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Status, Impacts, and Management of Invasive Alien Plant Species in India: A Review

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ABSTRACT
Biotic invasion poses a growing threat to ecosystem sustainability, with Invasive Alien Plant Species (IAPS) serving as a key driver of biodiversity loss and altered ecosystem services. Therefore, effective management of IAPS is crucial for long-term conservation of biodiversity and sustainable functioning of ecosystems. The National Biodiversity Authority (NBA) framed criteria for determining the invasiveness of exotic invasive plant species, and based on these criteria, a total of 60 invasive plant species (53 terrestrial and 7 aquatic) are documented in India. These invasive species have various negative impacts on India's biological values and ecosystem functioning. Managers and scientists are employing various strategies to manage exotic invasive species, and strategies such as physical, chemical, biological, and cultural controls are implemented in India to manage exotic invasive species. As isolated mechanical, chemical, biological, and cultural control methods often provide limited effectiveness for invasive species management, an integrated approach is essential for achieving long-term control and sustainable outcomes.

Key words: Exotic, Biological invasion, Allelopathy, Toxicity, Management, Mechanical, Chemical, Biodiversity

INTRODUCTION

In the last few decades, biological invasion has become a serious threat to biodiversity conservation, causing species extinction (Anonymous 2018) and habitat loss (Reddy 2008, Kohli et al. 2012, Reshi and Khuroo 2012, Kumari and Choudhary 2016). It is one of the major reasons for biodiversity loss worldwide, and alien species invasion is considered the second-worst threat after habitat destruction (Reddy 2008, Mandal 2011, Kohli et al. 2012, Yadav et al. 2016, Raj et al. 2018). Biological invasion occurs when one species is introduced, either accidentally or intentionally, from one geographical region to another (Reddy et al. 2008, Singh et al. 2016, Kumari and Choudhary 2016, Rajasekaran et al. 2020), where they establish, proliferate, and persist (Mack et al. 2000, Richardson et al. 2000, Kohli et al. 2012). Invasive species have important adaptation traits as compared to native species, such as faster rates of growth and biomass, high reproductive efficiency including production of a large number of seeds, higher efficient dispersal, competitive ability, rapid establishment, vegetative reproduction and several other factors that help them to adapt to new habitats (Richardson and Pysek 2004) and a broader range of tolerance (van Ham et al. 2013).

Invasive alien plants are those that have higher densities, greater performance in their introduced habitats than in their native ones, and greater effects on native species (Dogra et al. 2011). Several biological attributes have been identified as important determinants of global variation in the invasiveness of alien species. However, the relationship between species attributes and invasiveness is subject to numerous conceptual limitations (Lloret et al. 2005). According to CBD (Anonymous 2024), the key traits of species invasiveness are rapid reproduction and growth, multiple high dispersal ability (seed pollination by wind, birds, animals, anthropogenic activities, etc.), phenotypic plasticity (ability to adapt physiologically to new conditions) and ability to survive in various habitats and in a wide range of environmental conditions. A good predictor of invasiveness is whether a species has successfully or unsuccessfully invaded elsewhere. These invasion attributes affect ecosystem function and services, biodiversity loss, economic loss and health hazards. These attributes allow categorisation of the status of alien species using only objective biogeographical and ecological criteria, for the assessment of impact

(Pysek and Richardson 2010).

There are many terms and definitions used to describe an alien species as invasive. Invasive plant species are also referred to as exotic, alien, foreign, non-native, or noxious weeds, depending on the ecological and management context (Mack et al. 2000, Singh et al. 2016, Yadav et al. 2016, Raj et al. 2018). The US National Invasive Species Council (Anonymous 2001) defines invasive alien species as "a species that is not native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health". Alternatively, the Convention on Biological Diversity (Anonymous 2024) defines invasive alien species (IAS) as *"an alien species whose introduction and/or spread threaten biological diversity"*. Furthermore, the Global Invasive Species Programme (GISP) defines invasive alien species as those that establish in new environments and subsequently proliferate and spread in ways that cause adverse impacts on biodiversity and human interests (McNeely et al. 2001). Most countries adopted the CBD definition and terminology for documentation and research studies on invasive alien species. Further, there are no prescribed guidelines for identifying and differentiating between naturalised species and invasive alien species. Therefore, a robust criterion needs to be developed for designating an alien species as invasive in an ecosystem. Since 2000, there has been an increase in studies on invasive alien species, as evidenced by the number of publications. Interestingly, 60% of the studies have been done only after 2000 (Hiremath and Sundaram 2013, Sandilyan et al. 2018). However, a comprehensive list of invasive alien species and uniformly accepted terminology are not available in India so far (Sandilyan et al. 2018).

About 40% of the species in the Indian flora are alien, of which 25% are invasive (Raghubanshi et al. 2005, Kathuria and Singh 2012). Invasive alien plants harm fragile ecosystems in several regions of India. Anthropogenic activities such as tourism, pollution, rapid industrialisation, urbanisation, and livestock-dependent lifestyles of forest-dependent communities are responsible for the establishment of invasions and the decline in biodiversity (Dogra et al. 2009, Mandal 2011, Kohli et al 2012, Raj et al. 2018). Invasive plants alter ecosystem functions, cause environmental damage, harm local biodiversity, pose a risk of extinction to native species, and lead to economic loss (Reddy 2008, Mandal 2011, Kohli et al. 2012, Singh et al. 2016). Many invasive species cause economic and environmental damage (Richardson et al. 2000) and reduce the value of economic services (Reddy 2008). Yadav et al. (2016) stated that terrestrial exotic species such as *Chromolaena odorata, Eupatorium adenophorum, Lantana camara, Mikania micrantha, Parthenium hysterophorus,* and *Prosopis juliflora*, as well as aquatic exotic species such as *Eichhornia crassipes,* pose a serious threat to the native flora of India.

Given their highly invasive nature, the National Biodiversity Authority (NBA) of India has identified 53 terrestrial and 7 aquatic invasive species (Sandilyan et al. 2018). Management of invasive plant species is a challenge for Protected Area (PA) managers and conservationists because they negatively affect native biodiversity. To ensure the long-term conservation of native biodiversity, it is necessary to control the rapid invasion of exotic species. The total cost of dealing with invasive species worldwide is estimated at hundreds of billions of dollars, including the costs of control, detrimental effects on human health, and losses in agricultural production and ecosystem services (Raj et al. 2018). Various manual, mechanical, chemical, and biological techniques are used for effective management and to control the spread of exotic plants in India. The impacts of exotic plants on community structure and ecosystem processes are poorly understood in India, which is hampering the effective management of exotic alien species. Given the increasing spread and impacts of invasive alien plant species across India's diverse ecosystems, a comprehensive synthesis of current knowledge is urgently needed. This review aims to evaluate the status, impacts, and management approaches for invasive alien plant species in India, and to identify key research priorities and future directions for their effective management.

METHODOLOGY

This review synthesises existing knowledge on Invasive Alien Plant Species (IAPS) in India, focusing on their distribution, ecological and socio-economic impacts, management strategies, and research gaps. Relevant literature was collected through a comprehensive search of online scientific databases, including Google Scholar, Scopus, Web of Science, and ResearchGate. Keywords such as "invasive alien plant species in India," "exotic invasive plants," "impacts of invasive species," "biological invasions," and "management of invasive species" were used individually and in combination to identify relevant studies.

Peer-reviewed journal articles, books, book chapters, government reports, and other credible publications related to alien invasive plant species were screened and evaluated. The selected literature was reviewed to compile information on the status, pathways of introduction, impacts on biodiversity and ecosystems, management interventions, and future research needs. The findings from the reviewed studies were synthesized to provide a comprehensive overview of invasive alien plant species and their management in India.

STATUS OF INVASIVE PLANT SPECIES IN INDIA

The status and distribution of invasive alien plant species (IAPS) in India are summarized in Table 1. In India, 60 invasive alien plant species belonging to 25 families have been documented. The majority of the species belong to the families Fabaceae (20%), Asteraceae (16%), Amaranthaceae (12%), and Convolvulaceae (8%). The majority of exotic invasive species in India are native to Tropical American regions (66%). The remaining species are native to Australia, China, Madagascar, Asia, Africa, and North America. Many IAPS have been reported from tropical Asia, and a large proportion occurs in more than one country (Weber 2003, Ellison et al. 2017). There are multiple reasons for the introduction of invasive plants. Some were introduced as ornamental plants (e.g., *L. camara*, wild sage) or for agricultural purposes (e.g., *M. micrantha)*. In contrast, others arrived in India accidentally (e.g., *P. hysterophorus)* (Reshi and Khuroo 2012, Hiramath and Sundaram 2013). *L. camara* invades more than 40% of India's tiger range (Mungi et al. 2020), and the Shivalik Hills, Central India, and Southern Western Ghats are the worst hit by its invasion.

IMPACTS OF INVASIVE ALIEN PLANT SPECIES

On a global scale, the impacts of IAPS are diverse (Weber 2003), and many agricultural, semi-natural, and natural ecosystems are affected by them. Some species of invasive alien plants such as *Chromolena odorata, M. micrantha, Mimosa pigra, P. hysterophorus, Prosopis juliflora* and *L. camara* have been reported as particularly widespread and also problematic in Tropical Asia through their various impacts on agriculture, natural ecosystem and human and animal health (Reddy 2008, Dogra et al. 2009, Yadav et al. 2016, Ellison et al. 2017). IAPS have various negative impacts on biological systems, such as competition with native flora (Allelopathy), biodiversity loss, ecosystem functions and services, and human and livestock health (Raj et al. 2018).

Biodiversity loss

Invasive alien plants are the leading cause of native biodiversity loss. Invasive alien plant species spread quickly, displace native plants, prevent native plant growth, and create monocultures (Rai and Singh 2019). A healthy plant community has a variety of herbs, shrubs, and trees. Still, the invasion of invasive species causes biological pollution by reducing plant species diversity, altering plant community structure, and reducing the quality and quantity of wildlife habitat (Vilà et al. 2011). Many invasive species reduce biodiversity, including *Ageratina adenophora,* which suppresses native vegetation, impedes wildlife movement, depletes soil nutrients, and clogs irrigation channels (Tripathi et al. 2006). Dense mat formation by *Alternanthera philoxeroides* negatively affects ecosystem functioning by obstructing light penetration, restricting gas exchange, and facilitating sedimentation, resulting in the loss of aquatic biodiversity (Masoodi and Khan 2012). A current estimate suggests that *L. camara* has invaded more than 5 million ha in Australia, 13 million ha in India and 2 million ha in South Africa (Bhagwat et al. 2012). The invasion of *L. camara* affects local biodiversity and all ecosystem services and is known to pose a serious threat to biodiversity in several world heritage sites and endangered ecological communities in Australia (Queensland rainforest, islands, and the greater blue mountains),

Table 1. Status and distribution of Invasive Alien Plants Species (IAPS) documented in India

S. No.	English name	Scientific name of species	Family	Nativity	Distribution in India
Terrestrial species					
1	Bladder Mallow	*Abutilon crispum* (L,) Briziky	Malvaceae	Tropical America	Throughout
2	Northern black wattle	*Acacia auriculiformis* L.	Fabaceae	Australia	Throughout except Jammu &Kashmir
3	Silver wattle	*Acacia dealbata* Link	Fabaceae	Australia	Throughout
4	Back wattle	*Acacia mearsnii* De Willd.	Fabaceae	Australia	Western Ghats
5	Crofton weed	*Ageratum adenophora* (Spreng.) King & H. Rob.	Asteraceae	Mexico	Kerala, Tamil Nadu, Andhra Pradesh, Himachal Pradesh
6	Creeping crofton weed	*Ageratina riparia* (Regel) R. M. King & H. Rob.	Asteraceae	Mexico	West & East Himalaya
7	Red Calico plant	*Alternanthera bettzickiana* (Regel) G. Nichols	Amaranthaceae	Tropical America	Throughout
8	Brazilian joy weed	*Alternanthera brasiliana* (L). Kuntze	Amaranthaceae	South America	Assam, Meghalaya
9	Joseph's coat	A*lternenthera ficoidea* P. Beauv.	Amaranthaceae	Tropical America	Throughout
10	Smooth joy weed	*Alternanthera paronychioides*St. Hil.	Amaranthaceae	Tropical America	Assam, Kerala, Karnataka, Tamil Nadu
11	Khaki weed	*Alternanthera pungens* Kunth.	Amaranthaceae	Tropical America	Throughout
12	Coral vine	*Antigonon leptopus* Hook. & Arn.	Polyonaceae	America	Throughout
13	Mexican poppy	*Argemone mexicana* L.	Papaveraceae	T. C & S. America	Throughout
14	Black jack	*Bidens pilosa* L.	Asteraceae	Tropical & Central America	Throughout
15	Carolina fanwort,	*Cabomba caroliniana* A. Gray	Cabombaceae	North America	Western Ghats
16	Hemp/ Marijuna	*Cannabis sativa* L.	Cannabaceae	Central Asia	Throughout
17	Butterfly- pea	*Centrosema molle* Benth.	Fabaceae	America	Kerala
18	Orange cestrum	*Centrum aurantiacum* Lindl	Solanaceae	Tropical America	Western & Eastern Ghats
19	Siam weed	*Chromolaena odorata* (L.) King & Robin.	Asteraceae	Tropical America	Throughout
20	Canada thistle	*Cirsium arvense* (L.) Scop.	Asteraceae	Europe	North East India
21	Lesser swinecress	*Coronopus didymus* Sm.	Brassicaceae	Tropical America	Eastern &Western Ghats
22	Rubber vine	*Cryptostegia grandiflora* R. Br.	Apocynaceae	Madagascar	Throughout

S. No.	English name	Scientific name of species	Family	Nativity	Distribution in India
23	Dobber	*Cuscuta chinensis* Lam.	Convolvulaceae	China	Throughout
24	Scotch broom	*Cystisus scoparius* (L.) Link	Fabaceae	Europe	Western Ghats
25	Badi aankhphootani bel	*Dactylandra welwitschii* Hook. f.	Cucurbitaceae	Southern Africa	Gujarat, Rajasthan, Haryana
26	Viper grass	*Dinebraretro flexa* (Vahl) Panz.	Poaceae	Tropical America	Throughout
27	Brown flowered swamp grass	*Diplachne fusca (L.) P. Beauv.*	Poaceae	America	Throughout
28	Mexican tea	*Dysphania ambrosioides* Mosyakin & Clements	Amaranthaceae	Tropical America	Throughout
29	Horseweed	*Erigeron bonariensis* L.	Asteraceae	South America	Throughout
30	Canadian horseweed	*Erigeron canadensis* L.	Asteraceae	North America	Throughout
31	Round leaf Bindweed	*Evolvulus nummularius* (L.) L.	Convolvulaceae	Tropical America	Throughout
32	Pig nut	*Hyptis suaveolens* Poit.	Laminaceae	Tropical America	Throughout
33	Purple morning glory	*Ipomoea eriocarpa* R. Br.	Convolvulaceae	Tropical Africa, Madagascar	Throughout
34	Bush morning glory	*Ipomoea fistulosa* Mart. ex Choisy	Convolvulaceae	Tropical America	Throughout
35	Lantana	*Lantana camara* L.	Verbenaceae	Tropical America	Throughout
36	Subabool	*Leucaena leucocephala* (Lam.) de Wit	Fabaceae	Tropical America	Throughout
37	Umbrella- tree	*Maesopsis eminii* Engl.	Rhamnaceae	Africa	Kerala, Karnataka, Tamil Nadu
38	Mile-a- minute	*Mikania micrantha* Kunth	Asteraceae	Tropical America	Throughout
39	Giant sensitive plant	*Mimosa diplotricha* C. Wight ex Sauvalle var.	Fabaceae	Tropical America	Assam, Karnataka, Kerala, Uttar Pradesh
40	Cat claw mimosa	*Mimosa pigra* L.	Fabaceae	Mexico, Central & South America	Himalaya, Western Ghats
41	Jamaican cherry	*Muntingia calabura* L.	Muntigiaceae	Tropical America	Western Ghats
42	Prickly pear	*Opuntia dillenii* Haw.	Cactaceae	Central America	Throughout
43	Nag Phani	*Opuntia elatior* Miller	Cactaceae	South America	North &Western India
44	Congress weed	*Parthenium hysterophorus* L.	Asteraceae	Tropical America	Throughout
45	Elephant grass	*Pennisetum purpureum* Schumach.	Poaceae	Tropical America	Throughout
46	Mesquite	*Prosopis juliflora* (Sw.) DC.	Fabaceae	Mexico	Throughout
47	Kudzu	*Pueraria Montana* var. lobata (Wild.)	Fabaceae	East Asia	Throughout

S. No.	English name	Scientific name of species	Family	Nativity	Distribution in India
48	Calcerolaria shower	*Senna spectabilis* (DC.) Irwin & Barneby	Fabaceae	Central & South America	Karnataka, Rajasthan, West Bengal, Kerala, Tamil Nadu
49	Silverleaf nightshade	*Solanum elaeagnifolium*Cavanilles	Solanaceae	Central & Southwest America	Throughout
50	Bugweed	*Solanum mauritianum* Scop.	Solanaceae	South America	Western Ghats
51	Singapore daisy	*Sphagneticola trilobata* (L.) Pruski	Asteraceae	Tropical America	Kerala, Maharashtra, Tamil Nadu, Uttar Pradesh
52	Lesser bulrush	*Typha angustifolia* L.	Typhaceae	Tropical America	Throughout
53	Common gorse	*Ulex europeus* L.	Fabaceae	Western Europe	Western Ghats
Aquatic species					
1	Alligator weed	*Alternanthera philoxeroides* (Mart.) Griseb.	Amaranthaceae	Tropical America	Throughout
2	Water hyacinth	*Eichhornia crassipes* (Mart.) Solms	Pontedariaceae	Tropical America	Throughout except Sikkim
3	Pink morning glory	*Ipomoea carnea* Jacq.	Convolvulaceae	Tropical America	Throughout
4	Minute duckweed	*Lemna perpusilla* Torr.	Araceae	North America	Throughout
5	Common water clover	*Marsilea quadrifolia* L.	Marsileaceae	Europe	Throughout
6	Parrot's feather	*Myriophyllum aquaticum* (Vell.) Verdc.	Haloragidaceae	South America	Himalaya
7	Butterfly fern	*Salvinia auriculata* Aubl (syn. S. molesta)	Salviniaceae	Brazil	Throughout

Sources: (Reddy et al. 2008, Ellison et al. 2017, Sandliyan et al. 2018, Nayak et al. 2021) the fynbos of South Africa, and biodiversity hotspots in India (Western Ghats and Himalaya) (Bhagwat et al. 2012). *L. camara* threatens 300,000 km^2 of Indian forests and is a high-concern species in India, responsible for wildfires in many wildlife-rich parts of India (Raghubanshi et al. 2005, Priyanka et al. 2013). *L. camara* occupies approximately 154,000 km^2 of forested habitat within India's tiger range and poses a significant threat to native biodiversity (Mungi et al. 2020). Around 20% of the area of Gir National Park is covered by *L. camara,* leading to the replacement of native vegetation (Kaushik 2011). *P. juliflora* reduces biodiversity, blocks irrigation channels, obstructs roads, and completely blocks smaller trails, thereby severely limiting access to pasture and croplands and reducing fishing areas (Weber 2003). *P. hysterophorus* affects biodiversity and species richness in its invaded range and is directly hazardous to human and livestock health (Kumar 2014).

Competition with native flora/allelopathy

Allelopathy is basically an ecological process in which biotic interference occurs through bioactive molecules (Singh et al. 2016). It is a natural phenomenon that affects the physiology of other plants, either negatively or positively (Yadav et al. 2016). Allelochemicals are interestingly identified as Novel Weapons (NWs) (Kohli et al. 2012), which dramatically suppress native species and pave the way for IAPS colonisation in new habitats (Rai and Singh 2019). Basically, allelochemicals are secondary metabolites, mostly phenolics, organic acids, glucosinolates, nucleotides, terpenoids, and sesquiterpenes, that adversely affect native plant species (Yadav et al. 2016, Rai and Singh 2019). Allelochemicals found in invasive alien species disrupted cell division and root and shoot elongation in native species (Yadav et al. 2016). Many allelochemicals identified and isolated from the invasive species, such as *Eupatorium adenophorum* (syn. *Ageratina adenophora*), include 1-methyl-2-(1-methylethyl) benzene, hedycaryol, cetral, bornyl acetate, P-cymene, copaene, and longipinene (Yadav et al. 2016). They inhibit seed formation in several plants, such as clover, rye grass, and maize, which are commercially important crops (Yadav et al. 2016). *M. micrantha* contains terpinolene, limonene, ocimene, caryophyllene, etc., and they play a critical role in suppressing native vegetation (Yadav et al. 2016). The volatile oil of *M. micrantha* has allelopathic and inhibitory effects on several plants. They have allelopathic potential against various economically important crop plants such as pineapple, banana, cocoa, coconut, and rubber (Ellison et al. 2017), and are competitors against *Raphanus sativus*, *Lolium multiflorum,* and *Trifolium repens* (Yadav et al. 2016). The biomass and nitrogen content of tomato seedlings and some legume crops are also inhibited by *M. micrantha* (Yadav et al. 2016). *L. camara* is one of the ten worst weeds of the world (Raghubanshi et al. 2005), and it contains various allelopathic compounds, including salicylic acid, gentisic acid, coumarin, ferulic acid, p-hydroxybenzoic acid, and 6-methylcoumarin (Yadav et al. 2016). Due to allelopathic effects, its high abundance in forests leads to a drastic decline in the richness of native species (Yadav et al. 2016). The growth of commercially important crops such as tomato, radish, and cucumber is inhibited by *L. camara* leachates (Yadav et al. 2016). *Eichhornia crassipes* contains allelochemicals such as linoleic acid, glycerol-1,9-12(ZZ)-octadecadienoic acid, and N-phenyl-2-naphthylamine, and they reduce algal growth in aquatic ecosystems (Yadav et al. 2016). *P. hysterophorus* has strong invasive potential and is known for its strong allelopathic effects (Kumar 2014). The species contains major compounds like o-coumaric, gentisic, ferulic, p-coumaric, caffeic, vanillic acid, salicylic acid, trans-cinnamic, and p-hydroxybenzoic acids and sesquiterpene lactone, etc. (Yadav et al. 2016). Thus, it negatively affects crops and other native flora by releasing phenolics and sesquiterpenes, resulting in inhibited growth and development (Kumar 2014, Yadav et al. 2016).

Toxicity to livestock

Biological invasion by non-native species constitutes one of the major threats to livestock (Wittenberg and Cock 2001, Singh et al. 2016). Many invasive species negatively impact animal health. For example, *A. adenophora* is considered a serious weed in agricultural and wildlife habitats, reducing food availability to herbivores (Tripathi et al. 2011). Generally, it is unpalatable to grazing animals and is fatally toxic to horses, causing the blowing disease in Hawaii and the Numinbah disease, or Tollebudgera horse disease, in Australia (Tripathi et al. 2011). *P. hysterophorus* is a major health concern to livestock as its toxicity involves alopecia and dermatitis on the face, muzzle, neck, eye and thorax, abdomen and brisket region and causes salivation, anorexia, diarrhoea and death in extreme cases (Kumar 2014). *L. camara* has been reported to be toxic to some livestock species (Kumar et al. 2016) and wild ungulates (Sharma et al. 1981). Berries of *L. camara* are poisonous, though they are attractive to some bird species (Priyanka et al. 2013). The toxic effects of *L. camara* are evident both in ruminants and in non-ruminants (Kumar et al. 2016). The extensive feeding on *L. camara* has led to diarrhoea, liver failure and even the animal's death (Mungi et al. 2020). The most toxic components present in this weed are lantadenes, which lead to hepatotoxicity, photosensitization and jaundice (Kumar et al. 2016). *M. micrantha* also affect grazing animals' health by reducing the availability and quality of fodder resources (Kumar 2014).

Negative impact on human health

Biodiversity and its modification are intrinsically linked to human health, in both positive and negative senses (Ellison et al. 2017, Rai and Singh 2019). Invasive species affect human health through environmental contamination. IAPS have negative impacts on human health through direct exposure, as vectors, or through the transfer of toxins in edible products. *L. camara* provides a favourable habitat to tse-tse fly (*Glossina* spp.), which causes sleeping sickness (Priyanka et al. 2013). *P. hysterophorus* promotes the survival of the malaria vector (Rai and Singh 2019). *E. crassipes* is a high-risk IAPS, helping in the spread of Schistosomiasis (Rai and Singh 2019). Some IAPS cause allergies in humans, such as *P. hysterophorus, Acacia* spp., and *Eucalyptus* spp. (Priyanka et al. 2013). *P. hysterophorus* is highly allergenic and causes respiratory problems, dermatitis and asthma in human beings (Priyanka et al. 2013, Kumar 2014). It is also known to cause diarrhoea, breathlessness and choking in humans (Kumar 2014). *Alternanthera philoxeroides* can adversely affect human health by creating favourable breeding and refuge habitats for mosquitoes, thereby potentially increasing the risk of mosquito-borne diseases (Masoodi and Khan 2012)

Negative impacts on the environment and ecosystem services

IAPS reduce the biodiversity of native plants, which may have adverse implications for environmental functioning, ecosystem services and climate change (Rai and Singh 2019). IAPS affects the quantity of surface and groundwater (Rai and Singh 2019). Many IAPS are well known for their influence on ecosystem services, viz., aesthetic, recreational, cultural and regulatory and have negative impacts on the delivery of food, freshwater and fibres as well as water purification, pollination, natural pest control, disease regulation, soil fertility, and nutrient water cycle (Charles and Dukes 2007, Rai and Singh 2019). They also alter soil stability, resulting in soil erosion (Charles and Dukes 2007). Furthermore, they also affect regulatory ecosystem services, such as hazard mitigation, water treatment, pest management, pollination, and climate regulation, which are inextricably linked to agriculture and forestry (Rai and Singh 2019).

Infestation by *P. juliflora* leads to the replacement of native vegetation, causing massive negative impacts on water resources, nutrient cycles, succession processes, and soil conservation. *L. camara* is responsible for wildfires in many wildlife-rich parts of India (Raghubanshi et al. 2005, Priyanka et al. 2013). It has many adverse effects on ecosystem, including; (i) loss of native biodiversity, (ii) replacement of native plant communities in forest ecosystem by the formation of dense, implementable thickets (Kathuria and Singh 2012), (iii) contribution to the erosion of soil, (iv) adverse impact on forest regeneration (Kumari and Choudhary 2016), (v) harboring of vectors that carry infectious diseases, and (vi) creation of a fire hazard (Priyanka et al. 2013, Love et al. 2009). Due to its allelopathic effects, *L. camara* contributes to decreased biodiversity and environmental degradation (Yadav et al. 2016). *Acacia dealbata* reduces native plant diversity by adversely affecting soil chemistry and microbial functions, and it often negatively affects ecosystem structure and functions (Bhat et al. 2012). *E. crassipes* hinders navigation, blocks rivers, lakes, and irrigation systems, and reduces the quality of water bodies (Kathuria and Singh 2012).

Economic loss

Invasive alien species may cause substantial economic losses to society through direct impacts, such as losses in agricultural or fisheries production, and indirect impacts associated with human health problems. Several IAPS introduced for human welfare are known to create environmental and economic loss (Rai and Singh 2019). The invasion of water hyacinth (*E. crassipes*) cost Uganda US$112 million in 1999 due to reduced fish production and eco-tourism potential (Rai and Singh 2019). The toxicity of *L. camara* causes a reduction in potential production, manifested in abortion, loss of milk production in dairy cows (Priyanka et al. 2013). *L. camara* is also harmful to herbivores, and its management costs US$70 ha^{-1} (Mandal 2011). The cost of *L. camara* control in India is approximately INR 9000 ha^{-1} (Bhagwat et al. 2012). The economic loss from *L. camara* is estimated to be US$924 million per year (Mandal 2011).

STRATEGIES FOR THE MANAGEMENT OF INVASIVE ALIEN SPECIES

Management of invasive species is essential for biodiversity conservation and has been recognized as a global priority by the US National Invasive Species Council (NISC). The Centre for Agriculture and Bioscience International (CABI) and the Global Invasive Species Program (GISP) recommended various strategies for management of invasive alien plant species, including both short- and long-term actions: Prevention (keep the invasive species out), Early Detection and Rapid Response/Eradication (EDRR) (detect and eradicate invasive species to stop them from spreading), control and management (eliminate or control the problem of invasive species), Rehabilitation and Restoration (heal, minimize, or reverse the harmful effects from invasive species) are useful to control the impact of invasive species (Wittenberg and Cock 2001). Prevention is the stopping of the introduction of new species and is considered the least expensive and most effective method for managing invasive species (Venette and Koch 2009). EDRR is the second line of defence after prevention; it is short-term and cost-effective (Venette and Koch 2009). Early detection focuses on a concern species and is a critical component of any effective invasive species management plan (Mandal 2011, Wittenberg and Cock 2001). When prevention fails, eradication is the only option, aiming to reduce the abundance and spatial extent of IAS below the acceptable threshold level. Rehabilitation is a short-term mitigation strategy aimed at ensuring minimum site stability and functionality, and may include site preparation and seeding of desirable non-native vegetation. Restoration is a long-term strategy that aims to return ecosystem structure and function to a state approximating pre-invasion condition by restoring natural ecosystem functioning and re-establishing native species (Venette and Koch 2009).

An integrated management approach that combines several control methods or strategies is generally required for the effective management of invasive alien plants. The various methods used to manage invasive alien plants are typically categorised as physical/mechanical, chemical, biological, and cultural. They are often used in combination to control and manage invasive alien plant species (Wilgen et al. 2001, Mandal 2011, Yadav et al. 2016, Raj et al. 2018).

Physical/mechanical method

Mechanical control is usually the first option to consider when planning an invasive plant removal project and includes hand-picking, hoeing, tilling, suffocating, cutting, and burning of invasive species. These practices are effective when the soil is moist, and the weed's roots are not very deep. Mowing can effectively control hard weeds by reducing seed production and preventing the buildup of reserve food stores, and is typically conducted during the flowering stage (Wilgen et al. 2001, Love et al. 2009, Yadav et al. 2016). Other mechanical methods, such as chopping, cutting, and ploughing, can be used for invasive shrubs or trees (Yadav et al. 2016). Mechanical methods are often short-term strategies suitable for smaller plant invasions and generally require repeated follow-up to achieve effective control or complete eradication of the target species (Willis 2017).

Mechanical controls for *L. camara* have been used to control large-scale infestations in India. A cut rootstock method is the most effective management strategy for controlling *L. camara* (Love et al. 2009) and has been widely used in India. Management of *P. hysterophorus* can be done through uprooting, and such operations should be completed before flowering (Kumar 2014). Mechanical removal using a tractor, plough, etc., is possible in the open field. It was estimated that INR182,000 million were spent in 2009 to manage weeds by manual methods on 35 million ha of land in India (Kumar 2014). Mechanical removal is highly labour-intensive and causes significant site disturbance, which can lead to rapid reinvasion if not properly managed (Wilgen et al. 2001, Mattrick 2016). *E. crassipes* can be manually removed by netting from the water surface and is assumed to be the best method to control, as it is less costly, and not degradative to water bodies and the environment (Raj et al. 2018). *Manual control of Alternanthera philoxeroides* is an effective management strategy for eradicating the weed. Still, once the weed is well established, eradication is very difficult and very expensive, especially in developing countries (Masoodi and Khan 2012).

Chemical method

Chemical control is an effective management strategy because it can target specific species; however, it is a short-term strategy suited to smaller-scale plant invasions and may achieve complete eradication of the target species when implemented with repeated follow-up treatments (Willis 2017). Chemical control includes the use of herbicides, pesticides, fungicides, and insecticides to control invasive species. Herbicides control all vegetation because they affect the physiological processes and suppress the growth. A selective herbicide will damage only those plant groups that express the biological pathways it targets. Herbicides are the primary method of invasive species control in non-crop situations and in agriculture because they are selectively effective, reliable, cost-efficient, safe, and easy to use. The use of chemical control is extensive and yields rapid, satisfactory effects against unwanted plants (Yadav et al. 2016). Chemical treatment can only kill the existing population at the given sites, but cannot prevent the entry of seeds from neighbouring places (Kumar 2014).

Several synthetic chemicals, such as herbicides and weedicides, are being used, including Paraquat, glyphosate (the active ingredient in Roundup and Rodeo), and triclopyr (the active ingredient in Brush-B-Gone and Garlon). Glyphosate is non-selective; it kills everything it contacts, whereas triclopyr is selective and does not affect monocots (Mattrick 2016). The management of *P. hysterophorus* with herbicides was considered the only viable option (Kumar 2014), but the effect was temporary, and repeated applications are required. Simazine, 2,4-D, 2,4,5-T, dicamba, etc., are usually growth regulators, but at high doses they can kill plants (Yadav et al. 2016). 2,4-D is widely used to control water hyacinth (Raj *et al.* 2018). Other herbicides that act on amino acid synthesis in plants, such as glyphosate, imazapyr, and metsulfuron, are also effective in controlling weeds by inhibiting photosynthesis (Yadav et al. 2016). Glyphosate herbicide is the most effective treatment for large infestations of *L. camara* (Raj et al. 2018). Herbicides tend to be less toxic, have shorter residence times, and be more specific; concern regarding their detrimental environmental impacts remains (Wilgen et al. 2001).

Biological control

Biological control, or biocontrol, involves using species-specific insects or other invertebrates and pathogens from the alien plants' region of origin and aims to reduce the effects of invasive species and to achieve a situation in which the formerly invasive alien plant becomes a non-invasive naturalised alien (Wilgen et al. 2001). Biocontrol is typically a long-term, environmentally acceptable approach for controlling target species and is a cost-effective, self-sustaining option for weed control (Yadav et al. 2016). The biological agents reduce seed production, thereby controlling the spread of weeds on a large scale (Yadav et al. 2016). In India, *L. camara* is controlled by *Teleonemia scurpulosa,* commonly known as *the lantana* lace bug (Yadav et al. 2016). Various biological agents are used to eradicate weeds; for example, the Mexican beetle *Zygogramma bicolorata* has been used to control *P. hysterophorus* (Kumar 2014), while Weevils of the genus *Neochetina* have been used to control *E. crassipes* (Mandal 2011). Biological control agents used in India for the management of water hyacinth include *Neochetina bruchii* (hyacinth weevil), *Orthogalumha terebrantis* (hyacinth mite), and *Sameodes albiguttalis* (hyacinth moth), all of which have been employed to suppress *Eichhornia crassipes* populations (Rai et al. 2019). Biocontrol is often less competitive than mechanical or chemical control methods in short-term efficacy assessments because its effects are typically gradual and may require extended periods to achieve measurable suppression. However, once established, biocontrol agents can provide sustainable and self-perpetuating suppression of invasive species (Barratt et al. 2018).

Cultural control

Cultural control methods involve introducing and managing desirable plants to cover invasive and other undesirable plants. Many native plants are poor competitors in their early stages of growth; however, once established, they can crowd out most other plants with minimum management (Yadav et al. 2016). Long-term control of non-native invasive plants requires not only controlling the problem plants but also creating a system that prevents the establishment of undesirable species. Numerous cultural practices can be used to effectively control non-native plants. Cultural practices, including burning, grazing, water-level manipulation, and the establishment of competitive plant species, have been used for decades to reduce invasive plant populations and limit their spread (Manning and Miller 2011). Among these approaches, grazing, fire management, and the planting of competitive native or desirable species are considered major cultural control strategies. Grazing is useful only to some extent, depending on the nature of the invasive plant. Grazing works if the species is palatable to cattle, such as *Cyperus* and *Cynodon*. However, grazing does not work for toxic weeds such as *P. hysterophorus* and *L. camara,* which are harmful to livestock if consumed. Grazing can be effective when done just before the flowering period and defoliation. Burning has been proven effective in controlling non-woody invasive species. It may be time-dependent, which will help check seed dispersal and destroy viable seeds (Yadav et al. 2016). Revegetation is another cultural practice used to control noxious weeds, which involves establishing competitive plant species that can suppress invasive flora through resource competition. This approach has been recognized as an effective long-term strategy for reducing invasive plant dominance and promoting ecosystem recovery (Sheley and Krueger-Mangold 2003).

CONCLUSIONS

The spread of exotic invasive plant species has emerged as a significant global conservation challenge, adversely affecting biodiversity, ecosystem functions, and ecosystem services. It is considered one of the most significant threats to global biodiversity, ranking second only to deforestation and other forms of land-use change. Invasive alien plant species expand rapidly and threaten local flora by competing for water, space and nutrients. A huge loss to human society is incurred in terms of the quantity and quality of crop production, the degradation of native biodiversity, and environmental and human health hazards caused by invasive species. Invasive plant species cause economic, social, and environmental damage and threaten natural and agro-ecosystems. The lack of prioritisation of invasive species for control and management is the biggest hurdle to achieving effective management of exotic invasive species. Invasive species threatened the landscape's ecological integrity by disrupting key processes, leading to local extinction of native species in some cases. Economic sectors such as agriculture, the timber industry, irrigation, and human healthcare are also affected by biological invasions worldwide. Such an impact across diverse sectors has severe consequences for the livelihoods, ecology, and economic growth of developing or underdeveloped countries, where knowledge of this subject is fragmented. Therefore, the effective management and control of invasive alien plant species should be prioritized as a key conservation strategy.

India, a mega-biodiversity country, is facing the issue of exotic plant species invasion, and considerable financial resources are being allocated for the management and control of invasive alien plant species. For example, *L. camara,* one of the worst invasive alien plant species in India, has spread extensively in various wildlife habitats, and its management and control incurs substantial costs, estimated at approximately US$70 ha{ ^{1}. Several control measures adopted to manage the invasive plant species remain insufficient. In India, the management and control of exotic invasive species are limited due to a lack of research and unequal funding across diverse ecosystems. Current knowledge of biological invasion as a contributor to biodiversity loss, particularly from exotic plant invasions, is severely limited by insufficient research. The impact of invasive species on ecosystem services is still emerging, and our understanding of their effects on some services is not yet fully developed. Further research on predictive factors influencing invasion, comparing invader and native traits, and evaluating environmental impacts is needed. Despite extensive research on the impacts of many exotic species in other countries, their ecological and socio-economic consequences remain largely understudied in India. The impacts of many non-native species are poorly understood. Unless their impact is understood, insufficient efforts will be made to manage and control them. So, we need not only to document the IAPS but also to identify the pathways of invasive species and prioritise the IAPS for the control, eradication or prevention of future introduction and establishment.

Various control and management strategies have been implemented worldwide using mechanical, chemical, and biological control methods; however, data on their long-term effectiveness in controlling invasive alien plant species remains limited and often context-specific. Given the increasing threat posed by invasive alien plant species, there is an urgent need for comprehensive assessments of their distribution, impacts, and invasion dynamics, as well as the development of scientifically informed, region-specific management strategies. Such efforts are essential for improving control and management strategies and ensuring the long-term conservation of India's biodiversity and ecosystem integrity.

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