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Invasive alien plant species as underexploited sources of bioactive compounds: A review of phytochemistry and pharmacological potential

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Abstract
Invasive alien plant species (IAPS) are major drivers of biodiversity loss and economic damage, yet their success often rests on a rich, sometimes novel, secondary metabolism used for allelopathy, defence and stress tolerance. The same chemistry makes them attractive for bioprospecting, because they are abundant, fast-growing and available at low cost. This review explains why invasive plants are chemically rich in the light of the novel weapons and evolution of increased competitive ability hypotheses, summarises the main classes of bioactive compounds and their antimicrobial, antioxidant, anticancer and agrochemical activities, and evaluates case studies of *Lantana camara*, *Parthenium hysterophorus*, *Reynoutria japonica*, *Chromolaena odorata*, *Prosopis juliflora* and *Opuntia* spp. The promise of this approach is tempered by toxicity, chemical variability, uncertain economics and the risk of creating incentives to spread the plants. Green extraction technologies, such as ultrasound-assisted and supercritical CO_2 methods, and a biorefinery concept are discussed as routes to sustainable valorisation. It is proposed that harvesting for bioactives be confined to existing infestations and integrated with invasive species management, and identify research gaps in screening, validation, safety assessment and genomics. Used responsibly, invasive plants can therefore become sustainable sources of valuable bioactive compounds while their populations are reduced.

Keywords: Allelochemicals, bioprospecting, invasive alien plants, phytochemicals, secondary metabolites, sustainable management

Introduction
Biological invasions are accelerating: a global analysis found no saturation in the accumulation of alien species over two centuries [1]. Invasive species cause serious ecological damage and economic costs that exceed US$1 trillion since 1970 and are still rising [2, 3]. Plant invasions alter nutrient cycling, fire regimes and hydrology, displace native flora and affect agriculture and human health [4–6]. Mechanical, chemical and biological control are costly and rarely complete, which has prompted interest in utilization-based approaches in which invasive biomass is put to productive use. Extraction of bioactive compounds is among the most promising, because many invaders have ethnomedicinal histories and are available in large, renewable quantities at low cost. Natural products remain central to drug discovery [7–9], but bioprospecting has traditionally targeted rare, slow-growing species, raising sustainability concerns [10]. Harvesting abundant invaders could instead be ecologically beneficial. This review (i) explains why invasive plants are chemically rich, (ii) summarises major compound classes and bioactivities, (iii) examines representative case studies and (iv) discusses safety, technological and ecological considerations for responsible use.

Chemical Ecology Underlying Invasiveness
Invasive plants are often chemically potent because several invasion hypotheses are explicitly chemical. Under the novel weapons hypothesis, invaders release allelochemicals to which native neighbors and soil biota have no evolved tolerance [11, 12], as with parthenin from *Parthenium hysterophorus* and phenolics from *Solidago* species [13]. Under the evolution of increased competitive ability hypothesis, invaders freed from specialist enemies may shift resources from defence to growth [14], although many retain strong defenses against generalist herbivores and chemical profiles often differ between native and introduced ranges. Colonization of disturbed, saline or arid habitats also favors accumulation of antioxidants such as polyphenols and flavonoids, which are of direct nutraceutical interest (Fig. 1). Together, these processes imply enrichment in biologically potent metabolites, a desirable trait in a drug lead or agrochemical [15]; potency, however, also means toxicity.

Major Classes of Bioactive Compounds
Terpenoids, phenolics and alkaloids dominate the chemistry of invasive plants (Table 1). Pentacyclic triterpenoids (lantadenes) from *Lantana camara* show antimicrobial, anti-inflammatory and cytotoxic effects [16], while sesquiterpene lactones such as parthenin, from *Parthenium*, are cytotoxic, antimicrobial and allelopathic [17]; essential oils of *Lantana*, *Chromolaena* and *Ageratum* have been tested as natural insecticides and antimicrobials. Phenolics and flavonoids account for much of the antioxidant capacity of invasive plants. The stilbene resveratrol and its glycoside polydatin, abundant in rhizomes of Japanese knotweed (*Reynoutria japonica*, syn. *Polygonum cuspidatum*), are the best-known examples [18], and resveratrol has been widely studied for cardioprotective, anti-ageing and chemopreventive effects [19]. Alkaloids occur in *Prosopis juliflora*, whose piperidine alkaloids such as juliprosopine show antimicrobial and cytotoxic activity [20], although many alkaloids are also neurotoxic or hepatotoxic. Mucilage and betalains from *Opuntia* offer antioxidant, hypoglycemic and gelling properties for food and cosmetic uses [21].

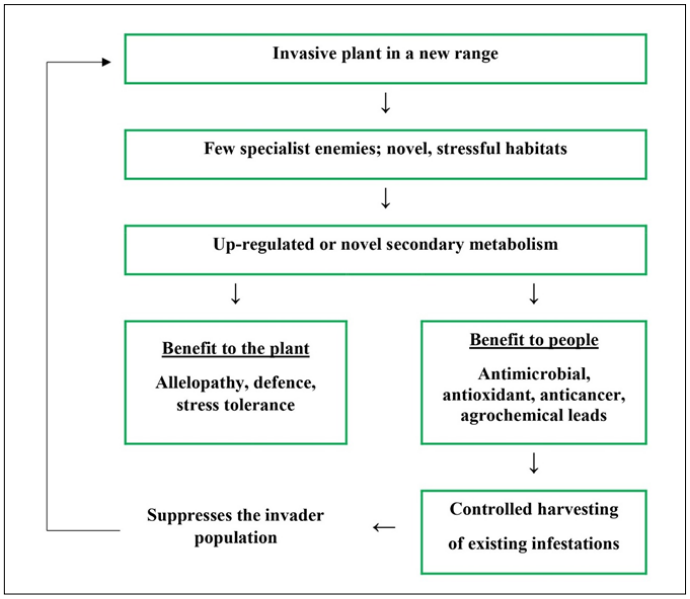

Fig 1: Conceptual link between invasion ecology and bioprospecting.

Table 1: Selected invasive plants, principal bioactive compounds and reported activities.

Species (family)	Native range	Representative compounds	Reported bioactivities	Reference
Lantana camara (Verbenaceae)	Tropical Americas	Lantadenes, verbascoside, essential oils	Antimicrobial, insecticidal, cytotoxic	[16]
Parthenium hysterophorus (Asteraceae)	Tropical Americas	Parthenin, hymenin	Cytotoxic, antimicrobial, herbicidal	[17]
Reynoutria japonica (Polygonaceae)	East Asia	Resveratrol, polydatin, emodin	Antioxidant, anti-inflammatory	[18]
Chromolaena odorata (Asteraceae)	Tropical Americas	Flavonoids, terpenoids	Wound healing, antimicrobial	[22]
Prosopis juliflora (Fabaceae)	Central and South America	Juliprosopine, flavonoids, tannins	Antibacterial, antifungal	[20]
Opuntia spp. (Cactaceae)	Americas	Betalains, mucilage	Antioxidant, hypoglycaemic	[21]

Pharmacological and Agrochemical Activities

Most reports describe crude extracts, and far fewer progress to isolated compounds, mechanisms or *in vivo* validation. With antimicrobial resistance rising, extracts of *Lantana camara*, *Chromolaena odorata* and *Prosopis juliflora* have inhibited Gram-positive and Gram-negative bacteria and pathogenic fungi *in vitro*, often at high concentrations [16, 20, 22]. High phenolic content makes invasive plants strong radical scavengers; *Reynoutria japonica* already serves as a commercial resveratrol source [18], and *Chromolaena* and *Lantana* extracts show anti-inflammatory effects consistent with their traditional use in wound care. Parthenin and related sesquiterpene lactones are cytotoxic to cancer cell lines *in vitro* [17], as are *Lantana* triterpenoids [16], although selectivity for tumour over normal cells remains a major hurdle. Because many invaders are allelopathic, their metabolites are also logical leads for bio-herbicides, insecticides and nematicides [11, 13], and botanical pesticides degrade rapidly, but standardisation and registration remain barriers. Finally, plant extracts serve as reducing and capping agents in green nanoparticle synthesis [23], and weed extracts, including those of *Eichhornia crassipes* and *Lantana camara*, have been used this way, although nanoparticle toxicity and environmental fate still need evaluation (Fig. 2).

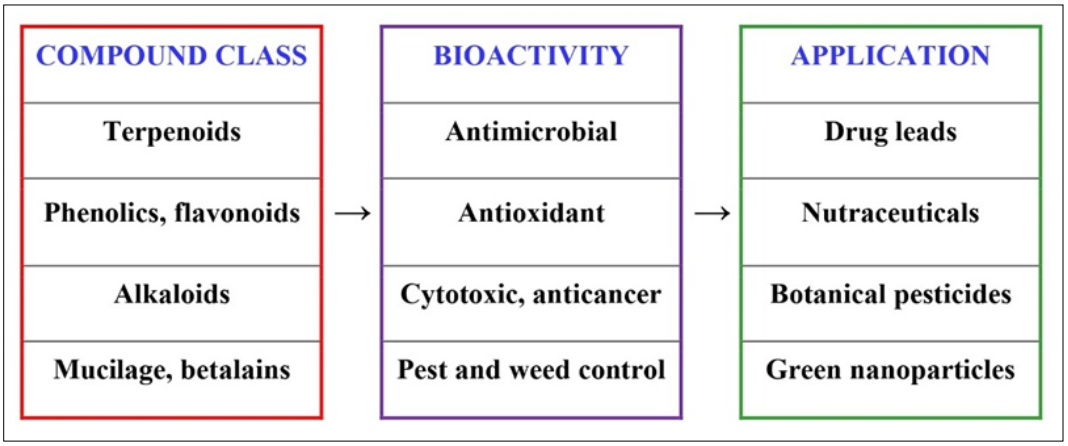

Fig 2: Compound classes, bioactivities and applications.

Case Studies

Lantana camara, one of the world's worst invasive shrubs, contains triterpenoids, flavonoids, iridoid glycosides and essential oils [16], yet lantadenes cause hepatotoxicity and photosensitisation in livestock [24]; pharmacological interest and toxicity thus coincide, so any application must rest on toxicology data. *Parthenium hysterophorus*, a major weed in Australia, Africa and South Asia, causes allergic dermatitis and respiratory problems as well as crop losses. Its sesquiterpene lactones underlie both harm and bioactivity, and proposed uses include bio-herbicides, antimicrobials and, after detoxification, compost or biogas feedstock [17], although occupational exposure during harvest is a serious safety issue. *Reynoutria japonica*, among the costliest invaders in Europe and North America, regenerates from small rhizome fragments yet is a rich source of resveratrol, polydatin and emodin [18]; it is the clearest case of an invader supporting an extract market, but harvesting must not spread rhizome fragments. *Chromolaena odorata* has traditional wound-healing use and antimicrobial, antioxidant and anti-inflammatory activity linked to flavonoids and terpenoids [22], while *Prosopis juliflora*, invasive in arid regions, yields protein-rich pods for flour and feed and alkaloid- and flavonoid-rich fractions with antimicrobial potential [20]. Cactus pear (*Opuntia*) provides edible cladodes, betalain pigments and mucilage [21], and water hyacinth (*Eichhornia crassipes*), a notorious aquatic weed [25], is used for bioenergy, compost and phytoremediation, although harvesting enough biomass is costly.

Challenges and Risks

Many metabolites in invasive plants are toxic: lantadenes, parthenin and numerous alkaloids exemplify this, so toxicological profiling and clear labelling must precede human or veterinary use [15, 24]. Metabolite profiles also vary with genotype, season, habitat and plant part, so reproducible extracts need standardised harvest and chemical fingerprinting (HPLC, LC–MS). A market for an invader could encourage cultivation or spread; utilization should therefore be confined to existing infestations, tied to eradication or containment targets and run under biosecurity protocols that avoid creating new introduction pathways [26]. Non-native species can have conservation or social value, but this should not justify new introductions [27, 28]. Finally, harvest and processing costs may exceed product value in remote or aquatic habitats, and bioprospecting must respect the Nagoya Protocol and the rights of local communities (Table 2).

Table 2: Opportunities and constraints for bioactive-driven use of invasive plants.

Dimension	Opportunity	Constraint	Mitigation
Ecological	Biomass removal lowers invader density	Spread during harvest; cultivation incentive	Contain sites; ban cultivation; monitor
Chemical	Abundant, potent metabolites	Toxicity; variable chemistry	Toxicology; standardised extracts
Economic	Cheap, renewable feedstock	High collection cost	Local processing; multi-product biorefinery
Social and regulatory	Rural livelihoods	Worker exposure; varied approval rules	Training; Nagoya Protocol compliance

Enabling Technologies and Valorisation

Green extraction methods (ultrasound, microwave, supercritical CO_2, subcritical water, natural deep eutectic solvents) cut hazardous solvent use [29], while LC–MS/MS, GC–MS, NMR and metabolomics speed dereplication and map chemotypic variation. A biorefinery approach suits invasive biomass: high-value bioactives are recovered first, then residues go to fibre, biogas, biochar, compost or feed, which improves the economics and, after detoxification, handles toxic residues safely (Fig. 3).

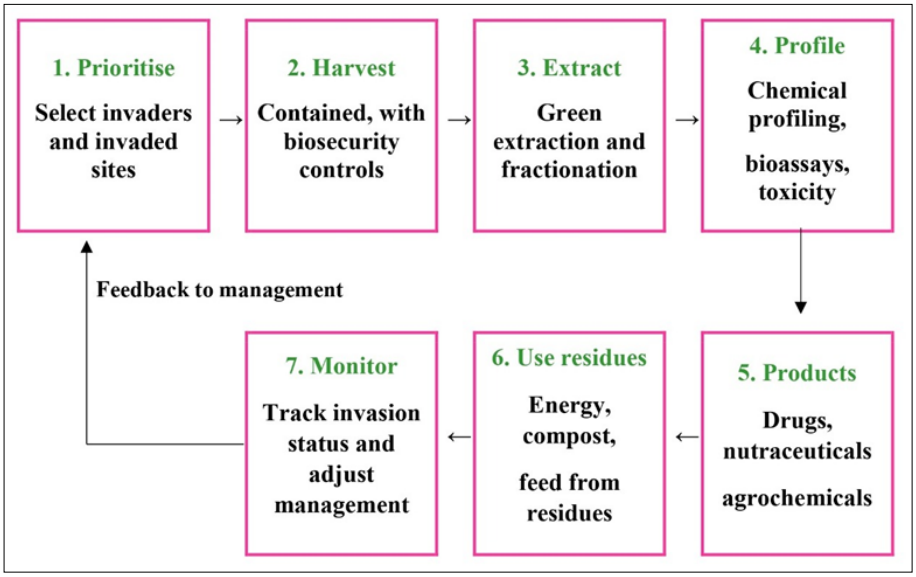

Fig 3: Proposed workflow for responsible bioprospecting of invasive plants.

Research Gaps and Future Perspectives

Several gaps limit progress. Most work covers a few notorious species, and native and introduced populations are rarely compared, so systematic, chemotype-aware screening of the many uncharacterized invaders is a priority. Activity is usually reported for crude extracts, while bioassay-guided

isolation, mechanism studies and *in vivo* validation are scarce. Toxicology, life-cycle assessment and techno-economic models are needed to show that harvesting offsets management costs without encouraging spread. Genomic and transcriptomic data could identify biosynthetic gene clusters [30], enabling heterologous production of valuable compounds and reducing wild harvest. Finally, close collaboration among invasion biologists, chemists, pharmacologists, economists and local communities will be essential to align ecological, scientific and social goals.

Conclusion

Invasive plants are ecological problems with a chemical upside. Their enriched secondary metabolism supplies antimicrobial, antioxidant, cytotoxic and agrochemical leads and, with resveratrol from Japanese knotweed, an established commercial product. Realizing this potential demand attention to toxicity, standardisation and economics and, above all, to the risk of encouraging the species being controlled. Bioprospecting should complement invasive species management: confined to existing infestations, linked to measurable reductions in invader populations and integrated into biorefinery models.

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Conflict of Interest

The author declares that there is no conflict of interest.

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