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Challenges in scaling management of the invasive tree *Prosopis juliflora*: A review

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Abstract

Prosopis juliflora is an invasive tree species native to Central and South America, is listed among the world's 100 worst invasive species, severely impacts biodiversity, soil chemistry, human livelihoods, and poses health risks, potentially endangering native species. Despite global efforts to control this species using mechanical, chemical, biological, and integrated methods, it continues to spread, suggesting current strategies are ineffective. This review evaluates the effectiveness of various management approaches and highlights challenges and lessons from global experiences. Findings reveal that management efforts have mostly been small-scale trials, with mechanical, chemical, biological, and integrated methods applied at 12%, 38%, 12%, and 17% scales, respectively. These strategies often fail due to their unsustainability, lack of follow-up, and poor documentation of scalable protocols. *Prosopis juliflora*'s adaptability to diverse environments further complicates management. The review underscores the urgent need for sustainable strategies that account for environmental factors and community perceptions. It recommends developing tailored management plans for each country, raising awareness in affected regions, and integrating various control methods to improve effectiveness.

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Introduction

Invasive plants are the species or strains that rapidly increase their spatial distribution by expanding into native plant communities (Zedler and Kercher, 2004). Invasive plants may exert a range of impacts on native communities, they can alter resource availability to native plants and fire regimes (Aslan and Rejmanek, 2012). These invasive plants can be introduced in a new area either intentionally or unintentionally and are likely to cause economic or environmental harm or harm to human health. As trade and travel increase worldwide, invasive plant introductions continue to rise through different pathways such as trade and human movement (Mehta *et al.*, 2007). Other drivers include wind, water, floods, birds, animal movements, and transport machines like cars and cargo ships (Hulme, 2009; Lyimo *et al.*, 2009; Mortensen *et al.*, 2009). Invasive plants not only destroy biodiversity but also soil chemistry, hydrology and lower human livelihood and may result in the extinction of native plants, alter the native species composition and spatial distribution (Foxcroft *et al.*, 2006; Ngondya and Munishi, 2021; Rahman *et al.*, 2010) and after establishment their management is often costly and ineffective in the long term (Clewley *et al.*, 2012).

There are three fundamental management objectives when dealing with invasive species and these are as follows: prevention/exclusion; Early detection/rapid assessment; and Control/containment/eradication (Crowley *et al.*, 2017; Mehta *et al.*, 2007; Rejmánek, 2000). How to meet these objectives, in particular within political and economic limitations, is more a question of policy and technology (Mehta *et al.*, 2007). By increasing resources to detect invasive species, managers may increase their chances of finding a species at a smaller population level, lessening the extent of damage and making subsequent control potentially less expensive and more effective (Mehta *et al.*, 2007). Generally there are four methods employed in the control of the invasive plant species including the use of chemical, mechanical removal, biological method that involve release of herbivores and pathogens to manage the invasive plants (Seastedt, 2015; Zachariades *et al.*, 2011) and integrated management which involve in cooperating all possible management approaches for control the invasive species (Ehi-Eromosele *et al.*, 2013). The cost and time for managing these invasive alien plants (IAPs) vary depending on the level of invasiveness and the choice of the management options depending on the scale of invasion.

Management strategies targeting *Prosopis juliflora* have predominantly been trialed and implemented at a small scale (Shackleton *et al.*, 2016a; Wise *et al.*, 2012a). Despite these efforts, the effectiveness of these management approaches has been limited due to their unsustainable nature, time of intervention, no effective management practices available or not correctly implemented, failure to follow up, replacement by other IAPs, conflicts of stakeholder interests, and no restoration of desired land use. Additionally, once the projects were phased out, there was a lack of further implementation strategies. *Prosopis juliflora* hereafter referred to as *P. juliflora* has infiltrated around 54 million hectares worldwide (Shiferaw *et al.*, 2022). It is now on the International Union Conservation of Nature (IUCN) list of the 100 worst invasive species (Mwangi and Swallow, 2008; Shiferaw *et al.*, 2019; Simberloff and Rejmanek, 2019).

The effectiveness of the methods used, time spent in controlling and acceptance of the control methods used have not been systematically documented. Literature on this subject lacks documentation on the extent of efforts and their equity by geography and by types of methods to enable quantification of the magnitude of successes and challenges associated with the efforts taken to management. *P. juliflora* continues spreading where it is invasive which indicates that management strategies are not always successful. To fill this gap, this review paper focuses on different regions of the world that *P. juliflora* has colonized and examines whether the control methods applied were able to eradicate the species or reduce further spread. This involves reviewing the existing literature on the reasons for the introduction of *P. juliflora*, the negative impacts of *P. juliflora*, factors that contribute to the globally spread of *P. juliflora*, and control methods of *P. juliflora*. Further, the review discusses the challenges and lessons learned about the management strategies employed in fighting *P. juliflora*. This review paper acts as a prerequisite to decision-makers to come up with a holistic approach to the management of *P. juliflora* and it provides an edge to prioritizing management options and a knowledge base for fighting against *P. juliflora* at different stages of invasion.

Materials and Methods

Data used to prepare this review paper were primarily gathered from the following databases: Web of Science (883) and other sources (435) including Google, Google Scholar, Science Direct, and CABI digital library. A total of 1318 literature were obtained (Fig. 1).

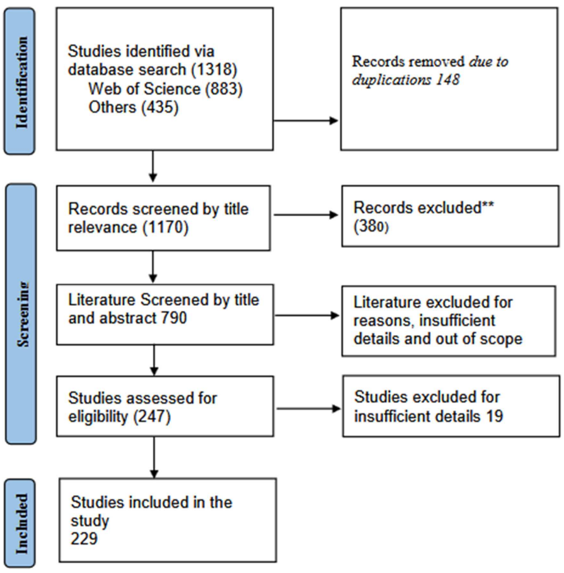

Fig. 1. PRISMA (Preferred reporting items for systematic reviews and meta-analyses) flow diagram illustrating the selection process for the inclusion of studies on *P. juliflora* as an invasive tree species

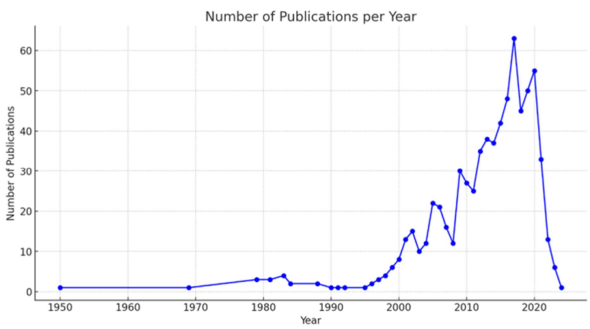

Fig. 2. The number of publications per year related to *P. juliflora* as an invasive tree species from 1950 to 2023

The reviewed literature search was limited to the English language and with the assistance of Zotero software the literatures were attached and duplication removed. The CSV file was exported to R software that was used for further scanning, screening and visualization of the searches. The included literature has information about "*Prosopis juliflora*, Mesquite" AND, OR" *impacts, distribution, management, challenges, intervention, chemical control methods* mechanical control methods* biological control methods* integrated/utilization control methods*. Finally, a total of 229 studies that were published between 1950 to 2023 were selected (Fig. 2) PRISMA diagram of studies selection.

Results

P. juliflora is an evergreen woody shrub or tree species with spreading branches that can grow up to 12m long and has a deep laterally spreading root system ("*Prosopis juliflora* (Sw.) DC.," 2019). The genus *Prosopis* belongs to the family Fabaceae or Leguminosae, subfamily Mimosoideae it has 44 species , also the genus *Prosopis* has recently disintegrated into three genera named *Anonychium*, *Neltuma* and *Strombocarpa* and thus Juliflora relocated to the genus *Neltuma* (Hughes *et al.*, 2022). *P. juliflora* has seeds with higher dormancy ability and can stay in the soil for more than 10 years with high seeds production whereby one pod contains an average of 25 seeds and a mature tree can produce an average of 800,000 seeds per year (Howari *et al.*, 2022). *P. juliflora* tree species is native to North America in Mexico and Central America in Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama (Howari *et al.*, 2022). It is a drought resistant and can grow in semi-arid and arid tracts of tropical and sub-tropical regions of the world (Sawal *et al.*, 2004).

Reasons for the introduction of P. juliflora

P. juliflora has become widely popular due to its remarkable adaptability to diverse ecological conditions, thriving in saline semi-arid and desert areas, regions with low soil fertility, and disturbed forest areas (El-Keblawy and Al-Rawai, 2007; Howari *et al.*, 2022). *P. juliflora* was purposely introduced in the United Arab Emirates during the 1970s to counteract desertification. Simultaneously, the plant acts as an ornamental plant in Saudi Arabia, where it is strategically planted along roadsides in areas such as Abha, Qassim, Hofuf, and Giza (Al-Frayh *et al.*, 1999; Howari *et al.*, 2022). It was first used in India in the 1870s, mostly for fuelwood and desert restoration projects (Walter and Armstrong, 2014). Meanwhile, *P. juliflora* was introduced in Pakistan to control sand dune movement (Kazmi, 2010).

Turning to the African regions, *P. juliflora* first appeared in West Africa in 1822, notably in Senegal. It was then planted strategically in the Sahel region to mitigate desertification and address fuelwood consumption (Felker and Moss, 1996). In Ethiopia it was introduced in 1970 to restore land and in Kenya during the 1980s, it played an important role in preventing desertification while also serving as a source of fodder and fuelwood in several counties (Shiferaw and Demissew, 2023; Wakie *et al.*, 2014). In Tanzania, donkeys and livestock from Taveta accidentally introduced *P. juliflora* into the Kilimanjaro region in 1988 (Kilawe *et al.*, 2017).

Negative impacts of P. juliflora

P. juliflora has long roots *and* has been reported to affect surface and groundwater movement, reduce foraging areas for livestock, cause health problems for humans and livestock, and decrease plant species richness (Bukombe *et al.*, 2018; Muller *et al.*, 2017; Ravhuhali *et al.*, 2021). *P. juliflora* invasion threatens biodiversity by weakening natural ecosystems and causing them to fail to deliver ecosystem services; it also reduces bushland, grassland, and bearland (Wudad and Abdulahi, 2021). In the range land, *P. juliflora* was found to reduce the species richness of native plants and increase the cover of alien species. In the Delhi ridge forest, a study conducted in 2008 in 19 areas invaded by *P. juliflora* revealed low abundance and diversity of bird species in areas with high density of *P. juliflora* (Khera *et al.*, 2009). Landsat imagery analysed between 1977 to 2011 at India's Wild Ass Wildlife Sanctuary revealed that *P. juliflora* poses significant challenges to plant biodiversity and wildlife population (Vazeed Pasha *et al.*, 2015). Because of the rapid spread rate of *P. juliflora*, communities have been compelled to evacuate their property. For example in Kenya people from Chemonke abandoned their land owing to thick invasion and moved to Keper and Loropil, increasing social turmoil (Mwangi and Swallow, 2005; Wakie, Hoag *et al.*, 2016; Wakie *et al.*, 2016). Landsat imagery analysis in the savanna ecosystem of Baringo Kenya from 1988 to 2016 revealed a 40% loss in land usage and cover, with a rate of spread of 640 ha per year. As a result, grasslands, native vegetation, and crop area are reduced by 86%, 42%, and 47%, respectively (Mbaabu *et al.*, 2021). Further, Landsat data analysed for three years in Garissa County between 2003 and 2006 revealed that the riverine ecosystem was most damaged by *P. juliflora*, with a rate of spread of 30 ha/year (Dubow, 2011).

Factors contribute to the globally spread of P. juliflora

Globalization enables the proliferation of invasive alien species by fostering the emergence of new trade routes, markets, and products in international commerce. Advancements in technology further accelerate the speed at which both humans and commodities can traverse the globe (Meyerson and Mooney, 2007). Also climate change contributes to the spread of this invasive tree as it makes unsuitable regions favorable for the species growth. It has been reported that due to climate change causes drought hence agropastoralists abandon their farms for some years which increases the rate of invasion (Dakhil *et al.*, 2021; Eckert *et al.*, 2020). African countries have high risk of invasion and one of the most critical barriers in the management of *P. juliflora* and this has been associated with climate factors as the species prefers most tropical, subtropical and desert areas also lack of strategic control planning (Dakhil *et al.*, 2021; Eckert *et al.*, 2020).

The nomadic life of some communities and wildlife animals that feed on the pods increase the spread (Degefu *et al.*, 2022a; Eckert *et al.*, 2020). Also the absence of natural enemies in the invaded areas to feed on the seed pods make the species to flourish in the invaded region (Gemeda, 2019; Shiferaw *et al*., 2004; Shiferaw and Demissew, 2022; Wudad and Abdulahi, 2021).

East Africa regions have highest expansion rate ever recorded in tropical regions (Witt, 2010) for example in the Afar region in Ethiopia since it was introduced in 1970 a total of 1.17 million hectares have been invaded (Shiferaw and Demissew, 2022) and it expands at the rate of 31,127 ha per annum (Shiferaw and Demissew, 2022). Some wild animals like rabbits, apes, monkeys, rodents, deer and warthogs had also contribute to the spread of the seeds but in a short distance (Degefu *et al*., 2022).

Agriculture activities in which farmers use the water from rivers which are already polluted by cattle dungs with the seeds for irrigation (Magid, 2014; Sintayehu *et al*., 2020). Livestock were means of seed dispersal to and from the water channels (Rembold *et al*., 2015).

Control methods of P. juliflora

Several control methods have been investigated for the management of *P. juliflora*, including mechanical removal, felling and herbicide treatment of cut stumps, foliar spraying of saplings, and burning (Table 1). However, on a larger scale, mechanical, chemical, biological, and integrated approaches have been practiced at rates of 12%, 38%, 12%, and 17% respectively. Moreover management by an integrated approach that involves utilization, fire, disruption of its phenological stages, and biological are among the control methods of the species *P. juliflora* (Abdulahi *et al*., 2017). None of these are affordable or have been practiced on a large scale and costs of control generally far exceed the value of invaded land (Zachariades *et al*., 2011). Current management practices are also not satisfactory for sustaining the containment of *P. juliflora* in the invaded areas. Additionally, unless improved management interventions are adopted, the sustainability of ecosystem services will be at stake in the near future.

Table 1. Showing *P. juliflora* control practices

Practice	Description	Aim	Application
Mechanical method	Involve the use of machines and manual removal of branches and stems, as well as roots to at least 30cm under the surface to avoid resprouting, followed by removal of emerging seedlings for two years (Shiferaw and Demissew, 2022). -Removal of small trees using a tree popper during the rainy season.	Killing of trees, clearing land for subsequent agriculture	Early detection and rapid removal (EDRR), local eradication, asset protection
Prevention of seed dispersal by livestock through physical barriers to exclude grazers	Implementation of physical barriers to prevent livestock from dispersing seeds	Involves a combination of management methods tailored to specific objectives.	Implementation of physical barriers to prevent livestock from dispersing seeds
Basal bark herbicide application	Application of herbicide to the lower part of each stem using a knapsack sprayer or paintbrush	Killing of trees	EDRR, local eradication, asset protection
Cut stump herbicide application	Removal of stems using a chain saw or panga, followed by immediate herbicide application on the cut surfaces	Killing of trees, charcoal making to cover cost of management.	EDRR, local eradication, asset protection
Biological control	Utilizes natural enemies of *P. juliflora* like seed feeding bruchid beetles to control its spread (Abdulahi *et al.*, 2017; Clewley *et al*., 2012)	Reduction in the number of viable seeds	Control of widespread populations

The deployment of *P. juliflora* management strategies differs between developed and developing countries, with the former employing mechanical and chemical control and the latter employing the utilization approach because it is less expensive compared to others (Obonyo *et al*., 2017; Shackleton *et al*., 2017; van Klinken *et al*., 2006).

Table 2. *P juliflora* management approaches

Management Approach	Success and challenge	Effectiveness	Scale	Countries
Mechanical	-Successful in small-scale trials -Challenges with long-term control after project phase out (Walter and Armstrong, 2014)	Moderate	Large	Ethiopia, Kenya, Tanzania, Somalia, Southern Africa, Asia, Australia (Magid, 2014).
Chemical	-Effective in localized areas -Expensive and difficult to access dense cover and needs to be repetitive. (Ghosheh, 2005; Shanwad *et al*., 2015)	Moderate	Small	India, USA, Ethiopia, Sudan, Tanzania, South Africa, Australia
Biological	-Promising results with certain biological agents -Slow process with long-term effectiveness (Van Driesche *et al*., 2010; Van Klinken *et al*., 2003)	Moderate	Small	USA, Australia, South Africa, Sudan
Integrated	-Balanced approach combining multiple methods	Limited	Extensive	Kenya, Ethiopia, Somalia, Nigeria, India
Utilization	-Successful in creating economic opportunities -Provides livelihood options for communities			

The efforts made by different countries vary depending on social and economic aspects such as the impact of *P. juliflora* in a country, public awareness, community and stakeholder attitudes (Degefu *et al*., 2022; Shackleton *et al*., 2015). Management strategies such as biological and chemical control have been widely used in developed countries such as the United States of America and Australia, while in developing countries they are mostly used for trial purposes (Shackleton *et al*., 2016; Wise *et al*., 2012). Despite these efforts, disparities in implementation efforts and implementation barriers continue to pose major challenges in the successful management of *P. juliflora* in various areas where it has been colonizing, the current global distribution is shown on Fig. 3 below.

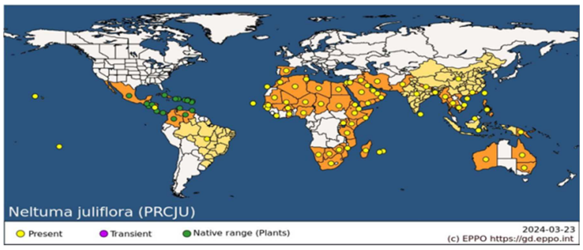

Fig. 3. Global distribution of *P. juliflora* (www.gbif.org)

Table 2 summarizes the success of different management approaches for controlling *P. juliflora* based on their effectiveness and scale of implementation. The effectiveness is categorized as "Moderate" for approaches that have shown some success but with limitations, while "Limited" indicates approaches that have not been highly successful. The scale refers to the size or extent of implementation, categorized as "Large" for widespread application across significant areas and "Small" for more localized efforts.

Discussion

Management of P. juliflora by using mechanical approach

There has been several attempts all over the world to eradicate *P. juliflora* from invaded areas by using mechanical approach where it has become a noxious particularly in East Africa region which include, Ethiopia, Kenya, Tanzania and Somalia which have highly affected (Magid, 2014; Mwangi and Swallow, 2005; Rembold *et al*., 2015). Other regions with high invasion rate include Southern Africa, Asia and Australia (van Klinken *et al*., 2003; Walter and Armstrong, 2014; Zachariades *et al*., 2011). In Ethiopia a farm Africa project abled to clear about 396 ha (Tessema, 2012). In Tanzania mechanical removal was practiced in Kahe ward for demonstration plots trials, (Jumanne *et al*., 2021). The practice succeeded 100% to control the *P. juliflora* in a small area of less than 5 hectares but after the phase out of the Wood Weed Project and the land returned to owners' reinvasion has occurred because no continuation of seasonal removal of the seedling in the area. This challenge of reinvasion after the project phase out occurred in almost every region including East Africa, Southern Africa and Australia which applied mechanical removal. These mentioned few regions are the one that showed a serious initiative toward the management of *P. juliflora* by mechanical approach through eradication and it accounts for 33% of the affected regions. After eradication, the soil needs to be re-planted with another preferable indigenous species to restrict the seeds of *P. juliflora* to germinate from its belowground seed bank. However, complete eradication can only be implemented in limited spaces because of the high costs involved and the low success rate (Walter and Armstrong, 2014). Different mechanical practices including burning and cutting of the juvenile tree at 10 cm and mature tree at 40 cm down to the ground were tried by the Ethiopian Institute of Agricultural Research in the management of *P. juliflora* (Shiferaw and Demissew, 2022). In Awash Fentale and Amibara in Ethiopia the social survey showed that 10% of the respondents propose the control of *P. juliflora* by mechanical control by cutting mature stems also 20% propose to apply fire on the stems to prevent coppicing (Shiferaw *et al.*, 2022). The study conducted in Salabani Baringo County in Kenya reported that 28% were ready to use the uprooting method while 49% burn the stump using cattle dung such as of cows and goat and used motor engine oil (Masakha and Wegulo, 2015). However, this practice of using animal dung has doubled the effects since burning the dung destroys seeds which pass undigested in animal dung and are spread in grazing fields.

Mechanical interventions using bulldozers, tractor-drawn ploughs or other machines to clear extensive weed infestations have the obvious drawback of being indiscriminate and of raising non-target plant species as well, while at the same time creating conditions that may be ripe for reinvasion (Abdulahi *et al.*, 2017). In South Africa it was found that the benefit of managing *P. juliflora* by mechanical approach in wetlands exceeded the costs but the opposite is true in the upland, the data from the Northern Cape show that the cost for controlling varies on invasion density and range from 15$ to 534$ per hectare and these costs often excess the value of land to be cleared (Wise *et al.*, 2012). In a study carried out in 2001 in Ng'ambo and Loboi areas in Kenya the respondents spent an average of 16-83 (Mwangi and Swallow, 2005) depending on the tree abundancy in their farmland, this cost is low compared to other parts of the world because it was individually based and did not estimate into the standard of a hectare. Moreover, the estimated costs by the respondent in both South Africa and Kenya there is no exact number of stems per hectare when one says it's 16$ for low invasion and 83$ to 543$ for high invasion. Also no documentation of the cost and benefits analysis of the applied mechanical method in the area. Regions that applied mechanical methods report to be more effective but machines like tractors and bulldozers are not affordable and accessible by the community. Ecologists have criticized the mechanical removal methods as they can cause soil compaction and criticized to damage and removal of other small plants as it is difficult to remove *P. juliflora* selectively (Degefu *et al.*, 2022). Moreover, it is difficult to use tractors in a land which have been massively invaded as the tree thorns and stumps harm the tires, this has either forced the landowners to sell their farmers at a low price or make a contract with an individual to cut the trees and uproot the stump and utilize for fuelwood and charcoal production in exchange of payment. In South Africa about 100 barriers to managing invasive *P. juliflora* were identified (Shackleton *et al.*, 2016) and most of them are social including limited knowledge, conflict of interest, shortage of funds and the ecology nature of the invasive such as high seeds production, adaptation, long life seed bank which can stay for about 40 years in the soil.

Management of P. juliflora by using chemical approach

Control methods for managing *P. juliflora* indicated that individuals or combination of chemical pesticides were used. The chemical applied either aerial or stem and its effect on the applied tree is determined by the diameter size, number of stems and time of application (Jumanne *et al.*, 2021; Shanwad *et al.*, 2015). In India between 2009 and 2011 at different trial sites, they used Mera – 71 (Glyphosate), Paraquat, 2, 4-D amine and ester, Diuron, Keroscene and Coaltar (Shanwad *et al.*, 2015) for trials. The study indicated the most effectively chemical in affecting weed recovery was Mera-71 (Glyphosate) when applied two times it reduced the growth and development of *P. juliflora* while Diuron was the least effective (Shanwad *et al.*, 2015). Herbicides that have been tested in the USA include clopyralid, dicamba, picloram, triclopyr and 2, 4, 5-all performed successfully when used single or in combination but the most effective is clopyralid (Abdulahi *et al.*, 2017). In Gezira State central Sudan, the basal bark application of a tank mixture of 2, 4-D 5% + glyphosate 5% was tested and resulted to 100% control of *P. juliflora* trees within 90-120 days after treatment. The foliar application of 2, 4-D at 7% and 9% also tested and caused complete death of *P. juliflora* within 60-90 days after treatment (Talab *et al.*, 2020). The study conducted in Ethiopia correlates with that of Sudan and results showed that a combination of herbicides (Mera-71 and 2, 4- D) control *P. juliflora* better than the individual application of Glyphosate and 2, 4- D (Abdulahi *et al.*, 2017). Additionally a Triclon mixed with diesel has been tested in 3 experimental sites in Kahe-Tanzania, Baringo-Kenya and Afar-Ethiopia this chemical performed well and the mortality rate was 85% (Eschen *et al.*, 2023). Nevertheless, this control method lacks information about costs per land size and or based on the invasion intensity, and also does not indicate scale protocol for the trials to be repeated in other regions.

Our observation indicates that Chemical control methods have been widely explored and reported in India, USA, Ethiopia, Netherlands, Australia, Sudan, Tanzania, and South Africa. This accounts 66.7% of the invaded regions however, the use of chemical control approach has been only applied in a small area and generally this intervention has become unsuccessfully in managing large-scale infestation of *P. juliflora* due to inadequate control, expensive and difficult to access dense cover with hand sprayer and mounted spray equipment. For this method to function effectively in bigger invasive tree species such as *P. juliflora* it should be tested and validated in the field by cutting the tree first and then applying the chemical at the stump to allow for large scale implementation. However due to chemical expensiveness majority of the local community cannot afford the use of this method in control of *P. juliflora* in their farms (Shiferaw and Demissew, 2022). Moreover, chemical application needs to be repetitive, to be effective so it needs to be applied at least twice to make it more effective (Shanwad *et al.*, 2015). It can be done after 3 to 5 years depending on the type of chemical used and follow up is important to ensure large and multstem trees are killed. Despite the effectiveness of chemical method in the trial sites it cause resistance to the weeds, water contamination and cause several hazards to both human and animals (Ghosheh, 2005). Another challenge of using chemicals is the nature of the species *P. juliflora* it has a thick bark and leaf protected by waxy layer this makes chemicals perform effectively on small trees with diameters less than two centimeters and for big trees you should cut the stem part and smeared (Shanwad *et al.*, 2015).

Controlling *P. juliflora* through chemicals at juvenile stages is highly effective than mature tree stages. Eradication of *P. juliflora* has been attempted in several countries through chemicals but has proved unsuccessful and chemical eradication is not environmentally friendly (Ghosheh, 2005). In Ethiopia this management strategy was also tried to control *P. juliflora* but failed to manage it (Shiferaw and Demissew, 2022). A study about management perception conducted in the Afar region in Ethiopia found that about 20% of the population were propose to use chemical methods for the management of *P. juliflora* (Shiferaw and Demissew, 2022). A similar study carried in Loboi and Ng'ambo sites in Kenya, a public survey revealed that about 85% of the respondents suggested the eradication of *P. juliflora* (Mwangi and Swallow, 2005). This is different from the study conducted in Salabani Baringo County in Kenya where by 0% of the community proposed to use chemicals due to their expensiveness (Masakha and Wegulo, 2015).

Management of P. juliflora by using biological approach

Classical biological control using specialized, coevolved natural enemies from the native region of the invader is often advocated as a preferred alternative to chemical and mechanical control methods when it comes to dealing with invasive species (Clewley *et al.*, 2012). Management of *P. juliflora* by using biological agents is gradually gaining prominence in United States of America, Australia and South Africa for its cost-effectiveness, ecological and environmental compatibility and no disturbance to the soil (Masakha and Wegulo, 2015; Seastedt, 2015; van Klinken *et al.*, 2003).

This accounts for about 33% of the affected regions. Biological agents *Algarobiuos prosopis* and *A. bottimeri* (Bruchid beetles) have been used in USA, South Africa and Australia with great success as they attack seeds in pods and reduce their viability. In South Africa 70% success has been reported in open grazing fields (Masakha and Wegulo, 2015). In Australia four biological agents were introduced, the beetle *Algarobius bottimeri* and *Algarobius prosopis juliflora* whose larva feeds on the pods, the *Prosopidopsylla flava* which suck the tree sap and causes dieback disease and *Evippe* spp that cause defoliation (Abdulahi *et al.*, 2017). The sap sucking psyllid is only tenuously established in south west Queensland, which has similar climate to the native range of origin in Argentina while the leaf tier is established at all sites. In Australia biological method has proven to be effective by causing prolonged defoliation, reducing growing season and seed production (van Klinken *et al.*, 2003). Other potential agents have been identified, including nine beetle species, four months and a gall midge (Zachariades *et al.*, 2011). Of these, a straight-snouted weevil whose larvae attack seeds within green pods is considered especially promising and has been subjected to host-range tests. Ongoing debates about the relative value and costs of the trees continue to hamper progress with the planned escalation of biological control. Recent assessments show that the costs of *P. juliflora* will soon outweigh the benefits in most situations, opening opportunities to clear additional agent species for release (Zachariades *et al.*, 2011). However, none of these attempts have managed to control the spread of the *P. juliflora* in the region. In Australia biological control agents introduced failed to establish at a required density to be able to cause mass damage to the *P. juliflora* trees. Techniques other than climate matching are therefore required to improve our prediction of relative performance at the regional level (van Klinken *et al.*, 2003).

Biological control methods using the leaf defoliator and sap-sacking psyllids which feed on immature sap and cause dieback showed a promising result in Australia however the challenge of this method is climate matching factor, the use of climate prediction models such as CLIMEX can therefore be misleading because it does not take account of the individual climatic requirements of each species. This was proved in Australia after 3 years the abundance of the biological agents were at climax only in one site (van Klinken *et al.*, 2003). Another challenge is the presence of natural enemies such as aunts which reduce the population of the biological agents. Moreover, biological control is a slow process and the agents need sometimes to reach the required abundance to be able to reduce the effect of the invasive. It requires about 5-20 years to completely eradicate the invasive species (Van Driesche *et al.*, 2010) and when the project phases out becomes difficult for the intervention that are not funded by the government to continue.

Additionally there is a risk of the introduced biological agents feeding on the non-targeted native plants or crops and when its population increases becomes detrimental in the introduction area. A substantial number of introduced biocontrol agents do indeed feed on non-target species. In Hawaii, 22% of 243 agents were documented to attack organisms other than their intended targets (Messing and Wright, 2006).

In Africa though the goal of cooperation for biological control of *P. juliflora* in South Africa with other countries, it delayed trendy due to the controversy over the introduction of biological control agents onto *P. juliflora*. Additionally, debates about the relative value and costs of trees continued to hinder progress with the planned increase of biological control (Shiferaw and Demissew, 2022). Sudanese researchers found some predator insects that attack the leaves that leading to the deterioration of the tree canopy (Abdulahi *et al.*, 2017c) though there is not much detail about their efficacy and success in the management of *P. juliflora*. Experiences from America, Asia and Australia indicate that eradication of *P. juliflora* entirely is difficult because these biological agents do not eradicate the invasive tree but rather weaken its competitiveness with native plant species, slowing the population to the level that does not cause economic loss, suppressing invasive density and environmental impacts, so allowing the native vegetation to recover (Ghosheh, 2005; Seastedt, 2015; Zachariades *et al.*, 2011).

Management of P. juliflora by using Integrated Management Approach

Integrated management strategy involves explores and taking a balanced approach across all management options, tailoring their implementation to what will best address each of the management objectives (Fulton *et al.*, 2014). It can also include managing the species using a combination of biological, chemical, and mechanical methods. This strategy focusses on targeted removal of *P. juliflora* trees and reclaiming these sites by introducing active land use systems that involve planting alternative tree species, appropriate pasture grass, perennial browse shrubs, horticultural, and food crops that all offer a range of alternative livelihood options to the affected communities sustainably (Eschen *et al.*, 2023; Jumanne *et al.*, 2021; Walter and Armstrong, 2014). Management of invasive *P. juliflora* it has been controversial as this tree has both impacts on biodiversity, economy and several benefits to human livelihood this make community members to have different perception of the management strategy to be implemented while some prefer total eradication others prefer the tree to remain in their land (Mwangi and Swallow, 2005; Patnaik *et al.*, 2017). Perception study conducted in Salabani Baringo County in Kenya showed that about 85% preferred utilization option: 44% of respondents were willing to use *P. juliflora* for charcoal making, 12% for pods collection, 22% by pruning and 7% through thinning (Masakha and Wegulo, 2015). Similar study conducted in Nga'mbo and Loboi revealed that 15% of the respondent preferred *P. juliflora* to remain in their land due to various benefit (Mwangi and Swallow, 2005).

Management of P. juliflora by using utilization approach

P. juliflora is used by both human and livestock, its pods are rich in sugar, protein and carbohydrates (S. Choge *et al.*, 2022; Choge *et al.*, 2007; Kazmi, 2010). The pods are used to make bread, coffee, cocktails, brandy and flour (Kazmi, 2010). *P. juliflora* leaves, barks, and roots are used to prepare medicine to treat eye infections, stomach disorders, skin ailments, wounds oral and periodontal infections. It also used to nourish children and elderly, diabetes and increase lactation for livestock (Kazmi, 2010; Nagar, 2011; Walter and Armstrong, 2014).

Globally the large scale utilization approach to control *P. juliflora* has been practiced in Kenya, Ethiopia, Somalia, Nigeria and India this account 22.2% of the invaded regions (Abdulahi *et al.*, 2017; Pandey *et al.*, 2019; Wakie *et al.*, 2016). Large scale projects employed as the means to manage *P. juliflora* trees include the construction of charcoal factory, milling pods factory, goat and sheep grazing. Among the three projects the charcoal making factory was found to be more profitable in Kenya, Ethiopia and India (Pandey *et al.*, 2019a, 2019; Wakie *et al.*, 2016). In Ethiopia a one year charcoal making project conducted by

FARM Africa between 2004/2005 were able to clear about 396 hectares (Tessema, 2012).

The social interview to community at Athur desert in India confirm that the utilization method has contributed to the reduction of the *P. juliflora*, created about 391,000 job opportunities and reduce the desert wind velocity (Pandey *et al.*, 2019). In Kenya individuals are collecting *P. juliflora* pods and sell one bag of 25kg at the price of 2 USD, in Somalia farmers used to sell *P. juliflora* pods to the mills at 0.5ETB/Kg and cooperative sell the crushed pods at 2.5 ETD/Kg (Admasu, 2008; Choge *et al.*, 2022). The pods are crushed by machine to powder form so as to totally destruct the seed to germinate after eaten and pass to cattle dungs, the flour is used for horse, camels and cattle and is very helpful fodder during the dry season.

Unforeseen Consequences of utilization strategy as part of integrated method in management of P. juliflora

The utilization aspect of *P. juliflora* has become very popular because the impacts of these trees start being realized when it has already colonized the area and application of other control methods such as mechanical, chemical and biological become very expensive and difficult to be implemented. Moreover, utilization methods received more acceptability by the society due to the fact that in every region in which *P. juliflora* was introduced, was to solve problems like, desertification, land restoration, fuelwood shortage and fodder for livestock. By the time negative impacts of *P. juliflora* start emerging still other members found it is usefulness.

Furthermore, the farmer communities are likely to experience less negative impacts of *P. juliflora* compared to pastoralists because farmers tend to cultivate their land every growing season and when found the *P. juliflora* seedlings in their farm area they can remove them at early stage so they can continue maintain the farming area. Also, farmers they may perform silvicultural practices like pruning and thinning for the trees which grown in the boundary of their farms so as to decrease shade for their crops to perform good and these practices make farmers to experience little negative impacts of the *P. juliflora*. This makes farmers likely to become reluctant on utilization ideology over control methods like chemical and mechanical. Unlikely pastoralists communities who used to feed livestock's the *P. juliflora* pods particular during the dry season and this tendency contribute much in the distribution of the *P. juliflora* in their grazing land through their livestock dung. After their grazing land being colonized the pathways and foraging grasses decrease and at that stage it become too late to control the tree.

Challenges on management of P. juliflora by using utilization approach

Despite the large scale *P. juliflora* utilization projects found initiated in few countries like Kenya, Ethiopia, Somalia, Nigeria and India but literary the utilization approach has adopted in many invaded regions particularly in developing countries. In Kenya although the government has embraced the concept of management and control of *P. juliflora* invasions through utilization for more than 20 years now. Unfortunately, it has not worked and the species has continued to spread at an exponential rate of between 4% to 15% per year (Choge *et al.*, 2007). Moreover, in some countries such as India, and Ethiopia the rate of *P. juliflora* spread in the region is very high (Pandey *et al.*, 2019; Wakie *et al.*, 2016). This utilization management strategy has been reported to be efficient but it was not sustainable due to many reasons as discussed in hereafter. The challenge faced charcoal making industries was the presence of many unregulated merchants which led to an unsustainable supply of charcoal to the existing enterprises. On the other hand the sheep rearing enterprise faces drought which occurs after 2-3 years (Pandey *et al.*, 2019). In Ethiopia the utilization of charcoal was banned due to producers' tendency to include indigenous trees like acacia in the charcoal. In Somalia it was banned due to some farmers leaving stumps, including unauthorized species in charcoal making and passing permits to unauthorized traders (Admasu, 2008). After the phase out of the project which was implementing the buying of the *P. juliflora* pods for fodder production, there was unreliable market for the pods (Degefu *et al.*, 2022). Moreover, individual charcoal producers claim the long distance and high transport cost from the local area to town to sell the charcoal hence they cannot make a profit. Also, *P. juliflora* charcoal is sold at a low price compared to other tree species.

In Kenya the machine brought to utilize *P. juliflora* trees to generate electrical energy failed due to the tar produced by the tree also the individuals who are processing the charcoal face challenges from natural resource managers who require them to officialize their business. Another challenge of the utilization approach was the rapid rate of spread of *P. juliflora* compared to the existing utilization means, severe droughts in the invaded area led to a shortage of livestock pasture and forced cattle to feed on *P. juliflora* pods (Degefu *et al.*, 2022). Lack of good landuse planning example the charcoal and *P. juliflora* pods mills projects implemented by FARM - AFRICA showed improvements however it was not supported with a good landuse plan hence the pilot got reinvaded.

Conclusion

Despite various efforts to manage *P. juliflora* in invaded regions, there is limited evidence assessing the effectiveness of each control method applied in the field. Management strategies have been implemented in only a few regions and on a small scale, primarily for research trials. Additionally, different regions have adopted varying approaches to managing *P. juliflora*. For instance, in 2001, India developed a technical manual for its effective utilization and established nurseries for seedlings, which inadvertently contributed to its further spread.

Mechanical control, such as using tractors, is costly and often unaffordable for local farmers, with the expense of clearing dense hectares ranging widely. This method provides only temporary relief, as seeds stored in the soil can germinate later. To ensure long-term control, continuous land cultivation is necessary so that newly germinated plants can be uprooted in time. Furthermore, agricultural lands cleared of *P. juliflora* should be fenced to prevent livestock from reintroducing seeds, as both domestic and wild animals play a significant role in its dispersal.

The management strategies applied so far have not been executed on a large scale in colonized areas. A more effective approach would involve an integrated strategy combining mechanical, chemical, biological, and utilization methods. Further studies are needed to evaluate the cost, time, and overall effectiveness of different control methods, either individually or in combination, to develop a sustainable and practical management plan.

Recommendations

1. Every country should develop a management strategy specifically for the invasive *P. juliflora*, Australia is the first country to do so since 2001 and revised it in 2012. Also every affected country should have its implementation strategy based on the nature of the existing society and rate of invasion because among the reasons for the failure of the applied management strategies is that they were not applicable and accessible by the community.
2. Awareness creation in the invaded areas and neighboring regions is very important because in the affected regions members have different views regarding benefits and effects of *P. juliflora* and some are even total depending on this species for livelihood. In order to achieve general public understanding about the impact of *P. juliflora* on livelihood, economy and biodiversity this activity should not only performed by non-governmental organization or institutes level it should be in cooperated in policy and advocated as public threat tree species so others should avoid planting this tree despite its short term benefits.
3. *P. juliflora* tree nursery owner should be educated to stop growing the seed and distribute it to other individuals. This activity should go perpendicular to the introduction of alternative tree species in the areas in which *P. juliflora* has been removed. In

the new areas in which *P. juliflora* have recently been planted there should be a plan to supply them with alternative trees and to compensate the likely loss which owners will encounter this will encourage peoples to show up in public and voluntarily agree to remove *P. juliflora* in their land. For example, in the northern part of Tanzania particularly in Kilimanjaro, Arusha and Manyara regions community members have recently increased the rate of planting *P. juliflora* as a fast-growing and drought tolerant tree. This rapid increase in demand of *P. juliflora* seedlings has forced entrepreneurs to jump into this tree nursery business and now at Mto Wa Mbu area in Monduli district there is a big nursery which sell the seedlings to Lake Natron basin and nearby regions. This implies that if joint measures will not be taken in collaboration with the central government and other stakeholders in the next few years *P. juliflora* will be already spread into many parts of the country and become more difficult and impossible to be eradicated.

4. Full participation of the governments including collaboration with agriculture, conservationists and other stakeholders to provide training to the community in the management and control of the *P. juliflora*. This is very important because among the factor for the failure of the introduced projects to control *P. juliflora* is that after the project phase out no further implementation measure was applied and this is a challenge in both developing and developed countries.
5. Invaded regions should invest in large scale utilization projects like the use of *P. juliflora* biomass to generate electricity and industries to transform lignocellulosic biomass into bio-ethanol. However, these large scale *P. juliflora* utilization projects should be designed only to provide short term benefits to the community members while the government and stakeholders will be implementing mechanical, chemical, biological and integrated approaches in the long run.
6. Grafting using root sucker of various *P. juliflora* species including *Prosopis alba, Prosopis chilensis, Prosopis glandulosa, Prosopis velutina* and *Prosopis juliflora*. In less colonized area *P. juliflora* can be grafted with useful scions.
7. The use of chemicals should be discouraged from being applied in the water sources also respective government should subsidize the import tax for these chemicals so can be affordable to locals.
8. Biological methods have been found to work well in Australia and South Africa, more research should be invested in testing climate matching and these biological pathogens introduced to other invaded regions.

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