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REVIEW ARTICLE

Senna spectabilis (DC.) H. S. Irwin & Barneby invasion in India: Impacts, challenges and management - A review

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Abstract

Invasive species pose significant risks to ecosystems, disrupting biodiversity and ecological stability. *S. spectabilis*, initially introduced for decorative purposes, has become a major invader worldwide, particularly in India. This review explores its ecological and biological impacts, emphasizing its effects on native plant diversity, animal life and ecosystem functioning. The species' rapid growth, prolific seed production and allelopathic properties enhance its competitiveness, allowing it to displace indigenous flora and alter habitat dynamics. The invasion of *S. spectabilis* leads to habitat modification, loss of native species and disruptions in trophic interactions, ultimately threatening ecosystem stability. A key factor driving its successful spread is its diverse seed dispersal mechanisms. Ballistic dispersal occurs when elongated pods split open, releasing seeds that are carried by wind or water, enabling colonization of new areas. Gravity dispersal allows seeds to drop and establish locally. Zoochory by vertebrates, particularly birds and mammals, aids in long-distance dispersal as seeds are consumed and later excreted. Additionally, epizoochory occurs when seeds attach to animal fur or feathers, facilitating movement across landscapes. These mechanisms contribute to its widespread invasion, making control efforts more challenging. Various management approaches, including mechanical, chemical, biological and cultural methods, have been employed with varying success. Strategies like uprooting, girdling and debarking are commonly used alongside habitat restoration efforts. Community engagement and international cooperation are essential for mitigating its spread. This review highlights the urgent need for coordinated action through assessment, monitoring and strategic interventions to effectively manage *S. spectabilis* invasions and protect native ecosystems.

Keywords: distribution; invasive alien species; restoration and rehabilitation; *Senna spectabilis*

Introduction

Invasive alien species pose a severe threat to native ecosystems. These plant species are introduced by human activities or other means, either intentionally or accidentally, into regions beyond their natural range. With the absence of natural predators or competitors, they can proliferate rapidly, causing extensive harm to native biodiversity, even within protected areas (1). Many invasive plants employ similar strategies to dominate new environments. They often display rapid growth rates, short life cycles, high reproductive capacity, lightweight seeds for easy dispersal, strong competitive abilities and allelopathic traits-chemical compounds that suppress the growth of other plants (2). These characteristics enable them to outcompete and displace native species, leading to ecosystem disruptions.

The consequences of plant invasions are widespread and extensively documented. Invasive alien plants (IAPs) are recognized among the most critical threats to the structure and function of natural and semi-natural ecosystems globally (3-7). They compete with native species for essential resources such as sunlight, space, water and nutrients, resulting in a decline in native species abundance and diversity (8). By altering the composition and structure of plant and animal communities, IAPs disrupt ecosystem balance, triggering cascading effects on food webs, nutrient cycling and overall ecosystem functionality. Moreover, they can modify physical and chemical environmental conditions, creating unfavorable circumstances for native species. Biological invasions, along with climate change, are the two primary drivers of biodiversity loss and ecosystem service disruption worldwide (9). In fact, biological invasions rank as the second most significant threat after habitat destruction, with nearly one-fifth of Earth's surface, including global biodiversity hotspots, predicted to be at risk of invasion (10).

S. spectabilis is a comfortably sized, fast-growing tree, with an origin in Central and South America. The name *S. spectabilis* stands for its legendary use as a laxative, with Arabic roots indicating the purgative effects of this plant. Belonging to the *Senna* genus with over 200 species (11), it first gained attention in India when discovered in the Sathyamangalam forest and Wayanad Wildlife Sanctuary of Kerala (12). This tree can reach over 10 m in height, with young branches often covered in fine hair. Its leaves are impressive, with numerous pairs of leaflets averaging 20 per leaf. Each leaflet is lance-shaped, reaching 3-8 cm long and 2 cm wide. While hairy on the underside, they are smoother and shinier on top. The flowers appear in clusters at the ends of branches in vibrant yellow colour. They have five unevenly sized petals and sepals, the largest reaching up to 2.5 cm. It is interesting to note that the plant has three types of stamens, with some being rudimentary and barely functional. The pod is long and flat in which the pericarp splits open along one side (13).

Initially introduced to India's gardens for its beautiful flowers and aesthetic value, the fast-growing *S. spectabilis* has unfortunately escaped cultivation and invaded forest areas like Mysore. This aggressive invader thrives in Wayanad and Tamil Nadu, producing vast numbers of seedlings that threaten native species. This ecological menace has earned it the unwanted label of 'Invasive Alien Species', highlighting its significant negative impact on biodiversity. It has become a nightmare for natural forests and swallowed significant areas, displacing and harming native species (14). Even herbivores, meant to control its spread, contribute to its deeper penetration of forests by consuming and dispersing its seeds (15). But the true danger lies in its stubborn resilience. *S. spectabilis* is incredibly difficult to eradicate and the invasive character holds true due to the characteristics such as viable seeds for a long time and even injured branches, cut stems and even uprooted trees can sprout new life (16, 17). Thus, *S. spectabilis* presents a major challenge to the preservation of native biodiversity.

S. spectabilis, often viewed as a menacing invader, may harbour an unexpected benefit for livestock farmers. This fast-growing tree possesses a unique ability to form a symbiotic relationship with nitrogen-fixing bacteria called rhizobia (a free -living soil microbiota). These tiny allies help the plant convert atmospheric nitrogen into usable forms, enriching its leaves with vital nutrients like protein and fibre. These nutrient-rich leaves could potentially serve as a valuable supplementary food source for animals like goats, sheep and cattle (18). This could be particularly beneficial during periods of scarcity of feed when traditional forage options are limited due to factors like drought or overgrazing (18, 19).

Distribution of *S. spectabilis*

S. spectabilis (DC.) H.S. Irwin & Barneby serves as a crucial food source for both livestock and wildlife, particularly during the dry season. The leaves and pods of these trees generally possess a higher forage nutritive value compared to herbaceous plants, especially legumes (20, 21). The advantages of retaining these trees in grasslands are demonstrated by the widespread traditional use of silvopastoral systems in various regions across the globe (22).

S. spectabilis species demonstrate extensive global distribution, with distinct patterns of introduction, naturalization and invasiveness across continents. In Africa, *Senna* has been introduced in numerous countries, including Angola, Botswana, Ethiopia, Kenya and Uganda. Notably, it is invasive in Kenya, Malawi, Tanzania and Uganda. Introductions have occurred primarily for ornamental and agricultural purposes, with references citing its presence as early as the 1980s (Fig. 1). In Asia, *S. spectabilis* is widely distributed across India (Fig. 2), China and Southeast Asia. It has been introduced in regions like Guangdong, Yunnan and Hong Kong in China and is cultivated in parts of Malaysia, the Philippines and Sri Lanka. In Bhutan, its introduction dates back to 1984, highlighting its relatively recent establishment (61, 67, 70).

In the Caribbean and Central America, *S. spectabilis* is native to Guatemala, Honduras and Panama, while it has been introduced to Jamaica, Cuba and Trinidad and Tobago. In these regions, its presence ranges from naturalized populations to cultivated ornamental varieties.

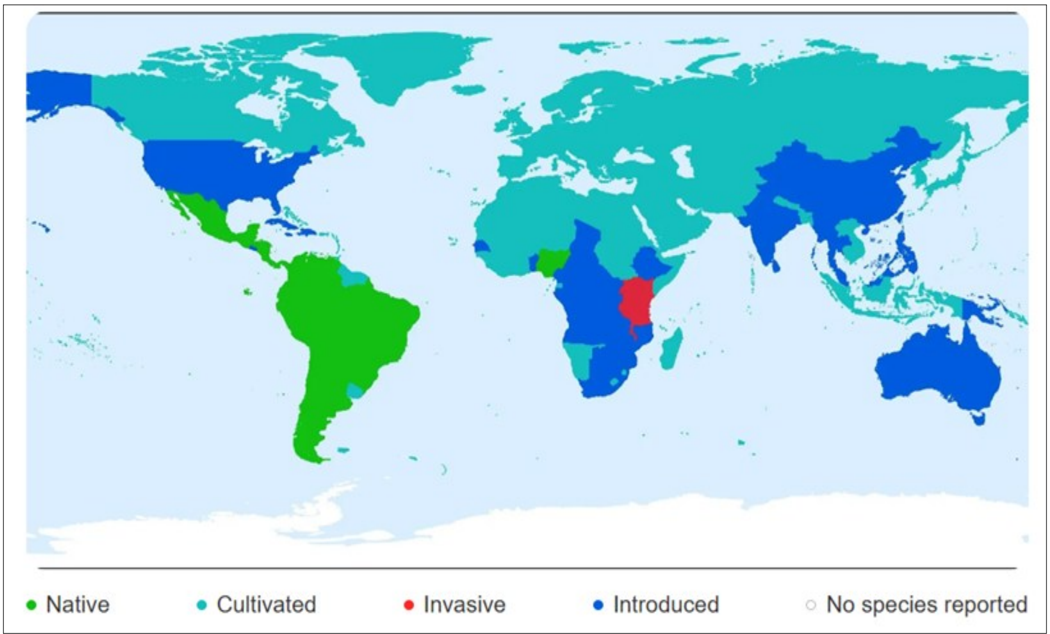

Fig. 1. World-wide distribution of *S. spectabilis* (Source: Internet).

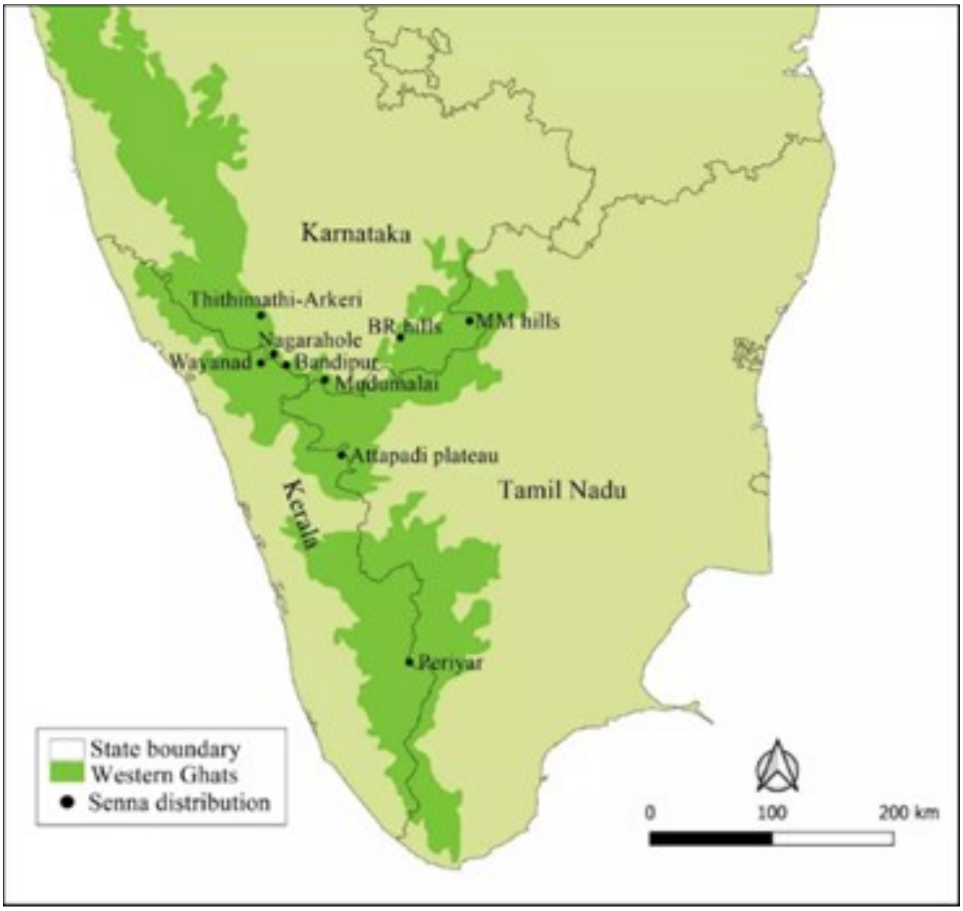

Fig. 2. Distribution of *S. spectabilis* in Southern parts of India.

Table 1. Geographical presence and origin of *S. spectabilis*

Continent/Country/Region	Distribution	Origin	First Reported	Invasive	Planted	Reference	Notes
Africa							
Angola	Present	Introduced				60	
Botswana	Present	Introduced				61	
Burundi	Present	Introduced				60	
Cameroon	Present	Introduced				60	
Central African Republic	Present	Introduced				60	
Chad	Present	Introduced				60	
Congo, Democratic Republic of the	Present	Introduced				60	
Ethiopia	Present	Introduced				61	
Kenya	Present	Introduced		Invasive		61,62	
Malawi	Present	Introduced		Invasive		61	
Mauritius	Present	Introduced				60	
Mozambique	Present	Introduced				61	
Nigeria	Present	Introduced				60	
Rwanda	Present	Introduced				61	
South Africa	Present	Introduced				60	
Tanzania	Present	Introduced		Invasive		61	
Togo	Present	Introduced				60	
Uganda	Present	Introduced		Invasive		61,63,64	
Zambia	Present	Introduced				60	
Zimbabwe	Present	Introduced				60	
China							
Guangdong	Present	Introduced				65	Cultivated
Yunnan	Present	Introduced				66	
Hong Kong	Present	Introduced				66	Cultivated
India							
Karnataka	Present					60	
Rajasthan	Present					60	
Sikkim	Present					60	
West Bengal	Present					60	
Kerala	Present					60	
Tamil Nadu	Present					60	
Malaysia	Present	Introduced				60	
Philippines	Present				Planted	60	
Singapore	Present	Introduced				67	
Sri Lanka	Present	Introduced				60	
Thailand	Present	Introduced				60	
Bhutan	Present	Introduced	1984			68	

Caribbean					
Haiti	Present	Introduced		10	
Barbados	Present	Introduced		69	
Jamaica	Present	Introduced		10	
Trinidad and Tobago	Present			70	
Cuba	Present	Introduced		10	
Dominican Republic	Present	Introduced		10	
Puerto Rico	Present	Introduced		10	
Central America					
Belize	Present			70	
Costa Rica	Present			70	
El Salvador	Present	Introduced		60	
Guatemala	Present	Native		65	
Honduras	Present	Native		60	
Panama	Present	Native		60	Chiriquí
Nicaragua	Present	Native		65	
Guadeloupe	Present	Introduced		67	
Martinique	Present	Introduced		67	
United States, North America and South America					
Florida	Present	Introduced		70	Present based on regional distribution.
Hawaii	Present	Introduced	Invasive	65	Reported invasive only on O'ahu. Also found on Hawai'i and Maui.
Mexico	Present	Native		71	
Argentina	Present	Native		71	Entre Rios, Jujuy, Salta
Bolivia	Present	Native		69	Southeastern Bolivia. Cultivated. Chuquisaca, La Paz, Pando, Santa Cruz, Tarija, Cochabamba
Chile	Present	Native		65	
Colombia	Present	Introduced	Naturalized	69	Naturalized, cultivated
Ecuador	Present	Native		69	Cultivated. Guayas, Loja, Los Ríos, Manabí
Paraguay	Present	Native		60	Depts Amambay, Central
Peru	Present	Native		60	
Venezuela	Present	Introduced		10,72	
Brazil					
Acre	Present	Native		73	
Alagoas	Present	Native		73	
Bahia	Present	Native		73	
Ceara	Present	Native		73	
Goias	Present	Native		73	
Maranhao	Present	Native		73	
Mato Grosso	Present	Native		73	
Mato Grosso do Sul	Present	Native		73	
Minas Gerais	Present	Native		73	
Para	Present	Native		73	
Piaui	Present	Native		73	
Rio Grande do Norte	Present			65	
Sergipe	Present	Native		73	
Tocantins	Present	Native		73	
Australia and Oceania					
Northern Territory	Present			74	Present based on regional distribution.
Queensland	Present			74	Cultivated
French Polynesia	Present	Introduced	Invasive	65,75	Introduced and cultivated. Marquesas Is: Nuku Hiva (invasive); Society Is: Tahiti; Austral Is: Tubuai
Guam	Present	Introduced		65	
New Caledonia	Present	Introduced		64	Cultivated. Ile Grande Terre
Papua New Guinea	Present	Introduced		60	

In South America, *S. spectabilis* is predominantly native, with significant populations in Brazil, Bolivia and Argentina. Native habitats span diverse ecosystems such as tropical rainforests, savannas and semi-arid regions. However, introductions in Colombia and Venezuela have led to naturalization and cultivation in localized areas.

In Oceania, *S. spectabilis* is present in countries such as Australia, French Polynesia and New Caledonia. It is particularly invasive in French Polynesia, where it affects native ecosystems on islands like Nuku Hiva and Tahiti. Introductions in Guam and Papua New Guinea have also been documented for ornamental purposes (Table 1).

Invasion biology of *S. spectabilis*

Spread mechanisms and ecological impacts

A study delves into the spread of *S. spectabilis* that employs diverse dispersal strategies to colonize new habitats and outcompete native vegetation (23). These strategies encompass both abiotic and biotic vectors:

- Ballistic seed dispersal: Elongated pods split open, releasing seeds that can be dispersed by wind currents or water runoff over long distances, facilitating establishment in new areas.
- Gravity dispersal: Seeds fall due to gravity, colonizing neighboring areas.
- Zoochory by vertebrates: Birds and mammals consume fruits containing seeds. Seed dispersal occurs through defecation at various locations, enabling long-distance colonization.
- Epizoochory: Seeds adhere to the fur or feathers of animals, facilitating dispersal over longer distances.

The invasion of *S. spectabilis* has significant ecological implications, including alterations in ecosystem structure and function. Its rapid growth and ability to form dense thickets can lead to the displacement of native vegetation and reduction in species diversity (24). Furthermore, its allelopathic properties can inhibit the growth of native plants, leading to changes in community composition and nutrient cycling dynamics.

Allelopathic effects and biology

The allelopathic effects of *S. spectabilis* have been extensively studied, particularly in relation to germination and early growth inhibition of various plant species. Research has demonstrated that aqueous extracts from the leaves of *S. spectabilis* significantly inhibited the germination and growth of lettuce seedlings, highlighting its potential allelopathic activity (25). Furthermore, a study assessing the phytotoxic effects of *S. spectabilis* extracts on the germination of several weed species found statistically significant inhibition, suggesting its potential as a natural herbicide (26). While this research primarily focused on herbicidal effects, it also provided crucial insights into the allelopathic potential of *S. spectabilis*.

The allelopathic potential of essential oils derived from *S. spectabilis* and *Eucalyptus citriodora* has also been explored, with findings confirming inhibitory effects on the germination and growth of various weed species. This emphasizes the potential use of *S. spectabilis* essential oil as a biocontrol agent (24). Understanding the invasion biology of *S. spectabilis* is crucial for its effective management and control. Research on its reproductive biology, genetic diversity and interactions with native species can provide valuable insights into its invasive potential (24).

The global spread of IAPs, particularly in disturbed environments such as landfills and dumps, may significantly impact human health due to the release of toxic compounds and allergenic pollen (27). Numerous IAPs are actively invading terrestrial and aquatic ecosystems, necessitating an understanding of how these species replace indigenous climax communities that naturally arise through ecological succession (28-32). Additionally, investigations into the physiological traits of *S. spectabilis*, such as its water and nutrient uptake strategies, can shed light on its ability to adapt and thrive in diverse environmental conditions.

Allelopathy is a biological phenomenon in which organisms produce biochemical compounds that can either enhance or suppress the physiological and morphological attributes of other organisms (33). Allelochemicals are released through various mechanisms, including root exudation, leaching from aerial parts and plant decomposition (34). These allelochemicals also induce the production of reactive oxygen species (ROS), which serve as critical signaling molecules that regulate plant developmental responses. However, excessive ROS production can interfere with normal cellular processes, potentially leading to cellular damage or DNA denaturation (35, 36).

Invasive alien species often alter ecosystem structures and species composition by suppressing or displacing native species. Biological invasions involve the near-total domination of local plant or animal communities by one or multiple invasive species, often non-native to the region. Many invasive species possess chemical advantages over their competitors, which contributes to their remarkable success and dominance within biotic communities. These species proliferate rapidly, monopolize essential ecosystem resources and displace native flora, often resulting in extensive monocultures of invasive plants. Their ability to alter community structures and manipulate energy flows and material cycles to their advantage is facilitated by a combination of ecological dynamics, socio-political factors and successful physiological and life history strategies. Understanding these invasion mechanisms is essential for developing effective management strategies to mitigate the ecological and socio-economic impacts of *S. spectabilis* and other invasive species.

Indirect impacts on native flora and fauna

Habitat modification

S. spectabilis has the ability to change the structure of its habitat by impacting light availability, nutrient cycling and soil moisture dynamics, especially when it forms dense stands. These changes can have an impact on the types and numbers of native plant species, potentially favouring some species over others. One study highlighted the significance of comprehending the alteration of habitat by invasive species, specifically in the context of restoring tropical dry forests (37). It sheds light on how changes in habitat structure can impact native plants and animals.

Disruption of plant-pollinator interactions

The invasive *S. spectabilis* significantly disrupts native plant-pollinator mutualisms, thereby impacting the ecological balance within the affected ecosystems (38). This disruption occurs due to several factors:

- Competitive displacement: *S. spectabilis* outcompetes native flora for pollinator visitation and resources, disrupting established mutualistic relationships.
- Floral landscape modification: The presence of *S. spectabilis* alters the composition of floral resources, potentially disorienting pollinators and reducing native plant pollination success.
- Pollinator behaviour interference: *S. spectabilis* may impact pollinator foraging patterns, search image formation and ultimately reduce native plant pollination rates.

The spatiotemporal dynamics of plant invasions, emphasize the importance of context-dependent interactions between species traits and environmental factors in influencing invasion success and propose that the specific biological attributes, like rapid growth and efficient dispersal mechanisms, can significantly influence a non-native species' ability to establish and spread within new environment (39). The significant impact of anthropogenic activities such as trade and land-use changes, on facilitating or hindering the spread of non-indigenous plants. They advocate for integrated management strategies that address the multifaceted nature of invasive species by targeting different stages of the invasion process and considering the complex interplay between biological, environmental and human-induced factors.

Modifications in soil attributes

S. spectabilis has the potential to modify soil characteristics through litter accumulation and nutrient cycling, which in turn influence soil microorganisms and nutrient availability (40). These alterations in soil properties can indirectly impact native plant species and the fauna associated with them. The invasion of *S. spectabilis* not only affects soil fertility and productivity but also alters soil moisture dynamics, further shaping ecosystem processes (41).

Understanding the impacts of plant invasion on soil microbial diversity necessitates first elucidating the role of the soil microbiome in ecosystem functioning. Soil is a complex and dynamic environment where microorganisms play a crucial role in regulating biological processes including nutrient cycling, organic matter decomposition and soil structure maintenance (42). These microbial interactions are integral to maintaining soil health and ecosystem stability, making their response to invasive species a key area of study.

Impacts of *S. spectabilis* on forests

The cascading effects of plant invasions on ecosystems, particularly focusing on trophic interactions and tree dynamics. Initially, invasive plants alter trophic interactions, as highlighted by research on the relationship between herbivory and plant invasions (43). This disruption leads to competition for resources and space, which subsequently affects tree growth and regeneration. The reduced availability of resources impacts the habitat and food supply for herbivores, detritivores and higher trophic levels, thereby altering ecosystem balance. Furthermore, these changes heighten the susceptibility of ecosystems to additional disturbances, such as fire or pest outbreaks, thereby exacerbating the ecological consequences of invasive species (7) (Fig. 3).

Management strategies for curtailing the spread of *S. spectabilis*

Mechanical methods such as hand-pulling, mowing, cutting and uprooting are effective for controlling small infestations of *S. spectabilis* (44). These methods are particularly useful in areas where the use of herbicides may not be desirable or feasible. Additionally, biological control methods are being explored as part of an integrated management approach. A critical review of the history and current status of biological control of weeds in South Africa discusses the potential use of biological control agents such as herbivorous insects or pathogens for managing invasive plants like *S. spectabilis* (45). However, careful assessment is necessary to prevent unintended effects on non-target organisms. In addition to direct control measures, restoring native plant communities, fostering healthy ecosystems and minimizing disturbances are key to preventing *S. spectabilis* from establishing and spreading further (46).

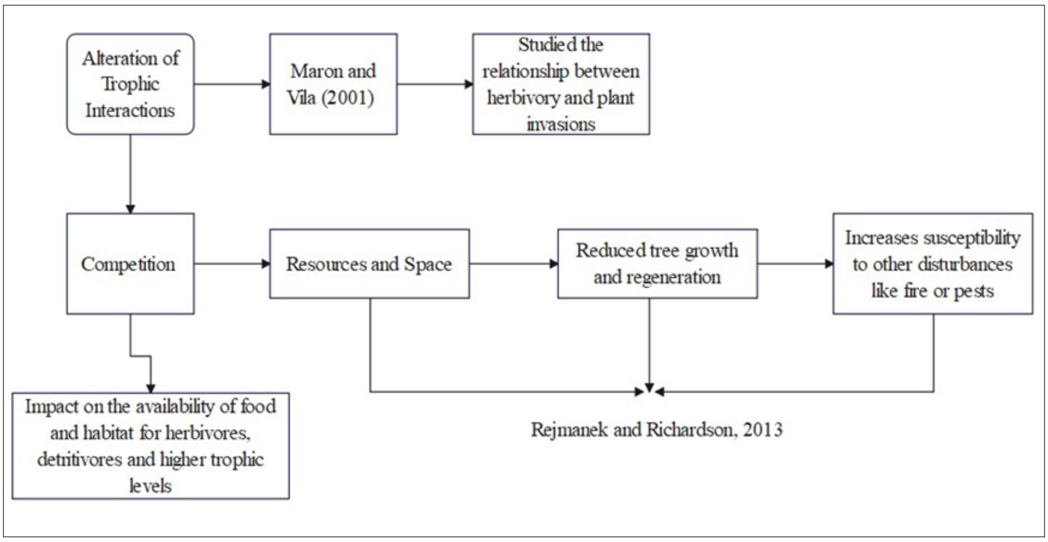

Fig. 3. Impact of *S. spectabilis* on forests.

An effective management strategy for *S. spectabilis* involves a three-pronged approach combining manual removal, mechanical extraction and debarking techniques. Small saplings, typically less than one meter in height, can be effectively managed through manual uprooting during regular field visits to prevent further establishment. For larger saplings exceeding one meter, a specialized weed puller is used to grip and extract the plant from the soil, ensuring complete root system removal. However, the most effective method for controlling mature trees is debarking, where the bark is stripped from breast height down to the collar region, including a 5-10 cm excavation below the soil surface to remove root bark. The removed bark and saplings are then heaped at the base of treated trees to prevent further dispersal. Regular monitoring at three-month intervals ensures the removal of any bark regrowth or coppicing shoots, preventing the tree from recovering (42).

This method has proven highly effective, with 65.2 % of debarked trees completely wilting and dying after 15 months, while seed germination under-treated trees was significantly reduced. However, 15.9 % of trees exhibited new shoot growth, 7.2 % had new foliage and 8.7 % regrew bark, necessitating continued intervention. Only 2.9 % of trees survived with no signs of wilting, highlighting the importance of thorough and efficient debarking. These findings emphasize that early detection and repeated management efforts are crucial for preventing the spread of *S. spectabilis*. A combination of manual removal for young saplings, mechanical extraction for larger ones and debarking for mature trees remains the most effective approach. By implementing this strategy with regular follow-up, the spread and invasive potential of *S. spectabilis* can be significantly curtailed (42).

Eradication techniques of *S. spectabilis*

The methodologies for forest management or landscaping involve various approaches, categorized as manual, mechanical, chemical or a combination of these methods. One approach is the manual removal of seeds and pods from the ground, which is labour-intensive but effective in preventing unwanted regeneration. Debarking, which involves removing the bark from trees to hinder their nutrient transport and eventually cause the tree to die, is carried out using either manual tools or mechanical equipment, depending on the scale and precision required. To accelerate the process, chemical methods such as applying kerosene to the debarked areas can be employed; this practice is particularly effective in ensuring the tree's death but requires careful handling to avoid environmental hazards. Another technique; girdling the tree, involves cutting a deep ring around the trunk to interrupt the flow of nutrients and this can be performed manually with tools like saws or mechanically using specialized machinery for larger operations. Lastly, total uprooting of the tree, which physically removes the tree and its root system from the ground, is achieved through mechanical methods such as excavators or tree-pulling equipment. Each of these methods serves specific objectives in forest landscaping and is selected based on environmental impact, resource availability and project requirements (Table 2).

Restoration and rehabilitation of infested areas

Native vegetation restoration

Implementation of native plant communities in *S. spectabilis*-infested areas can be employed to suppress its proliferation and establishment. This strategy focuses on introducing native species exhibiting high competitive ability against *S. spectabilis* and superior adaptation to local environmental conditions. The selection of restoration techniques including direct seeding, seedling transplantation or natural regeneration, should be guided by specific site characteristics and desired restoration objectives (47).

Habitat enrichment and enhancement

One of the primary causes of land degradation endangering both natural and managed ecosystems is the invasion of alien species. In order to enhance biotic resistance and prevent more land degradation, ecological restoration plays a critical role in limiting invasion (48, 49).

Elevating habitat suitability through native species prioritization can bolster resistance against invasive species and enhance ecosystem restoration. This entails strategically constructing habitat features like water sources, shelter and food resources tailored to local fauna. Implementing habitat management techniques such as controlled burns, targeted vegetation removal and soil fertility enhancements can optimize habitat quality and facilitate the establishment of indigenous plant communities (50).

Ecosystems affected by invasive species can recover in two ways: either to a known historic condition or to a desirable state that has been identified through rehabilitation. Generally, either before or in addition to restoration efforts, invasive species need to be reduced to a certain threshold. Restoration and rehabilitation efforts must prioritize creating an ecosystem that is resilient to future invasions in order to be successful in the long run. Passive restoration of invaded plant communities may occur if there is a sufficient native seed bank. One way to approach active restoration is to either introduce the intended final species or use a predictable successional trajectory that will eventually lead to the desired final species composition. Creating a diverse native plant community can strengthen a system's defence against re-entry (51, 52).

Table 2. Eradication techniques of *S. spectabilis*

Sl. No	Methodology	Manual/Mechanical/Chemical/Biological
1.	Removing the seeds and pods from ground	Manual method
2.	Debarking	Manual and mechanical methods
3.	Kerosene application in debarked areas	Chemical method
4.	Girdling of the tree	Manual and mechanical methods
5.	Total Uprooting	Mechanical methods

Soil working and remediation

An earlier study investigated the complex interplay between soil microbiome composition and ecological services, highlighting the critical role of microbial communities in maintaining soil health and agricultural yield (53). Optimizing soil microbiome composition and function is crucial for biogeochemical cycling and sustaining ecological services. Augmenting the microbiome with beneficial microbes through inoculation or passive restoration strategies can facilitate soil remediation.

Community education

A study highlighted the role of community education programs in fostering environmental stewardship and encouraging grassroots involvement to address the challenges posed by invasive species (54). Engaging local populations in surveillance, eradication and habitat restoration empowers communities to take coordinated action, improving the efficacy of invasive species management strategies.

- Environmental stewardship: Community education emphasizes the interconnectedness of humans and ecosystems, fostering a sense of responsibility for environmental protection.
- Grassroots involvement: Instead of relying solely on top-down management by experts, community-based initiatives tap into the local knowledge and resources of residents.
- Surveillance, eradication, restoration: Engaging the community in these different stages of invasive species management offers a multi-pronged and comprehensive approach.
- Collective action: By bringing the community together, these initiatives amplify individual efforts and build a stronger front against invasive species.
- Efficacy: When communities are informed and empowered, their actions are more targeted, consistent and have a larger overall impact on invasive species control.

Long-term sustainability

A study emphasized that ensuring the long-term success of invasive species management strategies requires sustained engagement and support from local communities (55). This can be achieved through:

- Capacity building: Equipping communities with the knowledge and skills required to identify, monitor and control invasive species.
- Collaborative partnerships: Fostering strong working relationships between local communities, resource managers and relevant stakeholders.
- Promoting environmental stewardship: Cultivating a sense of responsibility and care for the local environment within the community.

By implementing these elements, community education programs contribute to the long-term sustainability of invasive species management efforts.

Implications for invasive species management and biodiversity conservation

Ecosystem stability and resilience

The invasion of non-native species, in particular those that bear the status of a pest disrupting ecological balance cause it to be easily prone to environmental disruptions and propelling ecosystems resistance against change into a downward spiral. The restoration of ecosystem stability and function can be done through the implementation of successful management strategies (56). However, once an invasion has reached a certain level of impact on the landscape, full restoration back to baseline may be impracticable and the strategic shift is towards achieving optimal ecosystem services for maximum benefits (57).

Policy and regulations

The successful control and mitigation of invasive alien species necessitates a multi-pronged approach supported by robust policy frameworks at local, national and international levels. These policy interventions should prioritize preventative measures to minimize the risk of introduction and establishment, coupled with robust early detection and rapid response (EDRR) mechanisms for newly identified incursions (58).

Call to action for addressing the invasion

International collaborations

Establishing a collaborative framework with neighbouring countries and international organizations to facilitate the mitigation of *S. spectabilis* transboundary dispersal. This necessitates the exchange of experiences, knowledge and best practices in invasive species management, fostering a unified approach to containment and potential eradication (59).

Facilitate inter-organizational collaboration

Engender collaborative efforts between governmental agencies, research institutions, Non-Governmental Organizations (NGOs) and local communities surrounding the invasion of *S. spectabilis* are followed by the following ways (49);

Establishing multi-stakeholder platforms or working groups to:

- Facilitate exchange of information regarding monitoring, management and research related to the invasion.
- Enable joint decision-making on strategies and resource allocation for effective management of the *S. spectabilis* invasion.

Conclusion

The spread of *S. spectabilis* from a decorative plant to a worldwide invader exemplifies the significant danger invasive species pose to indigenous ecosystems. Initially introduced for its aesthetic value, this rapidly growing tree has quickly expanded beyond its original habitat, infiltrating forests and disturbing natural environments. Its vigorous colonization and strong resilience pose a substantial challenge to preserving biodiversity on a global scale. The arrival of *S. spectabilis* leads to profound ecological consequences, including changes in ecosystem functioning, displacement of local species, vegetation composition and disruption of ecological interactions, made worse by its allelopathic properties that hinder the growth of native plants and alter soil conditions. Urgent action is highly essential to address this threat, requiring thorough assessment, monitoring, surveillance and the development of comprehensive management strategies incorporating various control methods and fostering international cooperation to manage its spread across borders and exchange effective approaches for invasive species management. Taking proactive steps is vital to restrain the proliferation of *S. spectabilis* and maintain the resilience of native ecosystems, ensuring their preservation for future generations.

Way forward

One aspect of curtailing the invasiveness of *S. spectabilis* is by efficiently using these plants as value-added products. In state of Tamil Nadu, the eradicated *Senna* has been used for production of pulp and paper. In African continents, *Senna* has been tested for fodder qualities wherein the leaves are used as feed for livestock. Restoration of these *Senna*-infested areas by planting native trees and grasses can reclaim the soil and help us to reduce the adverse effects of *Senna* in natural forests.

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Authors' contributions

BS worked in the collection of the literatures and writing the manuscript. BK guided in writing the manuscript and bringing it to a sequence. TM assisted in the correction of the manuscript. RR assisted in additional inputs that was needed in the manuscript. GKN, RKP and VM provided an outline and interpretation of the manuscript. RR and HP assisted in correcting the manuscript. KV and SD helped in reviewing and editing the manuscript.

Compliance with ethical standards

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