissues, structure, size and type of cells present) and the choice of an extraction method can influence the recovery of phenolic acids. The aerial parts of the plant consist mainly of parenchyma tissue composed of thin-walled cells, whereas the roots consist of many mechanically resistant structures that may hinder the penetration of the solvent and therefore a more rigorous approach may be required to release the compounds from the plant matrix. Another important factor that should be considered is the strong interaction between lignin and phenolic substances. Extraction methods such as ultrasound-assisted extraction, in which the cell structure is more efficiently perturbed, have proven to be rather effective (Middleton Jr et al., 2000).

Quite a few types of flavonoids such as flavones, flavanones, and flavonol monoglucosides and diglucosides were found in different species of the genus *Impatiens*, but reports on *I. glandulifera* in particular are less abundant. A series of glycosylated and/or acylated derivatives of four common flavonoids were identified in *I. glandulifera's* flower (Vieira et al., 2016): eriodictyol (eriodictyol-7-*O*-glucoside), quercetin (quercetin-3-*O*-galactoside (hyperoside) and quercetin-3-*O*-6″-malonyl-glucoside), kaempferol (kaempferol-3-*O*-rhamnosyl-diglucoside, kaempferol-3-*O*-glucoside (astragalin) and kaempferol-3-*O*-6″-malonyl-glucoside) and myricetin (myricetin-3-*O*-galactoside), including aglycones quercetin, kaempferol and dihydromyricetin (ampelopsin). Interestingly, ampelopsin is thought to reduce the infection of brown bumblebees (*Bombus pascuorum*) by the parasitic alveolates of *Apicystis bombi* (Vieira et al., 2016). Findings of Szewczyk et al. were similar. They extracted eight flavonoids from the aerial parts of the plant, which were derivatives of eriodictyol, quercetin, and kaempferol (Szewczyk et al., 2019). Hyperoside, isoquercetin and eriodictyol 7-*O*-β-D-glucoside showed particularly strong antioxidant activity. In yet another study, flavanols (epicatechin, catechin, and two procyanidin dimers), flavanones (two eriodictyol hexosides and naringenin hexoside), and flavonols (isorhamnetin-3-rutinoside, kaempferol acetyl hexoside, two kaempferol hexosides, kaempferol rhamnosyl dihexoside, quercetin malonyl hexoside, quercetin-3-rutinoside, and myricetin-3-glucuronide) were found in both alcoholic and aqueous extracts of leaves, flowers and fruits (Mikulic-Petkovsek et al., 2024).

While the specific structures of anthocyanins present in *I. glandulifera* remain to be conclusively identified, this class of compounds is produced in limited amounts within the root cap cells, which contain amyloplasts and are involved in gravity perception (Mumford, 1990). Based on the chemical composition of related *Impatiens* species, anthocyanins such as acylated malvidin-3-*O*-glucoside could be the main pigment responsible for the characteristic pink or purple colour of the flowers (Tatsuzawa et al., 2009). In a recent study, six anthocyanins, namely cyanidin, delphinidin, and malvidin, which were glycosylated with alkylhexosides, were tentatively identified in the alcoholic extract of *I. glandulifera* shoots (Mikulic-Petkovsek et al., 2024). Anthocyanins, recognised as some of the most potent antioxidants among flavonoids, exhibit significant scavenging activity against reactive oxygen and nitrogen species with significant implications for human health.

5.3. Water-soluble polysaccharides

I. glandulifera produces also water-soluble polysaccharides with diverse therapeutic potential as they exhibit anti-inflammatory, antitumor, antioxidant, immunomodulatory, wound-healing and anti-atherosclerotic effects (Ghildyal et al., 2010). The molecular mechanisms underlying these effects are linked to their interaction with the innate immune system, particularly through modulation of cytokine release and reactive oxygen species (Schepetkin et al., 2008).

A detailed compositional analysis of water-soluble polysaccharide fractions isolated from the aerial parts and roots of *I. glandulifera* identified galactose, arabinose, mannose, glucose, rhamnose, xylose, and fucose as the main monomeric units (Szewczyk et al., 2018b). Notably, the extraction yield for these polysaccharide fractions was 7.74 % in roots and 8.32 % in aerial parts, indicating a substantial presence of these macromolecules within the plant. Size exclusion chromatography (SEC) of the aerial parts revealed a considerable number of components with high molecular weights, reaching up to 2.3 MDa, predominantly classified as arabinogalactan proteins (AGPs). With potent immunomodulatory effects, high molecular weight polysaccharides from *I. glandulifera* aerial parts reduced interleukin-8 (IL-8) production by 33 %, suggesting therapeutic potential for inflammatory disorders given IL-8's central role in inflammation. Moreover, higher amounts of carbohydrate acids – uronic acids – were found in the aerial parts compared to the roots, leading to an increased antioxidant activity (Szewczyk et al., 2018b).

5.4. Lipophilic compounds (phytosterols, triterpenoids and fatty acids)

A comprehensive study was conducted that details the chemical composition of *I. glandulifera's* lipophilic extracts (Table 2), specifically focusing on phytosterols, triterpenoids, and fatty acids across its roots, leaves, and seeds (Szewczyk et al., 2018a).

The main phytosterols in leaves were α-spinasterol, chondrillasterol, and Δ^7-sitosterol. In roots and seeds, β-sitosterol was the most abundant. On the other hand, α-spinasterol (phytosterol) acetate, 5α-lup-20(29)-en-3β-ol acetate, and β-amyrin acetate prevailed among triterpenoid acetates. These terpenoids indicate their possible role in plant defence mechanisms and their potential use in anti-inflammatory and anticancer therapies (Szewczyk et al., 2018a). Among fatty acids, α-linolenic acid, palmitic acid, and oleic acid were the most abundant. Importantly, ω-3 fatty acids were also found, especially α-linolenic acid, which is recognised for its beneficial role in supporting cardiovascular health. The fatty acid and triterpenoid fractions exhibited strong antioxidant activity and moderate cytotoxicity against human leukaemia cells HL-60 and HL-60/MX2. This is not unusual since these compounds are well-known for their antimicrobial, anti-inflammatory, antitumor and antioxidant biological activities (Dzubak et al., 2006). In addition, several other fatty acids have also been identified in the flowers of *I. glandulifera*, e.g. myristic acid, lauric acid, arachidic acid, capric acid, and other (Jakubska-Busse et al., 2023; Najberek et al., 2024). These findings further confirm their contribution to the plant's bioactive profile.

The flowers and seed pods were shown to contain another, rather uncommon α,β-unsaturated fatty acid – *trans*-tetradec-2-enoic acid – which is associated with specific pheromones of the *Apis mellifera* queen and can be involved in lipid-mediated signalling pathways. The acid was co-extracted from *I. glandulifera* with α-linolenic acid and several saturated fatty acids (palmitic acid, stearic acid and arachidic acid) (Ortin and Evans, 2013). A non-polar extract yielded also a hydroxylated aliphatic ketone 1-hydroxyeicosan-3-one, which impacts different signalling pathways as a lipid mediator (Lau et al., 2023).

Table 2
Lipophilic compounds found in the extracts of different plant parts of *I. glandulifera*.

Compound	Plant part		
	Leaf	Root	Seed
Phytosterols			
stigmasta-7,24(28)-dien-3β-ol (Δ^7 -avenasterol)	✓		
ergosta-7,22-dien-3-ol	✓	✓	
ergosterol	✓	✓	
3β-hydroxy-5α-cholestane-6-one	✓	✓	
5α-ergost-7-en-3β-ol	✓	✓	
campesterol	✓	✓	✓
β-sitosterol	✓	✓	✓
sitostanol	✓	✓	✓
spinasterol + chondrillasterol	✓	✓	✓
Δ^7-sitosterol	✓	✓	✓
cholesterol		✓	✓
campestanol		✓	✓
ergost-8(14)-en-3-ol		✓	✓
stigmasterol		✓	✓
Δ^5-avenasterol		✓	✓
Δ^7-stigmastenol		✓	✓
Triterpenoid acetates			
13,27-cycloursan-3-ol, acetate, (3β,13β,14β)-	✓		
cycloeucalenyl acetate	✓	✓	
Ψ-taraxasteryl acetate	✓	✓	
olean-12-en-3,28-diol, diacetate, (3β)-	✓	✓	
9,19-cyclolanostan-3-ol, 24-methylene-, acetate, (3β)-	✓		✓
5α-ergost-7-en-3β-ol acetate	✓	✓	
taraxasteryl acetate	✓	✓	✓
α-spinasterol acetate	✓	✓	✓
β-amyrin acetate	✓	✓	✓
β-simiarenol acetate	✓	✓	✓
stigmast-7-en-3-ol, acetate, (3β,5α)-	✓	✓	✓
5α-lup-20(29)-en-3β-ol, acetate	✓	✓	✓
lupan-3-ol acetate	✓	✓	✓
Fatty acids			
azelaic acid (C9:0)	✓		✓
arachidonic acid (C20:4)	✓	✓	✓
caprylic acid (C8:0)	✓	✓	✓
palmitic acid (C16:0)	✓	✓	✓
stearic acid (C18:0)	✓	✓	✓
oleic acid (C18:1)	✓	✓	✓
linoleic acid (C18:2) ω-6	✓	✓	✓
α-linolenic acid (C18:3) ω-3	✓	✓	✓
γ-linolenic acid (C18:3)	✓	✓	✓

5.5. Essential oils

Essential oils from *I. glandulifera* have recently gained attention due to their complex chemical composition and potential bioactivity. Szewczyk et al. conducted a comprehensive phytochemical analysis of essential oils obtained by hydrodistillation from aerial parts and roots of *I. glandulifera* (Szewczyk et al., 2016a). Analysis of the oil from the aerial parts identified a total of 76 compounds. Oxygenated monoterpenes (28.2 %) were the dominant class, with α-terpinyl acetate being the most prominent. Notably, phthalide derivatives such as (*Z*)-ligustilide and butylphthalides, rarely reported outside *Apiaceae*, were identified as signature volatiles in *I. glandulifera*. These monoterpenic compounds warrant further investigation due to their established neuroprotective, antispasmodic, and anti-inflammatory properties, observed in extracts from various plant sources (Astudillo et al., 2004). Monoterpene hydrocarbons comprised 9.9 % of the total essential oil content from aerial tissues, with β-phellandrene occurring in considerable amounts. Such compounds are commonly associated with antimicrobial (Badawy et al., 2019) and insect-repellent (Yildirim et al., 2013) activity, suggesting a potential ecological role in plant defence.

The volatile profile of the root-derived essential oil differed significantly in composition where 94 compounds were identified. Oxygenated aliphatics, oxygenated monoterpenes and oxygenated sesquiterpenes were the main compound groups detected, each accounting for about 20 % of total volatiles, while sesquiterpene hydrocarbons amounted to 13 %. Vulgarone B was the main constituent identified, a sesquiterpene ketone previously reported in some *Asteraceae* species and associated with potent antibacterial (Chung et al., 2009) and antifungal (Meepagala et al., 2003) activities. The predominant monoterpenes were linalool, borneol and bornyl acetate. These compounds are known for their calming, anti-inflammatory, and analgesic properties (Zhao et al., 2023). A total of twenty compounds were shared between both oils (aerial and root-derived). Similar types of compounds have also been reported in other studies on *I. glandulifera* (Jakubska-Busse et al., 2023; Najberek et al., 2024), where they were recognised primarily as chemical insect attractants, further emphasizing their ecological significance in plant–insect interactions.

Although bioactivity studies on the essential oils of *I. glandulifera* are limited, the compositional profile — rich in monoterpenes, sesquiterpenes, and phthalides — suggests potential antimicrobial, neuroprotective, and anti-inflammatory applications. Several of the identified compounds, such as α-terpinyl acetate, linalool, and (*Z*)-ligustilide, have well-documented effects in both in vitro and in vivo models, suggesting further pharmacological evaluation of *I. glandulifera* extracts.

5.6. Glanduliferins A and B

Two novel glycosylated steroids, glanduliferin A and B, were recently isolated from *I. glandulifera* stems (Cimmino et al., 2016). These cholestane-type steroidal glycosides showed moderate in vitro cytotoxicity (IC_{50} 30–100 μM across A549, SKMEL-28, and U373 cell lines), with glanduliferin A causing complete cell death at 100 μM, while glanduliferin B exhibited only a weak cytostatic effect at the highest concentration. These findings underscore how minor structural variations (hydroxylation, glycosylation) in cholestane derivatives significantly impact their interaction with cellular targets. Overall, *I. glandulifera* emerges as a previously unrecognised source of biologically active steroidal glycosides. Glanduliferin A's potent and selective activity in glioblastoma and other tumor models positions it as a promising lead for further development, either as a direct chemotherapeutic agent or a pharmacophore for more potent derivatives, warranting future exploration of its molecular targets, selectivity, mechanism, and pharmacokinetic properties.

6. Effects of plant extracts on animals

While still limited, the number of scientific reports on the biological effects of *I. glandulifera* and its extracts has increased in the last decade. The scarcity of industrial applications could be partly attributed to the lack of confirmed in vivo effects in humans. However, promising preliminary findings from murine and in vitro cell-line model studies (presented below) warrant further investigation into the development of potential therapeutics based on *I. glandulifera*.

Hydroethanolic extracts of *I. glandulifera* leaves, flowers, and roots have demonstrated antinociceptive and anti-stress effects in mice (Szewczyk et al., 2018c). Recent findings also indicate that hyperoside and protocatechuic acid, isolated from the aerial parts of *I. glandulifera*, inhibit monoamine oxidase, a target of antidepressant drugs (Orzelska-Górka et al., 2019). Furthermore, 2-MNQ and glanduliferin A extracted from the roots and leaves exhibited anti-cancer effects in vitro (Cimmino et al., 2016), while low molecular weight plant peptides showed potential as candidates for new antibacterial agents against dental caries due to their low cytotoxicity (Miazga-Karska et al., 2017).

7. Potential practical applications of *I. glandulifera*

The unique biological characteristics of *I. glandulifera*, including its rapid growth, high biomass yield, diverse phytochemical profile, and adaptability to various ecological niches, position it as a plant species with significant, but underexploited, biotechnological potential. This section reviews its documented and prospective applications across traditional medicine, natural product chemistry, environmental science, and apiculture.

7.1. Traditional and therapeutic uses

Despite its rich phytochemical profile and ubiquity, *I. glandulifera* remains largely unexploited in commercial applications, being represented only in Bach Rescue Remedy® (BRR). BRR, a product of complementary and alternative medicine, is promoted for the relief of conditions such as acute anxiety, stress, restlessness, trauma, attention deficit hyperactivity disorder (ADHD), and even as supportive care for pain in cancer and HIV patients (Thaler et al., 2009). The formulation contains five flower essences, which, owing to their extensive dilution, contain no pharmacologically relevant levels of phytochemicals. Their mode of preparation renders them conceptually similar to homeopathic remedies, whose biological plausibility is widely disputed. Despite the broad range of claimed indications, only one experimental study has investigated BRR, reporting possible effects on cardiovascular risk factors in rats (Resende et al., 2014). However, no rigorous clinical evidence supports any therapeutic effect in humans, and current consensus holds that BRR, like other flower essences, is unlikely to exert more than placebo effect (Armstrong and Ernst, 2001).

While its commercial applications are currently limited, *I. glandulifera* has a rich history of traditional and culinary use. Its edible components include raw seeds (unripe or ripe, with a nutty, pungent flavour), immature seed pods (cooked like sugar snap peas or radish pods for stir-fries and curries), and cooked young shoots/stems (mineral-rich, though requiring moderation due to oxalate content). Young leaves and flowers are ideal for salads, with older, bitter leaves reserved for stews and soups; the flowers are also used to dye drinks. Ethnobotanical research, notably from Pakistan, further documents its traditional medicinal application, with oral consumption of seeds or aerial part extracts/pastes used for anxiety, joint pain, and musculoskeletal disorders like rheumatism (Ijaz et al., 2021). The plant's high quantitative ethnobotanical indices reveal its frequent and well-known use by local populations, suggesting its potential efficacy for certain ailments within Western medicine and opening promising avenues for commercial utilisation through further research and innovation.

7.2. Natural dyes

Driven by a demand for natural alternatives to synthetic dyes, *I. glandulifera* shows potential as a dye source, though its violet flower extract requires human safety confirmation (Bahtiyari et al., 2013). The extract's specific colour and hue depend on the relative amounts of quinones and flavonoids, with anthocyanins being the primary pigments, shifting from red to blue, depending on pH (Khoo et al., 2017).

Acidified methanolic extracts of violet petals were recently used in screen-printing inks for various substrates (recycled paper, virgin fiber paper, and textiles), achieving good rub fastness but significant light fading. Varying pH of the ink produced different colours with slight substrate variations. Thus, *I. glandulifera* extract shows potential as a natural paper dye, though its poor wet fastness could limit its wider use (Klančnik, 2021).

7.3. Phytoremediation

The discovery of hyperaccumulator plants such as *Brassica juncea*, *Helianthus annuus* and *Z. mays* has made it possible to use phytoremediation as a sustainable rectification strategy for sites contaminated with heavy metals. The ideal hyperaccumulator should be easy to harvest, fast-growing, resistant to pests and diseases and tolerant to the toxic substances it accumulates. In addition, it must be able to quickly absorb, bioconcentrate and translocate the toxin (Ali et al., 2013).

Coakley et al. investigated *I. glandulifera's* potential for cadmium (Cd) removal from soil (Coakley et al., 2019). They observed that exposure to Cd concentrations up to 150 mg/kg did not affect the plant's biomass gain. The plant accumulated significant amounts of Cd, ranging from 276 mg/kg to 1562 mg/kg in its tissues. The bioconcentration factor (BCF), indicating accumulation efficiency, ranged from 64.6 to 236.4, while the translocation factor (TF), representing root-to-shoot transfer, showed values between 0.2 and 1.2. On average, *I. glandulifera* achieved a total removal of 29 mg Cd per plant, demonstrating its high tolerance to the metal. In addition, *I. glandulifera* has shallow roots, making it easy to harvest, remove, and properly discard the whole plant with the accumulated pollutant. However, before this species could be classified as a hyperaccumulator, the results of the study should be reproduced in the field.

It should also be mentioned that a plant from the same genus, *Impatiens walleriana*, can also accumulate mercury, but in smaller amounts compared to Cd (Zhu et al., 1999). These findings raise the possibility that *I. glandulifera* may also serve as a bioaccumulator for other toxic elements such as lead, arsenic, or chromium, warranting broader investigation into its multielement remediation potential.

7.4. Pollinator attraction and apiculture

I. glandulifera is one of the most nectariferous invasive plant species in Europe, with high sugar content and prolonged flowering that makes it extremely attractive to pollinators, particularly honeybees (*Apis mellifera*) and bumblebees (*Bombus* spp.). This attraction stems from its high nectar production and purple, fragrant flowers, and it may lure pollinators away from co-occurring plant species that share pollinators and have overlapping flowering periods (Chittka and Schürkens, 2001). Frequent visits of honeybees to *I. glandulifera* can cause an increase in the transmission of pathogens through flower sharing, which can reduce pollination efficiency (Najberek et al., 2023). Najberek et al. conducted a study in Poland to identify fungi colonising *I. glandulifera* flowers and their pollinators. All three types of pathogens were found on the flowers: primary pathogens, secondary pathogens and also saprotrophs, where *Botrytis cinerea* and *Fusarium graminearum* proved to be the most detrimental (Najberek et al., 2023). These are among the ten most hazardous fungal pathogens in molecular plant pathology and cause devastating diseases in native plant species and many crop species worldwide. In a follow-up experiment with *I. glandulifera*, tomatoes, and their shared pollinators, Najberek et al. demonstrated that pollinators can vector floral pathogens not only among invasive alien species but also to co-occurring native and cultivated plants (Najberek et al., 2024). This highlights the risk that *I. glandulifera* may indirectly facilitate the transmission of harmful pathogens into agricultural systems, with potential consequences for crop health and productivity, thereby amplifying its ecological impact beyond direct competition for pollinators. Nevertheless, little is known about the effects of these pathogens on the pollinators that carry them (Najberek et al., 2023). Parasitic infection of pollinators is probable, but further studies on interactions between these plant pathogens and pollinators are needed. One study also reports a beneficial interaction, suggesting that *Botrytis cinerea* may have nutritional value for *Apis mellifera* (Parish et al., 2020).

From an apicultural perspective, *I. glandulifera*'s honey has a unique chemical and sensory profile: high pollen content, naturally high diastase activity, negative specific rotation, and a very light amber colour. Its characteristic monosaccharides are fructose and glucose, with maltose being the dominant disaccharide, contributing to a pleasant taste and moderate aroma. It exhibits moderate crystallisation with gelatinous crystals and an opalescent appearance (Prđun et al., 2022).

8. Knowledge gaps, challenges, and future research prospects

Despite the increasing scientific interest in *I. glandulifera* over the last two decades, this invasive species remains significantly under-researched from a phytochemical, pharmacological, ecological, and biotechnological perspective. Although several promising bioactive compounds have been identified — including naphthoquinones, flavonoids, and phytosterols — there is a substantial disparity between the known phytochemical complexity of the plant and its current commercial, therapeutic, and ecological applications. Here, we outline the key knowledge gaps and highlight prospective academic and commercial opportunities, providing a framework to guide future research and unlock the valorisation potential of *I. glandulifera*.

Strategies which are currently in place to control the spread of *I. glandulifera* pose several challenges from socioeconomic and environmental perspective. Containment by chemical means is the most effective, but also the most controversial, both in terms of economics and environmental impact. Biological control remains underexplored. Some studies have shown promising results under laboratory conditions, but field trials are usually unverified or give poor results (Pollard et al., 2021). There is also the question of the specificity of the biological agents and the possibility of their evolution, which could cause considerable damage to other plants in the ecosystem (Seastedt, 2015). Mechanical control can be effective, but at present, it is time consuming and leaves a significant environmental footprint as the cut plant debris is often burnt on-site to prevent contamination of additional areas during transport to landfill sites (Čuda et al., 2020). The future of *I. glandulifera* management may lie in combining mechanical control with the utilisation of harvested biomass to produce high-value, health-promoting products. Unlocking this potential requires detailed studies that qualitatively and quantitatively assess the outcomes of such strategies. While life cycle assessment (LCA) is indispensable for evaluating environmental footprints, complementary techno-economic, socio-economic, risk, and market analyses are equally vital to establish real-world feasibility. With this integrated approach, valorisation strategies could not only mitigate the ecological challenges posed by *I. glandulifera* but also transform it into a driver of environmental, economic, and societal benefits.

It should be stressed that the plant should not be cultivated under any circumstance, but exclusively harvested in the wild. As a result, its spreading dynamic and availability are important factors that could substantially affect a streamlined commercial exploitation strategy. While the remarkable ability of *I. glandulifera* to rapidly colonise diverse ecosystems is well documented, the mechanistic basis of its invasive success is not yet fully understood. The mechanism of explosive seed dispersal certainly plays a major role, but the relative importance of other invasive strategies — such as allelopathy, efficient resource use, or potential zoochoric dispersal by rodents or ants — has not yet been systematically quantified. The ecological role of root exudates in modulating the soil microbiota, which can contribute to niche dominance, is another poorly investigated aspect of invasion. Furthermore, the impact of global climate change on the distribution, phenology, and invasiveness of *I. glandulifera* requires urgent attention (Beerling and Perrins, 1993). Recent climate modelling predicts an expansion of its habitats to higher altitudes and latitudes due to increasing temperatures and changing precipitation regimes (Willis and Hulme, 2002); however, there is a lack of empirical data on phenotypic plasticity and adaptation in the context of climate stressors. Longitudinal ecological studies are needed to predict and mitigate future invasions under changing climatic conditions.

Moreover, although several classes of compounds have been reported for *I. glandulifera*, the chemical diversity across plant organs has not yet been adequately mapped. Current data are fragmented and often lack quantitative rigor, highlighting the urgent need for a systematic and organ-specific inventory of secondary metabolites, including anthocyanins, proanthocyanidins, coumarins, triterpenoids, sterols, and flavan-3-ols. Furthermore, the identity, distribution, and biosynthetic function of anthocyanins in *I. glandulifera* are unclear, as specific anthocyanin glycosides or acylated forms remain to be isolated and structurally elucidated (Mikulic-Petkovsek et al., 2024). Compounds that play protective biological roles in many plants (e.g., flavan-3-ols, phenolic acids, and proanthocyanidins) and reduced naphthoquinones, including 1,2,4-trihydroxynaphthalene glucoside (THNG), are particularly understudied. THNG may function as a transient endogenous antioxidant but readily oxidizes to 2-HNQ under environmental stress (Tříska et al., 2013). The redox cycling and the biological relevance of such compounds remain unknown.

In addition, a lack of toxicological data on medicinal plants can present a major obstacle to commercial utilisation (Ohiagu et al., 2021). While bioactive compounds with health-promoting effects have been highlighted for *I. glandulifera*, no study has systematically searched for potentially harmful plant constituents such as alkaloids or cyanogenic glycosides that could concentrate during extraction and pose a risk to human and animal health. European regulations on novel foods and botanicals (e.g., Regulation (EU) 2015/2283) require solid data on composition, standardisation, safety, and efficacy. As *I. glandulifera* is not cultivated but rather harvested from wild populations, its phytochemical composition is highly variable and influenced by environmental factors such as soil type, altitude, and light availability (Defossez et al., 2021; Gololo, 2018). This variability undermines the reproducibility of extraction yields, bioactivity, and safety profiles. In addition, the levels of potential exogenous environmental pollutants and hazardous substances taken up by the plant, such as polycyclic aromatic hydrocarbons (PAHs), *per*- and polyfluoroalkyl substances (PFAS), heavy metals, and pesticides, can vary significantly between harvest locations. Thus, pre-market development should include standardisation protocols, geographical chemoprofiling, and toxicological risk assessments, ideally within the framework of good agricultural and collection practices (GACP). For any prospective commercial use, it is critical to emphasize that only wild populations should be utilized, as intentional cultivation of this invasive species in economically favourable areas would risk deliberate spread and significantly undermine eradication efforts.

The only current commercial appearance of *I. glandulifera* is as a component of Bach Rescue Remedy®, which itself lacks scientific validation. There are no clinical studies evaluating the safety, efficacy, or organ system-specific bioactivity of *I. glandulifera*-based products in humans. This lack of translational research is arguably the single most important obstacle to commercial development, particularly in the context of regulatory frameworks for nutraceuticals, botanicals, or functional foods.

I. glandulifera represents a paradoxical species: a globally invasive plant with documented phytochemical richness, multiple traditional uses, and high ecological adaptability, yet one that remains commercially and scientifically underexploited. Future research must bridge this gap through multidisciplinary efforts, including ecology, phytochemistry, toxicology, pharmacology, and regulatory science. Transforming this practically inexhaustible invasive plant into a source of health-promoting and environmentally valuable products could not only mitigate its negative ecological impact but also contribute to sustainable innovation.

CRediT authorship contribution statement

Marcel Žafran: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Lovro Žiberna:** Writing – review & editing, Methodology, Conceptualization. **Mitja Martelanc:** Writing – review & editing, Conceptualization. **Alen Albreht:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

Data will be made available on request.

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