ECOLOGICAL STUDIES ON IMPACTS OF INVASIVE ALIEN PLANT SPECIES ON VEGETATION AND THEIR SOIL ALLELOPATHIC INTERACTIONS IN AIZAWL, MIZORAM, INDIA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

SARAH LALLIANPUII

MZU REGISTRATION NO.: 1600700

Ph.D. REGISTRATION NO.: MZU/Ph.D./ 1193 of 01.08.2018

DEPARTMENT OF ENVIRONMENTAL SCIENCE

SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES MANAGEMENT

OCTOBER, 2024

ECOLOGICAL STUDIES ON IMPACTS OF INVASIVE ALIEN PLANT SPECIES ON VEGETATION AND THEIR SOIL ALLELOPATHIC INTERACTIONS IN AIZAWL, MIZORAM, INDIA

BY

SARAH LALLIANPUII

Department of Environmental Science

Under the supervision of

Prof. P.K. RAI

Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Environmental Science of Mizoram University, Aizawl

ACKNOWLEDGEMENT

First and foremost, I would like to express my heartfelt gratitude to the Almighty God for his countless blessings and guidance throughout my education.

My most sincere and heartful gratitude to my supervisor Prof. P.K. Rai for his immense guidance, patience, cooperation, kindness and constant support throughout my research work.

My deepest gratitude to the Head of department, faculties and all non-teaching staffs and the research scholars of the Department of Environmental science, whose guidance have given me the opportunity to complete my research work.

I would also like to thank the Finance department, Mizoram University and The National Fellowship for Scheduled Tribe (NFST) for their financial support during my research work.

I thank my parents, my siblings and my husband for their constant prayers, encouragement and support which have held me and lead me this far.

'To God be the Glory'

SARAH LALLIANPUII

TABLE OF CONTENTS

CERTIFICATE

DECLARATION

ACKNOWLEDGEMENT

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION **1-9**

1.1 Scope of the study

1.2 Objectives

CHAPTER 2: REVIEW OF LITERATURE **10-23**

2.1 Effect of invasive alien plant species on native vegetation

2.2 Mechanism of invasive alien plants

2.3 Allelopathy and Allelochemicals

2.4 Threats of Invasive Alien Plant Species: Global Scenario

2.5 Threats of Invasive alien plants: Indian Scenario

2.6 Threat of IAPS: North-East Indian scenario

CHAPTER 3: METHODOLOGY **24-40**

3.1. Plant-plant interactions

3.2. Plant-soil interactions

3.3. Plant debris-soil bioassay

3.4. Total phenolic content analysis

3.5. Canopy openness, leaf area index, and light intensity

CHAPTER 4: RESULTS **41-99**

4.1 Vegetation analysis

4.2 Soil Analysis

4.3 Plant Debris Soil Bioassay

4.4 Total phenolic content estimation

4.5 Canopy openness, Leaf Area Index (LAI), and Light Intensity

CHAPTER 5: DISCUSSION **100-119**

5.1. Assessment of Phytosociological Parameters

5.2. Assessment of Physicochemical parameters

5.3. Soil nutrient impacted by invasive alien plants

5.4. Plant debris-soil Bioassay

5.5 Total Phenolic Contents (TPC)

5.6. Canopy Openness, Leaf Area Index (LAI), And Light Intensity

CHAPTER 6: MANAGEMENT **120-127**

CHAPTER 7: CONCLUSION **128-131**

7.1. Plant-plant interactions

7.2. Plant-soil interactions

7.3. Bioassay and Total Phenolic Contents Analysis

7.4. Canopy Openness, Leaf Area Index (LAI), And Light Intensity: Management and containment implications.

APPENDICES

REFERENCES

BIO-DATA

PARTICULARS OF THE CANDIDATE

LIST OF TABLES

Table No.	LIST OF TABLES
1.	Phytosociological attributes recorded at disturbed site of Aizawl, Mizoram, Northeast India (2019-2021)
2.	Phytosociological attributes recorded at moderately disturbed site of Aizawl, Mizoram, Northeast India (2019-2021)
3.	Phytosociological attributes recorded at undisturbed site of Aizawl, Mizoram, Northeast India (2019-2021)
4.	Shannon- Weiner diversity index, Margalef's index and Pielou's evenness index in Disturbed (D), Moderately disturbed (MD) and Undisturbed (UD) sites of Aizawl.
5.	Estimation of total phenolic contents by Catechol
6.	Estimation of total phenolic content by Gallic Acid
7	Canopy openness, Leaf area index and light intensity of Disturbed, Moderately disturbed and Undisturbed study sites

LIST OF FIGURES

Figure No.	LIST OF FIGURES
1.	Seasonal variation in pH of soil in the disturbed study site
2.	Seasonal variation in pH of soil in the moderately disturbed study site
3.	Seasonal variation in pH of soil in the undisturbed study site
4.	Seasonal variation in the soil moisture content of soil in disturbed study site
5.	Seasonal variation in the soil moisture content of soil in moderately disturbed study site
6.	Seasonal variation in the soil moisture content of soil in undisturbed study site
7.	Seasonal variation in the soil organic carbon of soil in disturbed study site
8.	Seasonal variation in the soil organic carbon of soil in moderately disturbed study site
9.	Seasonal variation in the soil organic carbon of soil in undisturbed study site
10.	Seasonal variation in soil organic matter of soil in disturbed study site
11.	Seasonal variation in soil organic matter of soil in moderately disturbed study site
12.	Seasonal variation in soil organic matter of soil in undisturbed study site
13	Seasonal variation in the total nitrogen content of soil in disturbed study site
14	Seasonal variation in the total nitrogen content of soil in moderately disturbed study site
15	Seasonal variation in the total nitrogen content of soil in undisturbed study site
16.	Seasonal variation in the available phosphorus content of soil in disturbed study site
17.	Seasonal variation in the available phosphorus content of soil in moderately

disturbed study site

18. Seasonal variation in the available phosphorus content of soil in undisturbed study site

19 Seasonal variation in the available potassium content of soil in disturbed study site

20 Seasonal variation in the available potassium content of soil in moderately disturbed study site

21 Seasonal variation in the available potassium content of soil in undisturbed study site

22 Variation in germination of *L. sativa* at different selected soil samples

23. Variation in Seedling height of *L. sativa* at different selected soil samples

24 Variation in Root length of *L. sativa* in different selected soil samples

25 Variations in the Shoot length of *L. sativa* at different selected soil samples

26 Variation in the Seedling Biomass of *L. sativa* in different selected soil samples

27 Variation in the Germination percentage of *L. sativa* at different selected soil samples

28 Variation in Germination Potential of *L. sativa* at different selected soil samples

29 Variation in the Germination index of *L. sativa* at different selected soil samples

30 Variation in the Germination rate index of *L. sativa* at different selected soil samples

31 Variation in Vigor index of *L. sativa* at different selected soil samples

32 Variations in the germination of *C. arietinum* at different selected soil samples

33 Variations in seedling height of *C.*

	arietinum at different soil samples
34	Variations in root length of *C. arietinum* at different selected soil samples
35	Variations in shoot Length of *C. arietinum* at different selected soil samples
36	Variation in sseedling biomass of *C. arietinum* in different selected soil samples
37	Variation in germination percentage of *C. arietinum* at different selected soil samples
38	Variation in germination potential of *C. arietinum* at different selected soil samples
39	Variation in ggermination index of *C. arietinum* at different selected soil samples
40	Variation in germination rate index of *C. arietinum* at different selected soil samples
41	Variation in vigor index of *C. arietinum* at different selected soil samples
42	Hemispherical photos used for estimation of canopy openness in the Disturbed site
43	Hemispherical photos used for estimation of canopy openness in the Moderately Disturbed site
44	Hemispherical photos used for estimation of canopy openness in the undisturbed site

CHAPTER – 1

INTRODUCTION

1. INTRODUCTION

The spread of invasive alien plant species around the world is one of the greatest scientific challenges of the Anthropocene. In addition to having serious negative consequences for human existence, invasive plants also have a number of detrimental effects on the biodiversity and health of ecosystems (Bolpagni, 2021). In recent past, biological invasions are increasing at an alarming rate as a result of global connectivity and human population growth, with complex effects on biogeographic realms, native species abundance, extinction risk, and genetic composition that are often only apparent when invasive alien plants are well-established and abundant (Pysek *et al.* 2020).

India is well known for its rich plant diversity, which is highly influenced by the country's diverse topography, climate, and ecosystems. It has a rich flora with a high number of endemic plant species found within the hotspot regions and is also home to a large number of ethnobotanical plant species that play a very important role in the long history of India's traditional medicines (Rai and Lalramnghinglova, 2010). Along with a variety of native plant species, India is also home to a number of invasive alien plant species that have colonized the global landscapes and are now posing a serious threat by altering socioeconomic conditions, fragmenting habitats, and contributing to climate change as well as biodiversity loss (Rai and Singh, 2020). Moreover, the Convention on Biological Diversity (1992) cited biological invasion as the third-biggest threat after habitat loss and ecosystem degradation and as one of the primary factors contributing to the decline in biodiversity. Understanding which alien species will naturalize and increase or which alien species will adversely impact biodiversity or other resources is, therefore, one of the main challenges associated with invasion ecology (Tollington *et al*. 2015; Bartz *et al*. 2019).

Urban forests in mountain ecosystems are ideal sites for studying plant invasion ecology through phytosociology and soil attributes (Mandal and Joshi, 2014). Phytosociology is the study of plant community composition, evolution, distribution, and relationships, with a focus on the role of soil in habitat heterogeneity, which affects vegetation structure and plant diversity (Rodrigues *et al*.

2018). The value of phytosociological data increases over time as plant locations are well-documented and studies are repeated, capturing vegetation changes and assisting with interpretation (Konatowska and Rutkowski, 2019). Vegetation's complexity varies due to climatic conditions and topography (Raturi, 2012).

The health of the soil and the cycling of nutrients both depend heavily on the abundance of soil microbes (Chodak *et al*. 2015). The effects of root allelochemicals from invasive plants on soil's physical, chemical, and microbial composition are critical for understanding plant invasion mechanisms (Qu *et al*. 2021). Allelopathy, the phenomenon which modifies soil conditions through underground root exudates, thereby allowing invasive plants to outcompete and replace native vegetation (Callaway *et al*. 2000). Allelochemicals released from invasive plants can alter soil characteristics, impacting microbial diversity and composition (Puig *et al*. 2018). Invasive alien plants threaten native biodiversity and soil resources, thereby accelerating the environmental degradation (Rai, 2022). It has also been stated that success of invasive alien plants are influenced by soil nutrients, contributing to environmental degradation (Gao, 2021). Invasive alien plants negatively impact soil and ecosystem processes, causing environmental degradation through plant-soil-microbe interactions having a high influence on soil composition and competitiveness of native species community (Rai, 2022).

Invasive alien plant species

Invasive alien plant is defined by the International Union for Conservation of Nature and Natural Resources “as species that become established in natural or semi-natural ecosystems or habitats, acting as a change agent that threatens native biological diversity (IUCN, 2000)”. An invasive alien plant species is a “species that is not native to the ecosystem in question and whose introduction has had or will likely have negative effects on the economy, the environment, and human health”. An introduced species that tends to spread to an extent and harm the environment and people's quality of life is considered an invasive alien species (Ehrenfeld, 2010). Because invasive alien plant species and native species frequently coexist for an extended period of time, the superior competitive ability of invasive species gradually emerges as their population expands and densifies and as it adapts to their new environment (Richardson *et al*. 2000).

India is invaded by several invasive alien plant species, such as *Ageratum conyzoides* L., *Lantana camara* L., *Mikania micrantha* (L.) Kunth ex H.B.K. *and Chromolaena odorata* (L.) R.M. King & H. Rob. (Basumatary *et al.* 2021). Invasive plant species can negatively affect the native vegetation composition of a large area and their movement beyond natural boundaries alters the distribution of native biodiversity (Sharma *et al*. 2022). Invasive alien plant has seriously threatened the Indian subcontinent's ecosystems, including both terrestrial (forest and agricultural) and aquatic ecosystems, thereby affecting its normal functioning and disrupting the native vegetation (Rahel, 2002). In addition to the productivity of these disturbed ecosystems, there are financial losses associated with eradicating these invasive alien plant species and ecosystem restoration (Inderjit *et al*. 2005; Larson, 2007). Displacement of beneficial vegetation, disease spread, soil nutrient composition, and seed germination impact fisheries, agriculture, and water quality (Chaudhary *et al*. 2022). It is noted that invasive alien plants cause species extinction and endanger freshwater wetlands and aquatic environment, affecting Indian research and inland environments (Arya, 2021).

Invasive alien plants should be evaluated and prioritized for management based on their impacts, such as reduction in native diversity and changes to nutrient pools (Davis, 2009). Invasive alien plant species in India have caused adverse ecological, economic, and social impacts, especially in inadequately managed forests and cultivated areas (Dogra *et al*. 2009). The invasion of these alien plant species has significantly reduced the native diversity of flora and fauna. The changes to nutrient pools have also affected the ecological balance, leading to soil erosion and degradation. The economic impact of these invasive plants is also substantial, as they can cause damage to crops and affect agricultural productivity (Zenni *et al*. 2021). In addition, the social impact of invasive alien plants cannot be ignored, as these plants can cause health hazards for humans and animals alike. It is crucial that we take measures to control the spread of invasive alien plant species in India, through effective management strategies such as early detection and eradication, monitoring and surveillance programs, and public awareness campaigns. By doing so, we can protect our natural resources and ensure a sustainable future for generations to come. Native ecosystems have suffered significant harm in terms of their structure and functionality, as a result of plant invasions. Since invasive alien plants can release certain secondary metabolites or chemicals which can have an allelopathic effect on the germination of seeds and the growth of coexisting native plants, they are able to successfully invade specific environments (Wang *et al*. 2017)

According to the International Union for Conservation of Nature (IUCN) “India is a mega-diverse country with North East India as one of the biodiversity richest regions and lies in the Indo-Burma Region hotspots”. The state of Mizoram is located in the North-Eastern region of India and has an international boundary with Myanmar and Bangladesh. Mizoram is an integral component of Indo-Burma biodiversity hotspot with dense forests, diverse species of flora and fauna, and a rich diversity of medicinal plants. Mizoram plays an important role in biodiversity conservation and vegetation analysis.

Mechanisms of Plant Invasion and Novel Weapon Hypothesis:

Biological invasions have been known to cause biodiversity loss, impacting services and ecosystems in many regions of the world, and invasive species are growing in terms of diversity and distribution (Gallardo *et al*. 2019). The invasion pathway is a sequential process by which invasions occur through the use of an introduction vector wherin, non-native species are brought to new areas, leading to colonization. The introduced species is regarded as established if they thrive and reproduce within their non-native range. The species expands its range within the non-native region as the last stage of secondary spread (Sorte, 2016). Plant invaders alter ecosystem processes, facilitating invasive alien plants (Brandt *et al*. 2023). It has also been noted that invasive alien plants often outcompete native species due to greater tolerance in introduced habitats (Kuebbing and Nunez, 2015; Golivets and Wallin, 2018).

There are a number of theories linked with successful spread of invasive alien plants into introduced environment. Anthropogenic disturbances allow invasive alien plant species to bring along traits like prolific seed production, efficient dispersal, increased propagule mobility, and allelochemical properties. These traits are used by the invasive alien plants to establish themselves in new environments threatening the native biodiversity (Callaway and Aschehoug, 2000; Sakachep and Rai, 2021; Rai and Singh, 2021). It has been widely established now that invading plants often exhibit allelopathic activity. The "novel weapons hypothesis" (NWH) is demonstrated as a key factor in this development since it states that unusual invaders would succeed through release of distinctive biochemicals, or secondary metabolites, to their new territories (Callaway and Aschehoug, 2000). The NWH postulates that the invaders have chemicals that are allelopathic, defensive, or antimicrobial that native organisms have not yet adapted to and further this hypothesis considers that invasions are successful due to a lack of evolutionary relationships between native and invasive species in non-native ranges (Callaway *et al*. 2008; Vivanco *et al*. 2004). According to the NWH, invasive plant species are effective due to their ability to produce toxic biochemicals, such as allelopathic antimicrobial root exudates, that obstruct plant growth and soil microbial activity (Qu *et al*. 2021).

Molish (1937) proposed allelopathy as a mechanism of invasion for the first time. Allelopathy is the negative effect of one plant on another caused by the release of chemical compounds into the environment (Muller, 1969). “Allelopathy is the interaction between plants and microorganisms, which can exert either inhibitory or stimulatory effects”. “Allelochemical interaction is the process of regulating the production and release of allelochemicals by abiotic and biotic components of the ecosystem. It also plays an important role in soil nutrient dynamics, as plants make allelochemicals available through residues, litter decomposition, and degradation” (Rice, 1984). Numerous studies have shown that allelopathy may be a factor in the dominance of exotic species in invasive plant communities (Abdul-Wahab and Rice, 1967; Vaughn and Berhow, 1999; Ridenour and Callaway, 2001; Qu *et al*. 2021). Henceforth, allelopathy i.e., the release of phytotoxins by plants, has been proposed as an alternative theory for the success of many invasive plants, threatening to change communities and ecosystems (Uddin and Robinson, 2018)

Allelopathic effects significantly reduce neighboring plants' performance in terms of growth and soil nutrient availability (Zhang *et al*. 2019; 2020). In this context, Hale and Kalisz (2012) have observed that allelopathic properties in plants can kill microbes in soil and disrupts plant-microbe mutualism associated with their normal growth and development (Parniske, 2008; Soudzilovskaia *et al*. 2020). A potential direct method for investigating allelopathic interactions is demonstrated through bioassay experiments (Inderjit and Nilsen, 2003). These tests involve making aqueous extracts of the shoot and root material and observing how they affect the intended species' germination and early seedling development. Allelochemicals may also linger in soils, leaving a trace of the previous inhabitant. Research evidence mostly reveals that plant invasion-mediated allelopathy supports or validates the concept of the novel weapon hypothesis (Del Fabbro *et al*. 2014). Allelochemicals such as fatty acids, phenols, flavonoids and terpenoids are metabolites secreted by some plant species that prevent neighboring vegetation from reproducing, growing, and developing (Hassanuddin, 2021). Rainfall leachates, plant residue decomposition, root exudation, and volatilization from living plant components together contribute to the discharge of allelochemicals into nearby surroundings and plant rhizosphere soil (Kato-Noguchi *et al*. 2021). Invasive alien plants may increase the intensity or extent of production of allelochemic substances in the novel introduced to increase the capacity of plant invaders to compete with local native plants (Yuan *et al*. 2013,2021).

1.1 SCOPE OF STUDY

During the past decades, it was considered that the tough geographical terrains (e.g., biodiversity-rich mountain ecosystems) are resistant to invasive alien plants, however, complex ecological mechanisms linked with these plants lead to their success in such landscapes. There exists scanty research on the invasion ecology of NE India, especially, Mizoram, an integral part of the Indo-Burma hotspot. The novel weapons hypothesis holds that some exotics transform from native to invasive by exuding biochemicals that are highly inhibitory (allelopathic) to native plants or soil microbes in invaded communities, but relatively ineffective against natural neighbors that had adapted over time. Allelochemicals, the secretions of plants, are the chemical substances that can affect the growth, behavior, and population biology of other living beings, including chemical substances between plants, as well as plants and animals. Allelopathy also plays an important role in soil nutrient dynamics. Therefore, using the setting of a novel weapon hypothesis, we can directly test the potential effects of allelopathy by comparing the effects of a biochemical released from an invasive alien plant on native ones.

In light of the above state of art knowledge the present study will be based on vegetation analysis to study the impacts of invasive species on native species (plant-plant interaction) and soil attributes (plant-soil interactions), especially in the context of chemical ecology/allelopathy. Identifying the mechanisms which help the highly noxious plant invaders to succeed is important for conceptual issues in ecology and for ecosystem management.

Therefore, the present study aimed to ecologically investigate impacts of invasive alien plant species on vegetation and their soil allelopathic interactions in Aizawl, Mizoram, India with the following objectives -

1.2 OBJECTIVES

1) To perform the vegetation analysis of certain invasive alien/native plant species at study sites, along the disturbance gradient.

2) To study the plant-soil interactions of invasive alien plant species, in context of nutrients/chemicals

3) To device the sustainable management options for invasive alien plant species.

CHAPTER- 2

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

2.1 Effect of invasive alien plant species on native vegetation

Invasive alien plant species have become a major threat of the century and continue to threaten biodiversity and ecosystems as a result of increased global connectivity and anthropogenic disturbances (Chong *et al.* 2021; Seebens *et al.* 2021). A species is considered to be invasive if it has established itself and spread outside its distribution area, endangering ecosystems, habitats, and native species. Interestingly, native species can also become invasive due to altered environmental conditions such as grazing, cyclones, nutrient cycles, or infestation by invasive alien plant species (Colautti *et al.* 2004). Ornamental plants have escaped from gardens to become invasive and thus their horticultural trade/transport continues to be a major driver of invasive alien plant invasions, even in protected areas (Hanspach *et al*. 2008; Foxcroft *et al*. 20013; van Kleunen *et al*. 2018). There is a wide range of potential effects that invasive alien plants may have on native plant species, and these effects have been measured in various ways, allowing for a wide range of interpretations of their scope and consequences There are many possible impacts of invasive alien plants on native plants, and there are numerous ways to interpret the extent and implications of these effects (Kumschick *et al.* 2015). Invasive alien plants species are more tolerant and possess unique biological traits, offering competitive advantages over native species in various environmental conditions (Sundarapandian and Subashree, 2017; Lone *et al*. 2019). The widespread spread of these plants can be attributed to various performance-related factors such as physiology, growth rates, shoot allocation, leaf-area allocation, and size (Stefanowicz *et al.* 2018).

Ecological functioning and species abundance are at risk due to ecological imbalances brought about by introduced species (Sakachep and Rai, 2021). After habitat fragmentation, invasive alien plant are considered to be the second-greatest threat to biodiversity and have the potential to enforce local extinctions (Kohli *et al.* 2004;Gaertner *et al.* 2009; Hejda *et al.* 2009; Vila *et al.* 2011; Powell *et al.* 2011; Bhatt *et al.* 2011). Besides replacing native vegetation, invasive plants also change the ecology of a given habitat by changing the nutrient cycle and soil pH (Drenovsky *et al.* 2007). Invasive alien species break down biogeographic realms, affect native species richness and abundance, increase the risk of native species extinction, affect the genetic composition of native populations, alter phylogenetic diversity across communities, and modify trophic networks (Pysek *et al.* 2020). Many invasive alien species also change ecosystem functioning and the delivery of ecosystem services by altering nutrient and contaminant cycling, hydrology, habitat structure, and disturbance regimes (Pysek *et al.* 2020; Rai 2022; Lázaro-Lobo *et al.* 2023). These adverse influences of invasive alien plants on biodiversity and ecosystem impacts are accelerating and are predicted to worsen further (Backburn and Ricciardi, 2019; Pysek *et al.* 2020). Impacts of invasive alien plants vary greatly across species, regions, and ecosystems (Blackburn *et al.* 2014) and depend on the abundance of the alien species and their trophic levels relative to those of affected native species (Hejda *et al*, 2009; Bradley *et al.* 2019). Invasive alien plants disrupt ecosystems by increasing their persistence or distribution and suppressing native species through reinforcing feedback, leading to regime shifts that are difficult or impossible to reverse (Gaertner *et al.* 2014).

Invasive alien plants exert profound impacts on soil-nutrient cycling as demonstrated by invasive trees and shrubs in forests and by herbaceous invaders in wetlands which is in fact mediated by modifying the composition of soil seed banks (Gioria *et al.* 2014) changing fire regimes (Shackleton *et al.* 2018) and altering microbial communities (Bowen *et al.* 2017). Invasive macrophytes of wetlands pose a significant threat to freshwater ecosystems by decreasing depth and disrupting their structure and function (Shah and Reshi, 2011). Invasive alien plants are also reported to alter the soil nutrient pools and processes in ecosystems that they invade by altering the quality and quantity of litter inputs (Sharma and Raghubanshi, 2011). Invasive alien plants pose a serious threat to biodiversity and ecosystem services, negatively impacting economic growth, water quality, habitat fragmentation, and the spread of diseases (Raghubanshi and Tripathi, 2009; Mack and Smith, 2011; Chamier *et al*. 2012; Wijeratne, 2015). Invasive alien plants species have the potential to alter the native ecosystems, potentially declining diversity at small spatial scales and improving it at larger regional scales (Giejsztowt *et al.* 2020). By altering the diversity of native plant species, invasive alien plants can adversely impact the stability of ecosystems (Wang *et al.* 2021).

2.2 Mechanism of invasive alien plants

Many theories have been proposed to explain and predict biological invasions, but the extent to which these ideas are applicable across taxonomic categories and situations remains uncertain due to a lack of consistent assessment (Davis *et al.* 2000). Various hypotheses suggest the successful invasion of exotic plants and these include 'Enemy Release Hypothesis' i.e., escape from 'Natural Enemies' which states that natural enemies that regulate the population growth are longer affecting the invasive alien plants (Darwin, 1859; Williams, 1954; Elton, 1958). Further, 'Empty niche hypothesis' (Elton, 1958), 'Species richness hypothesis' (MacArthur, 1970), 'Disturbance hypothesis' (Gray, 1879; Baker, 1974), 'Propagule pressure hypothesis' (Williamson, 1996; Lonsdale, 1999), 'Evolution of Increased Competitive Ability Hypothesis' (Blossey *et al.* 1995), 'the evolution of invasiveness' (Lee, 2002; Stockwell *et al.* 2003), 'Diversity Resistance Hypothesis' (Kennedy *et al.* 2002), 'Novel weapon hypothesis' (Callaway and Aschehoug, 2000), 'Enemy Release Hypothesis' (ERH) are widely accepted in invasion biology, often used to explain the success of exotic species in their non-native range (Keane *et al.* 2002).

Several experiments have confirmed that allelopathy provides a means of widespread colonization facilitating their successful invasion (Callaway *et al.* 2000). The Novel Weapons Hypothesis (NWH) suggests that some exotic plant species that have evolved from native plants to invasive plants emit highly inhibitory biochemical or secondary metabolites into invaded communities. However, these secondary metabolites are ineffective against the already existing naturally adapted neighboring plants. These biochemicals act as a defense mechanism for exotic plants, allowing them to outcompete and dominate the native species. However, natural neighboring plants have developed resistance or tolerance to these chemicals over time, enabling them to coexist with the invasive species without being negatively affected (Rabotnov, 1982; Mallik and Pellisier, 2000). Rabotnov's hypothesis of 1982 suggests allelopathic interactions in ecosystems, where co-existing plants adapt to chemical releases from other neighboring species. Exotic plant species can introduce harmful chemicals, affecting native communities (Rabotnov, 1982; Callaway and Aschehoug, 2000). The "novel weapons hypothesis" is supported by comparisons of allelopathy linked to invasive species in native and introduced ranges (Kim and Lee, 2011; Inderjit *et al.* 2011).

Several studies indicated that interactions between exotic plants and soil communities, including the impact and fate of allelochemicals produced by the invader, influence success of invasive alien plants (Inderjit *et al.* 2011; Lorenzo *et al.* 2012). Plant invaders with novel weapons gain an advantage due to regional differences in coevolutionary trajectories (Thompson, 1999). Soil microbiota significantly influences the structure and dynamics of plant communities, and this can be remarkably influenced by plant invasions (Elgersma and Ehrenfeld, 2011; Lorenzo *et al.* 2010, 2012). Biochemicals produced by invasive plants that interact with local plants or soil biota are referred to as new or novel weapons and these invasive plants can have several negative consequences on the composition and ecology of soil biota which can be harmful to native plants and have shown to alter plant-soil-microbe interactions (Zuppinger *et al.* 2016; Chen *et al.* 2017).

The NWH also suggests that mixing of biota from different regions could disrupt plant co-evolution, potentially leading to species coexistence and increased community diversity (Callaway and Ridenour, 2004; Vivanco *et al.* 2004; Rai, 2013). One such example is *Centaurea maculosa*, which appears to have a "novel weapon" in the form of (±)- catechin, which it exudates from its roots/rhizospheres. (Bais *et al.* 2003; Weir *et al.* 2003; Blair *et al.* 2005; Ridenour *et al.* 2008). Research indicates that unique biochemistry-based geographic co-evolutionary trajectories may impact plant coexistence and community development. (Thompson, 1999). Biogeographic studies on the allelopathic effects of invasive plants in natural and invaded communities may provide new evidence for allelopathy's role in shaping community dynamics (Baldwin, 2003; Fitter, 2003).

2.3 Allelopathy and Allelochemicals

Allelopathy, derived from the Greek compounds ‘allelo’ and ‘pathy’, refers to the mutual harm or suffering caused by plants. The term was coined by Austrian scientist Hans Molisch in his 1937 book entitled ‘Der Einfluss einer Pflanze auf die andere – Allelopathie (The Effect of Plants on Each Other)’ (Willis, 2010). Allelopathy is a traditional definition that includes ‘plant-plant chemical interactions, including inhibitory and stimulatory effects involving microorganisms in the plant’ (Rice, 1984). Allelopathy can also be defined as the inhibition of plant growth caused by the release of toxic compounds by other plant species (Lambers *et al.* 2008). It is also known as chemical compounds that are released by plants or microorganisms that can have direct or indirect stimulatory or inhibitory effects on the environment, which are mediated by the environment (Lotina-Hennsen *et al.* 2006). It can also be stated that allelopathy is the direct or indirect effect of plants on each other through chemical release, playing a crucial role in shaping the various ecosystems (Singh *et al.* 2001). Allelopathy has potential applications in various fields such as crop production, forest tending, plant protection, and biological control (Yang *et al.* 2007). Allelopathy is an important non-resource interaction in terrestrial plant communities that may influence the plant invasion ecology (Svensson *et al.* 2013).

Allelopathy involves three key features i.e., the interaction between plants, the interaction between secondary metabolites of plants, and the use of allelochemicals to influence plant growth and development (Wang *et al.* 2016; Mushtaq *et al.* 2020; Kalisz *et al.* 2021; Khamare *et al.* 2022). Allelopathy research focuses on understanding the mechanism by which invasive alien plants plants release allelochemicals to potentially inhibit the growth of native plants and crops (Kong, 1999; Hierro and Callaway, 2021; Mahé *et al*. 2022).

Allelochemicals are secondary metabolites produced by plants or microbes that primarily affect each other through primary metabolism (Levin, 1976). Allelochemicals are a diverse group of compounds including ‘fatty acids, alcohols, aldehydes, ketones, lactones, water-soluble organic acids, benzoic acid, coumarin, flavonoids, tannins, terpenoids, steroids, amino acids, peptides, and nucleotides and phenolic acids and terpenoid compounds' being the most prominent (Macías *et al.* 2019). Rice (1974) identified various plants, including roots, stems, leaves, flowers, pollens, fruits, and seeds, as potential sources of allelochemicals, with leaves being the most significant (Sisodia and Siddiqui, 2010). Understanding plant chemical constituents is essential for synthesizing complex substances, and phytochemical screening for various plants has been reported (Siddiqui *et al.* 2009). The phytochemical composition of invasive alien plants, particularly above-ground biomass, has been found to exhibit allelopathic potential, potentially affecting the diversity of native plants (Batish *et al*. 2002; Negi *et al.* 2016).

Allelochemicals cause plants to experience oxidative stress, leading to tissue damage and impaired biological function when concentration exceeds normal (Wardani *et al.* 2018). Allelochemicals can enhance the competitive ability of invaders against native plants, potentially maintaining or even increasing the production of allelopathic compounds into a new range (Yuan *et al.* 2021). Among the identified allelochemicals, phenolic compounds are crucial allelochemicals found in plant organs, studied for chemical, biological, agricultural, and medical purposes (Lupini *et al*. 2016; Yazaki *et al.* 2017; Aci *et al.* 2022). Their phytotoxicity depends on the types and quantity released by the plants and may vary depending on dosage or concentrations (Baziramakenga *et al.* 1994; Li *et al.* 2010; Al Harun *et al.* 2015).

Allelopathy of top obnoxious invasive alien plants such as *A. conyzoides*, a weed frequently seen in open areas and cultivation fields has shown that its leaf extracts can reduce plant growth, height, weight, and chlorophyll content in soybeans when present in high concentrations (Wardani *et al.* 2018; Singh, 2021) and the same has been observed in *Lactuca sativa* (Syngkli *et al.* 2022). *C. odorata* has shown inhibitory effects on the seed germination and seedling growth of selected food crops (Otusanya *et al.* 2015; Muzzo *et al.* 2018; Hasnauddin, 2021). Allelopathic potential effects of *L. camara* have been tested and shown to suppress the growth and germination of a food crop i.e., *L. sativa* (Ambika *et al.* 2012; Nongtri *et al.* 2022). In the case of *M. micrantha*, while conducting a pot bioassay it has been observed that they have a tendency to inhibit the growth and germination of *L. sativa* and also show negative allelopathic effects on the plant (Ma *et al.* 2021; Syngkli *et al.* 2022).

The invasive alien plants threaten the native biodiversity at global, regional, and local scale which is discussed in forthcoming sections for holistic overview and state of art knowledge.

2.4 Threats of Invasive Alien Plant Species: Global Scenario

Invasive species are widely recognized as serious global threat to biodiversity just after habitat fragmentation (Gaertner *et al.* 2009; Ni *et al.* 2021). In addition, human activities have altered global plant distribution mediated through influence of invasive alien plants' spread guided by multiple mechanisms (Kueffer, 2017). Climate change is facilitating the spread of invasive alien plants, leading to significant and irreversible native species loss (Myers, 1993; Tilman, 1999; Ziska, 2003; Hulme 2003, 2009; Walther *et al.* 2009; Tripathi *et al*. 2022). Recent research has focused on assessing the potential of alien plant species to become invasive in response to the on-going climate change (Roger *et al.* 2015; Fortini and Schubert, 2017; Ray *et al.* 2019). Climate change has a global impact on ecosystems and species, influencing the physiology, phenology, and phytosociology or distribution of plants (Walther, 2010). Therefore, it is essential to evaluate the potential for the spread of invasive alien plants in biogeographic areas, especially in global biodiversity hotspots (Bellard *et al.* 2014; Ray *et al.* 2019).

Numerous plant species have been introduced globally to biogeographic areas to which they are not native (van Kleunen *et al.* 2015). In due course of time these introduced plants have naturalized and become invasive to displace native plants and hence endangering native biodiversity and interfering with ecosystem processes and services to perturb ecological economics (Vila *et al.* 2011). In this respect, it has been mentioned that the primary cause of plants invasion is anthropogenic factors (Rai 2012, 2015). Several nations like China have experienced a significant impact from the invasion of alien plant species (Feng, 2022). The introduction of alien plants occurs mostly in two ways i.e., either unintentionally or deliberately. For instance, *Amaranthus retroflexus* and *Cannabis sativa* were manually introduced in China with the intention of growing them as edible crops or vegetables, however, later these introduced plants were transformed into hazardous weeds (Chengxu *et al*. 2011).

Further, *Eichhornia crassipes* was initially introduced as forage feed but soon became invasive and widely recognized as global threat to aquatic biodiversity (Ayanda *et al.* 2020). *Solidago canadensis and L. camara* were formerly grown as ornamental for their beautiful flowers while medicinal plants, such as *Mikania micrantha* H.B.K. and *Saponaria officinalis* which were introduced for their medicinal properties have now been classified as harmful weeds (Li *et al.* 2002, Zhao, 2003). *Acacia mangium*, a well-known invasive alien plant in the Amazon, negatively affects the water quality of introduced region, thereby significantly impacting the region's economy, environment, and human well-being (Souza *et al*. 2018).

The invasion of invasive alien plants poses major socioeconomic, environmental, and ecological challenges and threatens human health, the socio-economy, and global biodiversity (Rai and Singh, 2020; Iqbal *et al.* 2021; Yang *et al.* 2021). According to recent observations, it has been found that global invasion ecology has been mainly focused indeveloped countries whereas, in contrast, the study on plant invasion has been largely underreported in tropical countries (Pysek *et al.* 2008; Duboscq-Carra *et al.* 2021). This can cause significant harm to valued biodiversity of tropical ecosystems (Chiu *et al.* 2023). Moreover, invasive alien plants causes significant economic losses and endangers biodiversity, particularly due to climate change (Yang *et al.* 2022). Invasive alien plants impact cosystem functions and socioeconomic conditions, with global factors like climate change and human needs significantly impacting biodiversity and the spread of plant invaders (Rai & Singh, 2020; Manzoor *et al.* 2020; Sharma *et al.* 2022).

2.5 Threats of Invasive alien plants: Indian Scenario

According to the World Conservation Monitoring Centre, India is home to 15000 angiosperm plants, 4900 of which are native, making up 8% of all recognized plant species worldwide. India, a megadiverse country, faces species invasions due to rapid globalization and increasing trade and travel, with around 40% of its flora considered to be alien species (Arya *et al.* 2021). The Indian forest consists of incredibly resilient invasive alien plants from a wide range of families, including Mimosacceae, Asteraceae, Amaranthaceae, Papilionaceae, Solanaceae, and Convolvulaceae (Reddy, 2008; Padalia *et al*. 2014; Mushtaq *et al.* 2019). In India, the invasion of alien plants is plagued with ecological, economic, and social consequences (Bhatt *et al.* 2011). In this respect, Kimothi *et al.* (2010) observed that India is facing a significant threat from various terrestrial and aquatic exotic species such as *Cytisus scoparius* L., *C. odorata* King & H. Rob., *E.adenophorum* (Spreng.) King & H. Rob., *M. micrantha* Kunth, *Mimosa invisa*, *Parthenium hysterophorus.* and *Prosopis juliflora* and aquatic exotics like *E. crassipes* and *Pistia stratiotes* (Murali and Setty 2001; Negi *et al.* 2019). A study in tropical rainforests of the Western Ghats in India reports that *C. odorata* and *L. camara* had invaded the understorey and *Maesopsis eminii*, a common plant used as shade tree in coffee plantations has invaded substantial areas of Anamalai Hills underlying in Western Ghats (Joshi *et al.* 2015). This has led to the replacement of native forests and palatable grasses, which are essential for herbivorous animals. The negative impacts of invasive alien plants on forest ecosystems are alarming and requires urgent attention. (dogrNegi *et al*. 2019; Joshi, 2022).

Invasive alien plants in India cause ecological, economic, and social impacts, primarily in unattended forests and cultivated areas (Dogra *et al*. 2009). Native biodiversity in the Shivalik hills of Himachal Pradesh is being adversely influenced by invasive weeds from India, including *A. conyzoides, L.camara, and P. hysterophorus* (Kohli *et al.* 2009; Dogra *et al.* 2009). In recent decades, invasive alien plants, such as *L. camara* negatively impacted forest ecosystems in the Himalayan foothills, particularly the Dudhwa, Corbett, and Rajaji National Parks, and have also invaded the wastelands and forest areas of Western Ghats and other ecosystems, especially in peninsular and northeast India (Murali and Setty, 2001; Negi *et al*. 2019).

The decline of valuable indigenous medicinal plants in Himachal Pradesh's Shivaliks is attributed to the invasion of *A. conyzoides* (Dogra, 2009). Invasive alien plant invasion has caused herb layer instability, disrupted reserve parks, and loss of vegetation in wildlife sanctuaries like Jim Corbett Tiger Reserve, Veerapuli Forest Reserve, and Mudumalai Wildlife Sanctuary (Kannan and Shaanker, 2013*)*. Invasive alien plants like *M. micrantha, C. odorata,* and *L. camara* have been noted to reduce plant species richness by adversely impacting the seedling growth in the Western Ghats of India (Mangla and Callaway 2008). These invasive alien plants also caused significant loss to species diversity in the Garhwal Himalayas Uttarakhand, India (Sharma and Raghubanshi, 2012). A survey in Nauradehi Wildlife Sanctuary, Central India, found eleven invasive alien plants, including *P. hysterophorus, L. camara, A. conyzoides*, and *A. leptopus*, which interfere with agriculture and forest growth due to their tolerance to harsh conditions driven by climate change (Kumar *et al.* 2021).

C. odorata is commonly found in the Western Ghats, eastern Himalayas, Eastern Ghats, and northeast India, indicating suitability for these regions. However, the absence in semi-arid regions suggests negative influences (McFadyen, 2002; Panda *et al.* 2019; Rai and Singh, 2024). Invasive alien plants including *A. mexicana, A.adenophora, C. tora, Rubus neivus,* and *Sapium sebiferum* persist and proliferative in a larger area of western Himalayan regions and *A. conyzoides, L. camara* and *Parthenium hysterophorous* are the established invasive alien species that have flourished and effecting the biodiversity from Western to eastern Himalayan regions of India (Gupta *et al*. 2020). The aforementioned invasive alien plants have a wide variety of effects on various classes of diversity, richness, crop fields, loss of nutrient components, and, to a greater extent, environmental services (Kohli *et al.* 2006). It is claimed that *L. camara* encroaches on a large amount of land, especially in the lower regions of the Himalayan foothill forests (Kohli *et al.* 2006), where it effectively replaces the subsurface layer of forest vegetation and prevents tree growth and normal development (Negi *et al.* 2013). In this Himalayan foothill region, *P. hysterophorus* is identified as one of the hazardous invasive alien plants that pose severe threat to ecology and socio-economy (Kohli *et al*. 2006; Dobhal *et al.* 2011).

According to a study by Chaudhary *et al.* (2022) in the Kailash region of India, invasive alien plants such as *A. conyzoides, L. camara*, and *A. adenophora* were the dominant and well-known species within the region and have been shown to have an impact on tree regeneration, rangeland forage production, native forage species, non-timber forest product habitat, and crop production costs (Chaudhary *et al.* 2022). The most frequently cited invasive alien plants species in Uttarakhand are *A. adenophora, L. camara,* and *A. conyzoides,* which pose a serious threat to native plant diversity and have been shown to suppress the growth of seedlings native tree diversity (Fu *et al.* 2018; Shrestha *et al.* 2019). The western ghats of India have seen noticeable disruptions in their vegetation structure due to the invasion of *L. camara* (Kannan *et al.* 2016; Soumya *et al.* 2019). A study on the Mandsour region of Madhya Pradesh shows the impact of *L. camara* on vegetation growth, species distribution, and natural regeneration (Pancholi *et al*. 2023). Apart from altering the vegetation of a region invasive alien plants like *Polygonum cuspidatum* and *L.camara* can influence the physico-chemical and biological characteristics of soil (Min and Suseela 2020; Ni *et al.* 2020). A case study on the Mirzapur region of India by Kumar *et al*. (2023) reveals that *L. camara* and *Hyptis suaveolene* negatively affects the soil fertility and crop production of surrounding areas since they are both found in agricultural lands and forest areas. Apart from these human allergy, mobility, toxicity and loss of diversity have also been observed as negative impacts of invasive alien plants (Potgieter *et al*. 2017; Pyšek *et al.* 2020).

2.6 Threat of IAPS: North-East Indian scenario

The Eastern Himalayas and Indo-Burma hotspots are crucial for India's biodiversity, containing a significant portion of its flora and fauna (Chakraborty *et al.* 2012). The Indian Himalayan Region (IHR), one of the 36 worldwide hotspots for biodiversity, are under threat due to their immense and distinctive biodiversity (Palni and Rawal, 2013; Sharma *et al.* 2016). An important contributor to this hotspot is the IHR, whose products and ecosystem services support millions of people both inside and outside of its territorial boundaries (Singh, 2014). The Indian National Action Plan on Climate Change (NAPCC) states that the Himalayan area is essential to the country's ecological security and also emphasizes how extremely susceptible the area is to both human activity and natural disruptions like biological invasion and climate change.

The NAPCC highlights the vulnerability of IHR to natural disturbances like biological invasion and climate change, as well as human activities (Adhikari *et al.*

2015; Negi *et al*. 2019). The IHR is reported with around 297 species of alien naturalized plants from 65 families (Sengupta and Dash, 2020). The climate change effects observed in IHR are intimately linked with the spread and effects of invasive alien plants such as *L. camara, C. odorata*, *A. houstonianum*etc (Lamsal *et al*. 2018; Shrestha *et al*. 2018).

The IHR alone comprises 190 invasive alien plants from various habitats (Sekar, 2012). Invasive species such as *L.camara*, *A.adenophora*, *P.hysterophorus*, *C.odorata*, and *A.conyzoides* have expanded across a larger area and have been reported from most states of the IHR (Pathak *et al*. 2019). Northeast India is a biodiversity rich region that underlie in the Indo-Burma hotspot, however, faced with the threat of invasive alien plants (Rai, 2012; Rai and Singh, 2021). Invasive alien plants such as *L.camara, A.adenophora, P.hysterophorus, A.conyzoides, R.niveus, S.sebiferm, C.tora, A.mexicana*, and *A.cotula*, have been reported from Indian Himalayan states, causing significant threats to the region's rich biodiversity and ecosystem functioning, affecting soil structure and nutrient content (Gupta *et al*. 2020;Sakachep and Rai, 2021). In this context, Ray *et al*. (2019) noted that *A.conyzoides* alone covers a total of 3977 km^2 in Assam, Meghalaya, and Mizoram, accounting for 1.2% of the entire geographical area of India's Northeast region and this is likely to increase with on-going predicted trends of future climate change. Climate and biological factors influence the altitudinal spread of invasive alien plants in mountainous environments and understanding their distribution patterns can help predict their likely distribution, especially in the context of climate change (Haider *et al*. 2010). The phyto-sociologically dominant invasive weeds found in Aizawl's urban forest were *L.camara*, *M.micrantha*, and *A.conizoides*, and they showed significantly different distribution pattern under disturbance regimes (Rai, 2015). In a study on the ecological assessment of Mizoram, a total of 163 invasive alien plants were noted with the maximum species belonging to the Asteraceae family including invasive species like *A.adenophora, C. odorata, M .micrantha*, and *A. conyzoides* (Sengupta and Dash 2020). An ecological study showed the occurrence of a total of 207 invasive alien plants in Murlen and Phawngpui National Parks of Mizoram with Asteraceae family being the dominant (Sengupta and Dash, 2023). Invasive alien plants such as *A.conyzoides*, *M.micrantha*, *C.odorata*, and *L.camara* have been recorded from the Halaikandi District of Assam and are perceived as aggressive and noxious weeds (Sakachep and Rai, 2021). The study of *Tithonia diversifolia's* impact on phytosociology and vegetation in Mizoram found that it has a competitive advantage over other invaders in the area (Vanlalruati and Rai, 2021; Rai *et al.* 2023).

In light of imminent threats at global, national, and regional scales, control and containment of invasive alien plants is necessary to maintain environmental sustainability. Several plant invaders such as *L. camara* has been equipped with invasive tendency however also act as the potential biomonitor for suspended particle matter as demonstrated in the urban forest of Mizoram (Rai and Singh, 2015). To this end, Rai and Kim (2020) also mentioned that plants like *Arundo donax* and *Eichhornia crassipes* are useful tools for pollution phytoremediation in the aquatic systems. The anti-microbial properties of *A. adenophora* and *C. odorata* from the forest of Mizoram were studied and found to be beneficial resources for medicinal as well as antifungal and antibacterial materials (Sengupta *et al.* 2023). Several studies attempted to use the biomass of invasive alien plants for environmental pollution mitigation (Prabakaran *et al.* 2019; Rai and Kim, 2020; Rai and Singh, 2020), ethno-medicine (Rai and Lalramnghinghlova, 2011; Rai, 2012), bioenergy (Liao *et al*. 2007; Rai *et al.* 2018; Rai and Kim, 2020; Rai, 2022; Rai *et al.* 2023), agro-ecosystem productivity or soil fertility (Gomes *et al*. 2018; Shrestha *et al.* 2019; Rai and Singh, 2020), however, their large-scale use is debatable.

CHAPTER- 3

METHODOLOGY

3. METHODOLOGY

STUDY AREA

The study area selected was Aizawl district, Mizoram, Northeast India. Mizoram has a total geographical area of 21,087 km^2 and falls between 21°56'N to 24°31'N latitude and 92°16'E to 93°26'E longitude (Lallianthanga *et al.* 2018). Aizawl is the capital of Mizoram and is located north of the Tropic of Cancer in the northern part of Mizoram. It is situated on a ridge 1,132 meters (3715 ft) above sea level, with Tlawng river valley to its west and the Tuirial river valley to its east and has a mild, sub-tropical climate due to its location and elevation. Under the Köppen climate classification, Aizawl features a humid subtropical climate (Cwa) with heavy rainfall. In the summer the temperature ranges from 20–30 °C (68–86 °F), and in the winter 11–21 °C (52–70 °F). According to the State Forest Report 2019, Aizawl district has a total geographical area of 3,576 sq km out of which 30.30 sq km is covered by very dense forest,1071.37 sq km by moderately dense forest and open forest covers a total of 1977.24sq km.

The rationale behind selecting the study sites along the disturbance gradient was on the basis of their proximity to the various anthropogenic disturbances.

- Highly disturbed/invaded sites

The site selected is Maubawk area and it is in close proximity to roads, habitation, and frequent anthropogenic disturbances. The light intensity measured using a lux meter at this site was 3758±1093.061LUX.

- Mildly disturbed sites

The site selected is Chawlhhmun area and is located in close proximity to home gardens and habitats which are not frequently disturbed by heavy anthropogenic activities. The light intensity measured using a lux meter at this site was 1017.60±243.47 LUX.

- Undisturbed sites with negligible invasion

The site selected is Mission Vengthlang area and was most distant from road network as compared to the other two sites. It is surrounded by a thick forested area with negligible invasion. The light intensity measured using a lux meter at this site is 414.87±191.88 LUX.

The light intensity was recorded highest at the disturbed site when compared with moderately disturbed and undisturbed sites. The distinct pattern in light intensity values along the disturbance gradients reflect the larger canopy gaps at the disturbed site which allow more penetration of photosynthetically active radiation. In this respect, the detailed study on canopy openness or gaps is described in forthcoming chapters.

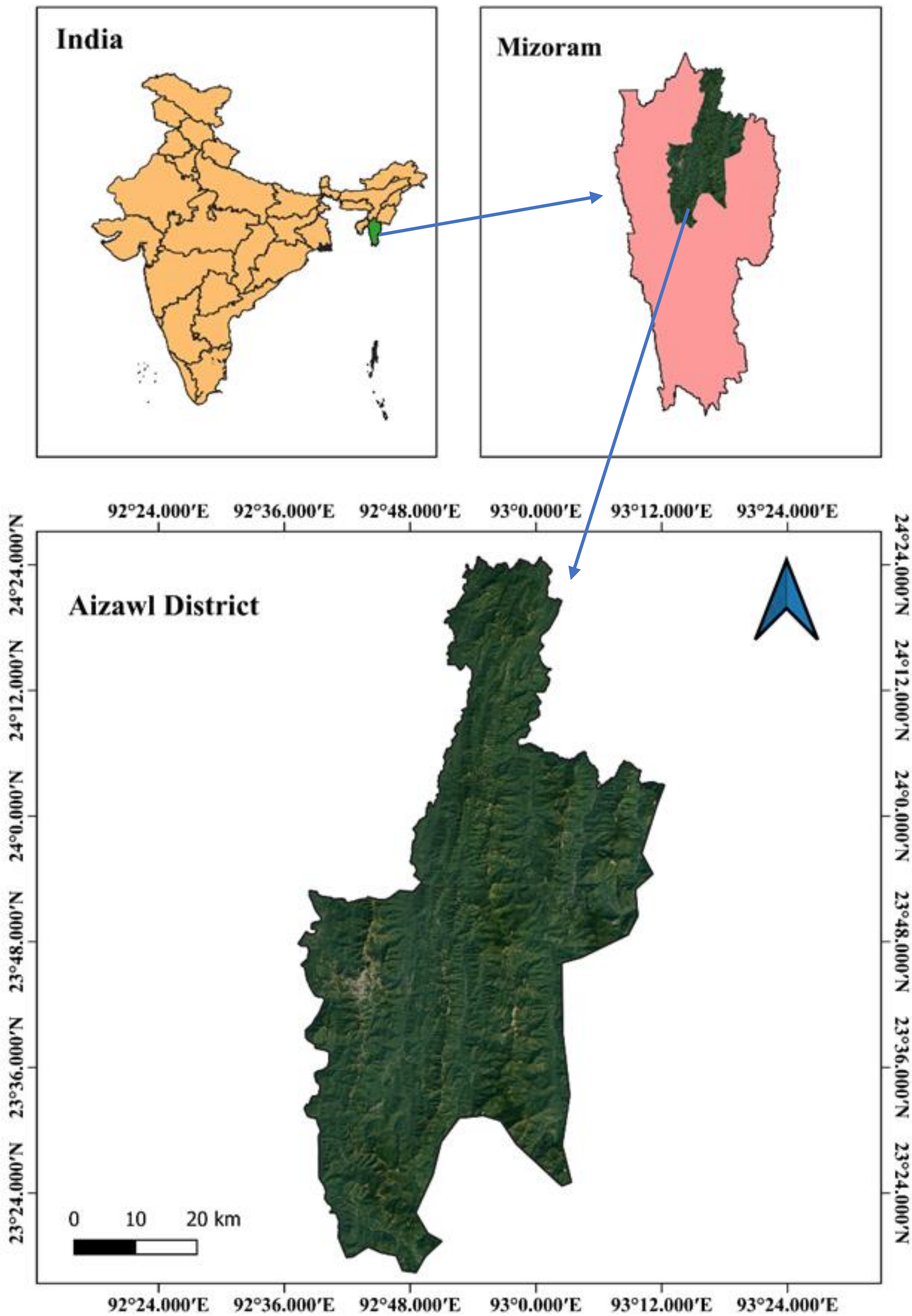
Rationale for site selection

For sampling, different sites were chosen based on reconnaissance and field observations to represent a range of conditions and ranked based on the intensity of disturbances experienced, including both natural and anthropogenic disturbances. The site with maximum distance from road, agricultural land, habitation, or market was given the impact factor 1. Impact factors for other sites were calculated as ratios of the distance of one site to the distance of the other sites, e.g., distance of the undisturbed site from the road was maximum at 1430m, the distance of the Moderately disturbed site from the road was 582.60 m. The impact of the road for the undisturbed site was 1, and that for the moderately disturbed site was 2.45 (582.60/1430). Similarly, grazing was done by sapling density obtained from phytosociological data. Other impacts were determined through visual estimation (Sagar *et al.* 2003).

Table 1 Disturbance Regime at the disturbed, moderately disturbed, and undisturbed study sites

Source of impact	Relative impact		
	Disturbed site	**Moderately disturbed**	**Undisturbed site**
Road	4.95	2.45	1
Agricultural land	1	2	3
Habitation	3	2	1
Market	3	2	1
Grazing	2	1	3
Soil erosion	3	1	2
Rockiness	1	3	2

Note- Relative impact ranges from 1-3, with 1 being the highest impact.


India
Mizoram
Aizawl District
92°24.000′E
92°36.000′E
92°48.000′E
93°0.000′E
93°12.000′E
93°24.000′E
24°24.000′N
24°12.000′N
24°0.000′N
23°48.000′N
23°36.000′N
23°24.000′N
0
10
20 km

3.1. Plant-plant interactions

The interactions between invasive and native plant species in disturbed, moderately disturbed, and undisturbed areas have been studied through methodologies prescribed for vegetation analysis (Misra, 1968). In this context, quantitative/phytosociological parameters such as the percentage, frequency, density, and abundance of each species present in quadrats have been recorded and analyzed as per the methods of Misra (1968) and Kershaw (1973).

(a) Density: 'Density is an expression of the numerical strength of species where the total number of individuals of each species in all the quadrats is divided by the total number of quadrats studied'.

$$\text{'Density} = \frac{\text{Total no of individuals of a species in all quadrats}}{\text{Total no.of quadrats studied}}\text{'}$$

(b) Frequency (%): 'This term refers to the degree of dispersion of individual species in an area and is usually expressed in terms of percentage occurrence. It will be studied by sampling the study area at several places at random and recording the name of the species that occurred in each sampling unit'.

$$\text{'Frequency (\%)} = \frac{\text{No.of quadrats in which species occurred}}{\text{No.of quadrats studied}} \text{ x } 100'$$

(c) Abundance: 'It is the study of the number of individuals of different species in the community per unit area, by quadrat method, samplings are made at random at several places and the number of individuals of each species was summed up for all the quadrats divided by the total number of quadrats in which the species occurred. It is represented by the equation':

$$\text{'Abundance} = \frac{\text{Total number of individuals of a species in all quadrat}}{\text{Total number of quadrats in which the species occurred}}\text{'}$$

(d) Relative Density: 'Relative density is the study of numerical strength of the species in relation to the total number of individuals of all the species and can be calculated as':

$$\text{'Relative Density} = \frac{\text{Density of a species}}{\text{Total desity of all species}} \text{ x } 100'$$

(e) Relative Frequency: 'The degree of dispersion of individual species in an area in relation to the number of all the species occurred':

$$\text{'Relative Frequency} = \frac{\text{Frequency of a species}}{\text{Total frequency of all species}} \text{ x } 100'$$

(f) Relative Abundance: 'Relative abundance is the abundance value of a species with respect to the sum of abundance of all the species in the area. It is represented by the equation':

$$\text{'Relative Abundance} = \frac{\text{Abundance of a species}}{\text{Total abundance of all species}} \text{ x } 100'$$

(g) Important Value Index (IVI): 'IVI have been used to express the dominance and ecological succession of any species. Species IVI will be computed by adding the values of relative density, relative frequency and relative dominance for that species':

'IVI = Relative density + Relative frequency + Relative dominance'

Also, the following diversity indices have been used at different sites to further assess the impact of invasion on species richness and evenness.

3.1.1. Measurement of diversity:

The type of diversity used here is α- diversity which is the diversity of species within a community or habitat. The diversity index was calculated by using the Shannon – Wiener diversity index (1949).

$$‘H' = -\sum_{i=1}^{s}\left(\frac{n_i}{N}\right) l_n \left(\frac{n_i}{N}\right)’$$

Where,

‘Pi = S / N S = number of individuals of one species

N = total number of all individuals in the sample

In = logarithm to base e’

3.1.2. Measurement of Species richness

Margalef’s index was used as a simple measure of species richness (Margalef, 1958).

$$'Margalef's\ index\ R = \frac{(S-1)}{ln\ N}\ '$$

Where,

‘S = total number of species

N = total number of individuals in the sample

In = natural logarithm’

3.1.3. Measurement of Species Evenness

For calculating the evenness of species, Pielou’s Evenness Index (e) was used (Pielou, 1966).

$$'E = \frac{H'}{ln\ S}'$$

Where,

‘H’ = Shannon – Wiener diversity index

S = total number of species in the sample’

3.2. Plant-soil interactions

Changes in soil attributes in disturbed, moderately disturbed, and undisturbed areas are done through a study on physico-chemical characteristics and allelochemicals, which may have profound impacts on success of invasive alien plants.

For soil analysis, soil samples (depth of 0- 15cm) were collected from different sites having soil temperature ranging from 26-27 ° C at disturbed site,24-25°C at moderately disturbed and 21-23°C at undisturbed sites. Part of the moist soil samples are air-dried and sieved to obtain fine soil samples (<2mm) and further soil analysis was done in triplicates.

3.2.1. Soil Moisture Content

The soil moisture content was calculated by taking '10g of freshly collected soil samples which are kept in a petri-dish and further kept in the oven at 105°C for twenty-four hours after which the oven-dried samples are reweighed'. Soil moisture content was calculated using the formula:

$$'\boldsymbol{Soil\ Moisture\ content}\ (\%) = \frac{\boldsymbol{W1 - W2}}{\boldsymbol{W2}}\ \boldsymbol{X\ 100}'$$

Where,

'W1 = Weight of fresh soil (g)

W2= Weight of oven-dried soil (g)'.

3.2.2. Soil pH

Soil pH was measured by taking '20 g of freshly collected soil samples in a beaker and mixing it with 50 ml of distilled water. The mixture was then stirred for 30 minutes with the help of a magnetic stirrer and the solution was kept overnight. The pH reading of the supernatant liquid was recorded with the help of a digital pH meter'.

3.2.3. Soil Organic carbon

Soil Organic carbon is determined according to ‘Walkley and Black’s Rapid Dichromate Oxidation Method (1934)’. In this respect, ‘oven-dried sieved soil of 0.5 g was taken into a 500 ml conical flask,10 ml of potassium dichromate was added, and swirled to mix them and to this mixture, 20ml of concentrated sulphuric acid was added and swirled 2-3 times and the flask was made to stand for 30 minutes for cooling. After cooling, 200 ml of distilled water,10 ml of orthophosphoric acid, and 1 ml of an indicator solution were added and mixed thoroughly. The solution is then titrated with ferrous ammonium sulphate solution till the colour changes from blue-violet to green. A blank is simultaneously run without soil sample’.

The Soil Organic Carbon was calculated using the following formula:

$$'\boldsymbol{Soil\ Organic\ Carbon}\ (\%) = \frac{\mathbf{10(}\boldsymbol{B-T}\mathbf{)}}{\boldsymbol{B}} \boldsymbol{X}\ \mathbf{0.003}\ \boldsymbol{X}\ \frac{\mathbf{10}}{\boldsymbol{S}}\,'$$

Where,

‘B= Volume of ferrous ammonium sulphate solution required for blank titration in ml.

T=Volume of ferrous ammonium sulphate solution required for soil sample in ml.

S= Weight of soil in grams’.

3.2.4. Total nitrogen content (TN)

The Total Nitrogen (TN) content of the soil was estimated by following ‘Kjeldahl’s Digestion Method (Bremner and Mulvaney, 1990)’. The process involves;

Wet digestion: ‘5g of soil sample was transferred to a digestion tube and to it 5 grams of digestion mixture and 20ml of concentrated sulphuric acid (H_2So_4) were added. The digestion tube was then heated for 24 hours till the sample colour turned colourless or light green in colour. To this 10 ml of distilled water was added and shaken well. The sample was then transferred to a 250 ml volumetric flask and to this 40ml of 40% sodium hydroxide (NaOH),20 ml of Boric acid (H_3BO_3), and a few drops of indicators Methyl Red and Bromocresol Green were added'.

Distillation: the flask was placed in the receiver end and the distillation process was run for six minutes.

Titration: 'The H_3BO_3 containing flask was titrated against 0.1 N Hydrochloric acid (HCl) or H_2SO_4 till the solution turned into pink colour. The burette reading was recorded'. The percentage of the Total Nitrogen was calculated using the formula:

$$'\boldsymbol{Total\ N}\ (\%) = \frac{(\boldsymbol{T_{1-}\ T_2})\ \boldsymbol{X\ N\ X\ 1.4}}{\boldsymbol{W}}'$$

Where,

'T1= volume of titrant used against sample (ml)

T2= Volume of titrant used against distilled water (blank) (ml)

N= Normality of titrant (0.01 N HCl)

W= Weight of soil (g)'

3.2.5. Available phosphorus (AP)

Available phosphorus was estimated by using 'Bray and Kurtz (1945) method'. The process involved '2.5 g of soil sample which was treated with 25 ml of Bray and Kurtz no.1 extract in a conical flask. A pinch of activated charcoal was added and the suspension was shaken for 5 minutes and filtered through a Whatman filter paper no.42. Further, 5 ml of an aliquot extract was taken in 25 ml of a volumetric flask and to these three drops of p-nitrophenol indicator and 3-5 drops of 0.5 M sodium bicarbonate was added. Acidification was done with each sample before diluting the solution with distilled water. A blank was simultaneously run during the AP analysis. Then the absorbance of blanks, standards and samples was taken using a spectrophotometer'. The available phosphorus is calculated using the formula

$$'\boldsymbol{Available\ Phosphorus}\ \left(\frac{\boldsymbol{kg}}{\boldsymbol{ha}}\right) = \boldsymbol{R\ X\ \frac{50}{5} X\ \frac{1}{5}\ X\ 2.24}'$$

Where,

'R = µg of phosphorous in aliquot (obtained from the standard curve)'

3.2.6. Available Potassium (AK)

The availability of potassium in soil was analyzed by the 'flame photometer method (Jackson, 1973)'. The process involved '5 g of soil sample which was treated with 25 ml of 1N neutral ammonium acetate solution in a conical flask. The conical flask was shaken for thirty minutes on a mechanical shaker and the solution was filtered using Whatman filter paper no.42'. The availability of potassium in the soil was calculated using the formula;

$$'\boldsymbol{AK}\ \left(\frac{\boldsymbol{kg}}{\boldsymbol{ha}}\right) = \boldsymbol{R\ X\ \frac{V}{W}\ X\ \frac{224X10^{6}}{10^{6}}}'$$

Where,

'R= ppm of K in the extract

V= Volume of the soil extract in ml

W= Weight of air-dried soil samples'.

3.3. Plant debris-soil bioassay

Plant debris-soil bioassay is an important tool for determining and investigating allelopathic interactions between plants. Bioassays consist of monitoring seed germination and or seedling growth in soils with surface debris or containing incorporated plant debris. Soils without debris or with biologically inert debris are used as controls. Concentration-dependent inhibition or stimulation of germinating or seedling growth is considered as evidence for allelopathic activity.

The following steps are used:

1. A site which is invaded by invasive alien plants was selected.
2. Soil samples are taken from the site and kept in experimental pots.
3. Another control pot experiment was set in which the pot was filled with healthy forest soil.
4. All the pots were provided with the same amount of sunlight and water.
5. The number of seed germination was noted on the 3rd and 7th day of the pot experiment.
6. All the plants were carefully examined at different time intervals in order to note the changes in morphology.
7. The measurements for plant height (root and shoot length) and weight (biomass) were taken when fully grown.

The various bioassay parameters were assessed such as:

a) ‘Seedling heights (H)’

It indicates the ‘seedling’s competitive ability for light. It is measured using a ruler’.

b) ‘Root Length and Shoot Length (RL&SL)’

It indicates the ‘seedling’s competitive ability for nutrition. It is also measured using a ruler’.

c) ‘Biomass (BM)’

It indicates ‘seedling’s growth and competitiveness. It is measured using an electronic balance with an accuracy of 0.001g’ (Wang et al.,2016)

d) ‘Germination Percentage (Gpe) ‘

It indicates the ‘germination ability of seeds. It is calculated using the ratio of the final numbers of seed germination to the total number of seeds when no new germination occurred after 7 days of incubation multiplied by 100’.

e) ‘Germination Potential (Gpo)’

It indicates the ‘germination speed and uniformity of seeds. It is calculated by dividing the number of germinations on the 3rd day by the total number of seeds’.

f) ‘Germination Index (GI)’

It indicates the ‘germination speed and vitality of seeds. It is calculated using the formula $\sum Gi/I$, where, Gi is the number of germinations in I [the time after cultivation (day)]’

g) ‘Germination Rate Index (GRI) ‘

It also indicates the ‘germination speed and vitality of seeds. It is determined using the equation: Gpe x GI. (Steinmaus et al.,2000)’

h) ‘Vigor Index (VI)’

It also indicates ‘the germination speed and vitality of seeds. It is determined using the formula: GI x BM. (Lin et al.,2000)’

3.4. Total phenolic content analysis

The total phenolic content for soil and leaf was quantified by following the method by Swain & Hills (1959) and Akomeng & Adusei (2021), with some modifications using Gallic acid and Catechol as a standard.

3.4.1. Sample collection, preparation, and extraction

The leaf was collected and air dried at room temperature. Further, 10 g of crushed air-dried leaves was immersed in a 100 mL methanol for 48 hours with frequent agitation. The solution was then filtered using filter paper (Whatman No. 41). The solution was evaporated using a Rotary evaporator (BUCHI Rotavapor R300) and crude extract were obtained.

Soil samples weighing 20 g were taken from disturbed study sites and kept in a conical flask containing 100 mL of distilled water which is a solvent for extraction. The soil samples were agitated for 1 h on a Rotary shaker (Rotary Flask Shaker, Scientech, Science Enterprises, Delhi, India) and kept for 24 hours at room temperature. The supernatant was filtered with filter paper (Whatman No. 41).

3.4.2 Quantification of total phenolic content in soil

For gallic acid, 0.5 mL aliquot of 20,30,40,60,80 and 100 µg/L were taken and mixed with 2 mL of Folin-Ciocalteu reagent (1:10 with distilled water). The mixture was neutralized with 4 mL of sodium carbonate solution (7.5%) and incubated at room temperature for 60 minutes with intermittent shaking for color development. The absorbance of the resulting blue color was measured at 765 nm with a UV-visible spectrophotometer (Microprocessor UV-VIS Double Beam Spectrophotometer, Igene Labserve). The same technique was repeated for the extracts with triplicates. The TPC was determined from the standard calibration curve of Gallic acid and expressed as mg/g gallic acid equivalent (GAE) of the dry extract.

For Catechol, 1mL aliquot of 1, 2.5, 5, 7.5, and 10 mg/L were taken and mixed with 1 mL of Folin-Ciocalteu reagent (50%). The mixture was neutralized with 1 mL of sodium carbonate solution (20%) and incubated at room temperature for 30 min with intermittent shaking for color development. The absorbance of the resulting blue color was measured at 700 nm with a UV-visible spectrophotometer (Microprocessor UV-VIS Double Beam Spectrophotometer, Igene Labserve). The same technique was repeated for the extracts in triplicate. The concentration and absorbance of TPC were determined from the standard calibration curve of catechol and expressed as mg/g Catechol equivalent (CE) of the dry extract.

3.4.3 Quantification of total phenolic content in leaves

The total phenolic content was determined by using the Folin-Ciocalteu colorimetric method. 20 mg of the crude extract and 20 ml of methanol were used to make the stock solution. 0.5 ml was taken from the stock solution mixed with 5 ml of 10% Folin-Ciocalteu and kept for 5 minutes. After 5 minutes 4 ml of 7.5 % Na_2CO_3 was added and incubated in the dark at room temperature for 60 minutes and optical density was read at 765 nm in a spectrophotometer. Gallic acid was used as a standard and the phenolic content was expressed in terms of gallic acid equivalent (GAE) per gram of extracts.

For Catechol, 1ml aliquot of 1, 2.5, 5, 7.5, and 10 mg/L were taken and mixed with 1 ml of Folin-Ciocalteu reagent (50%). The mixture was neutralized with 1 ml of sodium carbonate solution (20%) and incubated at room temperature for 30 min with intermittent shaking for color development. The absorbance of the resulting blue color was measured at 700 nm with a UV-visible spectrophotometer (Microprocessor UV-VIS Double Beam Spectrophotometer, Igene Labserve). The same technique was repeated for the extracts within triplicate. The concentration and absorbance of TPC were determined from the standard calibration curve of catechol and expressed as mg/g Catechol equivalent (CE) of the dry extract.

3.5. Canopy openness, leaf area index, and light intensity

The canopy openness of the selected study sites was analysed by hemispherical photography and Gap Light Analyzer (GLA) software. The hemispherical photographs were taken in a skyward direction perpendicular to the ground using a fish eye lens (Skyvik Signi One 10mm Fisheye Lens) mounted on a smartphone. Three replicates (best of 1 for analyzing on GLA) of the hemispherical photos were taken from 5 areas on a cloudy day. Coordinates and elevation of the sites were taken using Global Positioning system (GPS-Garmin GPSMAP 64s). Canopy openness was analysed using the hemispherical photos on GLA. The magnetic correction in the configuration settings of GLA was taken from the National Oceanic and Atmospheric Administration (NOAA) website. The light intensity and leaf area index (LAI) of the area were measured using a plant canopy analyser (Integration of handheld and Software from Kaizen Imperial and Quantum Sensors from Apogee Instruments, USA) from five random spots each on the study sites. The canopy openness/gap analysis was conducted to study the habitat ecology and assess that how canopy gaps can influence the spread of invasive alien plants which further intensify its allelochemic attributes.

CHAPTER- 4

RESULTS

4. RESULTS

The results of the study on certain invasive alien plants and their effects on phytosociology and plant-soil allelopathic interactions at study sites along the disturbance gradient during the study period of 2019-2021 are given as follows-

4.1 Vegetation analysis

Vegetation analysis from the three sites viz. disturbed, moderately disturbed, and undisturbed was recorded during the study period. A total of 24 plant species were identified and recorded at the disturbed site, 18 plant species at the moderately disturbed site, and 15 plant species at the undisturbed site respectively.

Density

The density of each plant species from the three sites ranged from 0.1 to 8.9 at the disturbed site (Table 1), 0.1 to 15.3 at the moderately disturbed site (Table 2), and 0.2 to 2.2 at the undisturbed site (Table 3) respectively.

Invasive alien plants such as *L. camara, A. conyzoides, C. odorata,* and *M. micrantha* were dominant at the disturbed site. The moderately disturbed site has a high species of plants like *S. media, C. accrescens, K. brevofolia* and *G. parvviflora*. The undisturbed site has a lower density of plant species such as *C. vialis and K. bervifolia* while it has sparse distribution of invasive alien plants.

Frequency

The frequency of each plant species from the three sites ranged from 10 to 100 at the disturbed and moderately disturbed sites (Table 1 and 2). However, the frequency ranged from 20 to 60 at the undisturbed site (Table 3). Invasive plants such as *L. camara, A. conyzoides, C. odorata, M. micrantha, B. biternate, S. alata G. parviflora, S. media,* and *C. accrescens* were abundantly present at both the disturbed and moderately disturbed sites while they were sparsely distributed at the undisturbed site.

Abundance

The abundance of each plant species from the three sites ranged from 1 to 18.5 at the disturbed site (Table 1), 1 to 15.25 at the moderately disturbed site (Table 2), and 1 to 4.2 at the undisturbed site (Table 3), respectively.

Plants such as *C. accrescens, P. conjugatum, I. cylindrica, K. brevifolia, A. conizoides, C. odorata, M. micrantha, and L. camara* were found in large abundance at the disturbed site as well as moderately disturbed sites. The undisturbed site on the other has a dispersed collection of plant species such as *A. conzyoides, C. odorata*, *C. accrescens, and C. vialis.*

Relative Density

The relative density was calculated highest in case of *C. odorata* (17.60) followed by *A. conyzoides* (16.00) at the undisturbed followed by *S. oleracea* (14.96), *I. cylindrica* (13.95) site (Table 3). The least relative density was found in *U. lobata* and *G. bicolor* (0.09 each) from the moderately disturbed site followed by *L. camara* (0.17), *C. glandulosum* (0.17), and *C. infortunatum* (0.17) (Table 1).

Relative Frequency

The relative frequency was recorded highest incase of *M. micrantha* (10.99), *A. conyzoides* (10.99) at the disturbed site (Table 1) followed by *C. odorata* (9.89), *C. vialis* (9.90), *G. parviflora* (9.90) from the undisturbed site (Table 3). The species with the least relative frequency was found to be *L. leucocephala, U. lobata*, and *C. glandulosum* (1.10 each).

Relative abundance

The relative abundance among the species was highest in *S. media* (10.95) followed by *K. brevifolia* (10.92), and *C. accrescens* (10.59) at the moderately disturbed site (Table 1), and *C. odorata* (10.56) at the undisturbed site (Table 3). The plant species with the least relative abundance was found to be *L. camara* (0.72) from the moderately disturbed site (Table 2).

Importance Value Index (IVI)

The estimation of the importance value index is ecologically relevant as it helps in assessing the most dominant and important plant species present at the study sites. It is estimated by calculating the total values of relative density, relative abundance, and relative frequency obtained from the quadrat analysis.

The vegetation analysis from the disturbed site recorded a total of 595 plant individuals belonging to different species with IVI ranging from 2.09 to 31.38 (Table 1). The vegetation analysis from the moderately disturbed site recorded a total of 1158 plant individuals belonging to different species with IVI ranging from 1.60 to 32.16 (Table 2). The vegetation analysis from the undisturbed site recorded a total of 146 plant individuals belonging to different species with IVI ranging from 36.53 to 7.89 (Table 3).

The IVI for the three sites was found to be high in plants like *G. parviflora, C. vialis, S. media, C. accrescens C. odorata,* and *A. conizoides* with IVI ranging from 23.00 to 36.53. On the other hand, plant species such as *G. bicolor, C. glandulosum, U. lobata, C. infortunatum, L. camara L. leucocephala,* and *S. torvum* were plants having lower values of IVI ranging from 1.60 to 2.49.

Table 1. Phytosociological attributes recorded at disturbed site of Aizawl, Mizoram, Northeast India (2019-2021)

Sl No.	Name of species	Quadrats										No. of individuals	Density	Frequency	Abundance	Relative density	Relative frequency	Relative abundance	IVI
		I	II	III	IV	V	VI	VII	VIII	IX	X								
1	*Mikania micrantha* (L.) Kunth ex H.B.K.	5	8	6	5	2	3	6	5	5	3	48	4.8	100	4.8	8.07	10.99	3.94	23.00
2	*Ageratum conizoides* L.	6	7	3	5	7	5	8	9	7	6	63	6.3	100	6.3	10.59	10.99	5.18	26.75
3	*Lantana camara* L.	2	0	1	0	1	1	0	0	0	1	6	0.6	50	1.2	1.01	5.49	0.99	7.49
4	*Chromolaena odorata* (L.) R.M. King & H. Rob.	7	6	5	0	2	6	6	10	12	15	69	6.9	90	7.67	11.60	9.89	6.30	27.78
5	*Mimosa pudica* L.	6	0	0	1	0	0	2	1	0	0	10	1	40	2.5	1.68	4.40	2.05	8.13
6	*Panicum conjugatum* Roxb.	22	0	0	0	0	16	12	0	5	6	61	6.1	50	12.2	10.25	5.49	10.02	25.77
7	*Leucaena leucocephala* (Lam.) de Wit	1	0	0	0	0	0	0	0	0	0	1	0.1	10	1	0.17	1.10	0.82	2.09

8	*Calopogonium mucunoides* Desv.	2	0	0	0	0	1	0	0	0	0	3	0.3	20	1.5	0.50	2.20	1.23	3.93
9	*Spilanthes oleracea* (L.) Hook.f.	5	0	0	20	0	18	13	10	12	11	89	8.9	70	12.71	14.96	7.69	10.44	33.09
10	*Solanum torvum* S.W	1	3	0	0	0	0	0	0	0	0	4	0.4	20	2	0.67	2.20	1.64	4.51
12	*Urena lobata* L.	2	0	0	0	0	0	0	0	0	0	2	0.2	10	2	0.34	1.10	1.64	3.08
13	*Clerodendrum glandulosum* Lindl.	1	0	0	0	0	0	0	0	0	0	1	0.1	10	1	0.17	1.10	0.82	2.09
14	*Bidens biternate* (Lour.)	5	7	0	2	3	5	9	0	0	0	31	3.1	60	5.17	5.21	6.59	4.24	16.05
15	*Spermacoce alata* Aubl.	4	0	0	0	0	5	0	0	0	0	9	0.9	20	4.5	1.51	2.20	3.70	7.41
16	*Calyptocarpus vialis* Less.	5	0	0	0	3	0	0	0	0	0	8	0.8	20	4	1.34	2.20	3.29	6.83
17	*Clerodendron infortunatum* L.	1	0	0	0	0	0	0	0	0	0	1	0.1	10	1	0.17	1.10	0.82	2.09
18	*Stellaria media* (L.) Vill	6	3	2	0	5	5	3	0	0	0	24	2.4	60	4	4.03	6.59	3.29	13.91
19	*Cyrtococcum accrescens*	24	13	0	0	0	0	0	0	0	0	37	3.7	20	18.5	6.22	2.20	15.20	23.61

	(Trin.)																		
20	*Kyllingia brevifolia* Rottb.	15	10	0	0	6	0	0	0	0	0	31	3.1	30	10.33	5.21	3.30	8.49	16.99
21	*Galinsoga parviflora* Cav.	5	0	0	0	6	0	0	0	0	0	11	1.1	20	5.5	1.85	2.20	4.52	8.56
22	*Gynura bicolor* (Roxb. ex Willd.)	1	0	0	0	1	0	0	0	0	0	2	0.2	20	1	0.34	2.20	0.82	3.36
23	*Imperata cylindrica* (L.) P.Beauv.	15	10	0	0	6	13	12	0	12	15	83	8.3	70	11.86	13.95	7.69	9.74	31.38
24	*Merremia umbellata* (L.) A.R.Simões & Staples	1	0	0	0	0	0	0	0	0	0	1	0.1	10	1	0.17	1.10	0.82	2.09

Table 2. Phytosociological attributes recorded at moderately disturbed site of Aizawl, Mizoram, Northeast India (2019-2021)

Sl No.	Name of species	Quadrats										No. of individuals	Density	Frequency	Abundance	Relative density	Relative frequency	Relative abundance	IVI
		I	II	III	IV	V	VI	VII	VIII	IX	X								
1	*Mikania micrantha* (L.) Kunth ex H.B.K.	6	4	3	5	4	3	2	5	3	3	38	3.8	100	3.8	3.28	8	2.72	14.00
2	*Ageratum conizoides* (L.) L.	5	2	7	4	7	5	5	7	8	7	57	5.7	100	5.7	4.92	8	4.08	17.00
3	*Lantana camara* L.	1	0	0	0	0	1	0	0	0	0	2	0.2	20	1	0.17	1.6	0.72	2.49
4	*Chromolaena odorata* (L.) R.M. King & H. Rob.	5	6	7	2	2	6	5	4	5	6	48	4.8	100	4.80	4.15	8	3.44	15.58
5	*Mimosa pudica* L.	1	0	0	0	1	0	2	1	0	0	5	0.5	40	1.25	0.43	3.2	0.89	4.53

6	*Panicum conjugatum* Roxb.	19	0	3	0	0	3	5	0	5	5	40	4	60	6.67	3.45	4.8	4.77	13.03
7	*Spilanthes oleracea* (L.) Hook.f.	5	0	0	8	0	6	4	0	0	2	25	2.5	50	12.50	2.16	4	8.95	15.11
8	*Solanum torvum* S.W	0	0	1	0	0	0	0	0	1	0	2	0.2	20	1	0.17	1.6	0.72	2.49
9	*Urena lobata* L.	0	0	0	1	0	0	0	0	0	0	1	0.1	10	1	0.09	0.8	0.72	1.60
10	*Bidens biternate* (Lour.)	8	12	0	4	2	5	9	7	5	3	55	5.5	90	6.11	4.75	7.2	4.37	16.32
11	*Spermacoce alata Aubl.*	15	12	9	14	12	6	0	5	18	3	94	9.4	80	11.75	8.12	6.4	8.41	22.93
12	*Calyptocarpus vialis* Less.	15	12	11	9	19	5	12	16	17	13	129	12.9	100	12.9	11.14	8	9.23	28.37
13	*Stellaria media*(L.)	13	15	22	20	19	15	13	11	19	6	153	15.3	100	15.3	13.21	8	10.95	32.16

	Vill																		
14	*Cyrtococcum accrescens* (Trin.)	15	10	12	20	14	16	16	12	19	14	148	14.8	100	14.8	12.78	8	10.59	31.38
15	*Kyllingia brevifolia* Rottb.	18	20	12	5	14	0	16	21	0	16	122	12.2	80	15.25	10.54	6.4	10.92	27.85
16	*Galinsoga parvviflora* Cav.	21	22	13	15	9	6	15	13	16	12	142	14.2	100	14.2	12.26	8	10.17	30.43
17	*Gynura bicolor* (Roxb.ex Willd.)	0	0	0	0	1	0	0	0	0	0	1	0.1	10	1	0.09	0.8	0.72	1.60
18	*Imperata cylindrica* (L.) P.Beauv.	20	9	15	3	0	14	13	0	12	10	96	9.6	90	10.67	8.29	7.2	7.64	23.13

Table 3. Phytosociological attributes recorded at undisturbed site of Aizawl, Mizoram, Northeast India (2019-2021)

Sl No.	Name of species	Quadrats										No. of individuals	Density	Frequency	Abundance	Relative density	Relative frequency	Relative abundance	IVI
		I	II	III	IV	V	VI	VII	VIII	IX	X								
1	*Mikania micrantha* (L.) Kunth ex H.B.K.	0	0	1	0	0	1	2	0	0	0	4	0.4	30	1.33	3.20	5.45	3.84	12.49
2	*Ageratum conizoides* (L.) L.	4	0	5	4	3	2	0	0	2	0	20	2	60	3.33	16.00	10.91	9.60	36.51
3	*Lantana camara* L.	0	0	1	0	0	1	0	0	0	0	2	0.2	20	1	1.60	3.64	2.88	8.12
4	*Chromolaena odorata* (L.) R.M. King & H. Rob.	5	4	0	2	0	3	0	6	0	2	22	2.2	60	3.67	17.60	10.91	10.56	39.07
5	*Spilanthes oleracea* (L.) Hook.f.	0	0	1	0	0	0	1	0	0	0	2	0.2	20	1.00	1.60	3.64	2.88	8.12

6	*Urena lobata* L.	2	0	0	1	0	0	1	0	0	0	4	0.4	30	1.33	3.20	5.45	3.84	12.49
7	*Clerodendrum glandulosum* Lindl.	0	0	1	0	0	1	0	0	1	0	3	0.3	30	1	2.40	5.45	2.88	10.73
8	*Bidens biternate* (Lour.)	1	0	0	0	2	0	0	3	0	3	9	0.9	40	2.25	7.20	7.27	6.48	20.95
9	*Spermacoce alata* Aubl.	0	2	0	0	0	3	0	0	2	0	7	0.7	30	2.33	5.60	5.45	6.72	17.77
10	*Calyptocarpus vialis* Less.	4	0	5	0	0	0	6	0	3	3	21		50	4.2	0.00	9.09	12.09	21.18
11	*Clerodendron infortunatum* L.	1	0	0	0	1	0	0	0	0	0	2	0.2	20	1	1.60	3.64	2.88	8.12
12	*Stellaria media* (L.) Vill	0	0	2	0	0	1	3	0	1	0	7	0.7	40	1.75	5.60	7.27	5.04	17.91
13	*Cyrtococcu*	5	3	0	0	0	2	0	2	0	0	12	1.2	40	3	9.60	7.27	8.64	25.5

	m accrescens (Trin.)																		1
14	*Galinsoga parviflora* Cav.	3	2	5	0	0	0	5	0	6	0	21	2.1	50	4.2	16.80	9.09	12.09	37.98
15	*Imperata cylindrica* (L.) P.Beauv.	0	0	5	3	0	0	0	2	0	0	10	1	30	3.33	8.00	5.45	9.60	23.05

4.1.1 Diversity Indices

In relation to diversity assessment using the different indices, Shannon-Weiner diversity index (H') at the disturbed site was recorded 2.54 while the Margalef's index (SR) based species richness using was 3.6. In addition to species richness, Pielou's evenness index (E) was recorded to be 0.40 at the disturbed site (Table 4).

The Shannon-Weiner diversity index (H') at the moderately disturbed site was 2.47, while the Margalef's index based species richness (SR) was 3.26, and the Pileou's evenness index (E) was calculated 0.35 (Table 4).

The Shannon-Weiner diversity index (H') at the undisturbed site was 2.42, while the Margalef's index based species richness (SR) was 4.62, and the Pileou's evenness index (E) was 0.49 (Table 4). The estimation of diversity indices revealed that H was highest at disturbed site whereas species richness and evenness were recorded highest at undisturbed site.

Table 4. Shannon- Weiner diversity index, Margalef's index and Pielou's evenness index in Disturbed (D), Moderatelyly disturbed (MD) and Undisturbed (UD) sites of Aizawl.

Shannon-weiner Diversity index H'			Margalef's index SR			Pielou's Evenness Index E		
D	MD	UD	D	MD	UD	D	MD	UD
2.54	2.47	2.42	3.60	3.26	4.62	0.40	0.35	0.49

4.2 Soil Analysis

The soil samples were taken from three study sites, disturbed, moderately disturbed, and undisturbed sites during the year 2019-2021. The sampling sites comprised of invasive alien plants especially *A. conyzoides*, *M. micrantha*, *L. camara* and *C.odorata* are present and recorded seasonally i.e., monsoon, post-monsoon, and pre-monsoon seasons, respectively.

Soil pH

The pH of the soil samples from the disturbed study site ranged from 5.1 (*M. micrantha* invaded soil, pre-monsoon season) to 6.1 (*L. camara* invaded soil, pre-monsoon season). Therefore, the pH during the study period (2019-2021) ranged from 5.1 to 6.05. The pH range was recorded lower in the pre-monsoon season than in the post-monsoon season while it was observed highest during monsoon season.

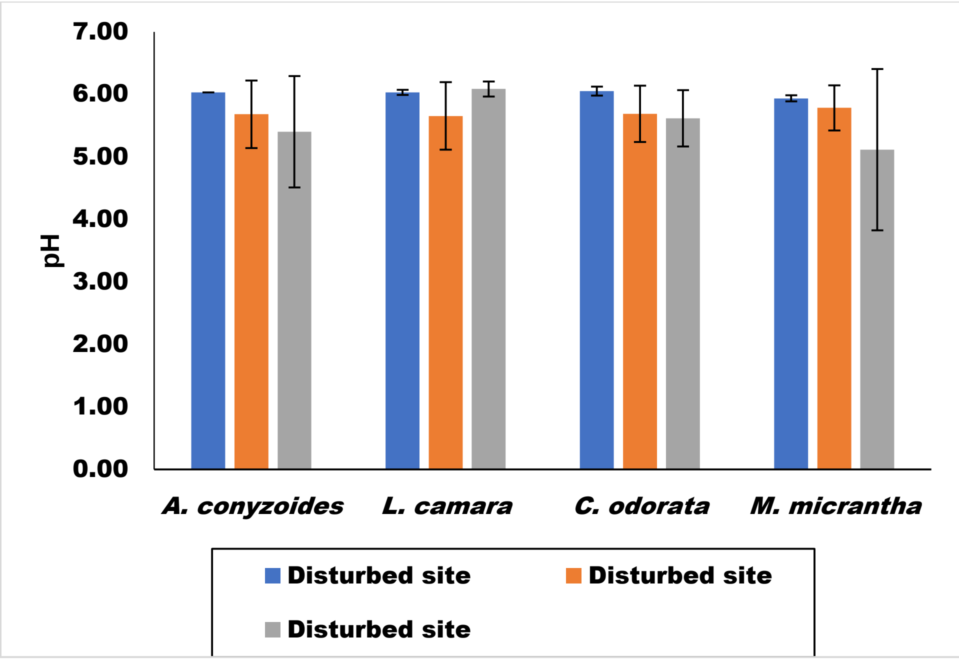


Figure 1. Seasonal variation in pH of soil in the disturbed study site

The pH of the soil samples from the moderately disturbed study site ranged from 5.4 (*M. micrantha* and *A. conyzoides* invaded soil, pre-monsoon season) to 6.02 (*L. camara* invaded soil, monsoon season). Therefore, the total range of the pH during the study period (2019-2021) was noted from 5.4 to 6.04. The pH range was found to be lower in the post-monsoon season than in the pre-monsoon season while it was observed highest during the monsoon season.

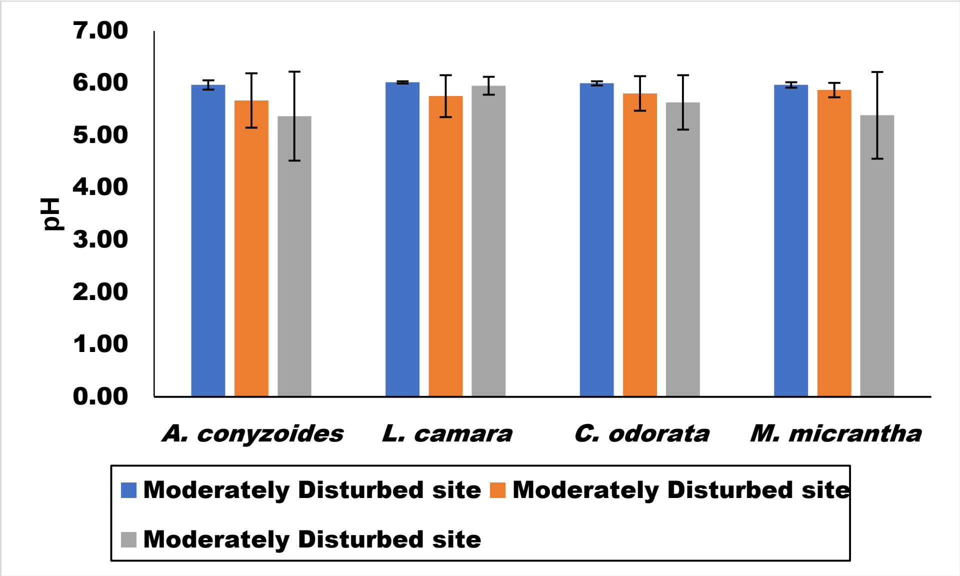


Figure 2. Seasonal variation in pH of soil in the moderately disturbed study site

The pH of the soil samples from the undisturbed study site ranged from 5.7 (*A. conyzoides*,*L. camara and C. odorata* invaded soil, post-monsoon season) to 6.00 (*C. odorata* invaded soil, monsoon season). Therefore, the total range of the pH during the study period (2019-2021) was from 5.7 to 6.0. The pH range was found to be lower in the post-monsoon season than in the pre-monsoon season while it was observed highest during the monsoon season.

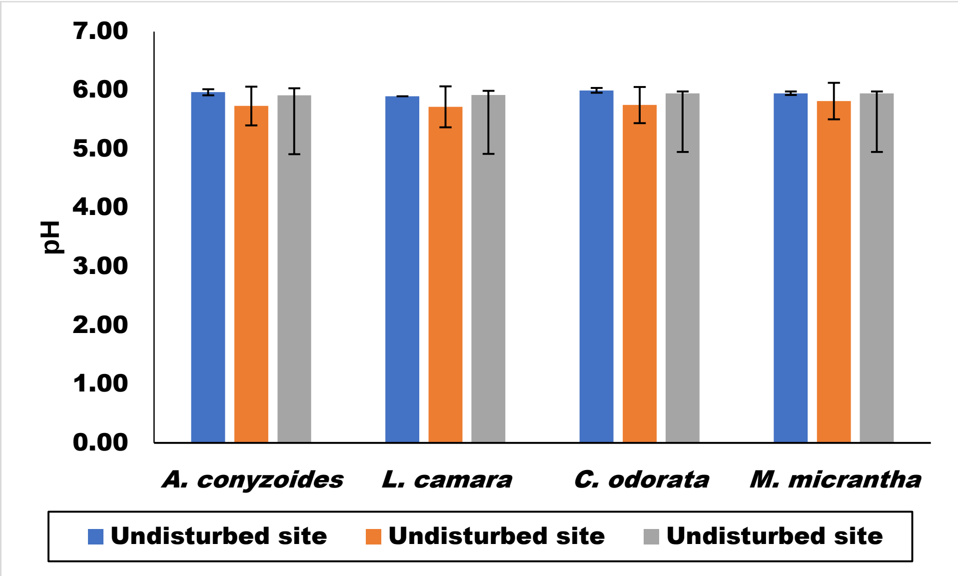


Figure 3. Seasonal variation in pH of soil in the undisturbed study site

Soil moisture content

The soil moisture content of the soil samples from the disturbed study site ranged from 23.1% (*C. odorata* invaded soil, pre-monsoon season) to 29.85% (*L. camara* invaded soil, monsoon season). Therefore, the total range of the Soil moisture content during the study period (2019-2021) was recorded from 23.1% to 29.85%. The soil moisture content range was found to be lower in the pre-monsoon season than in the post-monsoon season while it was observed highest during the monsoon season.

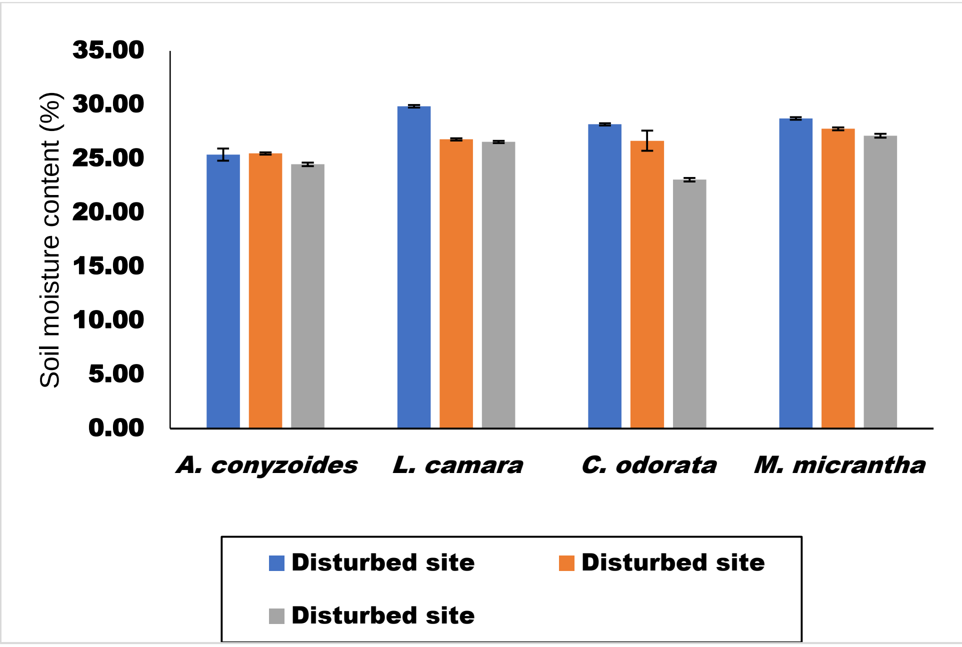


Figure 4. Seasonal variation in the soil moisture content of soil in disturbed study site

The soil moisture content of the soil samples from the moderately disturbed study site ranged from 21.41% (*A. conyzoides* invaded soil, pre-monsoon season) to 29.69% (L. camara invaded soil, pre- monsoon season). Therefore, the soil moisture content during the study period (2019-2021) ranged from 21.41% to 29.69%. The soil moisture content was recorded lower in the pre- monsoon season than in the monsoon season while it was observed highest during the post-monsoon season.

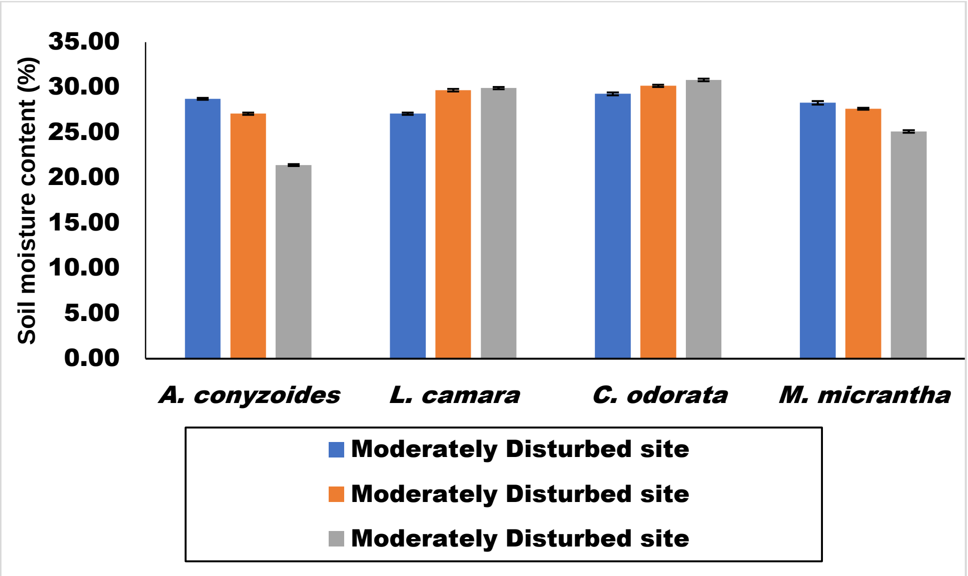


Figure 5. Seasonal variation in the soil moisture content of soil in moderately disturbed study site

The Soil moisture content of the soil samples from the undisturbed study site ranged from 20.22% (A. conyzoides invaded soil, pre-monsoon season) to 32.66 % (C. odorata invaded soil, monsoon season). Therefore, the soil moisture content during the study period (2019-2021) ranged from 20.22 % to 32.66 %. The soil moisture content range was recorded lower in the pre-monsoon season than in the post-monsoon season while it was observed highest during the monsoon season.

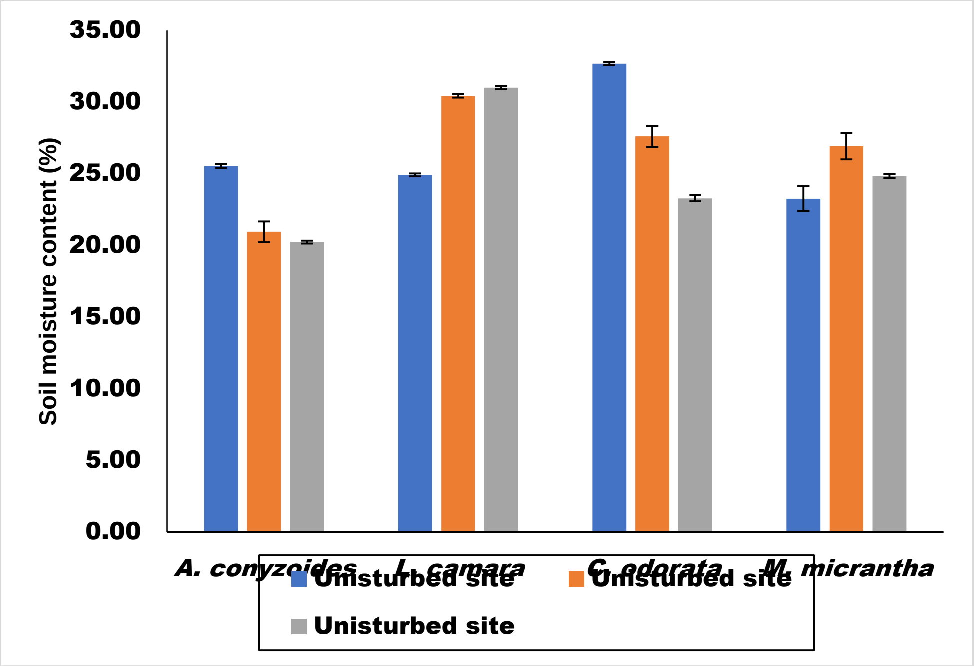


Figure 6. Seasonal variation in the soil moisture content of soil in undisturbed study site

Soil Organic Carbon

The soil organic carbon of the soil samples from the disturbed study site ranged from 0.03 % (*L. camara*, *C. odorata* invaded soil, pre-monsoon season) to 0.93 % (*C. odorata* invaded soil, monsoon season). Therefore, Soil moisture content during the study period (2019-2021) ranged from 0.03 % to 0.93 %. The soil organic carbon content range was recorded lower in the pre-monsoon season than in the post-monsoon season while it was observed highest during the monsoon season.

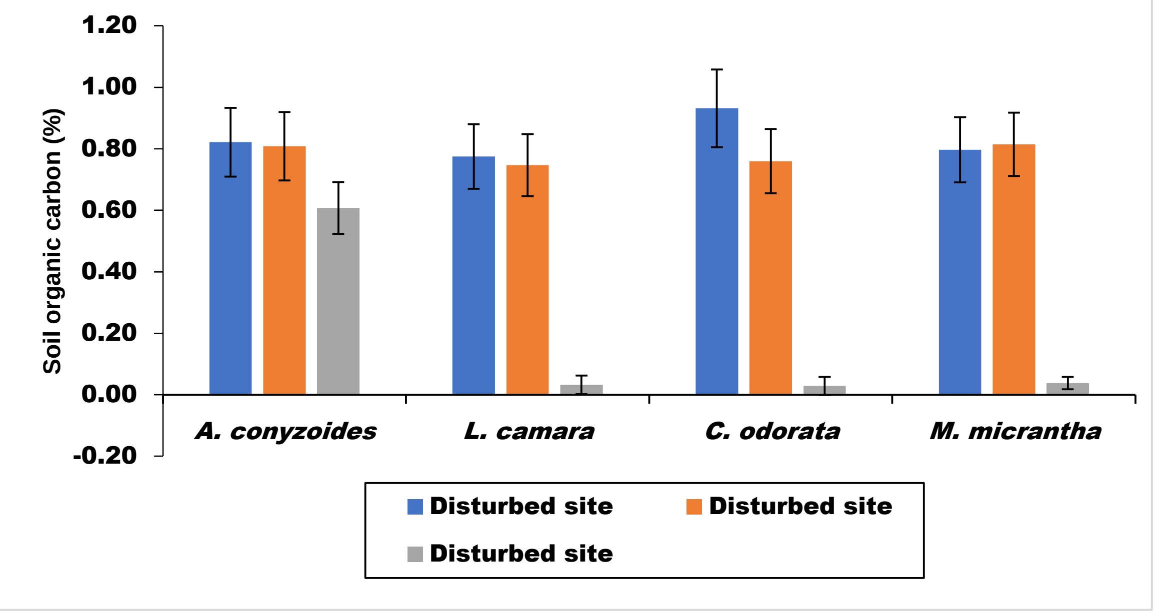


Figure 7. Seasonal variation in the soil organic carbon of soil in disturbed study site

The soil organic carbon of the soil samples from the moderately disturbed study site ranged from 0.03 % (*A. conyzoides, C. odorata* invaded soil, pre-monsoon season) to 0.77 % (*A. conyzoides* invaded soil, post- monsoon season). Therefore, the soil organic carbon content during the study period (2019-2021) ranged from 0.03 % to 0.77 %. The soil organic carbon range was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season.

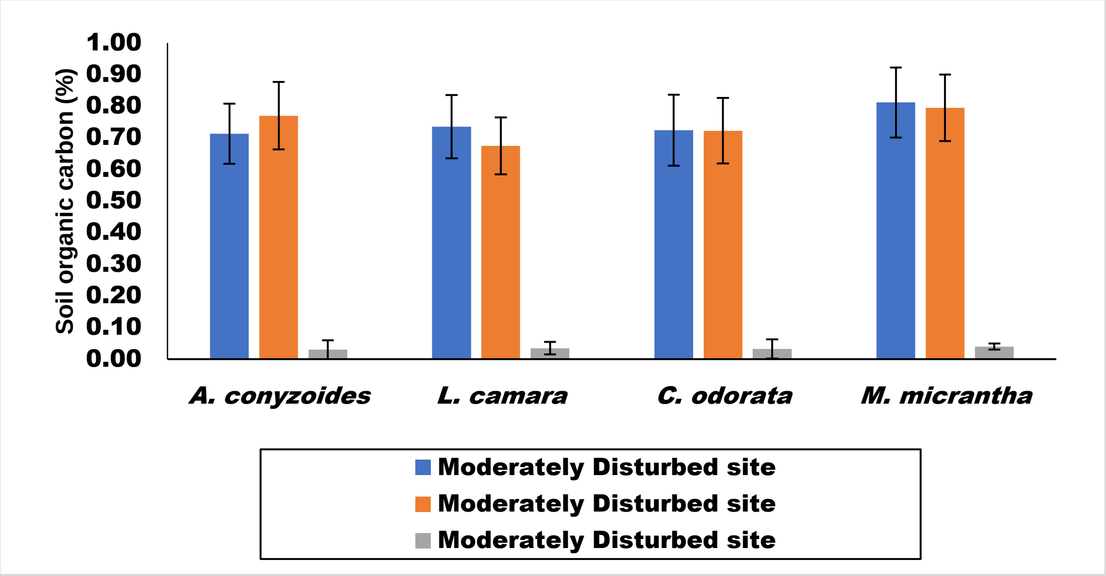


Figure 8. Seasonal variation in the soil organic carbon content of soil in moderately disturbed study site

The soil organic carbon of the soil samples from the undisturbed study site ranged from 0.03 % *A. conyzoides*, *C. odorata* invaded soil, pre-monsoon season) to 1.29 % (*L. camara* invaded soil, post- monsoon season). Therefore, the soil organic carbon content during the study period (2019-2021) ranged from 0.03 % to 1.29 %. The soil organic carbon content range was recorded as lowest in the pre-monsoon season while it was observed high during the post-monsoon season and monsoon season.

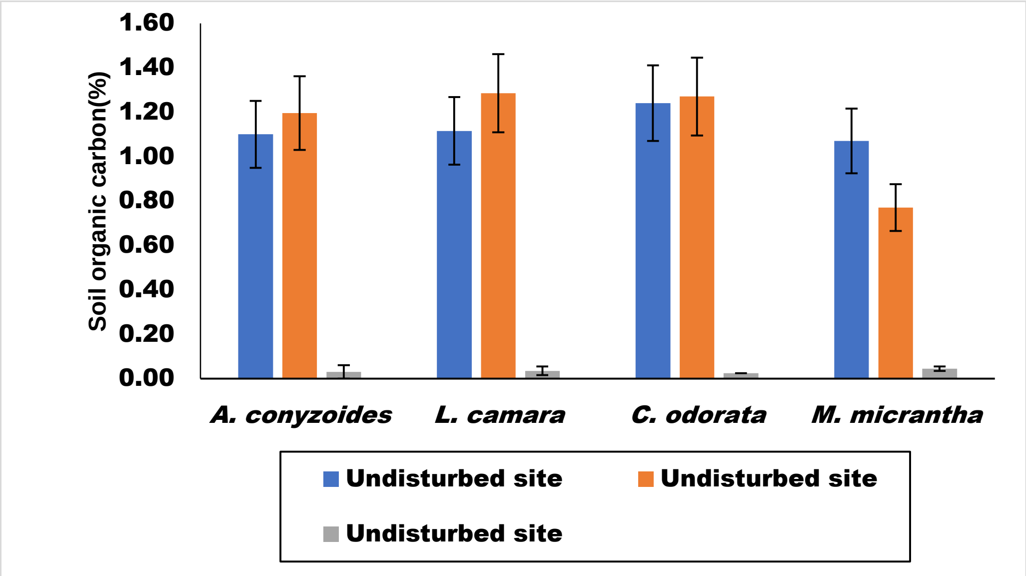


Figure 9. Seasonal variation in the soil organic carbon content of soil in undisturbed study site

Soil Organic matter

The soil organic matter of the soil samples from the disturbed study site ranged from 0.05 % (*C. odorata* invaded soil, pre-monsoon season) to 1.61 % (C. *odorata* invaded soil, monsoon season). Therefore, the soil organic matter during the study period (2019-2021) ranged from 0.05 % to1.61%. The soil organic matter range was recorded as lowest in the pre-monsoon season while it was observed high during the monsoon season.

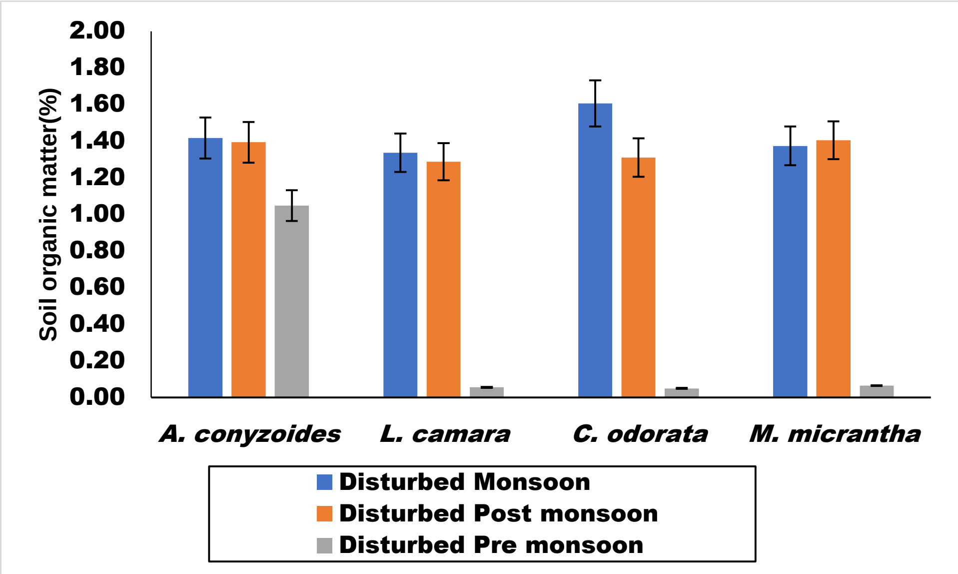


Figure 10. Seasonal variation in soil organic matter of soil in disturbed study site

The soil organic matter of the soil samples from the moderately disturbed study site ranged from 0.05 % (*A. conyzoides* invaded soil, pre-monsoon season) to 1.40 % (*M. micrantha* invaded soil, monsoon season). Therefore, the soil organic matter during the study period (2019-2021) ranged from 0.05 % to 1.40 %. The soil organic matter range was recorded as lowest in the pre-monsoon season while it was observed high during the monsoon season.

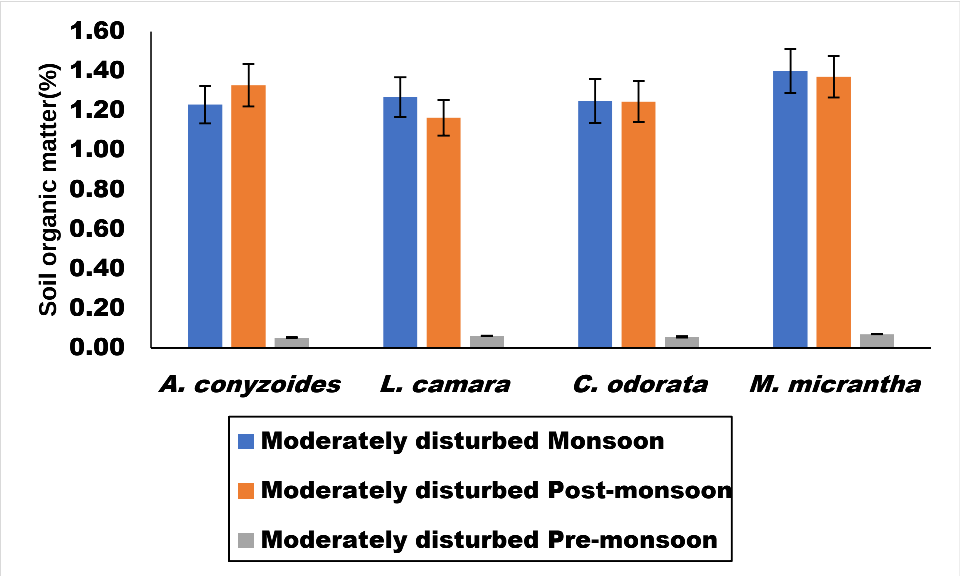


Figure 11. Seasonal variation in soil organic matter of soil in moderately disturbed study site

The soil organic matter of the soil samples from the undisturbed study site ranged from 0.04 % (*C. odorata* invaded soil, pre-monsoon season) to 2.22 % (*L. camara* invaded soil, post-monsoon season). Therefore, the soil organic carbon during the study period (2019-2021) ranged from 0.04 % to 2.22 %. The soil organic matter range was recorded as lowest in the pre-monsoon season while it was observed high during the monsoon season.

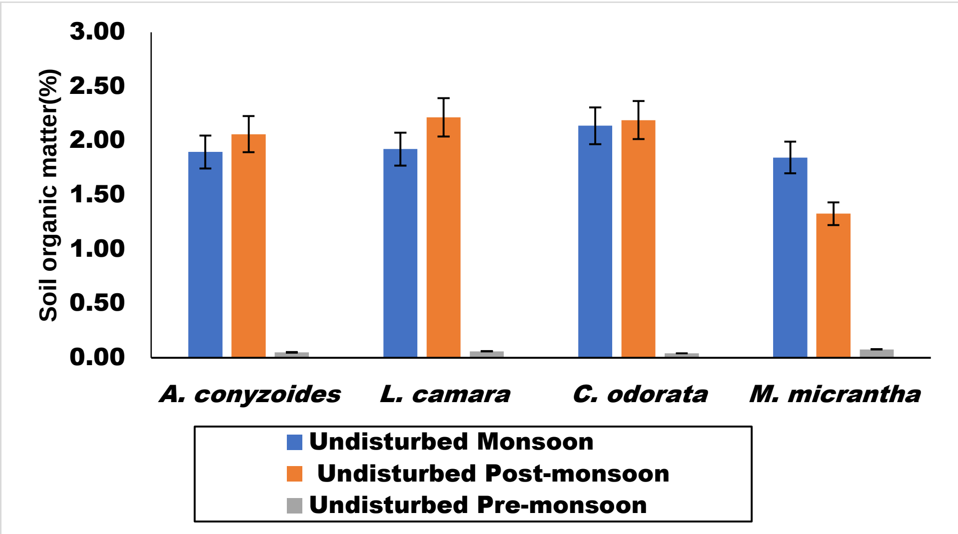


Figure 12. Seasonal variation in soil organic matter of soil in undisturbed study site

Total nitrogen

The total nitrogen content of the soil samples from the disturbed study site ranged from 148.05 Kg/ha (*A. conyzoides* invaded soil, pre-monsoon season) to 260.9 Kg/ha (*C. odorata* invaded soil, pre - monsoon season). Therefore, the total nitrogen content during the study period (2019-2021) ranged from 148.05 Kg/ha to 260.9 Kg/ha. The total nitrogen content range was recorded lower in the monsoon season while it was observed highest during the pre-monsoon season.

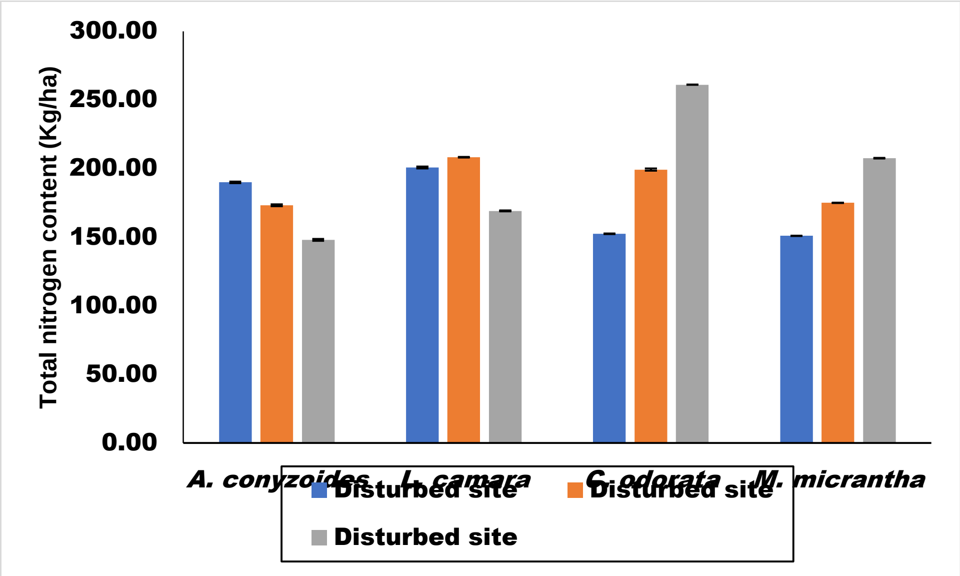


Figure 13. Seasonal variation in the total nitrogen content of soil in disturbed study site

The total nitrogen content of the soil samples from the moderately disturbed study site ranged from 135.7 Kg/ha (*M. micrantha* invaded soil, monsoon season) to 496.3 Kg/ha (*C. odorata* invaded soil, pre - monsoon season). Therefore, the total nitrogen content during the study period (2019-2021) ranged from 135.7 Kg/ha to 496.3 Kg/ha. The total nitrogen content range was recorded lower in the monsoon season while it was observed highest during the pre-monsoon season.

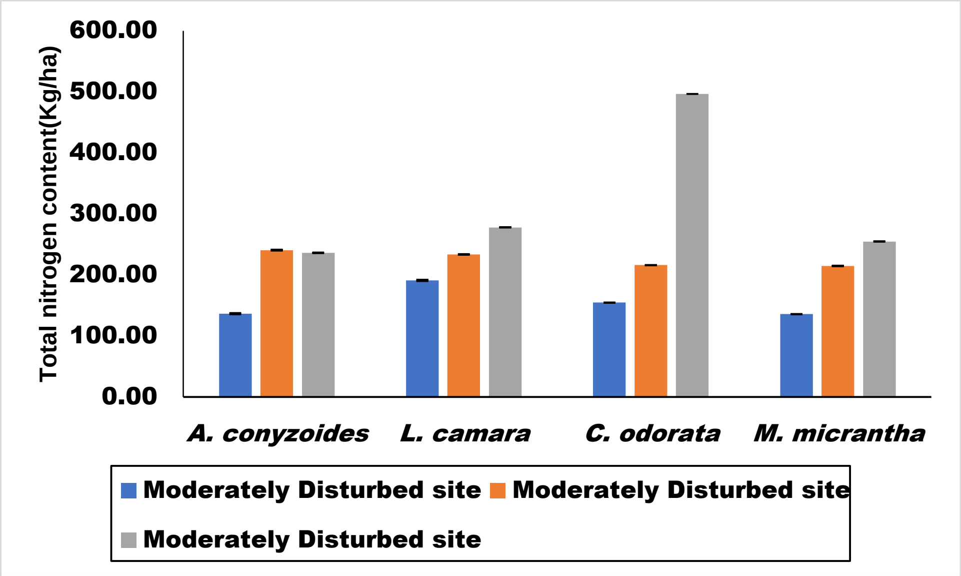


Figure 14. Seasonal variation in the total nitrogen content of soil in moderately disturbed study site

The total nitrogen content of the soil samples from the undisturbed study site ranged from 206.91 Kg/ha (*C. odorata* invaded soil, monsoon season) to 388.0 Kg/ha (*L. camara* invaded soil, pre - monsoon season). Therefore, the total nitrogen content during the study period (2019-2021) ranged from 206.91 Kg/ha to 388.0 Kg/ha. The total nitrogen content range was recorded lower in the monsoon season while it was observed highest during the pre-monsoon season.

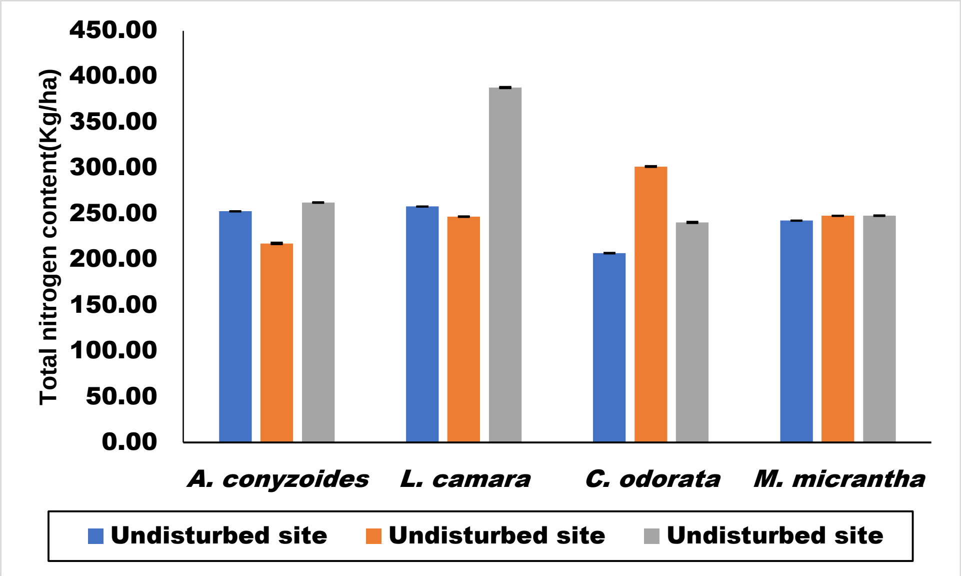


Figure 15. Seasonal variation in the total nitrogen content of soil in undisturbed study site

Available Phosphorous

The available phosphorous content of the soil samples from the disturbed study site ranged from 7.3 Kg/ha (*M. micrantha* invaded soil, monsoon season) to 72.4 Kg/ha (*L. camara* invaded soil, pre-monsoon season). Therefore, the available phosphorous during the study period (2019-2021) ranged from 7.3 Kg/ha to 72.4 Kg/ha. The available phosphorous range was recorded lowest in the monsoon season while it was observed highest during the in the pre-monsoon season.

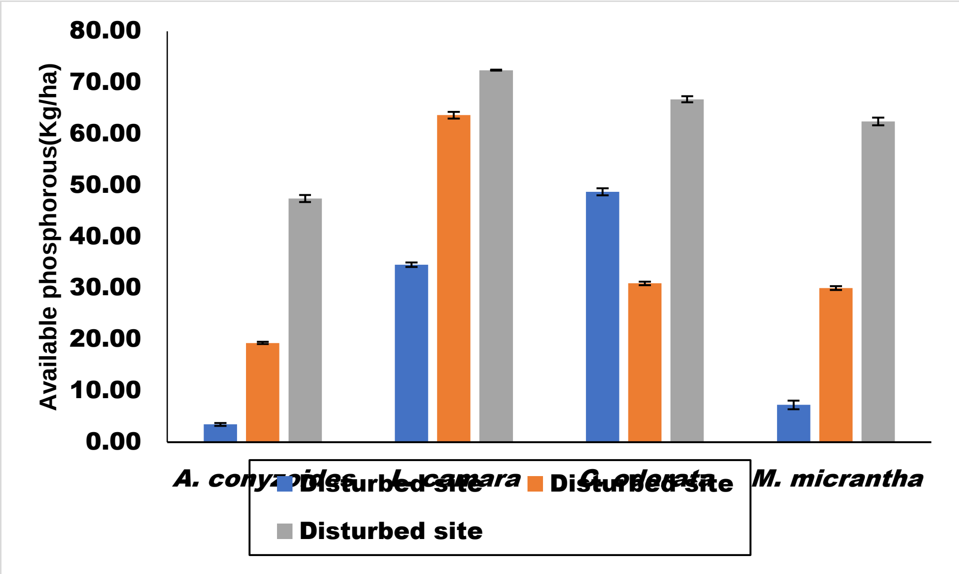


Figure 16. Seasonal variation in the available phosphorus content of soil in disturbed study site

The available phosphorous content of the soil samples from the moderately disturbed study site ranged from 4.065 Kg/ha (*C. odorata* invaded soil, monsoon season) to 173.1 Kg/ha (*M. micrantha* invaded soil, post-monsoon season). Therefore, the available phosphorous during the study period (2019-2021) ranged from 4.065 Kg/ha to 173.1 Kg/ha. The available phosphorous range was recorded lower in the monsoon season while it was observed highest during the in the pre-monsoon season.

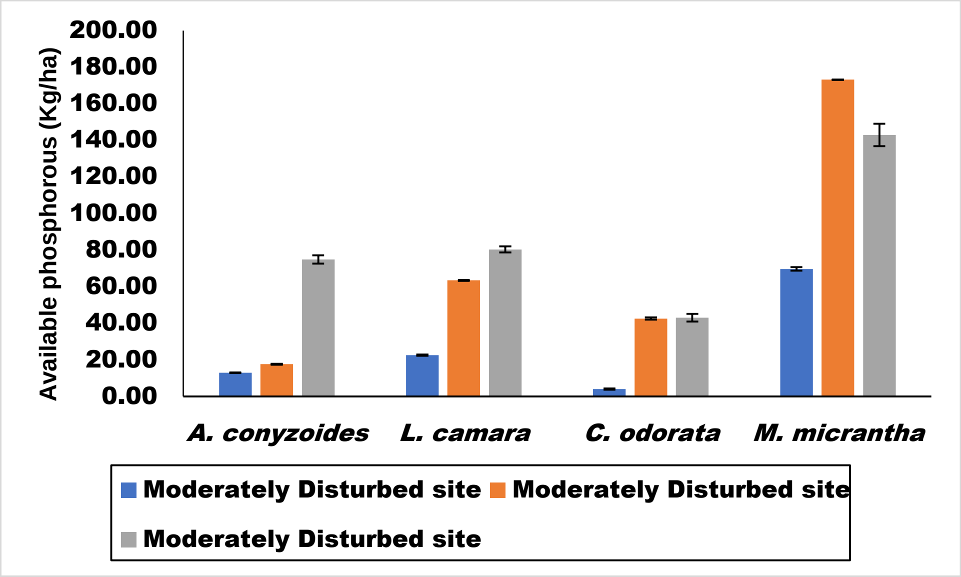


Figure 17. Seasonal variation in the available phosphorous content of soil in moderately disturbed study site

The available phosphorous content of the soil samples from the undisturbed study site ranged from 3.33 Kg/ha (*C. odorata* invaded soil, monsoon season) to 34.3 Kg/ha (*M. micrantha* invaded soil, pre-monsoon season). Therefore, the available phosphorous during the study period (2019-2021) ranged from 3.33 Kg/ha to 34.3 Kg/ha. The available phosphorous range was recorded lower in the monsoon season while it was observed highest during the in the pre-monsoon season.

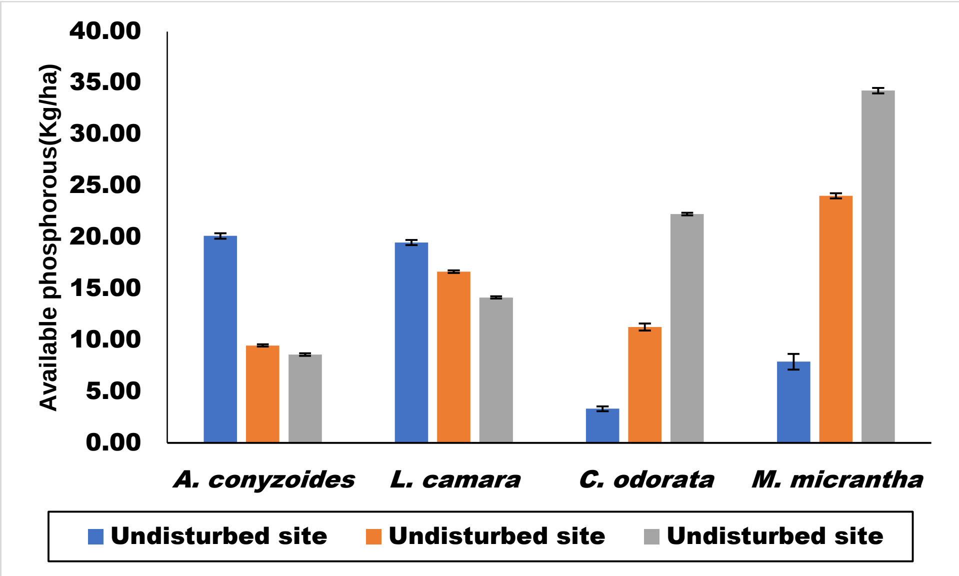


Figure 18. Seasonal variation in the available phosphorous content of soil in undisturbed site

Available Potassium

The available potassium content of the soil samples from the disturbed study site ranged from 47.45 Kg/ha (*A. conyzoides* invaded soil, pre-monsoon season) to 843.34 Kg/ha (*M. micrantha* invaded soil, monsoon season). Therefore, the available potassium during the study period (2019-2020) ranged from 47.45 Kg/ha to 843.34 Kg/ha. The available phosphorous range was recorded lowest in the pre-monsoon season while it was observed highest during in the monsoon season.

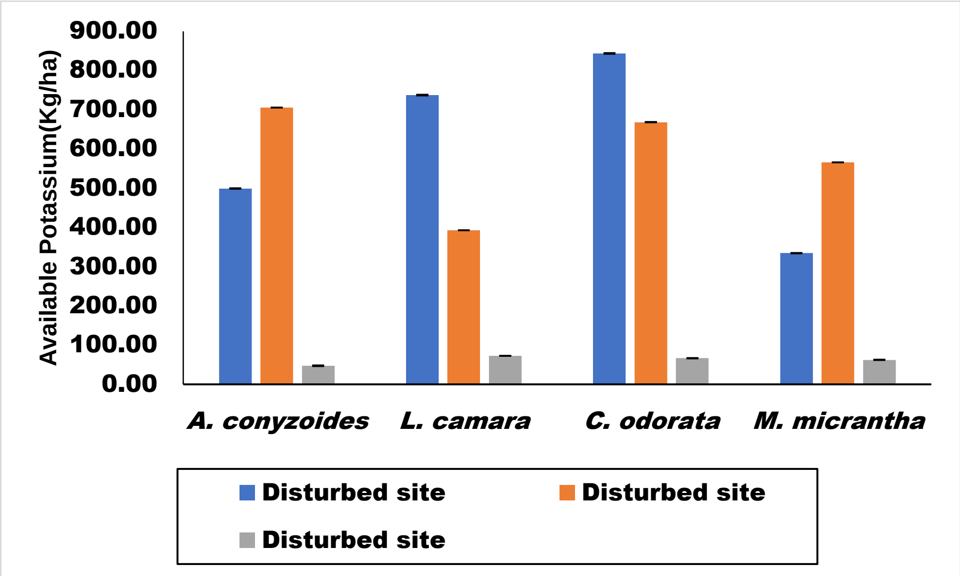


Figure 19. Seasonal variation in the available potassium content of soil in disturbed study site

The available potassium content of the soil samples from the moderately disturbed study site ranged from 43.0 Kg/ha (*C. odorata* invaded soil, pre-monsoon season) to 795.34 Kg/ha (L. camara invaded soil, post-monsoon season). Therefore, the available potassium during the study period (2019-2020) ranged from 43.0 Kg/ha to 795.34 Kg/ha. The available phosphorous range was recorded lower in the pre-monsoon season while it was observed highest during in the post-monsoon season.

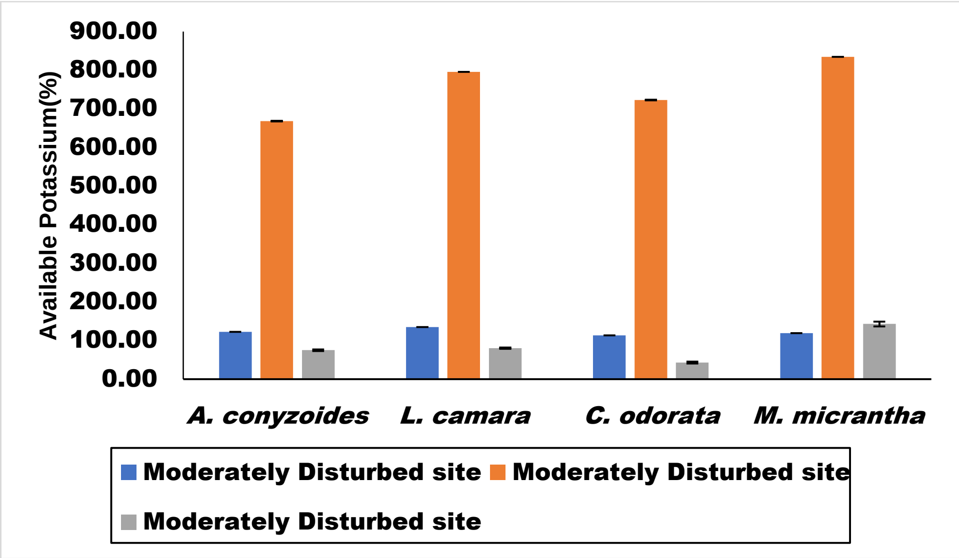


Figure 20. Seasonal variation in the available potassium content of soil in moderately disturbed study site

The available potassium content of the soil samples from the undisturbed study site ranged from 8.60 Kg/ha (*A. conyzoides* invaded soil, pre-monsoon season) to 733.1 Kg/ha (M. micrantha invaded soil, post-monsoon season). Therefore, the available potassium during the study period (2019-2020) ranged from 8.60 Kg/ha to 733.1 Kg/ha. The available phosphorous range was recorded lowest in the pre-monsoon season while it was observed highest during in the post-monsoon season.

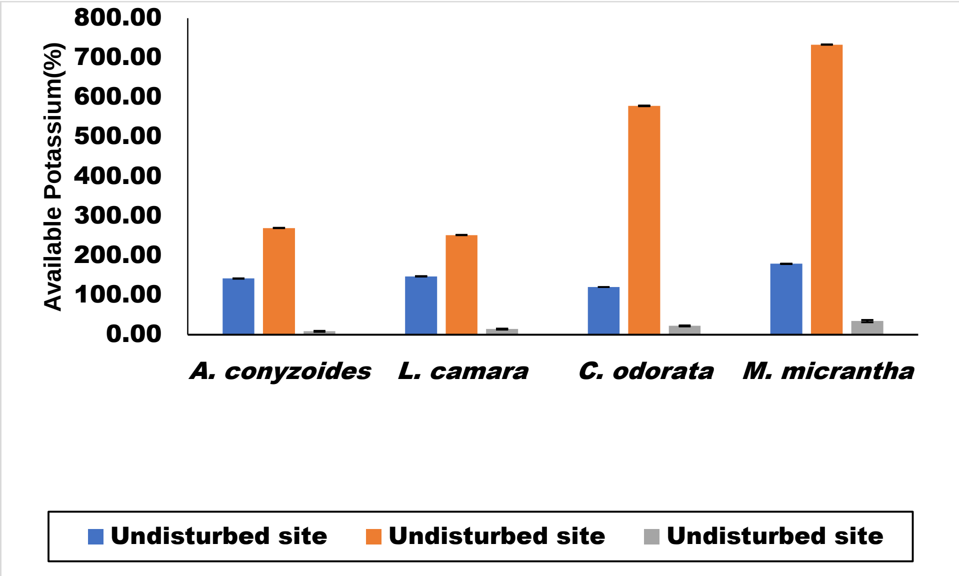


Figure 21. Seasonal variation in the available potassium content of soil in undisturbed study site

4.3 Plant Debris Soil Bioassay

The plant debris soil bioassay containing healthy/control soil sample and those from invaded soils of invasive alien plants *A. conyzoides*, *M. micrantha*, *L. camara* and *C. odorata* was tested against two edible crops, *Lactuca sativa* and *Cicer arietinum* during the study period of 2021- 2022 respectively. These food crops are widely used in bio-assay experiments due to their rapid response towards the allelochemicals.

4.3.1 *L. sativa*

Germination

A total of fifteen seeds were sown and the number of germinated seeds were observed on the third and seventh day, respectively. The highest number of germinations were recorded on the third day which was 14 for healthy/control soil while the lowest was counted 10 in case of *C. odorata* invaded soil. The highest number of germinations were observed on the seventh day which was 14 for healthy/control soil while the lowest was counted 6 in case of *C. odorata* invaded soil. Therefore, the number of germinations of *L. sativa* during the study period ranged from 6 (*C. odorata* invaded soil) to 14 (healthy/control soil).

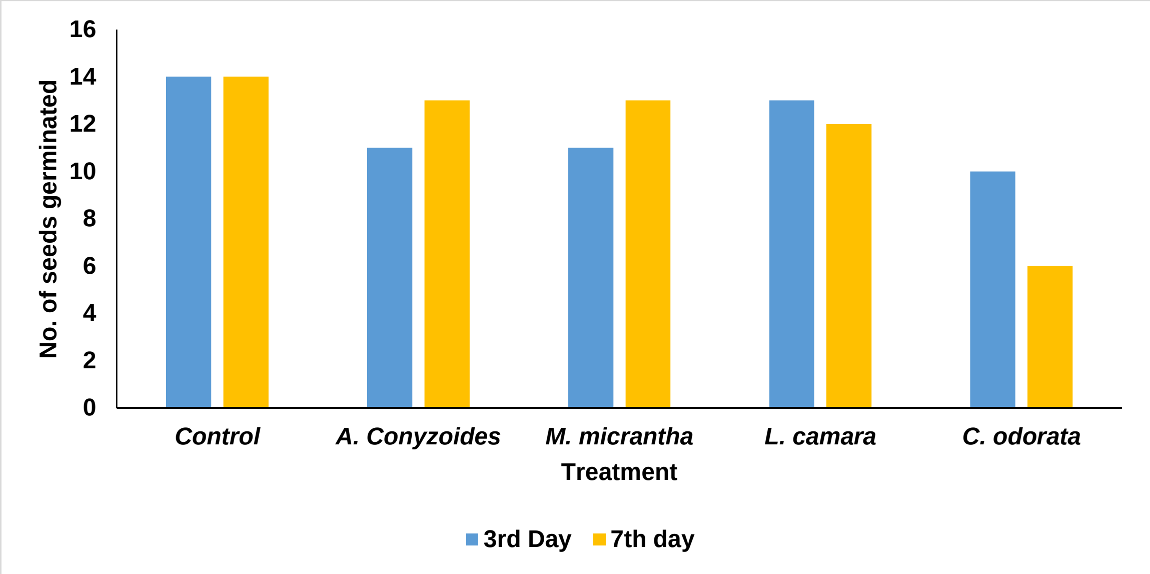


Figure 22. Variation in germination of *L. sativa* at different selected soil samples

Seedling height (H)

The highest seedling height was 32.35cm (*L. camara* invaded soil) and the lowest was 8.85cm (*M. micrantha* invaded soil). Therefore, the seedling height of *L. sativa* during the study period ranged from 8.85cm (*L. camara* invaded soil) to 32.35 cm (*M. micrantha* invaded soil).

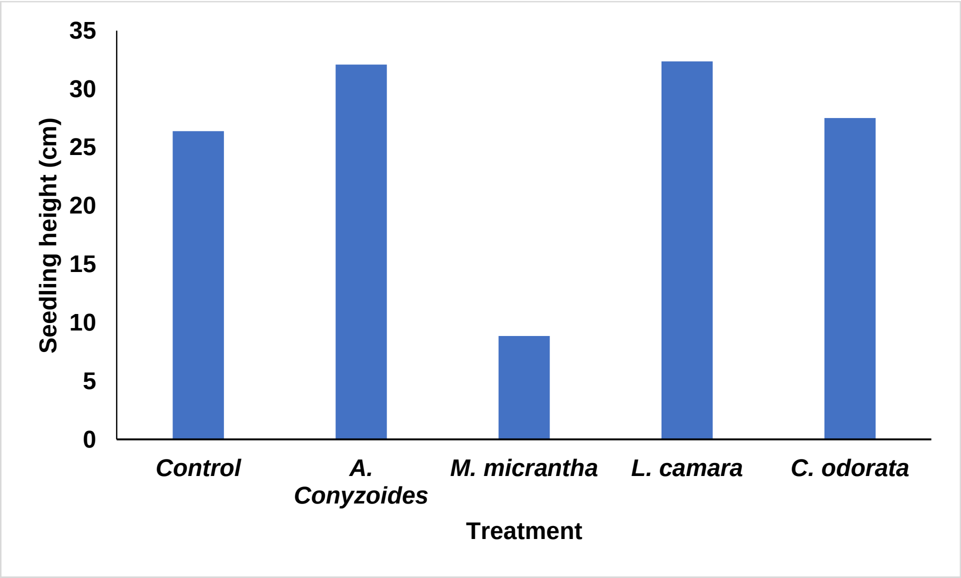


Figure 23. Variation in Seedling height of *L. sativa* at different selected soil samples

Root Length (RL)

The longest root length was 4.8cm (healthy/control soil) and the shortest root length was 0.091cm (*M. micrantha* invaded soil). Therefore, the root length of *L. sativa* during the study period ranged from 0.091cm (*M. micrantha* invaded soil) to 4.8cm (healthy//control soil).

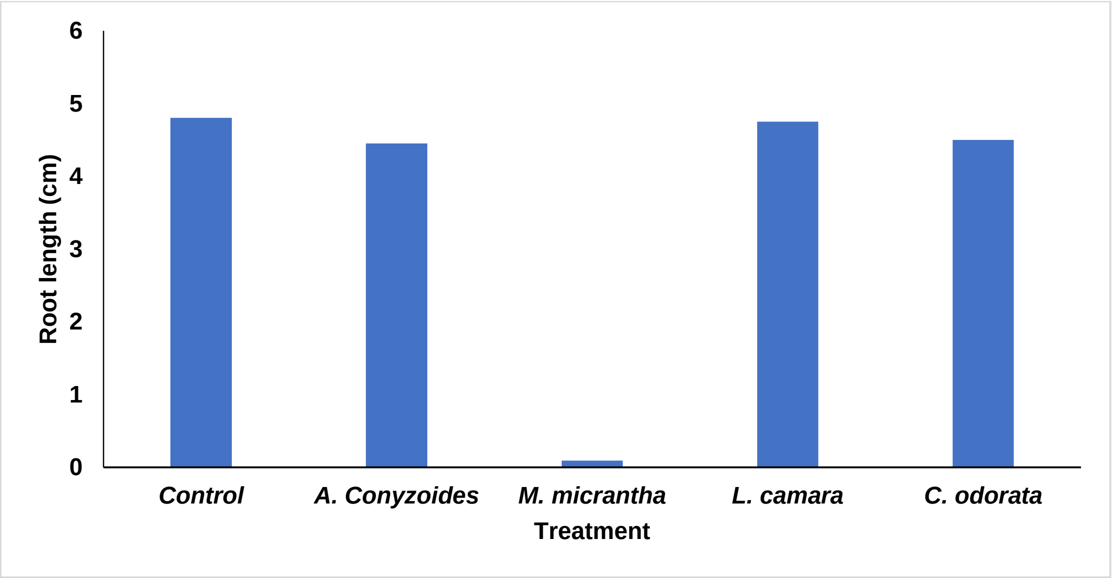


Figure 24. Variation in Root length of *L. sativa* in different selected soil samples

Shoot Length (SL)

The shoot length was longest i.e. 27.7 cm (*A. conyzoides* invaded soil) and the shortest was 8.76 cm (*M. micrantha* invaded soil). Therefore, the shoot length of *L. sativa* during the study period ranged from 8.76 cm (*M. micrantha* invaded soil) to 27.7 cm (*C. odorata* invaded soil).

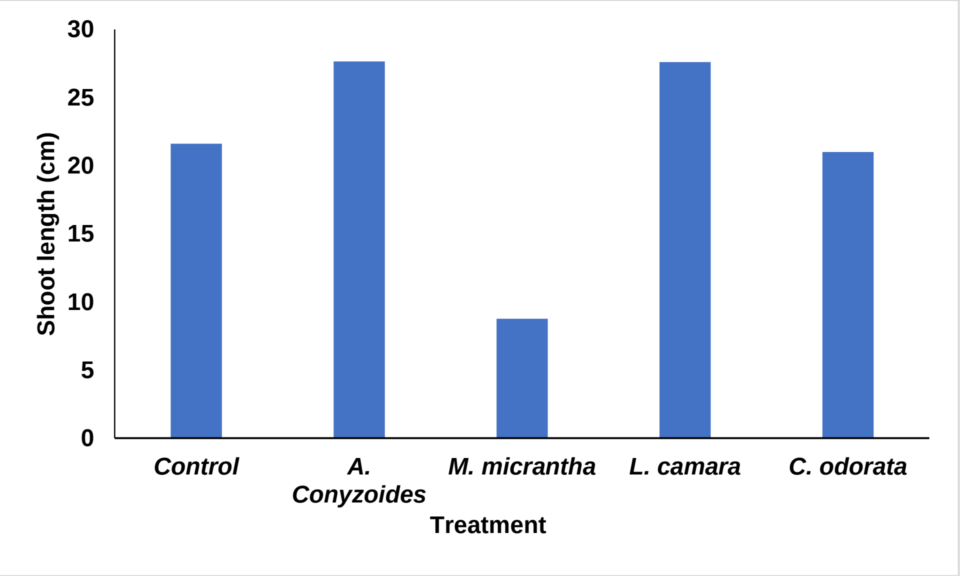


Figure 25. Variations in the Shoot length of *L. sativa* at different selected soil samples

Seedling biomass (B)

The highest seedling biomass was 1.87 g (*A. conyzoides* invaded soil) and the lowest seedling biomass was 0.41 g (*M. micrantha* invaded soil). Therefore, the seedling biomass of *L. sativa* during the study period ranged from 0.40 g (*M. micrantha* invaded soil) to 1.86 g (*A. conyzoides* invaded soil).

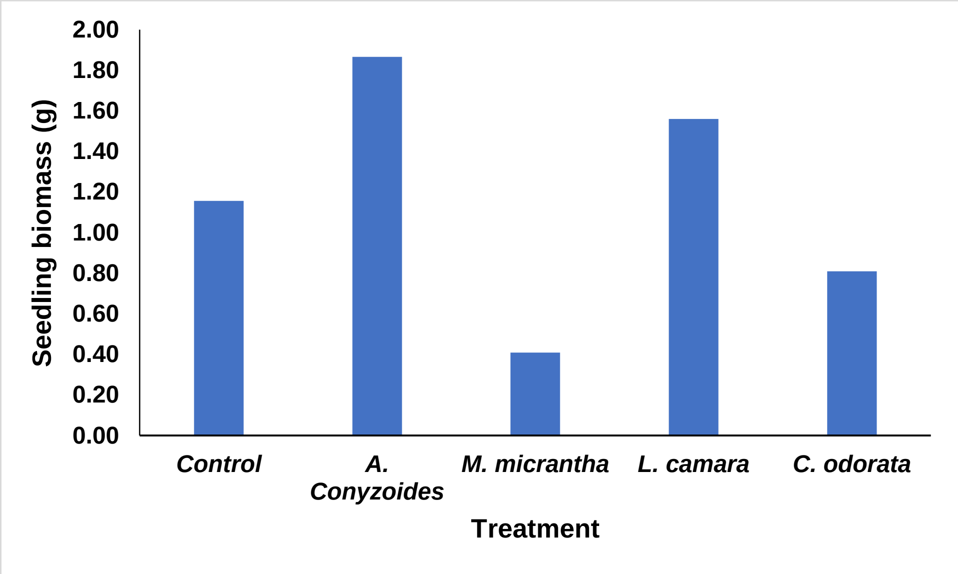


Figure 26. Variation in the Seedling Biomass of *L. sativa* in different selected soil samples

Germination Percentage (GPe)

The highest germination percentage was 93.33% (healthy/control soil) and the lowest was 40% (*C. odorata* invaded soil). Therefore, the germination percentage of *L. sativa* during the study period ranged from 40% (*C. odorata* invaded soil) to 93.33% (healthy/control soil).

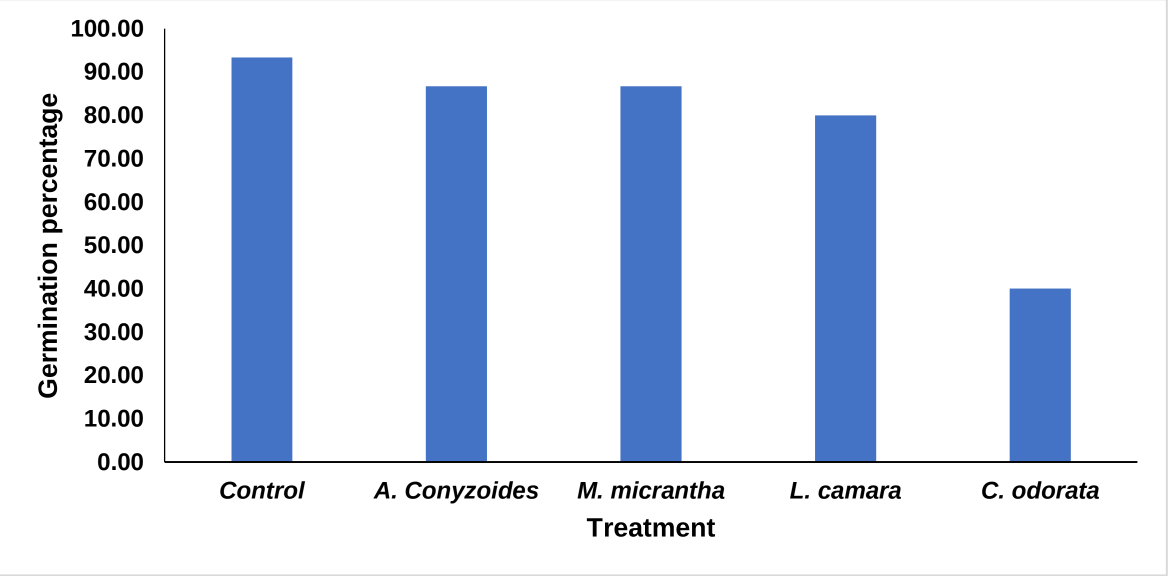


Figure 27. Variation in the Germination percentage of *L. sativa* at different selected soil samples

Germination Potential (GPo)

The highest germination potential was 0.93 (healthy/control soil) and the lowest germination potential was 0.67 (*C. odorata* invaded soil). Therefore, the germination potential of *L. sativa* during the study period ranged from 0.67 (*C. odorata* invaded soil) to 0.93 (healthy/control soil).

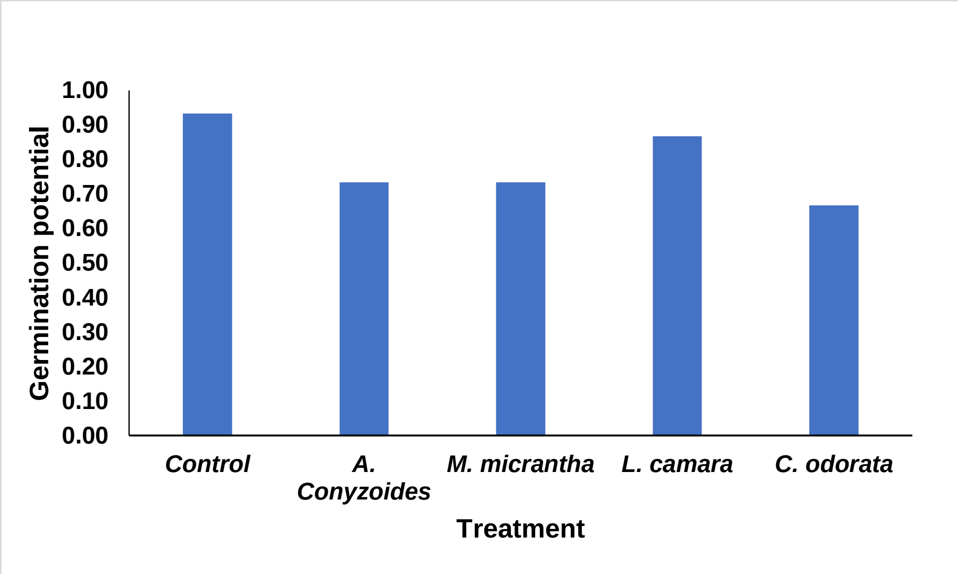


Figure 28. Variation in Germination Potential of *L. sativa* at different selected soil samples

Germination index (GI)

The highest germination index was 4.67 (healthy/control soil) and the lowest germination index was 3.33 (*C. odorata* invaded soil). Therefore, the germination index of *L. sativa* during the study period ranged from 3.33 (*C. odorata* invaded soil) to 4.67% (healthy/control soil).

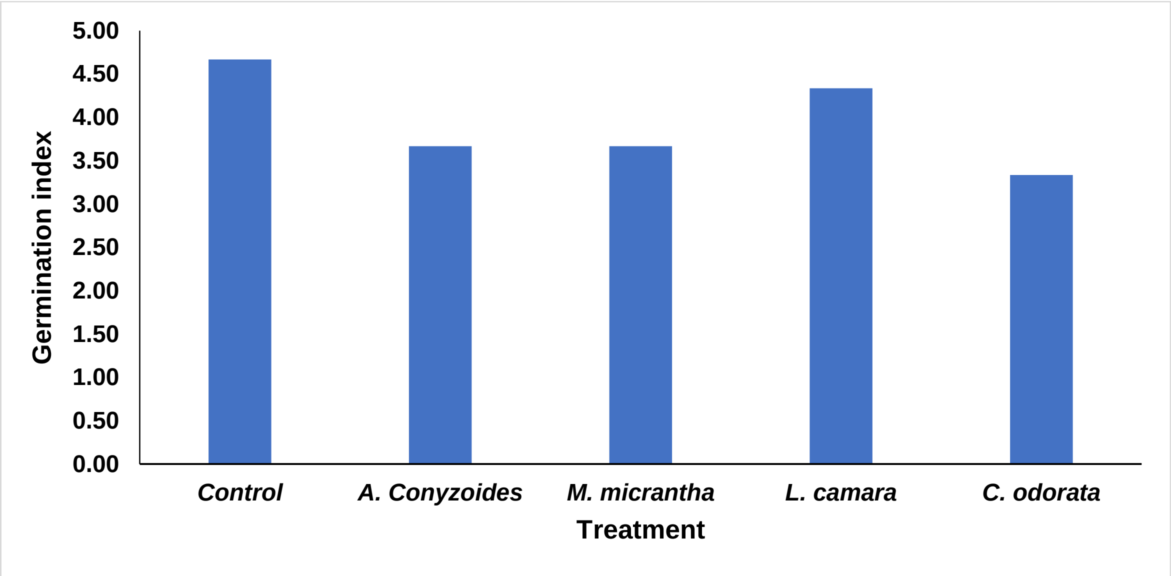


Figure 29. Variation in the Germination index of *L. sativa* at different selected soil samples

Germination rate index (GRI)

The highest germination rate index was 435.56 (healthy/control soil) and the lowest germination rate index was 133.33 (*C. odorata* invaded soil). Therefore, the germination rate index of *L. sativa* during the study period ranged from 133.33 (*C. odorata* invaded soil) to 435.56 (healthy/control soil).

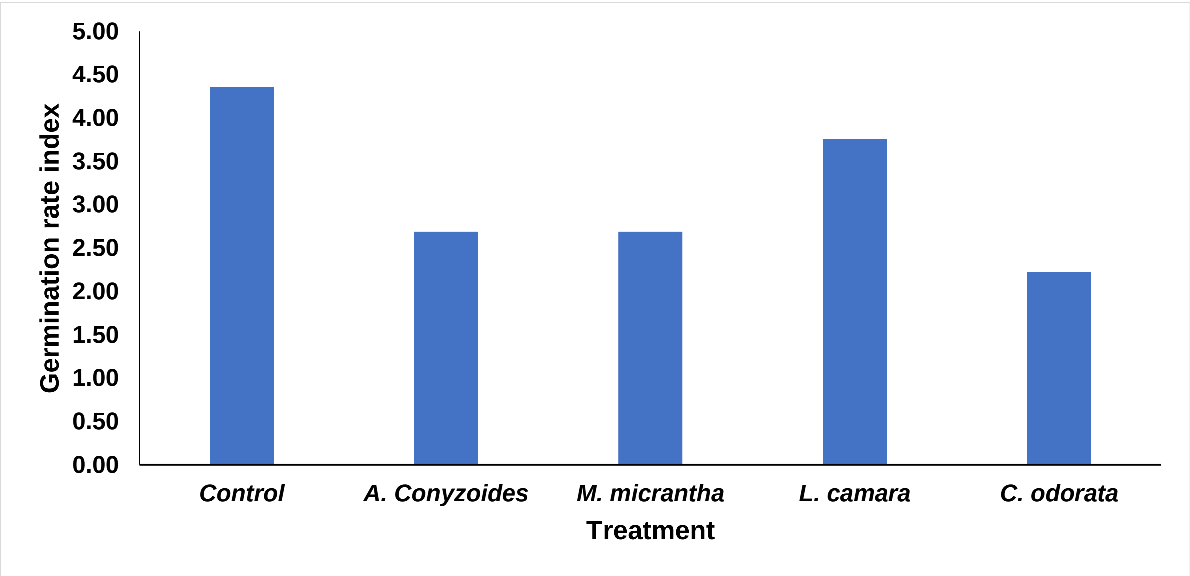


Figure 30. Variation in the Germination rate index of *L. sativa* at different selected soil samples

Vigor Index (VI)

The highest vigor index was 6.84 (*A. conyzoides* invaded soil) and the lowest was 1.50 (*M. micrantha* invaded soil). Therefore, the vigor index of *L. sativa* during the study period ranged from 1.50 (M. *micrantha* invaded soil) to 6.84 (A. *conyzoides* invaded soil).

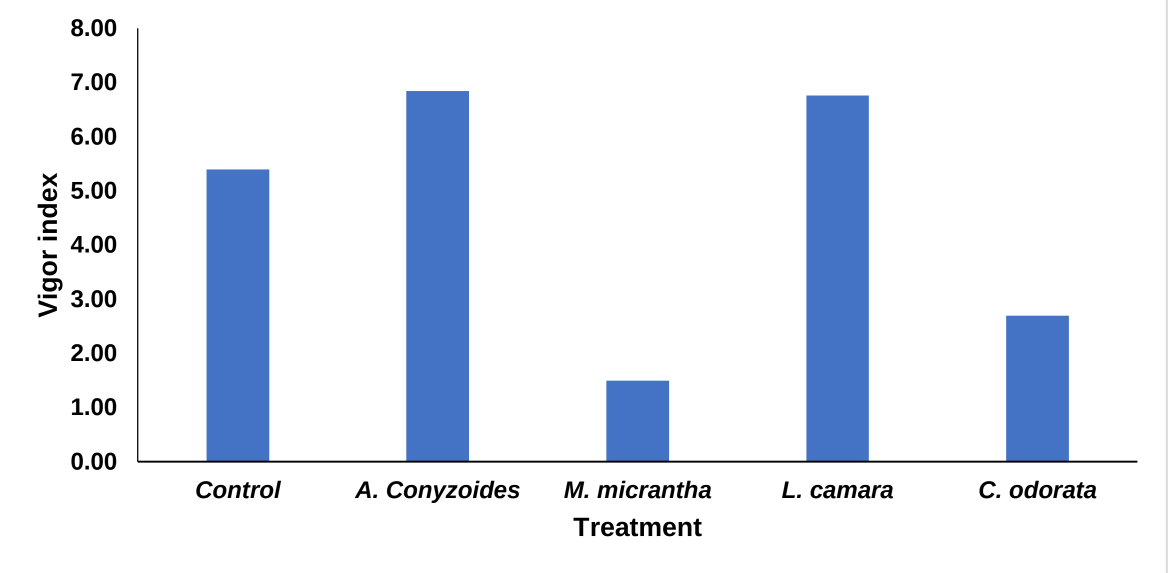


Figure 31. Variation in Vigor index of *L. sativa* at different selected soil samples

4.3.2 *C. arietinum*

Germination

A total of five seeds were sown and the number of germinations was observed on the third and seventh day respectively.

The highest number of germinations were recorded on the third day which was 5 for *C. odorata* invaded soil and the lowest was counted 2 in case of healthy/control soil. The highest number of germinations were observed on the seventh day was 4 for *A. conyzoides*, *M. micrantha* and *C. odorata* invaded soil respectively while the lowest was counted 3 in case of healthy/control soil and *L. camara* invaded soil. Therefore, the number of germinations of *C. arietinum* during the study period ranged from 2 (healthy/control soil) to 5 (*C. odorata* invaded soil).

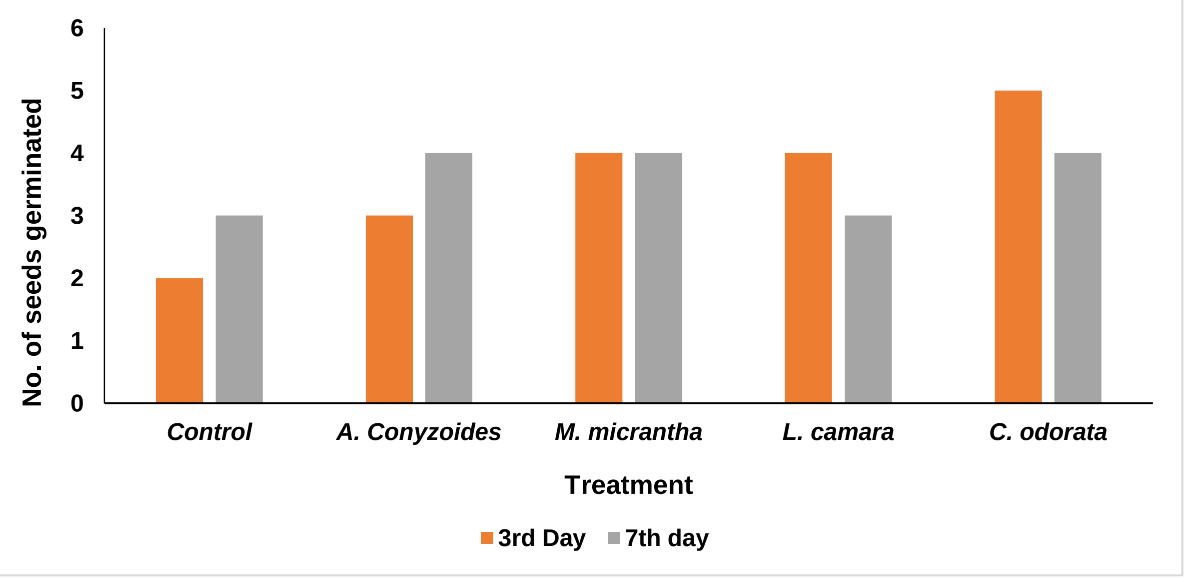


Figure 32. Variations in the germination of *C. arietinum* at different selected soil samples

Seedling Height (H)

The highest seedling height was 42.47 cm (*C. odorata* invaded soil) and the lowest was 27.4 cm (*M. micrantha* invaded soil). Therefore, the seedling height of *C. arietinum* during the study period ranged from 27.4 cm (*M. micrantha* invaded soil) to 42.47 cm (*C. odorata* invaded soil).

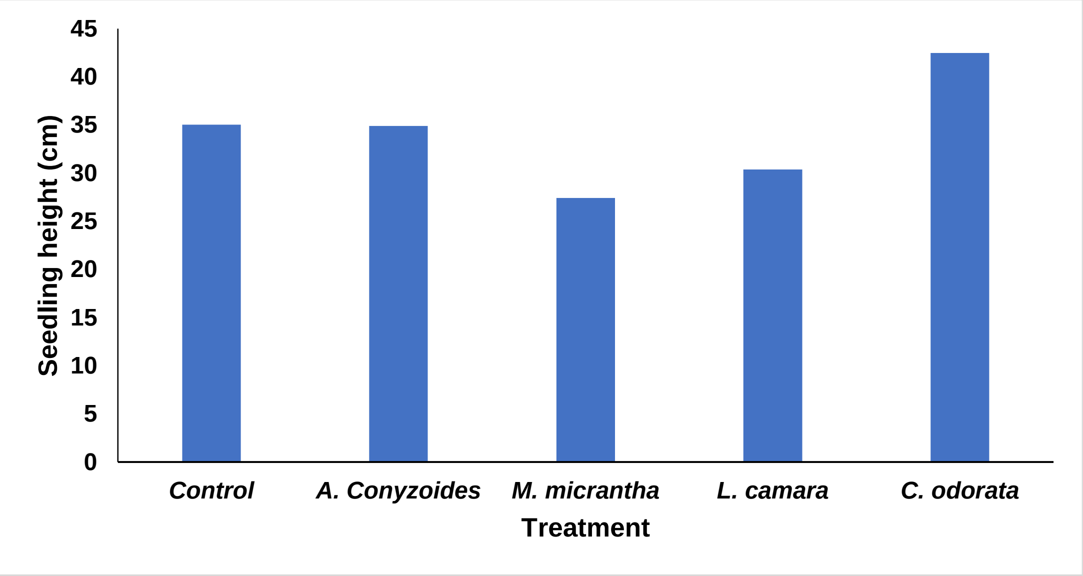


Figure 33. Variations in seedling height of *C. arietinum* at different soil samples

Root Length (RL)

The longest root length was 8.2 cm (*C. odorata* invaded soil) and the shortest root length was 3.42 cm (*L. camara* invaded soil). Therefore, the root length of *C. arietinum* during the study period ranged from 3.42 cm (*L. camara* invaded soil) to 8.2 cm (*C. odorata* invaded soil).

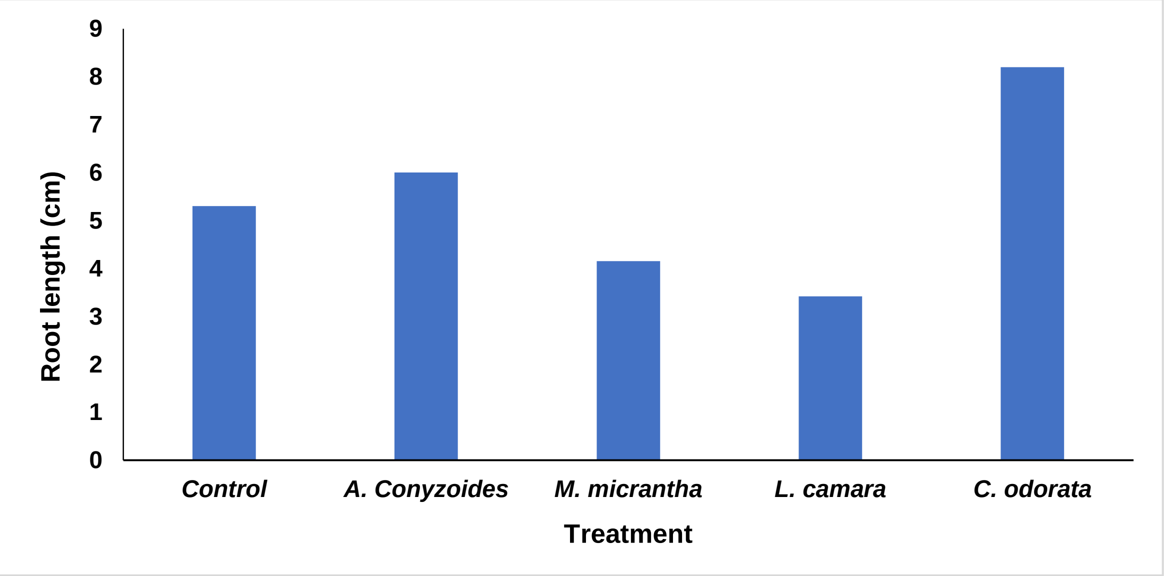


Figure 34. Variations in root length of *C. arietinum* at different selected soil samples

Shoot Length (SL)

The longest shoot length was 34.63 cm (*C. odorata* invaded soil) and the shortest was 23.22 cm (*M. micrantha* invaded soil). Therefore, the shoot length of *C. arietinum* during the study period ranged from 23.22 cm (*M. micrantha* invaded soil) to 34.63 cm (*C. odorata* invaded soil).

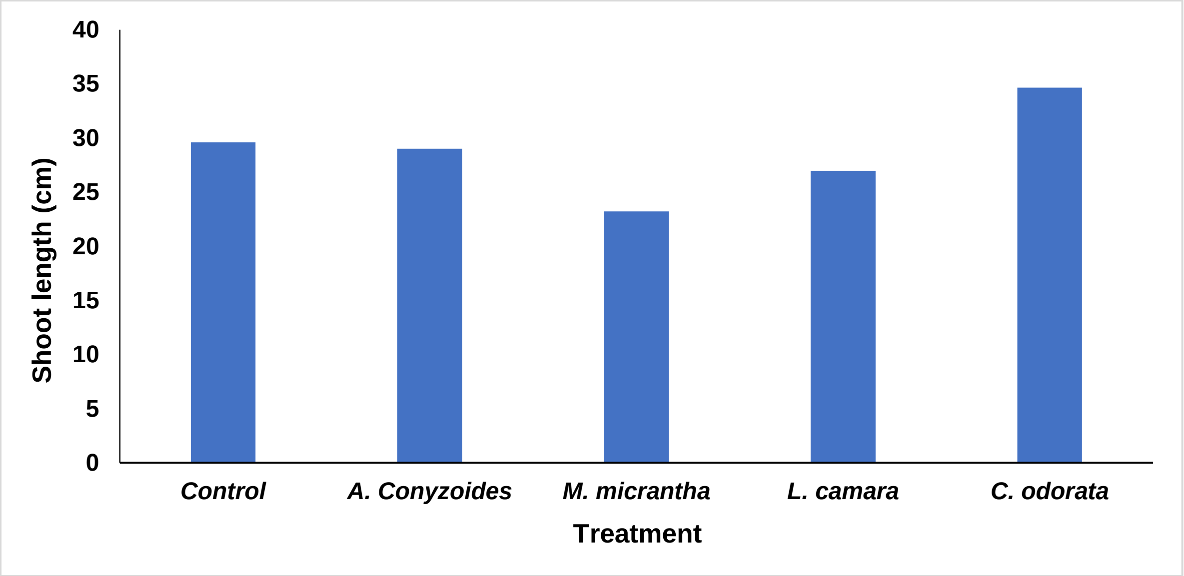


Figure 35. Variations in shoot length of *C. arietinum* at different selected soil samples

Seedling Biomass (B)

The seedling biomass was measured with the help of a weighing balance. The highest seedling biomass was 1.49 gm (*C. odorata* invaded soil) and the lowest seedling biomass was 0.38 gm (*M. micrantha* invaded soil). Therefore, the seedling biomass of *C. arietinum* during the study period ranged from 0.38 gm (*M. micrantha* invaded soil) to 1.49 gm (*C. odorata* invaded soil).

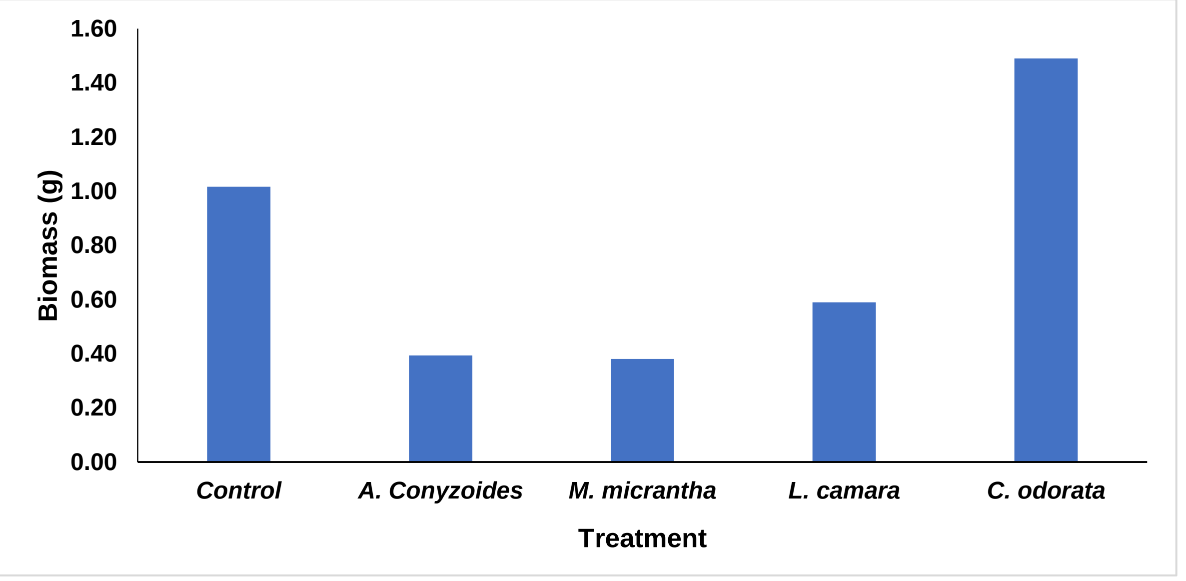


Figure 36. Variation in seedling biomass of *C. arietinum* in different selected soil samples

Germination Percentage (GPe)

The highest germination percentage was 80% (*A. conyzoides*, *M. micrantha* and *C. odorata* invaded soil) and the lowest was 60% (Healthy/control soil and *L. camara* invaded soil). Therefore, the germination percentage of *C. arietinum* during the study period ranged from 60% (Healthy/control soil and *L. camara* invaded soil) to 80% (*A. conyzoides*, *M. micrantha* and *C. odorata* invaded soil).

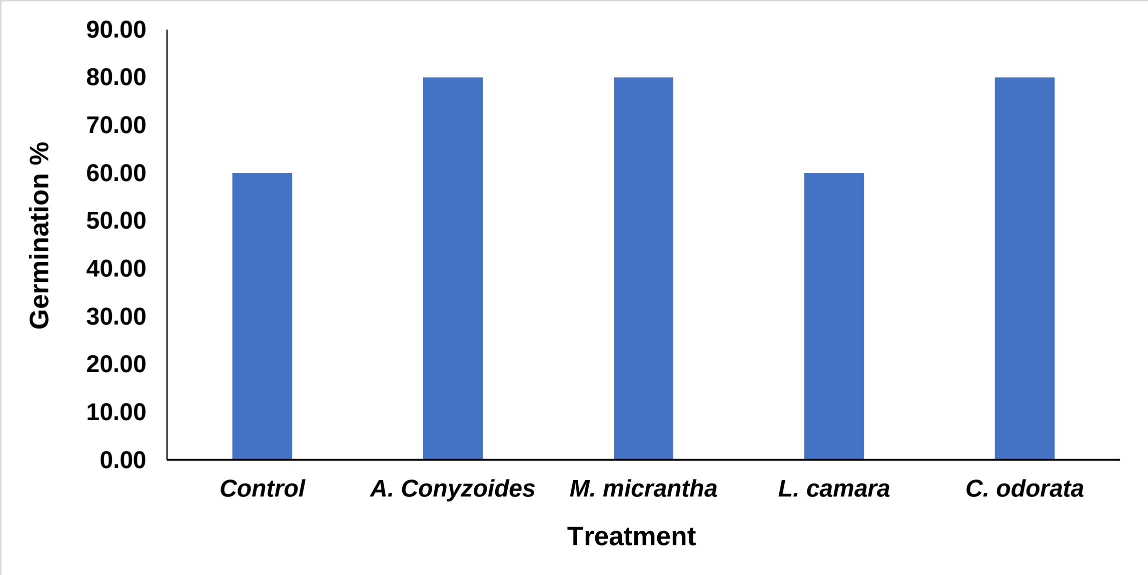


Figure 37. Variation in germination percentage of *C. arietinum* at different selected soil samples

Germination Potential (GPo)

The highest germination potential was 1% (*C. odorata* invaded soil) and the lowest germination potential was 0.4% (healthy/control soil). Therefore, the germination potential of *C.arietinum* during the study period ranged from 0.4% (healthy/control soil) to 1% (*C. odorata* invaded soil).

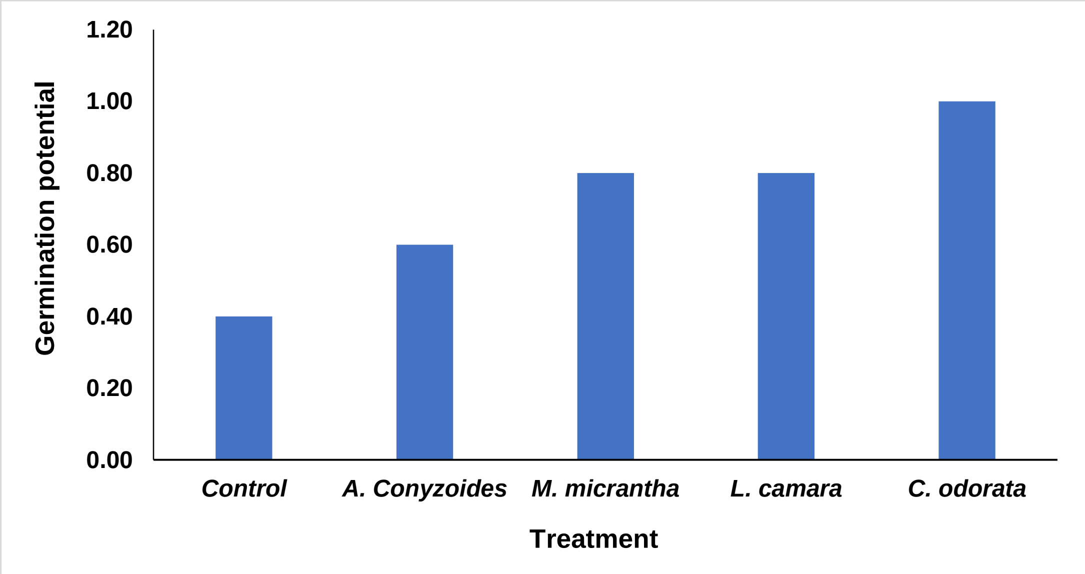


Figure 38. Variation in germination potential of *C. arietinum* at different selected soil samples

Germination index (GI)

The highest germination index was 1.67% (*C. odorata* invaded soil) and the lowest germination index was 0.67 % (healthy/control soil). Therefore, the germination index of *C. arietinum* during the study period ranged from 0.6% (healthy/ control soil) to 1.67% (*C. odorata* invaded soil).

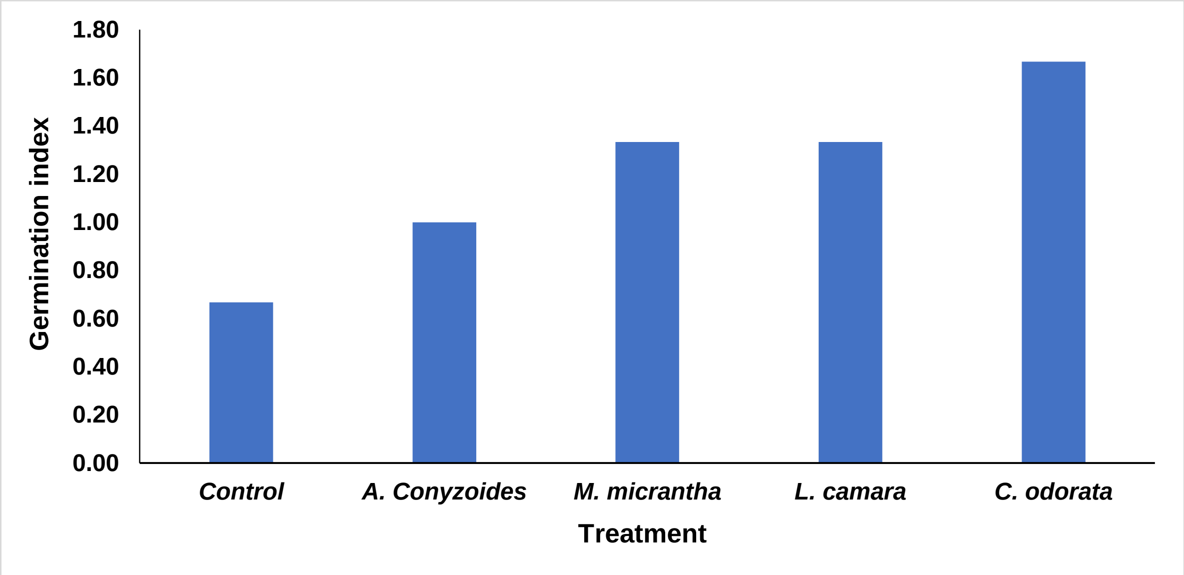


Figure 39. Variation in Germination Index of *C. arietinum* at different selected soil samples

Germination rate index (GRI)

The highest germination rate index was 133.33 (*C. odorata* invaded soil) and the lowest germination rate index was 40 (healthy/control soil). Therefore, the germination rate index of *C. arietinum* during the study period ranged from 40 (healthy/control soil) to 133.33 (*C. odorata* invaded soil).

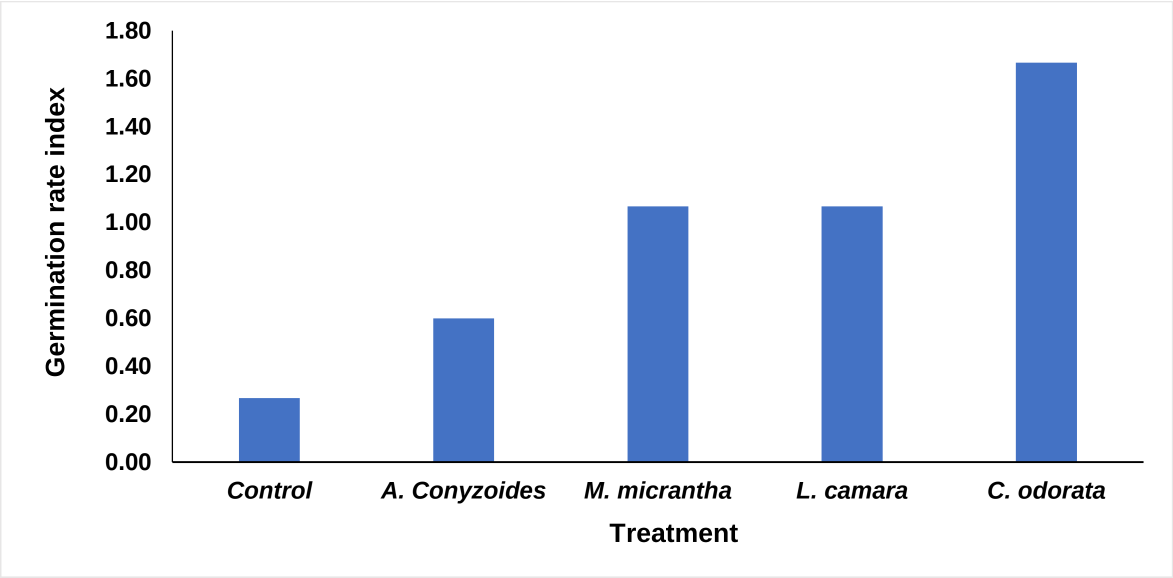


Figure 40. Variation in germination rate index of *C. arietinum* at different selected soil samples

Vigor Index (VI)

The highest vigor index was 2.48 (*C. odorata* invaded soil) and the lowest was 0.39 (*A. conyzoides* invaded soil). Therefore, the vigor index of *C. arietinum* during the study period ranged from 0.39 (*A. conyzoides* invaded soil) to 2.48 (*C. odorata* invaded soil).

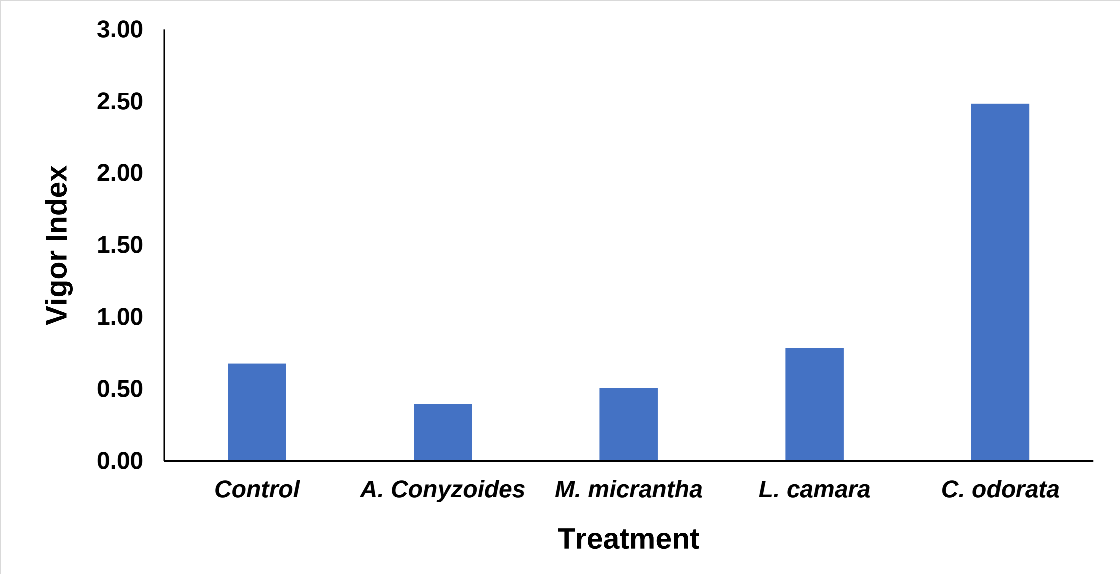


Figure 41. Variation in vigor index of *C. arietinum* at different selected soil samples

4.4 Total phenolic content (TPC) estimation

The total phenolic contents of both soil and leaf extracts were tested by Catechol and Gallic acid at different wavelengths.

Test by Catechol

Analysis of soil samples through catechol standard revealed that the total phenolic content was estimated highest (0.196 µg/mL) in case of *C. odorata* invaded soil while the lowest concentration was calculated 0.012 µg/mL in case of *M. micrantha* infested soil. Therefore, the total phenolic concentration of the soil extracts ranged from 0.012 µg/mL in *M. micrantha* invaded soil to 0.196 µg/mL in case of *C. odorata* infested soil.

Analysis of leaf samples through catechol standard revealed that the total phenolic content was estimated highest (3.71 µg/mL) in case of *L. camara* leaves while the lowest concentration was calculated 3.26 µg/mL in *M. micrantha* leaves.. Therefore, the total phenolic concentration of the leaf extracts ranged from 3.26 µg/mL in *M. micrantha* leaf extract to 3.71 µg/mL in case of *L. camara* leaf extract.

Table 5. Estimation of total phenolic contents by Catechol

Species	Soil	Leaf
	Concentration µg/mL	**Concentration µg/mL**
M. micrantha	0.012±0.00	3.26±0.05
A. conyzoides	0.052±0.00	3.68±0.00
C. odorata	0.196±0.001	3.66±0.002
L. camara	0.076±0.002	3.71±0.006

Each value represent the mean (±standard deviation) of three replicates

Test by Gallic Acid

Analysis of soil extract through gallic acid standard revealed that the total phenolic content was estimated highest (0.04 µg/mL) in case of *L. camara* invaded soil while the lowest concentration was calculated 0.001µg/mL in *M. micrantha,A. conyzoides*, and *C. odorata* infested soil. Therefore, the total phenolic concentration of the soil extracts ranged from 0.001 µg/mL in *M. micrantha,A. conyzoides,* and *C. odorata* infested soil to 0.04 µg/mL in case of *L. camara* infested soil.

Analysis of leaf extract through gallic acid standard revealed that the total phenolic content was estimated highest (68.947 µg/mL) in case of C. odorata leaves while the lowest concentration was calculated 13.52 µg/mL in M. micrantha leaves.. Therefore, the total phenolic concentration of the leaf extracts ranged from 13.52 µg/mL in *M. micrantha* leaf extract to 68.947µg/mL in case of *C. odorata* leaf extract.

Table 6. Estimation of total phenolic content by Gallic Acid (GAE denotes Gallic acid equivalent)

Species	Soil µg/mL GAE	Leaf µg/mL GAE
M. micrantha	0.01±0.00	13.52±0.01
A. conyzoides	0.01±0.00	34.64±0.07
C. odorata	0.01±0.01	68.947±0.04
L. camara	0.04±0.01	33.65±0.03

Each value represent the mean (±standard deviation) of three replicates

4.5 Canopy openness, Leaf Area Index (LAI), and Light Intensity

The canopy openness at the disturbed study site was 87.42% with incoming PAR at 1228.2 ± 57.14 μ mol m^{-2} s^{-1} and diffused PAR at 562.6 ± 368.38 μ mol m^{-2} s^{-1} and the total LAI was 1.65±1.30.

The canopy openness at the moderately disturbed site was 25.92% with incoming PAR at 1355.6±195.93 μ mol m^{-2} s^{-1} and diffused PAR at 206.2±62.01 μ mol m^{-2} s^{-1} and the total LAI was 3.20±0.36.

The canopy openness at the undisturbed site was 37.24% with incoming PAR at 400.8±66.49 μ mol m^{-2} s^{-1} and diffused PAR at 29.6±7.09 μ mol m^{-2} s^{-1} and the total LAI was 4.36±0.43.

Table 7. Canopy openness, Leaf area index and light intensity of Disturbed,Moderately disturbed and Undisturbed study sites

Site Name	Coordinate	Elevation (m)	Incoming PAR (μ mol m^{-2} s^{-1})	Diffused PAR (μ mol m^{-2} s^{-1})	Leaf Area Index	Canopy Openness (%)
Disturbed	N23°43'11.06" E092°41'50.71"	944	1203	1078	0.18	92.61
			1211	777	0.74	98.13
			1330	338	2.28	79.26
			1199	147	3.49	68.33
			1198	473	1.55	98.76
Mean ±SD			**1228.2±57.14**	**562.6±368.38**	**1.65±1.30**	**87.42±13.24**
Moderately Disturbed	N23°44'30.98" E092°41'20.82"	927	1475	255	2.92	30.36
			1008	103	3.80	23.55
			1440	233	3.03	22.49
			1450	245	2.96	26.73
			1405	195	3.29	26.45
Mean ±SD			**1355.6±195.93**	**206.2±62.01**	**3.20±0.36**	**25.92±3.08**
Undisturbed	N23°42'40.34" E092°42'10.24"	778	411	37	4.00	56.66
			493	30	4.66	28.66
			353	36	3.80	33.16
			425	24	4.79	33.31
			322	21	4.54	34.42
Mean ±SD			**400.8±66.49**	**29.6±7.09**	**4.36±0.43**	**37.24±11.08**

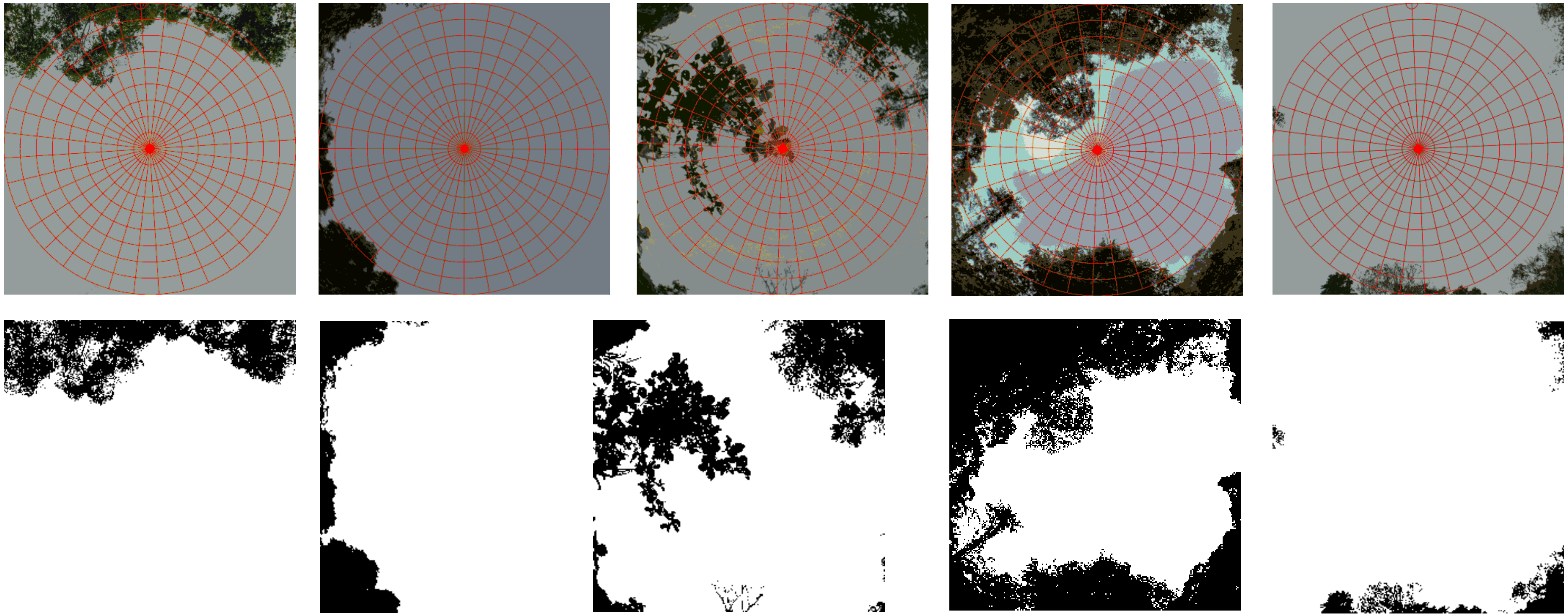


Figure 42. Hemispherical photos used for estimation of canopy openness in the Disturbed site. The colour photos are the original photos taken and the monochrome photos are the processed photos (after adjusting the settings) used for analysing canopy openness on GLA.

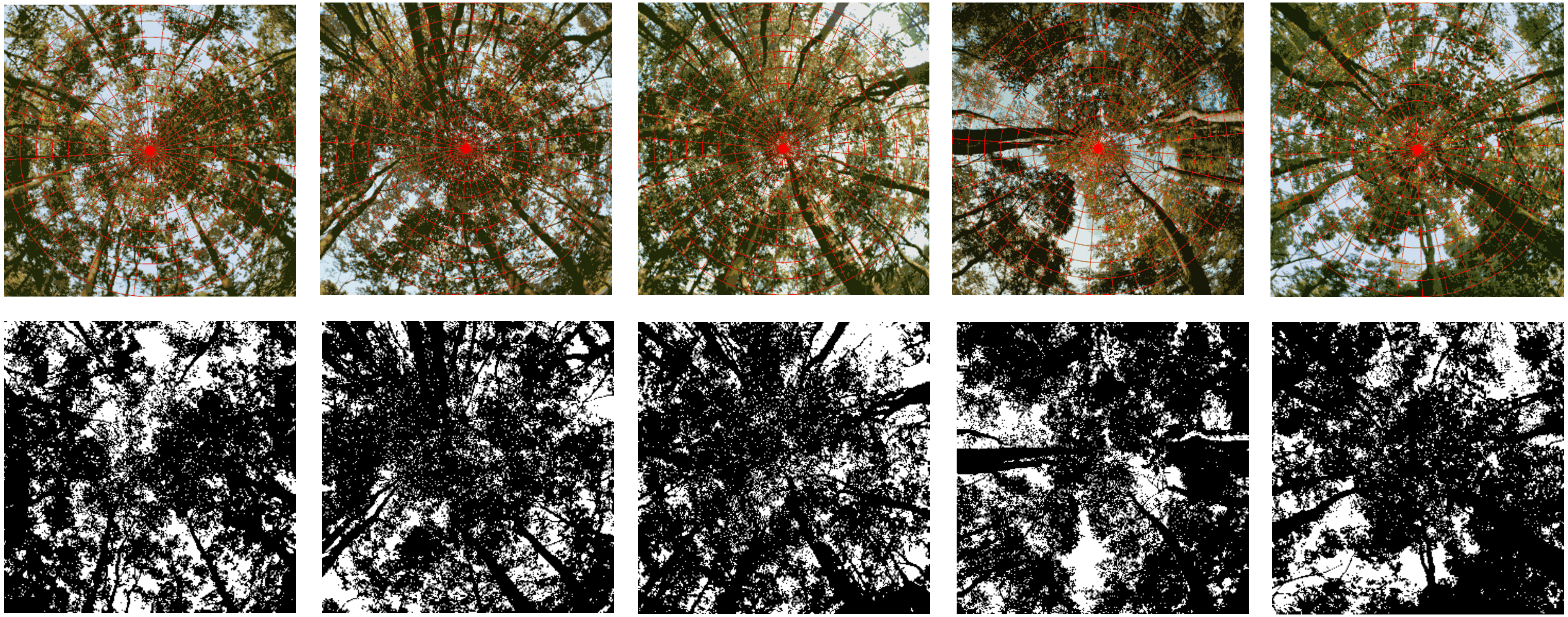


Figure 43. Hemispherical photos used for estimation of canopy openness in the Moderately disturbed site. The colour photos are the original photos taken and the monochrome photos are the processed photos (after adjusting the settings) used for analysing canopy openness on GLA.

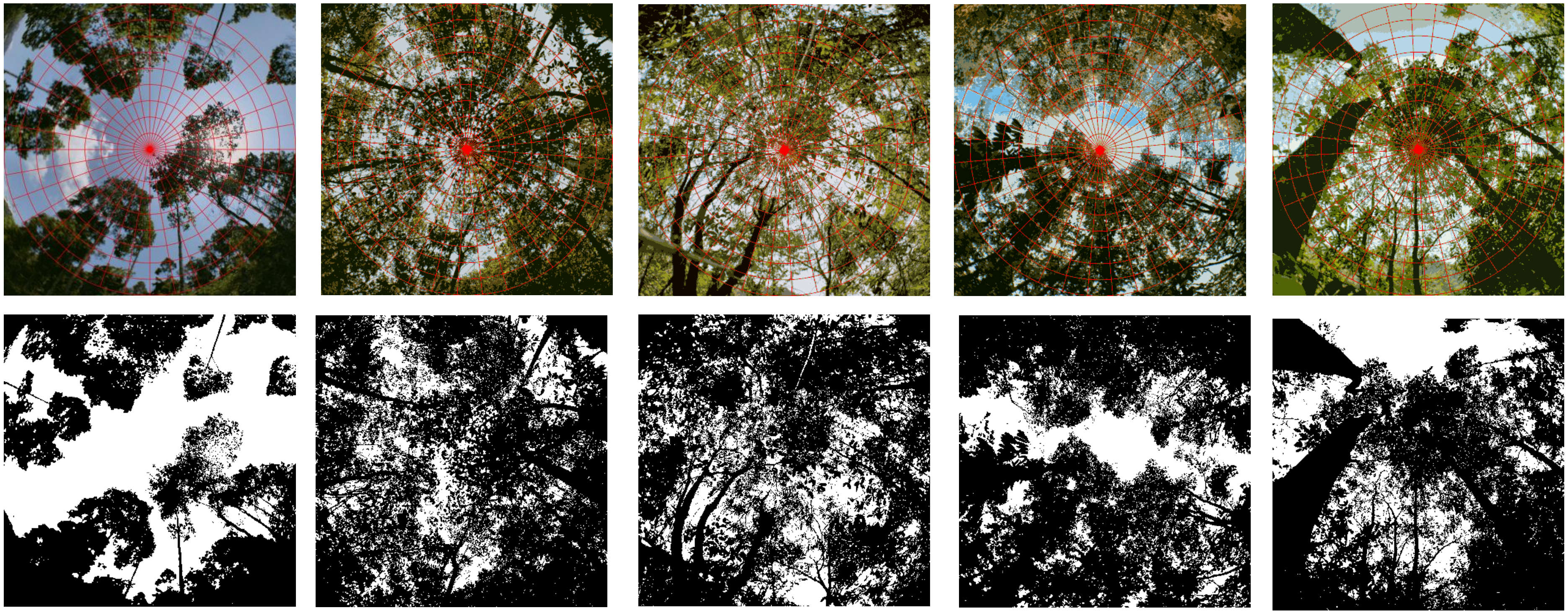


Figure 44. Hemispherical photos used for estimation of canopy openness in the Undisturbed site. The colour photos are the original photos taken and the monochrome photos are the processed photos (after adjusting the settings) used for analysing canopy openness on GLA.

CHAPTER- 5
DISCUSSION

5. DISCUSSION

5.1. Assessment of Phytosociological Parameters

Phytosociological attributes are of paramount relevance in assessing the effects of invasive alien plants on the existing native plants. Phytosociology is the 'discipline of vegetation science that focuses on the current plant collection at the resolution of vegetation stands and its primary goals are to establish and identify vegetation types based on the whole floristic composition of vegetation plots' (Dengler *et al.* 2017). The essential data record for phytosociology 'the relevé' is the layout that depicts a vegetation stand and contains a list of all plant taxa, their distribution across vertical strata, and their cover-abundance (Mueller-Dombois and Ellenberg, 1974; Dengler, 2007;).

The study on phytosociological attributes of all species at the three sites revealed the varying degrees of dispersion and species with low important value index indicated that they were of rare occurrence at the selected study sites. In the present study, the number of individuals of different species was recorded maximum at the moderately disturbed site (1158) which was in accordance with the 'Intermediate Disturbance Hypothesis' (IDH) which states that a moderate level of disturbance gives an equal opportunity for each and every plant individual to flourish (Roxburgh *et al*. 2004; Willig *et al*. 2017). Whereas, the undisturbed site (146) provides opportunities to few dominant plant individuals therefore they have recorded lesser number of individuals compared to disturbed sites (595).

5.1.1 Diversity indices

The difference in species diversity between communities generally results from variations in site quality (Denslow, 1980). The maximum diversity index using Shannon-Weiner diversity index was observed at the disturbed site (2.54), followed by the moderately disturbed site (2.47) and the undisturbed site showed the lowest diversity index (2.42). Shannon-Weiner diversity index was calculated with almost similar values at the sites along the disturbance gradient. The higher values of the species diversity index indicate the variability in the type of species and heterogeneity in the communities, whereas the lesser values point to the homogeneity in the community (Kohli *et al*. 2004). The decrease in species diversity depended on the complex interactions and variations among the species found within the community in response to disturbance factors (Hejda *et al*. 2009).

The species richness is one of the major criteria and reflect the number of individuals belonging to a particular species, thereby recognizing its dominance and hence important for conservation priorities. The Margalef's index-based species richness was highest at the undisturbed site (4.62), followed by the disturbed site (3.6) and the moderately disturbed site (3.2) has the lowest species richness. The decrease in species richness in the study sites depended on the types of plant species found within the community and species-specific differences in cover between the species (Hejda *et al*. 2009). The species richness was found to be lower at invaded sites (disturbed and moderately disturbed sites) when compared with the undisturbed areas (Kohli *et al*. 2004). The lower species richness at disturbed and moderately disturbed sites is attributed to the high population density of invasive alien plants which suppress the growth of neighboring native plants, thereby reducing the species richness. Similar findings were observed in the study of Mollot *et al*. (2017) who also found that presence of invasive alien plants leads to decline in species richness of invaded habitat. Another study in this respect noted that anthropogenic disturbances often increased the abundance of invasive alien plants, especially in the Indian tropical wet forests (Mungi *et al*. 2021).

Pielou's evenness index is a way to measure how evenly the species are distributed in a community. Evenness index is a vital parameter to adequately represent the diversity of a particular region as species richness only reflect the dominance of a single species. The Pielou's evenness index value is defined between 0 and 1. Evenness index value of 1 represent a community with perfect evenness while it's decreases towards zero indicate that the relative abundances of the species diverge from evenness. The evenness was highest at the undisturbed site (0.49), followed by the disturbed site (0.40), and the lowest was observed at the moderately disturbed site (0.35). The evenness index was higher in the undisturbed site showing that the species are evenly distributed whereas the lesser values in weed-infested regions showed patchiness in the distribution of plant species. Present results on evenness indices at different sites along the disturbance gradient were in accordance with previous ecological investigations (Kohli *et al*. 2004). Similarly, another study also observed significant differences in the species evenness along the disturbance gradient (Jamil *et al*. 2021).

5.2. Assessment of Physicochemical parameters

The soil biota and plant-soil interactions influence the naturalization as well as diversity and distribution of invasive alien plants in disturbed habitats (Majewska *et al.* 2018; Woch *et al.* 2021). Spread of above-ground invasive plants is remarkably regulated by soil physicochemical characteristics and resource (nutrient) availability (Ye *et al.* 2021). The process of plant invasion may be greatly impacted by changes in the plant-soil feedback, which are indicated by differences in the soil physicochemical characteristics before and after the invasion (Pergl *et al.* 2023). Plant invasions is a major factor in the development of forest ecosystems because it has a substantial impact on their physico-chemical and biological characteristics (Kumar *et al*. 2021).

5.2.1 Soil pH

The pH values represent the degree of acidity or alkalinity and is governed by various factors like the nature of the substratum, type of parent rock, precipitation, and microbial activity in the environment.

The pH of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during monsoon season. Particularly in *L. camara*-invaded soil recorded the highest pH value (6.1) whereas the lowest (5.1) was observed in *M. micrantha* invaded soil.

The pH values for *A. conyzoides* invaded soil demonstrated a positive and significant correlation with soil moisture content (r = 0.84). However, in case of *L. camara* invaded soil, no significant correlation was obtained between pH and other soil physicochemical parameters. Whereas, pH of *C. odorata* invaded soil showed a positive and significant correlation with soil moisture content (r = 0.70) and AK (r = 0.56). In this respect, a significant positive and significant of pH was obtained with soil moisture content (r = 0.71) for *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variation among pH values of different sites.

The pH of the soil samples from the moderately disturbed site was recorded lowest in the post-monsoon season while it was observed highest during the monsoon season. Particularly in *L. camara-invaded* soil which recorded the highest pH value (6.02) whereas the lowest (5.4) was observed in *A. conyzoides* and *M. micrantha* invaded soil.

The pH values for *A. conyzoides* invaded soil demonstrated a significant and positive correlation with soil moisture content (r = 0.71). However, in case of *L. camara* invaded soil, a positive and significant correlation was obtained between pH and soil moisture content (r = 0.58). Whereas, pH of *C. odorata* invaded soil showed a positive and correlation was obtained with soil moisture content (r = 0.63). In this respect, a positive and significant of pH was obtained with soil moisture content (r = 0.69) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variation ($F_{2,11}$=6.35; p<0.05) among pH values of different sites.

The pH of the soil samples from the undisturbed site was recorded lowest in the post-monsoon season while it was observed highest during the monsoon season. Particularly in *C. odorata*-invaded soil, highest pH value (6.0) was recorded whereas the lowest (5.7) was observed in *A. conyzoides* and *L. camara* invaded soil.

The pH values for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with soil moisture content (r = 0.72). Whereas, pH of *L. camara* invaded soil, a positive and significant correlation was obtained between pH and soil moisture content (r = 0.51). However, no significant correlation was obtained between pH and other soil physicochemical parameters in case of *C. odorata* and *M. micrantha* invaded soil. The two-way ANOVA revealed significant variation ($F_{2,11}$=54.9; p<0.05) among pH values of different sites.

The soil biota, nutrient availability, and plant-soil interactions influence the processes of naturalization and invasions and these causes changes in ecosystems (Pergyl, 2023). Invasive alien plants had a noticeably greater pH effect on the soil especially in the shrub layers (Xu *et al*. 2022). Significant changes in soil properties caused by invasive alien plants have the potential to increase invasions and to displace native species by impeding their natural regeneration (Lone *et al*. 2022). Disturbance-induced success of invasive alien plants tend to deplete the soil quality by altering the physicochemical characteristics. The alteration in physicochemical characteristics of soil can remarkably influence the phytosociology and diversity of native plants. In general, the invasive alien plants are better adapted to changes in physicochemical characteristics therefore they can successfully thrive even in disturbed habitats (Wamelink *et al*. 2018).

5.2.2. Soil Moisture Content

The three-phase system of soil consists of soil minerals (solids), moisture, and air. Soil moisture content is crucial for determining the engineering, agronomic, geological, ecological, biological, and hydrological characteristics of the soil mass. It also plays a significant role in plant growth, natural ecosystems, and biodiversity (Singh and Baghini, 2014).

The soil moisture content of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly, *L. camara* invaded soil recorded a high soil moisture content (29.85%) whereas the lowest value (23.1%) was observed in *C. odorata* invaded soil.

The soil moisture content for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with pH (r = 0.84). Whereas, in case of soil moisture content for *L. camara* invaded soil, a negative and significant correlation was obtained with TN (r = -0.61), in this respect a highly positive and significant correlation was obtained with SOC (r = 0.743067). For *C. odorata* invaded soil, a highly positive and significant correlation was obtained with pH (r = 0.70), and SOC (r = 0.67). Similarly, for *M. micrantha* invaded soil, a highly positive and significant correlation was obtained with pH (r = 0.71), SOC (r = 0.59), and TN (r = 0.53). The two-way ANOVA revealed significant variations ($F_{2,11}$=5.89; $p<0.05$) among the soil moisture content values of different sites.

The soil moisture content of the soil samples from the moderately disturbed study site was recorded lowest in the pre- monsoon season while it was observed highest during the post- monsoon season. Particularly in *L. camara* invaded soil which recorded a highest soil moisture content (29.69%) whereas the lowest (21.41%) was observed in *A. conyzoides* invaded soil.

The soil moisture content for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with SOC (r = 0.84), pH (r = 0.74) and AK (r = 0.58). Whereas, *L. camara* invaded soil demonstrated a positive and significant correlation with SOC (r = 0.63), AK (r = 0.56), and pH (r = 0.58). Similarly, *C. odorata* invaded soil demonstrated a positive and significant correlation with SOC (r = 0.63), AK (r = 0.51), and pH (r = 0.63). In this respect, a positive and significant correlation was obtained with SOC (r = 0.67), AP (r = 0.54), AK (r = 0.50), and pH (r = 0.69) for *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variations among the soil moisture content values of different sites.

The soil moisture content of the soil samples from the undisturbed study site was recorded lowest in the pre- monsoon season while it was observed highest during the monsoon season. Particularly, *C. odorata* invaded soil recorded a highest soil moisture content of (32.66%) whereas the lowest value (20.22%) was recorded in *A. conyzoides* invaded soil.

The soil moisture content for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with pH (r = 0.72). Whereas, in the case of *L. camara* invaded soil, a highly negative and significant correlation was obtained with AP (r = -0.75), however a significant positive correlation was obtained with pH (r = 0.51), SOC (r = 0.57), and AK (r = 0.57). Similarly, for *C. odorata* invaded soil, a positive and significant correlation was obtained with SOC (r = 0.57). in this respect, a negative and significant correlation was obtained with TN (r = -0.58) whereas a significant positive correlation was obtained with SOC (r = 0.51) and AK (r = 0.53) for *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variations among the soil moisture content values of different sites.

The primary productivity of vegetation can be altered directly or indirectly by invasive alien plants by affecting the site water balance, cycling of nutrients, and water regime. Disturbances in the soil facilitates the spread of invasive alien plants and changes in precipitation and temperature often leads to indirect effects on the plants (Walther *et al.* 2009; Orbán *et al.* 2021). Higher soil moisture content in *L. camara* invaded soil have also been noted in a study on the effects of invasive shrubs in South Africa (Ruwanza and Shackleton, 2016).

5.2.3. Soil Organic Carbon

The soil organic carbon content of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly, *C. odorata* invaded soil recorded a high soil organic carbon content (0.93%) whereas the lowest value (0.03%) was recorded in *L. camara* invaded soil.

The soil organic carbon for *A. conyzoides* invaded soil demonstrated a negative and significant correlation with TN (r = -0.52). whereas, in the case of *L. camara* invaded soil, a positive and significant correlation was obtained with soil moisture (r = 0.74). Similarly, for *C. odorata* invaded soil, a positive and significant correlation was obtained with soil moisture content (r = 0.67). In this respect a positive and significant correlation was obtained with soil moisture content (r = 0.59) and AK (r = 0.54) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=18.53; $p<0.05$) among the soil organic carbon values of different sites.

The soil organic carbon content of the soil samples from the moderately disturbed study site was recorded lowest in the pre- monsoon season while it was observed highest during the monsoon season. Particularly in *A. conyzoides* invaded soil which recorded a high (0.77%) soil organic carbon content of whereas the lowest (0.03%) was observed in *C. odorata* invaded soil.

The soil organic carbon for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with soil moisture content (r = 0.84) and AK (r = 0.77). Whereas, *L. camara* invaded soil demonstrated a highly negative and significant correlation with TN (r = -0.75), however a significant positive correlation was obtained with soil moisture content (r = 0.63), and AK (r = 0.67). In the case of *C. odorata* invaded soil, a positive and significant correlation was obtained with soil moisture content (r = 0.63), and AK (r = 0.69). In this respect, a positive and significant correlation was obtained with soil moisture content (r = 0.67), AK (r = 0.68) and AP (r = 0.61) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=600.71; $p<0.05$) among the soil organic carbon values of different sites.

The soil organic carbon content of the soil samples from the undisturbed study site showed that the soil organic carbon content was lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly in *L. camara* invaded soil which recorded highest (1.29 %) soil organic carbon content whereas the lowest (0.03%) was recorded in *A. conyzoides* and *C. odorata* invaded soil.

The soil organic carbon content for *A. conyzoides* invaded soil demonstrated a negative and significant correlation with TN (r = -0.61). Whereas, a highly positive and significant correlation was obtained with AK (r = 0.92). However, for *L. camara* invaded soil, a negative and significant correlation was obtained with TN (r = -0.55), AP (r = -0.70) whereas a highly positive and significant correlation was obtained with AK (r = 0.95) and soil moisture content (r = 0.57). In the case of *C. odorata* invaded soil, a positive and significant correlation was obtained with soil moisture content (r = 0.57) and AK (r = 0.78). In this respect, a highly negative and significant correlation was obtained with TN (r = -0.70) and AP (r = -0.59), whereas a positive and significant correlation was obtained with AK (r = 0.65) and soil moisture content (r = 0.51) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=85.61; $p<0.05$) among the soil organic carbon values of different sites

Soil microbes play a significant role in mediating the interaction between native and invasive plants. Invasive alien plants can degrade mycorrhizal networks or function together with native plants. Past studies demonstrated that soils from disturbed areas had higher levels of soil organic carbon and matter (Sakachep and Rai, 2021). The presence of soil microbes may indirectly affect competition between native and invasive alien plants thereby influencing their growth and developments (Van der Putten, 2010; Grove *et al.* 2017; Qu *et al.* 2021; Fahey and Flory, 2022).

5.3. Soil nutrient impacted by invasive alien plants

5.3.1 Total nitrogen content

The total nitrogen content of the soil samples from the disturbed study site showed that the total nitrogen content was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly *C. odorata* invaded soil recorded the highest (260.90 Kg/ha) whereas the lowest value (148.05 Kg/ha) was recorded in *A. conyzoides* invaded soil.

The total nitrogen content for *A. conyzoides* invaded soil demonstrated a negative and significant correlation with SOC (-0.52), and AP (r = -0.52) whereas a positive and significant correlation was obtained with AK (r = 0.72). However, in case of *L. camara* invaded soil, a negative and significant correlation was obtained with soil moisture content (r = -0.61), whereas a highly positive and significant correlation was obtained with AK (r = 0.83). Similarly, for *C. odorata* invaded soil, a positive and significant correlation was obtained with obtained with AP (r = 0.52). In this respect, a positive and significant correlation was obtained with soil moisture content (r = 0.53) and a highly positive and significant correlation was obtained with soil AP (r = 0.86) for *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variations among the total nitrogen content of different sites

The total nitrogen content of the soil samples from the moderately disturbed study site shows that the total nitrogen content was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly *C. odorata* invaded soil recorded the highest (496.3 Kg/ha) total nitrogen content whereas the lowest value (135.7 Kg/ha) was recorded in *M. micrantha* invaded soil.

The total nitrogen content for *A. conyzoides* invaded soil demonstrated a positive and significant correlation was obtained with AP (r = 0.53) and AK (r =

0.62). Whereas, in case of *L. camara* invaded soil, a highly negative and significant correlation was obtained with SOC (r = -0.75), however a highly positive and significant correlation was obtained with AP (r = 0.87). Similarly for *C. odorata* invaded soil, a positive and significant correlation was obtained with AP (r = 0.62). In this respect, a positive and significant correlation was obtained with AP (r = 0.68) for, *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variations among the total nitrogen content of different sites.

The total nitrogen content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *L. camara* invaded soil which recorded the highest (388.0 Kg/ha) total nitrogen content whereas the lowest (206.91 Kg/ha) was recorded in *C. odorata* invaded soil.

The total nitrogen content for *A. conyzoides* invaded soil demonstrated a negative and significant correlation with SOC (r = -0.61), whereas a highly positive and significant correlation was obtained with AP (r = 0.82). Similarly for *L. camara* invaded soil, a negative and significant correlation was obtained with SOC (r = -0.5). However, for *C. odorata* invaded soil, a positive and significant correlation was obtained with AK (r = 0.73). In this respect, a highly negative and significant correlation was obtained with SOC (r= -0.70), and soil moisture content (r = -0.58) for *M. micrantha* invaded soil. The two-way ANOVA revealed no significant variations among the total nitrogen content of different sites.

5.3.2. Available Phosphorous content

The available phosphorous content of the soil samples from the disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *L. camara* invaded soil which recorded the highest (72.4 Kg/ha) available phosphorous content whereas the lowest (7.3 Kg/ha) was recorded in *M. micrantha* invaded soil.

The available phosphorous content for *A. conyzoides* invaded soil demonstrated a negative and significant correlation with TN (-0.52181). However, in case of *L. camara* invaded soil, no significant correlation was obtained between available phosphorous and other soil physicochemical parameters. Whereas for *C. odorata* invaded soil, a positive and significant correlation was obtained with TN (r = 0.52). In this respect, a highly positive and significant correlation was obtained with TN (r = 0.86) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=11.36; $p<0.05$) and ($F_{3,11}$=4.94; $p<0.05$) of available phosphorus content within the sites and between the species.

The available phosphorous content of the soil samples from the moderately disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly *M. micrantha* invaded soil recorded the highest (173.1 Kg/ha) available phosphorous content whereas the lowest value (4.065 Kg/ha) was recorded in *C. odorata* invaded soil.

The available phosphorous content for *A. conyzoides* invaded soil demonstrated a positive and significant correlation between TN (0.536727). However, in the case of *L. camara* invaded soil, a highly positive and significant correlation was obtained with TN (r= 0.87). Whereas, the available phosphorous content of *C. odorata* invaded soil showed a positive and significant correlation with TN (r = 0.62). In this respect, a positive and significant correlation was obtained with SOC (r = 0.61), soil moisture content (r = 0.54), TN (r = 0.68) and AK (r = 0.81) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=7.04; $p<0.05$) and ($F_{3,11}$=11.59; $p<0.05$) among the available phosphorus content within the sites and between the species.

The available phosphorous content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly *M. micrantha invaded* soil recorded the highest (34.3 Kg/ha) available phosphorous content whereas the lowest value (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available phosphorous content for *A. conyzoides* invaded soil demonstrated a highly significant positive correlation with TN (r = 0.823309). Whereas,in case of *C. odorata* invaded soil, no significant correlation was obtained between available potassium and other soil physicochemical parameters. However, in case of *L. camara* invaded soil, a highly negative and significant correlation was obtained with SOC (r = -0.70), and soil moisture content (r = -0.75), and AK (r= -0.58). In this respect, a negative and significant correlation was obtained with SOC (r = -0.59) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=7.04; p<0.05) among the available phosphorus content of different sites.

5.3.3 Available Potassium

The available potassium content of the soil samples from the disturbed study site was observed highest during the pre- monsoon season. Particularly in *M. micrantha* invaded soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available potassium content for *A. conyzoides* invaded soil demonstrated a positive and significant correlation with TN (r = 0.72). However, in the case of *L. camara* invaded soil, a highly positive and significant correlation was obtained with TN (r = 0.83). Whereas, *C. odorata* invaded soil showed a positive and significant correlation with pH (r= 0.56). In this respect, a positive and significant correlation was obtained with SOC (r = 0.54) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=14.7; p<0.05) among the available potassium content of different sites.

The available potassium content of the soil samples from the moderately disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *M. micrantha invaded* soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available potassium content for *A. conyzoides* invaded soil demonstrated a positive and significant correlation with SOC (r = 0.77), soil moisture content (r = 0.58), and TN (r = 0.62). However, in case of *L. camara* invaded soil, a positive and significant correlation was obtained with SOC (r = 0.67), and soil moisture content (r= 0.61). Whereas, available potassium content for *C. odorata* invaded soil showed a positive and significant correlation with SOC (r = 0.69) and soil moisture content (r

= 0.51). In this respect, a positive and significant correlation was obtained with SOC (r = 0.68), SM (r = 0.50) and a highly positive and significant correlation was obtained with AP (r = 0.81) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=345.79; p<0.05) among the available potassium content of different sites.

The available potassium content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly in *M. micrantha invaded* soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available potassium content for *A. conyzoides* invaded soil demonstrated a highly positive and significant correlation with SOC (r =0.92). However, in the case of *L. camara* invaded soil, a negative and significant correlation was obtained with AP (r = -0.58), whereas a highly positive and significant correlation was obtained with SOC (r = 0.95), and soil moisture content (r = 0.57). However, the available potassium of *C. odorata* invaded soil showed a highly positive and significant correlation with SOC (r = 0.78), and TN (r = 0.73). In this respect, a positive and significant correlation was obtained between SOC (r = 0.65) and soil moisture content (r = 0.53) for *M. micrantha* invaded soil. The two-way ANOVA revealed significant variations ($F_{2,11}$=11.73; p<0.05) among the available potassium content of different sites.

The fundamental reason for the growth of invasive alien plants in newly introduced places is the variation in soil stoichiometry and element composition. Increased flexibility, enhanced nutrient absorption capacity, increased biomass, and increased photosynthetic rate contribute to an acceleration of the global nutrient accumulation process in the aboveground portions of invasive alien plants, particularly in nitrogen and phosphorus. Invasive alien plants have been found to respond to soil nitrogen forms nitrate and ammonium, thereby adapting or changing them and eventually releasing them back into the soil (Lee *et al.* 2012; Sardans *et al.* 2017; Lee *et al*. 2017; Sun *et al.* 2021). The primary factors that cause changes in the characteristics of soil are biological processes that are facilitated by invasive alien plants.

According to related research, invasive alien plants demonstrated to induce the concentrations of N and P in the soil (Castro-Díez *et al.* 2014; Zhang *et al.* 2021). These characteristics indicate that invasive species have a greater strategic or competitive advantage over native plants when it comes to using nutrients, and that advantage greatly increases the rates at which soil mineralize N, P and K (Ordonez *et al.* 2013; Funk *et al*. 2013). Thus, by speeding up their cycles within the ecosystem, invasive plants change the pools and fluxes of N, P, and K in the soil (Castro-Díez *et al.* 2014). Additionally, research from the past suggests that alien invasive plants might use distinct N-nutrition techniques than native plants and as such nitrate is preferred above ammonium by invasive alien plants such *M. micrantha*, *Microstegium vimineum*, and *Bidens pilosa* (Sun *et al*. 2021). In contrast, it has been observed that certain invasive alien plants favor ammonium and interspecific competition in invaded environments is significantly impacted by their availability (Uddin *et al*. 2018). Consequently, nutrient deposition encourages alien plant invasiveness within the environment and as such higher soil N and P stocks were found to be substantially correlated with invasion success (Vilà *et al*. 2011). Therefore, greater nutrient availability at investigated sites offers competitive advantage to invasive alien plants over natives which subsequently accelerate their spread.

5.4. Plant debris-soil Bioassay

Bioassay is an experimental technique which is used to assess the possible effects and risks associated with a specific chemical component of the abiotic environment (Cairns *et al.* 1989). It is a useful approach to study the chemical ecology. Bioassays are quantitative methods that offer a comprehensive assessment of detrimental impacts of allellochemicals associated with invasive alien plants on native biota. Practical needs, such as maintaining environmental quality in the face of significant socio-technological and bioecological changes, are fueling the increased interest in bioindication and bioassay techniques. Ecotoxicological testing such as bioassay attempts to forecast the ecological effects of chemicals and stressors with an emphasis on damage prevention over damage correction after it actually occurs (Cairns *et al.* 1989). The quality of natural media, such as soils and water can be regulated with the use of bioassay experiments (Terekhova, 2011). Bioassay investigations are extremely helpful in assessing the biological effects of specific chemicals on plants (Skripniov, 2023).

For the test of bioassay, soil and plant debris from four selected invasive alien plants *A. conyzoides*, *L. camara*, *C. odorata*, and *M. micrantha* were tested against two food crops *Lactuca sativa* and *Cicer arietinum* respectively.

L. sativa (lettuce) is a popular green leafy vegetable with medicinal properties, and is widely consumed for its taste and high nutritional value (Wani *et al.* 2020). Significant morphological and genetic variations (Noumedem *et al.* 2016) and a short life cycle (Pink and Keane, 1992) characterize it as model bioassay plant. It also contains high levels of phytonutrients with potential health benefits including vitamins and various phenolic compounds ((Llorach *et al.* 2008; Medina-Lozano *et al.* 2021).

C. arietinum (Chickpea), India's oldest pulse crop, is in fact a rich source of carbohydrates, protein, and dietary fiber with potential health benefits (Kaur *et al*. 2021). This nutrient-rich legume is also enriched with unsaturated fatty acids, minerals, and isoflavones which play important role in the treatment of various diseases (Wang *et al.* 2021).

The different growth parameters that were tested include germination of seed which is crucial for plant species to survive and proliferate as seeds which shields embryos as it is an integral component of plant’s life cycle (Pernas and Gomez, 2020). In the case of *L. sativa*, the highest number of germinations was observed on the third day and seventh day was from the healthy/control non-invaded soil. This shows that the germination of the seed was not affected by the plant debris. Meanwhile, the highest number of germinations of *C. arietinum* on the third and seventh day was from the plant soil bio-debris of *C. odorata*, *M. micrantha* and *A.*

conyzoides invaded soils. Similar observations of allelochemicals induced inhibition of seed germination were also noted in other food crops used in previous studies investigating allellopathy of different invasive alien plants (Syngkli *et al.* 2022; Nongtri *et al.* 2022).

Seedling height is a measure of the seedling's competitive ability for light. In the case of *L. sativa*, the highest seedling height was observed in *L. camara* invaded soil and the lowest in *M. micrantha* invaded soil. Whereas in another food crop i.e. *C. arietinum,* the highest seedling height was observed in case of *C.odorata* invaded soil whereas the lowest was in *M. micrantha* invaded soil. Root length and shoot length which indicates the seedling's competitive ability for nutrition was found higher in the pot bio-assay of the selected invasive alien plants than the healthy/control soil for both the selected food crops. Longer root length and shoot length in the invaded soil showed that the soil is less fertile and lacks nutrients, which might have facilitated the roots to penetrate longer to better utilize the nutrients. The seedling biomass which shows the seedling’s growth and competitiveness was also higher in the pot bio-assay of selected invasive plants *A. conyzoides* and *C. odorata*. This higher seedling biomass values indicated that the soils in the experimental pots are more fertile than the pot containing healthy/control non-invaded soil. This show that the presence of allelochemicals play a stimulatory role in the growth of the seedlings and such cases was also observed in *A. conyzoides* leachates which have higher nitrogen content (Kumar *et al*. 2018; Syngkli *et al*. 2022).

The germination percentage and germination potential of the plants indicate the germination ability and viability of seeds which were found higher in the healthy/control soil for *L. sativa* but for *C. arietinum* it was found higher in case of the invaded soils. The germination index, germination rate index, and vigor index indicate the germination speed and the vitality of seeds and these indices were found higher in the healthy/control soil for *L. sativa* but in case of *C. arietinum* it was found higher in the invaded soils. Among the dominant invasive alien plants, the maximum inhibitory effects on growth parameters of bioassay food crops were observed in case of *M. micrantha* invaded soil. In general, the effects of other invasive alien plants contaminated soil on bioassay food crops were rather stimulatory.

5.5 Total Phenolic Contents (TPC)

Phenolic compounds refer to a class of organic compounds that have one or more hydroxyl groups directly attached to an aromatic ring (Lattanzio. 2013). They constitute the most abundant secondary metabolites in plants and can be categorized into non-soluble compounds such as condensed tannins, lignins, cell-wall bound hydroxycinammic acids, or soluble compounds including phenolic acids, phenylpropanoids, flavonoids, and quinones (Khoddami, *et al*. 2013).

The total phenolic contents of both the soil and leaf extracts were tested by catechol standard and gallic acid at different wavelengths. Catechol is an allelochemical which belongs to a phenolic compound found in plants having antimicrobial (anti-fungal and anti-bacterial) activities (Kocaçalışkan and Terzi, 2006). Gallic acid (GA), also known as 3,4,5-trihydroxybenzoic acid, is a natural secondary metabolite and is widely isolated from various fruits, plants, and nuts. In recent years, GA has received increasing attention for its powerful anti-inflammatory properties.

The TPC assessment of the soil by catechol standard revealed the highest concentration (0.915mg/ml) in *C. odorata* invaded soil whereas, gallic acid recorded the highest i.e., 0.038mg/mL in *L. camara* invaded soil. The presence of these phenolic contents in the soil rhizosphere reveals that these plants can emit allelochemicals in the soil which have the potential to influence their neighboring crops and plants. Phenolic compounds enter soils as liquid or particulate matter from plant materials and industrial wastes (Hattenschwiler and Vitousek, 2000). Following their entry into soils, they influence soil organic matter decomposition and nutrient cycling (Fierer *et al*. 2001; Toberman *et al*. 2010). Phenolic compounds in soils may also play a role in controlling many aspects of plant-soil interactions, including the alteration of soil nutrient availability, root and hypocotyl growth inhibition and limitation of water and mineral uptake by plants (Inderjit *et al.* 2009; Akomeng and Adusei, 2021).

The TPC of the leaves by catechol standard revealed the highest concentration (12.38 mg/ml) in *L. camara* invaded soil whereas gallic acid recorded the highest (0.070 mg/ml) in *C. odorata* invaded soil. Since phenols are responsible for antioxidant activity, the recorded concentrations of total phenols in the extract indicated better plant defence which can facilitate the success of invasive alien plants (Sreelatha and Padma, 2009). The high concentrations of TPC showed that the leaves of invasive alien plants have high antioxidant properties and which make them potential bioagents for traditional medicine formulations, aromatherapy, and nutraceuticals (Azlim Almey *et al*. 2010; Dutta and Ray, 2019).

5.6. Canopy Openness, Leaf Area Index (LAI), And Light Intensity

The canopy openness was highest at the disturbed site (87.42%) while it was lowest at the moderately disturbed site (25.92%). The incoming PAR, which is the total incoming solar radiation received by the area above the forest canopy, was highest at the moderately disturbed site at 1355.6±195.93 $\mu\ mol\ m^{-2}\ s^{-1}$ whereas, the diffused PAR, which is the total solar radiation received by the area under forest canopy was highest at the disturbed study site 562.6±368.38 $\mu\ mol\ m^{-2}\ s^{-1}$. The highest LAI, which is the leaf area index of a particular site was observed at the undisturbed study site (4.36±0.43) and lowest (1.65±1.30) at the disturbed site.

Statistical analysis revealed that the invasion of alien plants at the disturbed study site showed a negative and highly significant correlation between canopy openness and LAI (r= - 0.85) and LAI and diffused PAR (r= -0.96). Whereas a highly significant positive relation was observed between canopy openness and diffused PAR (r= 0.70).

The invasive alien plants at the moderately disturbed study site showed a highly significant negative relation between LAI and incoming PAR (r= -0.95) as well as LAI and diffused PAR (r= - 0.99). Whereas a positive and significant correlation was obtained between canopy openness and diffused PAR (r= 0.51), while a highly significant positive relation was obtained between diffused PAR and incoming PAR (r= 0.96).

Statistical analysis revealed that the invasion of alien plants at the moderately disturbed study site showed a negative and highly significant correlation between LAI and incoming PAR (r= - 0.95) and LAI and diffused PAR (r= -0.99). Whereas a highly significant positive relation was observed between diffused PAR and incoming PAR (r= 0.96).

The invasion of alien plants at the undisturbed study site revealed a highly significant negative relation between LAI and incoming PAR (r= -0.90), LAI and diffused PAR (r= -0.95) and canopy openness and LAI (r= -0.93). Whereas a highly significant positive relation was obtained between diffused PAR and incoming PAR (r= 0.98), canopy openness and incoming PAR (r= 0.90), and between canopy openness and Diffused PAR r= 0.93).

Statistical analysis revealed that the invasion of alien plants at the undisturbed study site showed a negative and highly significant correlation between LAI and incoming PAR (r= - 0.90), LAI and diffused PAR (r= -0.95) and LAI and diffused PAR (r=0.95). Whereas a highly significant and positive relation was observed between diffused PAR and incoming PAR (r= 0.98), canopy openness and incoming PAR (r=0.90) and between canopy openness and diffused PAR (r=0.93).

CHAPTER- 6

MANAGEMENT

6. MANAGEMENT

The impacts of invasive alien plants play a major role in the decline of biodiversity threatening natural habitats worldwide (Weidlich *et al*. 2020). The increasing frequency and scale of alien plant invasions due to human-mediated activities necessitates a growing complexity and scale in managing invasive alien plants (Richardson *et al.* 2013; Auld and Johnson, 2014). Several countries have pledged to restore 170 million hectares of forest landscapes by 2030 (Chazdon, 2019). To this end, the United Nations has declared 2021-2030 as the decade for ecosystem restoration, potentially leading to increased global investments in restoring various native ecosystem types (UNEP, 2023).

Controlling invasive alien plants is an important restoration intervention because it prevents native plant communities from growing in degraded areas (D'Antonio *et al*. 2016; Prior *et al*. 2018; Brancalion *et al*. 2020). Invasive plant management can prevent native vegetation from recolonizing an area, aiding in ecological restoration and providing benefits to both native vegetation restoration and invasive plant management (Schuster *et al*. 2020). Effective management of invasive plant species in restoration projects may necessitate long-term investments (Norton, 2009) or environmentally conscious chemical applications (Wagner *et al*. 2017; Brancalion *et al*. 2020). Many methodologies can help to control invasive plant species at selected restoration sites (Dechoum *et al.* 2018). The best approach depends on factors such as the specific species being controlled, financial resources available (Kettenring and Adams, 2011), and legislations (Wagner *et al.* 2017; Dechoum *et al.* 2018). The management of invasive alien plants includes asset protection, eradication, and quarantine methods to exclude certain species, lessen their impact, and apply control measures (Auld and Johnson, 2014).

Management Strategies:Maintaining Intact Forest Canopy

Anthropogenic disturbances can lead to forest fragmentation, deforestation, degradation, and land reclamation, increasing light and nutrient availability, thereby intensifying resource competition for invasive alien plants (Langmaier and Lapin, 2020). Therefore, the state of forest canopy density play a crucial factor in forest management programs, as it indicates stock condition and is influenced by species composition, forest type, and other factors (Govaert *et al*. 2020). The reduction in invasive alien plants invasion in Central Nepal's broad-leaved forests suggests tree canopy resilience (Subedi, 2024). Therefore, maintaining the forest canopy can identify and manage invasive alien plants early and avoid their spread.

In the present study the canopy gaps were more pronounced at the disturbed habitats when compared with undisturbed habitats. The canopy gaps were tightly associated with light intensity which was recorded highest at the disturbed site when compared with moderately disturbed and undisturbed sites. The distinct pattern in light intensity values along the disturbance gradients reflect the larger canopy gaps at the disturbed site which allow more penetration of photosynthetically active radiation. Therefore, efforts in maintaining the intact canopy by increasing native plant species richness can regulate the spread of invasive alien plants. The use of native plant species has been widely advocated for the restoration of invaded grasslands, opencast coalmine areas, and degraded forests (Singh *et al.* 2022). Planting of diverse native species of trees in the western parts of India have shown to improve canopy cover and catalyze tropical forest recovery by controlling invasive plants and help in the recovery of degraded tropical forests (Osuri *et al.* 2022). Invasive alien plants mediated alterations in soil nutrients were noted in present study which can also be regulated through the maintenance of intact canopy.

In addition to present research based management approaches of invasive alien plants the other empirical studies also advocated multiple beneficial impacts. These advantages of invasive alien plants can also facilitate their sustainable management which are mentioned below as-

Regulating Nutrient Dynamics

It is well known that mutualistic microbial diversity of arbuscular mycorrhizal fungi (AMF) assists in the sustenance of forests and a few invasive alien plants have been reported to promote the diversity of AMF in Hawaiian forests (Gomes *et al*. 2018).

Further, it has been observed that plant species such as *Centaurea stoebe* and *Euphorbia esula* increased the abundance as well as the diversity of mycorrhizal fungi, which have an immense role in ecosystem functioning (Lekberg *et al*. 2013). Results also indicate that growth of an invasive plant in its native habitats could be restricted by the toxic effects associated with strong soil acidity in their native habitats (Soti *et al.* 2020). The efficient recycling of phosphorus by *Elodea nuttallii* result in nutrient enrichment, or eutrophication, which is detrimental to aquatic ecosystems (Stabenau *et al.* 2018). invasive alien plants like *Spartina alterniflora* can enhance soil properties, potentially leading to biorefinery prospects and sustainable economy (Syed *et al*. 2021).

Utilizing as food And fodder

The use of invasive alien plants as feed has been widely reported however their widespread use is debatable as they can lead to poisoning due to the complex nature of invasive alien plants. *Prosopis juliflora* and *Opuntia ficus-indica* also serve as food and fodder in their invaded landscapes (Mwangi and Swallow, 2008; Shackleton *et al*. 2019.). *Acacia dealbata* in Eastern Cape region of South Africa serves as an important livelihood resource (Shackleton *et al*. 2019). *Cenchrus ciliaris*, an invasive grass, is promoted by the farmers for grazing purposes (Marshall *et al*. 2011; Shackleton *et al*. 2019.). *L. camara* facilitates livelihood of several local villagers in India, as they use it for furniture and pulp making (Kannan *et al*. 2016). The dried leaves of *C. odorata* are used as feed additive in livestock rearing, but caution is advised due to few reports of animal poisoning (Rai and Singh, 2024).

Feed Stock In Bio Energy And Bio Fuel Production

Some Invasive alien plants can positively affect several areas, including agriculture, the ornamental horticulture industry, and wood production (Lorenzo and Morias, 2022). *Prosopis glandulosa* is considered to be a beneficial invader as its wood is marketed as a fuel wood in several countries of Africa and south-east Asia (Shackleton *et al.* 2019). *Australian Acacia*, an invasive alien plants in the Africa and Madagascar, are also used as fuel wood that serves as a source of livelihood to lowincome people (Kull *et al*. 2018, Shackleton *et al.* 2019). Plantations of bioenergy crops like rapeseed, soybean, jatropha, and castor beans in which raw materials can be used as feedstock can simultaneously combat land degradation (Singh *et al*. 2020).

Though some of the invasive alien plants release allelochemicals, bio-active compounds of *Parthenium hysterophorus* have been found to be a good source of biofuel and good for vermicomposting (Hussain *et al*. 2016). An invader plant *Robinia pseudoacacia* attracts more insect pollinators when compared with the native plant *Cytisus scoparius*. Thus**,** invasive alien plants can attract high numbers of insect pollinators in the disturbed regions (Buchholz and Kowarik, 2019). Similarly, *Parthenium hysterophorus* also attracted a greater number of bee pollinators than the native plants (Ojija *et al*. 2019).

Invasive alien plants also act as sources for bio-energy, animal feed, bio-polymers, and in augmenting the green economy (Rai and Kim, 2020**)**. *Spartina alterniflora*, has been demonstrated to act as a potent tool for carbon sequestration in bio-energy industry, besides acting as the bio-agent for heavy metals phytoremediation (Liao *et al*. 2007, Prabakaran *et al.* 2019). The production of bioenergy from invasive alien plants, such as *E. crassipes* and *Phragmites* sp., have the dual benefits of managing invasive weeds and providing sustainable renewable energy (Rai *et al.* 2018; Stabenau *et al.* 2018). A great opportunity for producing bioenergy is presented by other invasive alien plants such as *Heracleum mantegazzianum*, *Solidago gigantean*, *Fallopia japonica*, and *Impatiens glandulifera*, which produce large amounts of biomass with a high calorific value (Van Meerbeek *et al.* 2019). The use of invasive alien plants biomass combined with an efficient biomass digestion strategy is a promising bioenergy option for mitigating climate change (Van Meerbeek *et al.* 2019). *Panicum virgatum* and *Brassica carinata* are two non-food crops that can improve clean energy production, energy security, rural livelihood, and climate change mitigation without compromising food security (Abhilash, 2021; Feng *et al*. 2021; Rai, 2022)**.** The prospect of using invasive plants such as *Acacia holosericea* as biochar has also been studied and applied in many bio-based absorbants for environmental remediations (Reza *et al*. 2019; Gaurav *et al*. 2020; Feng *et al*. 2021; Nguyen *et al*. 2022).

In Environmental Pollution Phytoremediation

Invasive alien species, due to their adaptive strategies, can effectively remediate heavy metals from contaminated soil, reducing the risk of food chain contamination (Singh *et al*. 2021). Several Invasive alien plants can be wisely used in the phytoremediation of organics like polyaromatic hydrocarbons, heavy metals, and particulate matter (PM). Thus, using Invasive alien plants biomass for phytoremediation can assist in sustainable restoration and management (Prabakaran *et al*. 2019; Rai and Kim**,** 2020). Stress tolerance against pollutants, resistance to pathogens, and allelopathy are some of the characteristics of invasive alien plants that can be used as environmental remediation tools (Prabakaran *et al.* 2019). A few invasive alien plants like *E. crasspes*, *L. camara*, *P. stratiotes* and *A. donax* are potent bio-systems for phytoremediation (Prabakaran *et al.* 2019; Rai and Kim, 2020). These invasive alien plants can also act as an economically feasible tool for environment friendly genesis of nanoparticles (Rai *et al*. 2018). invasive alien plants such as *Chromolaena odorata, Bidens pilosa and Praxelis clematidea* have been recognized as hyper-accumulators for the phytoremediation of health hazardous heavy metal cadmium (Wei *et al.* 2018). The use of *L. camara* as a biomonitoring tool in particulate deposition may act as a sustainable manangement strategy for invasive alien plants (Rai and Singh, 2015). Similarly, potential candidates for the remediation of heavy metals Pb and Ni in soils are *C. odorata* and *A. conyzoides* (Obehi, 2020).

Green Synthesis Of Nanoparticles For Application In Healthcare And Chemical Industries

While some Invasive alien plants may be used as food sources, they may also have a detrimental effect on the yield of important crops (Shackleton *et al.* 2019). Research conducted in India and other nations has demonstrated the therapeutic value of invasive alien species, especially *Ocimum americanum*, whose biofabricated zinc oxide synthesized nanoparticles exhibit strong antimicrobial activity (Kumar *et al*. 2019). Certain Invasive alien plants, such as *L. camara* and *A. conyzoides*, have been shown to have ethnopharmacological uses in primary health care (Rai and Lalramnghinghlova, 2011; Rai, 2012). *Malvastrum coromandelianum* (L.) Garcke, an invasive weed, was found having enormous antioxidant activity in its leaves (Saxena and Rao, 2020)**.** The allelopathic effects of Invasive alien plants can be a viable resource for plant derived medicines for treatment of ailments such as infertility,hypertension etc. (McGaw *et al.* 2022). For example an invasive shrub *Tithonia diversifolia* has been used to traditionally treat a variety of ailements (Rai and Vanlalruati, 2022; Rai *et al*. 2023). *Cyperus roduntus* is extensively used in India for the treatment of diarrhea, worms,dysentery and stomach diseases (Bezerra and Pinheiro, 2022). A common invasive plant *A. conyzoides* have been studied to have multiple potential applications in the field of medical, agricultural and industial sectors (Kotta *et al.* 2020; Paul *et al.* 2022; Baral *et al*. 2022). Therefore, such reports confirm that the traditional practices using invasive alien plants are vital and their bioactive phytochemicals play an important role in various biomedical applications (Nguyen *et al.* 2023).

The pharmacological potential of plants such as *L. camara*, *C. odorata*, *Dolichandra unguis-cati*, *Parthenium hysterophorus* and *Gomphrena celosioides* showed strong antibacterial activities and have a strong anti-inflamatory properties (Omokhua *et al*. 2018; Wu *et al.* 2020; Leyu *et al*. 2022). *C. rotundus* extracts have been proven effective against several cancer cell lines (Bezerra and Pinheiro, 2022). *M. micrantha* silver nanoparticles have been noted to exhibit anti cancer activities in various cell lines acting as anticancer agents in the fields of healthcare industries (Saikia *et al.* 2020; Zohmachhuana *et al.* 2022; Lalsangpuii *et al.* 2024). Therefore, the utilization, control and management of invasive alien plants play an important role in the conservation of biodiversity and environmental sustainability.

Restoration of degraded sites

The Indian subcontinent faces a significant challenge in restoring degraded land, and agroforestry has shown significant potential for sustainable rehabilitation (Jinger *et al*. 2023). Restoration of degraded sites through plantation and afforestation (the role of agroforestry plants) measures especially in the tropical region have played an important role in biodiversity conservation, nutrient cycling, soil quality,carbon sequestration and water regulations (Montagnini, 2020; Nair *et al*. 2021; Singh *et al*. 2021; Udawatta *et al.* 2021; Boinot *et al.* 2022; Santos *et al*. 2022). Agroforestry is used to restore degraded lands from intensive agriculture, soil erosion, deforestation, rangeland degradation, mining, and over-extraction, involving various species of trees,plants and crops (Gupta *et al*. 2020). Restoring degraded environments can further enhance biodiversity, ecosystem services, and contribute to achieving the UN-Sustainable Development Goals (Edrisi *et al.* 2020; Rai, 2021).

CHAPTER-7

CONCLUSION

7. CONCLUSIONS

7.1. Plant-plant interactions

The results on the phytosociological parameters of all the species at the three distinct study sites along the disturbance gradient revealed varying degrees of dispersions in the sites and the species diversity showing low importance value index indicated that they were of rare occurrence. On the contrary, the plants with high IVI were marked as dominant. The diversity indices were recorded highest at the disturbed study site and lowest at the undisturbed study sites. This is due to variations in the quality of the study sites in terms of plant-soil interactions. Therefore, the differences in species diversity resulted from variations in the quality of the study sites where higher species diversity indicated variability in the type of species as well as the heterogeneity in the communities.

The species richness was found to be lower at invaded sites i.e., disturbed and moderately disturbed sites when compared with the undisturbed regime. The lower species richness at disturbed and moderately disturbed sites can be attributed to the high population density of invasive alien plants which suppress the growth of neighboring native plants, thereby reducing the species richness. The evenness index was higher at the undisturbed site showing that the species are evenly distributed whereas the lesser values in weed-infested regions showed patchiness in the distribution of plant species

7.2. Plant-soil interactions

The soil biota, nutrient availability, and plant-soil interactions influence the processes of naturalization and invasion leading to changes in the ecosystems. The changes in the soil due to invasive alien plants was noticeable in terms of soil pH and soil moisture content. Also, infestation leads to changes in the soil organic matter and soil organic carbon content. Soil microbes-nutrients feedback can play an important role in the ecosystem functioning. The presence and absence of nutrients and soil microbes influence the success of invasive alien plants.

The effect of invasive alien plants on soil nutrients is another key factor where they have been found to alter TN, AK,AP and SOC contents which can influence their diversity. The concentrations of N, P and K have been induced greatly by the presence of invasive alien plants leading to competitive advantage over native plants. Greater nutrient availability at investigated sites offers competitive advantage to invasive alien plants over natives which subsequently accelerate their spread.

7.3. Bioassay and Total Phenolic Contents Analysis

The test for bioassay is an important and helpful tool in assessing the biological effects of chemicals on plants. The germination of *C. arietinum* was inhibited by *C. odorata*, *M. micrantha* and *A. conyzoides* invaded soils. The seedling's competitive ability for light in the case of bioassay food crops such as *L. sativa* and *C. arietinum* pots was greatly inhibited in *M. micrantha* invaded soil. Similarly, root length and shoot length which indicates the seedling's competitive ability for nutrition was found higher in the pot bio-assay of the selected invasive alien plants than the healthy/control soil for both the selected food crops. The seedling biomass which shows the seedling's growth and competitiveness was also higher in the pot bio-assay of selected invasive alien plants. This higher seedling biomass values indicated that the soil in the experimental pots were more fertile than the pot containing healthy/control non-invaded soil. Interestingly, this showed that the presence of allelochemicals can play a stimulatory role also in the growth of the seedlings. Among the dominant invasive alien plants, the maximum inhibitory effects on growth parameters of bioassay food crops were observed in case of *M. micrantha* invaded soil. In general, the effects of other invasive alien plants contaminated soil on bioassay food crops were rather stimulatory. The presence of phenolic contents in the soil rhizosphere of invasive alien plants revealed that these plants emit allelochemicals in the soil that have the potential to influence their neighboring crops and plants. The high concentrations of TPC in the leaves of invasive alien plants demonstrated high antioxidant properties and which make them potential bioagents. The recorded concentrations of total phenols in the extract indicated better plant defense which can facilitate the success of invasive alien plants in introduced landscapes

7.4. Canopy Openness, Leaf Area Index (LAI), And Light Intensity: Management and containment implications.

Higher canopy openness was found at the disturbed study site when compared with undisturbed site, indicating that the area is more likely to experience disturbances, which may facilitate invasive alien plants infestation. Similarly, the total radiation received by the area beneath the forest canopy was highest at the disturbed site, whereas the incoming solar radiation received by the area above the canopy was highest at the moderately disturbed site.

This demonstrates how plant invasion can be accelerated by the presence or lack of plant canopy in a given area, and it offers valuable insights for managing invasive alien plant species and the invasion process.

In the present study the canopy gaps were more pronounced at the disturbed habitats when compared with undisturbed habitats. Therefore, efforts in maintaining the intact canopy by increasing native plant species richness can regulate the spread of invasive alien plants. Invasive alien plants mediated alterations in soil nutrients were noted in present study which can also be regulated through the maintenance of intact canopy.

APPENDICES

APPENDIX 1: ANOVA

pH (disturbed)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.156223	3	0.052074	0.859417	0.511204	4.757063
Seasons	0.438289	2	0.219144	3.616687	0.093206	5.143253
Error	0.363556	6	0.060593			
Total	0.958067	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$ =3.61

2. pH site 2 (MODERATELY DISTURBED)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.092864	3	0.030955	1.217932	0.38143	4.757063
Seasons	0.323176	2	0.161588	6.357819	0.032949	5.143253
Error	0.152494	6	0.025416			
Total	0.568534	11				

Significant variation of Site 2 was observed within the seasons
$F_{2,11}$=6.35

3. pH site 3 (UNDISTURBED)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.006454	3	0.002151	2.463815	0.159994	4.757063
Seasons	0.096048	2	0.048024	54.99594	0.000138	5.143253
Error	0.005239	6	0.000873			
Total	0.107741	11				

$F_{2,11}$=54.9
Significant Variation of Site 3 was observed within the seasons

4. SOC site 1 (Disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.093568	3	0.031189	1.086695	0.423649	4.757063
Seasons	1.063853	2	0.531927	18.53338	0.002704	5.143253
Error	0.172206	6	0.028701			
Total	1.329627	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$=18.53

5. SOC site 2 (Moderately disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.007792	3	0.002597	2.328152	0.174083	4.757063
Seasons	1.340384	2	0.670192	600.7115	1.23E-07	5.143253
Error	0.006694	6	0.001116			
Total	1.35487	11				

$F_{2,11}$=600.71

Significant variation of site 2 was observed within the seasons

6. SOC site 3 (undisturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	0.082067	3	0.027356	1.45999	0.316515	4.757063
Seasons	3.208363	2	1.604181	85.61658	3.88E-05	5.143253
Error	0.112421	6	0.018737			
Total	3.40285	11				

Significant variation of site 3 was observed within the seasons

$F_{2,11}$=85.61

7. SOIL MOISTURE SITE 1 (Disturbed)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	16.45043	3	5.483477	4.328569	0.060261	4.757063
Seasons	14.94281	2	7.471405	5.897807	0.038328	5.143253
Error	7.600864	6	1.266811			
Total	38.9941	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$= 5.89

8. MOISTURE site 2 (Moderately Disturbed)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	33.70411	3	11.2347	2.00808	0.214386	4.757063
Seasons	7.677704	2	3.838852	0.686153	0.539068	5.143253
Error	33.56849	6	5.594748			
Total	74.9503	11				

Significant variation of site 2 was observed within the seasons

$F_{2,11}$=0.68

9. SOIL MOISTURE Site 3 (Undisturbed)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	78.90473	3	26.30158	1.915684	0.228245	4.757063
Seasons	7.729115	2	3.864557	0.281476	0.76411	5.143253
Error	82.3776	6	13.7296			
Total	169.0114	11				

Significant variation of site 3 was observed within the seasons

$F_{2,11}$=0.28

10. TOTAL NITROGEN SITE 1 (Disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	2056.183	3	685.3942	0.501707	0.694869	4.757063
Seasons	1087.235	2	543.6176	0.397927	0.688211	5.143253
Error	8196.745	6	1366.124			
Total	11340.16	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$= 0.39

11. TOTAL NITROGEN SITE 2 (Moderately Disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	14829.82	3	4943.274	0.932726	0.480765	4.757063
Seasons	52539.76	2	26269.88	4.956757	0.053599	5.143253
Error	31798.87	6	5299.812			
Total	99168.45	11				

Significant variation of site 2 was observed within the seasons

$F_{2,11}$= 4.95

12. TOTAL NITROGEN SITE 3 (Undisturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	5884.442	3	1961.481	0.849398	0.515539	4.757063
Seasons	4199.904	2	2099.952	0.909362	0.451904	5.143253
Error	13855.55	6	2309.259			
Total	23939.9	11				

Significant variation of site 3 was observed within the seasons

$F_{2,11}$= 0.90

13. AVAILABLE PHOSPHORUS SITE 1 (Disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	2043.787	3	681.2622	4.948396	0.046165	4.757063
Seasons	3129.814	2	1564.907	11.36681	0.009105	5.143253
Error	826.04	6	137.6733			
Total	5999.64	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$= 11.36

14. AP site 2 (moderately disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	18685.36	3	6228.454	11.59187	0.006573	4.757063
Season	7567.239	2	3783.619	7.04175	0.026665	5.143253
Error	3223.874	6	537.3123			
Total	29476.48	11				

Significant variation of site 2 was observed within the seasons

$F_{2,11}$=7.04

15. AP site 3 (undisturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	185.3884	3	61.79612	0.703379	0.583808	4.757063
Seasons	103.0935	2	51.54677	0.586718	0.585156	5.143253
Error	527.1366	6	87.8561			
Total	815.6185	11				

Significant variation of site 3 was observed within the seasons

$F_{2,11}$= 0.58

16. AK site 1 (disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	64205.2	3	21401.73	0.836302	0.521271	4.757063
Season	752417.6	2	376208.8	14.70088	0.004868	5.143253
Error	153545.4	6	25590.91			
Total	970168.2	11				

Significant variation of site 1 was observed within the seasons

$F_{2,11}$= 14.70

17. AK site 2 (Moderately disturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	12181.26	3	4060.421	2.477415	0.158665	4.757063
Season	1133511	2	566755.4	345.7987	6.36E-07	5.143253
Error	9833.85	6	1638.975			
Total	1155526	11				

Significant variation of site 2 was observed within the seasons

$F_{2,11}$= 345.79

18. AK site 3 (undisturbed)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Species	66488.23	3	22162.74	1.279285	0.363498	4.757063
Season	406546.1	2	203273.1	11.7334	0.008442	5.143253
Error	103945.9	6	17324.32			
Total	576980.3	11				

Significant variation of site 3 was observed within the seasons

$F_{2,11}$= 11.73

APPENDIX 2: PEARSON'S CORRELATION

***Disturbed**

1. ***Ageratum conyzoides***

	pH	SOC	MOISTURE	TN	AP	AK
pH	1					
SOC	-0.0048	1				
MOISTURE	0.840851	0.150599	1			
TN	0.326154	-0.52852	-0.17341	1		
AP	-0.15844	0.060031	0.285627	-0.52181	1	
AK	0.398479	-0.02852	0.070056	0.722352	-0.42962	1

2. ***Lantana camara***

	pH	SOC	MOISTURE	TN	AP	AK
pH	1					
SOC	0.227003	1				
MOISTURE	0.317506	0.743067	1			
TN	-0.33395	-0.436	-0.61182	1		
AP	0.48898	-0.04902	0.077433	0.160255	1	
AK	0.075238	-0.10045	-0.25772	0.837631	0.16079	1

3. ***Chromolaena odorata***

	pH	SOC	MOISTURE	TN	AP	AK
pH	1					
SOC	0.46907	1				
MOISTURE	0.707949	0.67146	1			
TN	-0.02891	-0.13049	0.072076	1		
AP	0.30364	-0.47369	-0.25743	0.528322	1	
AK	0.567482	0.074685	-0.04064	-0.18885	0.499769	1

4. M*ikania* micrantha

	PH	SOC	MOISTURE	TN	AP	AK
PH	1					
SOC	0.381202	1				
MOISTURE	0.719736	0.596885	1			
TN	0.171343	0.239955	0.530531	1		
AP	-0.22385	-0.14307	0.234639	0.862102	1	
AK	0.487944	0.541116	0.171715	0.243707	-0.12114	1

***MODERATELY DISTURBED**

1. Ageratum conyzoides

	pH	SOC	MOISTURE	TN	AP	AK
pH	1					
SOC	0.441437	1				
MOISTURE	0.742849	0.845748	1			
TN	0.153852	0.14548	0.24209	1		
AP	-0.30084	-0.38851	-0.31363	0.536727	1	
AK	0.371492	0.771912	0.589498	0.627409	-0.05105	1

2.* L*antana camara

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.363658	1				
MOISTURE	0.589154	0.632188	1			
TN	-0.00817	-0.75821	-0.25366	1		
AP	0.081882	-0.40516	0.111533	0.87642	1	
AK	0.309354	0.67049	0.561536	-0.07372	0.310395	1

3. Chromolaena odorata

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.446872	1				
MOISTURE	0.634621	0.637271	1			
TN	-0.45671	-0.35225	0.046608	1		
AP	-0.34857	-0.26411	0.122977	0.628936	1	
AK	0.369058	0.69494	0.514789	-0.03468	0.338842	1

4. Mikania micrantha

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.339617	1				
MOISTURE	0.696129	0.671956	1			
TN	-0.46959	-0.11088	0.035399	1		
AP	-0.04778	0.619492	0.548605	0.682354	1	
AK	0.221701	0.683748	0.503937	0.437158	0.819838	1

*****UNDISTURBED**

1. Ageratum conyzoides

	pH	SOC	MOISTURE	TN	AP	AK
pH	1					
SOC	0.317327	1				
MOISTURE	0.723427	0.493295	1			
TN	0.264929	-0.61136	-0.21748	1		
AP	0.491147	-0.16853	0.229235	0.823309	1	
AK	0.341722	0.923886	0.463284	-0.40788	0.033422	1

2. Lantana camara

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.364544	1				
MOISTURE	0.514628	0.57007	1			
TN	0.358229	-0.55699	-0.21354	1		
AP	-0.37389	-0.70706	-0.75806	0.290386	1	
AK	0.365415	0.959382	0.575553	-0.44273	-0.5893	1

3. Chromolaena odorata

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.293061	1				
MOISTURE	0.259374	0.572488	1			
TN	-0.09355	0.162772	-0.07612	1		
AP	0.092969	-0.39527	-0.29258	0.340176	1	
AK	0.226727	0.782323	0.309522	0.733334	-0.02113	1

4. Mikania micrantha

	pH	*SOC*	*MOISTURE*	*TN*	*AP*	*AK*
pH	1					
SOC	0.448447	1				
MOISTURE	0.428206	0.518633	1			
TN	-0.11295	-0.70975	-0.58113	1		
AP	0.013339	-0.5945	0.094951	0.288453	1	
AK	0.467886	0.651661	0.538501	-0.18157	-0.01598	1

APPENDIX 3: PHOTOPLATES

1. Pot bioassay of Ageratum with Lettuce

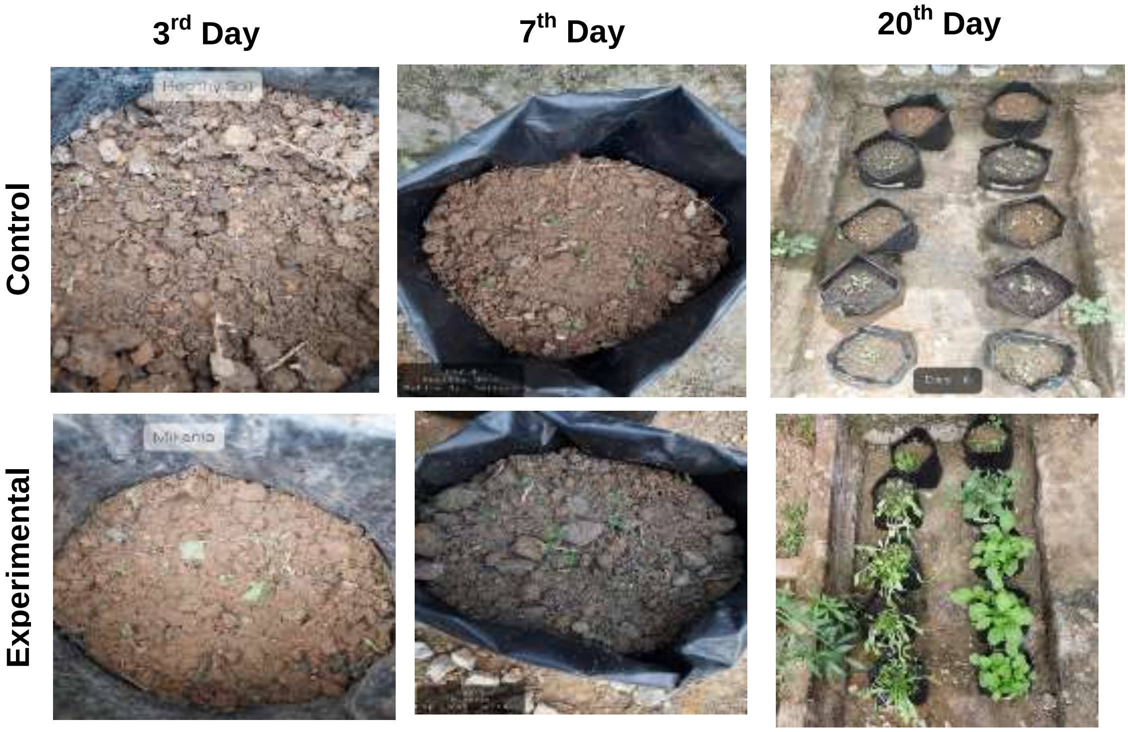
3rd Day **7th Day** **20th Day**

Control

Experimental

2. Pot bioassay of Lantana with Lettuce

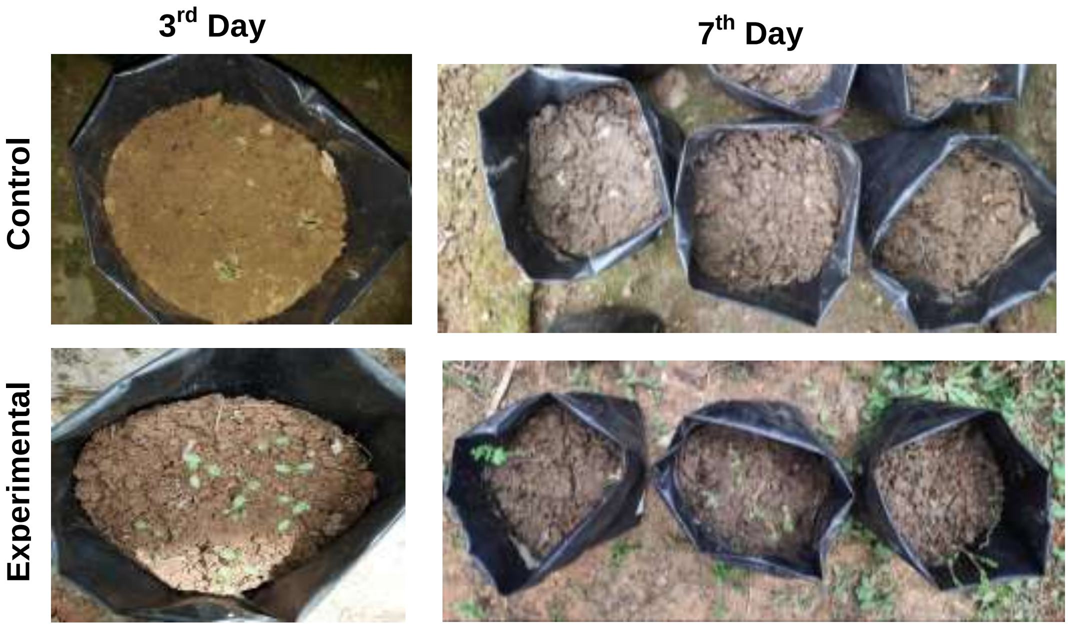
3. Pot bioassay of Mikania with Lettuce



4. Pot bioassay of Mikania with Cicer

5. Pot bioassay of Ageratum with Cicer

6. Pot bioassay of Lantana with Cicer



7. Pot bioassay of odorata with Cicer

References

Abdul-Wahab, A. S. and Rice, E. L. (1967) Plant inhibition by Johnson grass and its possible significance in old-field succession. Bull.Torrey Bot. Club 94, 486–497.

Abhilash PC (2021) Restoring the unrestored: strategies for restoring global land during the UN-Decade on Ecosystem Restoration (UN-DER). Land 10:201. https://doi.org/10.3390/land10020201

Aci, M. M., Sidari, R., Araniti, F., & Lupini, A. (2022). Emerging trends in allelopathy: A genetic perspective for sustainable

Adhikari D, Tiwary R, Barik SK (2015) Modelling hotspots for invasive alien plants in India. PLoS ONE 10(7): e0134665

Agaldo, J. A. (2020). Ecology of Lantana camara: An invasive plant species in Amurum Forest Reserve, Jos Plateau, Central Nigeria. African Journal of Ecology, 58(2), 291-298. https://doi.org/10.1111/aje.12698

agriculture. Agronomy, 12(9), 2043.

Akomeng, N., & Adusei, S. (2021). Organic solvent extraction and spectrophotometric quantification of total phenolic content of soil. Heliyon, 7(11), e08388. https://doi.org/10.1016/j.heliyon.2021.e08388

Al Harun, M. A. Y., Johnson, J., Uddin, M. N., & Robinson, R. W. (2015). The effects of temperature on decomposition and allelopathic phytotoxicity of boneseed litter. Journal of Environmental Sciences, 33, 1-11.

Aleixandre-Tudo, J. L., & Du Toit, W. (2018). The role of UV-visible spectroscopy for phenolic compounds quantification in winemaking. Frontiers and new trends in the science of fermented food and beverages, 200-204.

Ambika, S. R. (2012). Multifaceted attributes of allelochemicals and mechanism of allelopathy. In Allelopathy: Current trends and future applications (pp. 389-405). Berlin, Heidelberg: Springer Berlin Heidelberg.

Arya, A. K., Joshi, K. K., Bachheti, A. and Rawat, R. (2021). Status and impact of invasive and alien species on environment,and human welfare: an overview. Uttar Pradesh Journal of Zoology, 42(8): 49-58.

Assessing the environmental impacts of invasive alien plants: a review of assessment approaches

Auld, B. A., & Johnson, S. B. (2014). Invasive alien plant management. CABI Reviews, (2014), 1-12.

Ayanda, O. I., Ajayi, T., & Asuwaju, F. P. (2020). Eichhornia crassipes (Mart.) Solms: Uses, Challenges, Threats, and Prospects. The Scientific World Journal, 2020. https://doi.org/10.1155/2020/3452172

Azlim Almey, A. A., Ahmed Jalal Khan, C., Syed Zahir, I., Mustapha Suleiman, K., Aisyah, M. R., & Kamarul Rahim, K. (2010). Total phenolic content and primary antioxidant activity of methanolic and ethanolic extracts of aromatic plants' leaves. International Food Research Journal, 17(4).

Bais HP, Vepachedu R, Gilroy S, Callaway RM, Vivanco JM (2003) Allelopathy and exotic plant invasion: from molecules and genes to species interactions. *Science* 301:1377–1380.

Baker, H. G. (1974). The evolution of weeds. Annual review of ecology and systematics, 5(1), 1-24.

Baldwin IT (2003) At last, evidence of weapons of mass destruction. Science STKE: pp.42.

Baral, D., Chaudhary, M., Lamichhane, G., & Pokhrel, B. (2022). Ageratum conyzoides: A potential source for medicinal and agricultural products. Turkish Journal of Agriculture-Food Science and Technology, 10(12), 2307-2313.

Bartz, R., & Kowarik, I. (2019). Assessing the environmental impacts of invasive alien plants: a review of assessment approaches. NeoBiota, 43, 69-99.

Basumatary, D., Singh, M.S., Singha, K.L., Yadav, H.S., & Tripathi, O.P. (2021). 10 noxious invasive plant species in northeast India.

Batish DR, Singh HP, Pandher JK, Arora V, Kohli RK (2002) "Phytotoxic effect of *Parthenium* residues on the growth of radish and chickpea and selected soil properties." *Weed Biology and Manage*ment 2.2 :73-78.

Baziramakenga, R., Simard, R. R., & Leroux, G. D. (1994). Effects of benzoic and cinnamic acids on growth, mineral composition, and chlorophyll content of soybean. Journal of Chemical Ecology, 20, 2821-2833.

Bellard, C., Leclerc, C., Leroy, B., Bakkenes, M., Veloz, S., Thuiller, W., & Courchamp, F. (2014). Vulnerability of biodiversity hotspots to global change. Global Ecology and Biogeography, 23, 1376–1386.

Bezerra, J. J. L., & Pinheiro, A. A. V. (2022). Traditional uses, phytochemistry, and anticancer potential of Cyperus rotundus L. (Cyperaceae): A systematic review. South African Journal of Botany, 144, 175-186.

Bezerra, J. J. L., & Pinheiro, A. A. V. (2022). Traditional uses, phytochemistry, and anticancer potential of Cyperus rotundus L. (Cyperaceae): A systematic review. South African Journal of Botany, 144, 175-186.

Bhatt, J. R., Singh, J. S., Singh, S. P., Tripathi, R. S., & Kohli, R. K. (2011). Invasive alien plants an ecological appraisal for the Indian subcontinent (Vol. 1). Cabi.

Bhatt, J. R., Singh, J. S., Singh, S. P., Tripathi, R. S., & Kohli, R. K. (2011). Invasive alien plants an ecological appraisal for the Indian subcontinent (Vol. 1). Cabi.

Blackburn, T. M., Bellard, C., & Ricciardi, A. (2019). Alien versus native species as drivers of recent extinctions. Frontiers in Ecology and the Environment, 17(4), 203-207.

Blackburn, T. M., Essl, F., Evans, T., Hulme, P. E., Jeschke, J. M., Kühn, I., ... & Bacher, S. (2014). A unified classification of alien species based on the magnitude of their environmental impacts. PLoS biology, 12(5), e1001850.

Blair AC, Hanson BD, Brunk GR, Marrs RA, Westra P, Nissen SJ, Hufbauer RA (2005) New techniques and findings in the study of a candidate allelochemical implicated in invasion success. *Ecology Letters* 8:1039–1047.

Blossey, B., & Notzold, R. (1995). Evolution of increased competitive ability in invasive nonindigenous plants: a hypothesis. Journal of Ecology, 83(5), 887-889.

Boinot, S., Barkaoui, K., Mézière, D., Lauri, P. E., Sarthou, J. P., & Alignier, A. (2022). Research on agroforestry systems and biodiversity conservation: what can we conclude so far and what should we improve? BMC ecology and evolution, 22(1), 24.

Bolpagni, R. Towards global dominance of invasive alien plants in freshwater ecosystems: the dawn of the Exocene? Hydrobiologia 848, 2259–2279 (2021). https://doi.org/10.1007/s10750-020-04490-w

Bowen, J. L., Kearns, P. J., Byrnes, J. E., Wigginton, S., Allen, W. J., Greenwood, M., ... & Meyerson, L. A. (2017). Lineage overwhelms environmental conditions in determining rhizosphere bacterial community structure in a cosmopolitan invasive plant. Nature Communications, 8(1), 433.

Bradley, B. A., Laginhas, B. B., Whitlock, R., Allen, J. M., Bates, A. E., Bernatchez, G., ... & Sorte, C. J. (2019). Disentangling the abundance–impact relationship for invasive species. Proceedings of the National Academy of Sciences, 116(20), 9919-9924.

Brancalion, P. H., Amazonas, N. T., Chazdon, R. L., van Melis, J., Rodrigues, R. R., Silva, C. C., ... & Holl, K. D. (2020). Exotic eucalypts: From demonized trees to allies of tropical forest restoration? Journal of Applied Ecology, 57(1), 55-66.

Brandt, A. J., Png, G. K., Jo, I., McGrannachan, C., Allen, K., Peltzer, D. A., Dickie, I. A., French, K., Leishman, M. R., Ostertag, R., Parker, I. M., Stanley, M. C., Suding, K. N., & Bellingham, P. J. (2023). Managing multi-species plant invasions when interactions influence their impact. Frontiers in Ecology and the Environment. https://doi.org/10.1002/fee.2658

Buchholz, S., & Kowarik, I. (2019). Urbanisation modulates plant-pollinator interactions in invasive vs. native plant species. Scientific Reports, 9(1), 6375.

Cairns, J., Pratt, J.R. The scientific basis of bioassays. Hydrobiologia 188, 5–20 (1989). https://doi.org/10.1007/BF00027769

Callaway RM, Aschehoug ET (2000) Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science,290: pp.521-523.

Callaway RM, Ridenour WM (2004) Novel weapons: invasive success and the evolution of increased competitive ability. *Frontiers in Ecology and Environment*, 2(8): 436-443.

Callaway, R. M., & Aschehoug, E. T. (2000). Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science (New York, N.Y.), 290(5491), 521–523. https://doi.org/10.1126/science.290.5491.521

Callaway, R.M. & Aschehoug, E.T. (2000) Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science, 290, 2075–2075.

Carrera-Castaño, G., Calleja-Cabrera, J., Pernas, M., Gómez, L., & Oñate-Sánchez, L. (2020). An updated overview on the regulation of seed germination. Plants, 9(6), 703.

Castro-Díez, P., Godoy, O., Alonso, A., Gallardo, A., & Saldaña, A. (2014). What explains variation in the impacts of exotic plant invasions on the nitrogen cycle? A meta-analysis. Ecology letters, 17(1), 1-12.

Chakraborty, A., Saha, S., Sachdeva, K., & Joshi, P. K. (2018). Vulnerability of forests in the Himalayan region to climate change impacts and anthropogenic disturbances: a systematic review. Regional Environmental Change, 18, 1783-1799.

Chakraborty, R., et al. (2012). North-East India an ethnic storehouse of unexplored medicinal plants. Journal of Natural Product and Plant Resource, 2(1), 143–152.

Chamier, J., Schachtschneider, K., Le Maitre, D. C., Ashton, P. J., & Van Wilgen, B. W. (2012). Impacts of invasive alien plants on water quality, with particular emphasis on South Africa. Water Sa, 38(2), 345-356.

Chaudhary, A., Kala, A., Adhikari, B., & Rawat, G. (2022). Perception and knwledge of community people on invasive Alien Plant species in Chandak-Aunla Ghat and Hat-Kalika watersheds of Kailash sacred landscape - India: A case study. Environmental Challenges, 9, 100604. https://doi.org/10.1016/j.envc.2022.100604

Chaudhary, A., Kala, A., Adhikari, B., & Rawat, G. (2022). Perception and knowledge of community people on invasive Alien Plant species in Chandak-Aunla Ghat and Hat-Kalika watersheds of Kailash sacred landscape - India: A case study. Environmental Challenges, 9, 100604. https://doi.org/10.1016/j.envc.2022.100604

Chazdon, R. L. (2019). Towards more effective integration of tropical forest restoration and conservation. Biotropica, 51(4), 463-472.

Chen C,Wang QH,Wu JY, Huang D,Zhang WH,Zhao N,Li XF,Wang LX (2017)Historical introduction, geographical distribution, and biological characteristics of alien plants in China. *Biodiversity and Conservation* 26: 353–381.

Chengxu, Wang & Mingxing, Zhu & Xuhui, Chen & Bo, Qu. (2011). Review on Allelopathy of Exotic Invasive Plants. Procedia Engineering. 18. 240–246. 10.1016/j.proeng.2011.11.038.

Chiu, J. H., Chong, K. Y., Lum, S. K., & Wardle, D. A. (2023). Trends in the direction of global plant invasion biology research over the past two decades. Ecology and Evolution, 13(1), e9690.

Chiu, J. H., Chong, K. Y., Y. Lum, S. K., & Wardle, D. A. (2023). Trends in the direction of global plant invasion biology research over the past two decades. Ecology and Evolution, 13(1), e9690. https://doi.org/10.1002/ece3.9690

Chodak, M., Pietrzykowski, M., & Sroka, K. (2015). Physiological profiles of microbial communities in mine soils afforested with different tree species. Ecological Engineering, 81, 462-470. https://doi.org/10.1016/j.ecoleng.2015.04.077

Chong, K. Y., Corlett, R. T., Nuñez, M. A., Chiu, J. H., Courchamp, F., Dawson, W., ... & Wardle, D. A. (2021). Are terrestrial biological invasions different in the tropics? Annual Review of Ecology, Evolution, and Systematics, 52, 291-314.

Colautti RI, MacIsaac HJ (2004) A neutral terminology to define 'invasive'species. *Diversity and Distributions* 10: 135–141.

Corina Del Fabbro∗, Daniel Prati

D. Fu, X. Wu, N. Huang, C. Duan.Effects of the invasive herb Ageratina adenophora on understory plant communities and tree seedling growth in Pinus yunnanensis forests in Yunnan, China.J. For. Res., 23 (2) (2018), pp. 112-119

D'Antonio, C. M., August-Schmidt, E., & Fernandez-Going, B. (2016). Invasive species and restoration challenges. Foundations of restoration ecology, 216-244.

Darwin, C. (1859). On the origin of species: facsimile of the first edition.

Davis MA (2009) Invasion biology. Oxford, UK: Oxford University Press.

Davis, M. A., Grime, J. P., & Thompson, K. (2000). Fluctuating resources in plant communities: a general theory of invasibility. Journal of ecology, 88(3), 528-534.

Dechoum, M. D. S., Sampaio, A. B., Ziller, S. R., & Zenni, R. D. (2018). Invasive species and the Global Strategy for Plant Conservation: how close has Brazil come to achieving Target 10? Rodriguésia, 69, 1567-1576.

Del Fabbro, C., Güsewell, S., & Prati, D. (2014). Allelopathic effects of three plant invaders on germination of native species: a field study. Biological invasions, 16, 1035-1042.

Dengler, J. (2017). Phytosociology. International Encyclopedia of Geography: People, the Earth, Environment and Technology Phytosociology, 1-6. https://doi.org/10.1002/9781118786352.wbieg0136

Dengler, J., Chytrý, M., & Ewald, J. (2007). Phytosociology. Encyclopedia of Ecology, 2767-2779. https://doi.org/10.1016/B978-008045405-4.00533-4

Dobhal, P. K., Kohli, R. K., & Batish, D. R. (2010). Evaluation of the impact of Lantana camara L. invasion, on four major woody shrubs, along Nayar river of Pauri Garhwal in Uttarakhand Himalaya. International Journal of Biodiversity and Conservation, 2(7), 155-161.

Dobhal, P. K., Kohli, R. K., & Batish, D. R. (2011). Impact of Lantana camara L. invasion on riparian vegetation of Nayar region in Garhwal Himalayas (Uttarakhand, India). Journal of Ecology and the Natural Environment, 3(1), 11-22.

Dogra KS, Kohli RK, Sood SK (2009) An assessment and impact of three invasive species in the Shivalik hills of Himachal Pradesh, India. International Journal of Biodiversity and Conservation Vol. 1(1) pp. 004-010.

Dogra, K. S., Kohli, R. K., Sood, S. K., & Dobhal, P. K. (2009). Impact of Ageratum conyzoides L. on the diversity and composition of vegetation in the Shivalik hills of Himachal Pradesh (Northwestern Himalaya), India. International Journal of Biodiversity and Conservation, 1(5), 135-145.

Drenovsky RE, Batten KM (2007) Invasion by *Aegilops triuncialis* (BarbGoatgrass) slows carbon and nutrient cycling in serpentine grassland. Biological Invasions. 9: 107–116.

Duboscq-Carra, V. G., Fernandez, R. D., Haubrock, P. J., Dimarco, R. D., Angulo, E., Ballesteros-Mejia, L., ... & Nuñez, M. A. (2021). Economic impact of invasive alien species in Argentina: a first national synthesis. NeoBiota, 67, 329-348.

Dutta, S., & Ray, S. (2019). Comparative assessment of total phenolic content and in vitro antioxidant activities of bark and leaf methanolic extracts of Manilkara hexandra (Roxb.) Dubard. Journal of King Saud University - Science, 32(1), 643-647. https://doi.org/10.1016/j.jksus.2018.09.015

Edrisi SA, El-Keblawy A, Abhilash PC (2020) Sustainability analysis of Prosopis juliflora (Sw.) DC based restoration of degraded land in North India. Land 9:59. https://doi.org/10.3390/land9020059

Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. Annual Review of Ecology Evolution and Systematics 41(1):59-80.

Elgersma, K. J., & Ehrenfeld, J. G. (2011). Linear and non-linear impacts of a non-native plant invasion on soil microbial community structure and function. Biological Invasions, 13, 757-768.

Ellenberg, D., & Mueller-Dombois, D. (1974). Aims and methods of vegetation ecology (p. 547). New York: Wiley.

Elton, C. S., & Elton, C. S. (1958). The reasons for conservation (pp. 143-153). Springer US.

Fahey C., & Flory, S. L. (2022). Soil microbes alter competition between native and invasive plants. Journal of Ecology, 110(2), 404-414. https://doi.org/10.1111/1365-2745.13807

Feng Q et al (2021) Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: a review. Resour Cons Recycl 164:105204.

Feng Yu-Long. (2022) Global change and biological invasions, Journal of Plant Ecology, Volume 15, Issue 3, June 2022, Pages 425–428, https://doi.org/10.1093/jpe/rtac013

Feng, Q., Wang, B., Chen, M., Wu, P., Lee, X., & Xing, Y. (2021). Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: A review. Resources, Conservation and Recycling, 164, 105204.

Feng, Q., Wang, B., Chen, M., Wu, P., Lee, X., & Xing, Y. (2021). Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: A review. Resources, Conservation and Recycling, 164, 105204.

Fierer, N., Schimel, J. P., Cates, R. G., & Zou, J. (2001). Influence of balsam poplar tannin fractions on carbon and nitrogen dynamics in Alaskan taiga floodplain soils. Soil Biology and Biochemistry, 33(12-13), 1827-1839.

Fitter A (2003) Making allelopathy respectable. *Science* 301:1337–38.

Fortini, L., & Schubert, O. (2017). Beyond exposure, sensitivity and adaptive capacity: a response based ecological framework to assess species climate change vulnerability. Climate Change Responses, 4. https://doi.org/10.1186/s40665-017-0030-y.

Foxcroft, L. C., Pyšek, P., Richardson, D. M., Pergl, J., & Hulme, P. E. (2013). The bottom line: impacts of alien plant invasions in protected areas. Plant invasions in protected areas: patterns, problems and challenges, 19-41.

Fu, D., Wu, X., Huang, N., & Duan, C. (2018). Effects of the invasive herb Ageratina adenophora on understory plant communities and tree seedling growth in Pinus yunnanensis forests in Yunnan, China. Journal of Forest Research, 23(2), 112-119.

Funk, J. L. (2013). The physiology of invasive plants in low-resource environments. Conservation physiology, 1(1), cot026.

Gaertner M, Breeyen AD, Hui C, Richardson DM (2009) Impacts of alien plant invasions on species richness in Mediterranean-type ecosystems: a meta-analysis. *Progress in Physical Geography* 33:319–338.

Gaertner, M., Biggs, R., Te Beest, M., Hui, C., Molofsky, J., & Richardson, D. M. (2014). Invasive plants as drivers of regime shifts: identifying high-priority invaders that alter feedback relationships. Diversity and Distributions, 20(7), 733-744.

Gallardo, B., Bacher, S., Bradley, B., Comín, F. A., Gallien, L., Jeschke, J. M., ... & Vilà, M. (2019). InvasiBES: Understanding and managing the impacts of Invasive alien species on Biodiversity and Ecosystem Services. NeoBiota, 50, 109-122.

Gao, F. L., He, Q. S., Zhang, Y. D., Hou, J. H., & Yu, F. H. (2021). Effects of soil nutrient heterogeneity on the growth and invasion success of alien plants: a multi-species study. Frontiers in Ecology and Evolution, 8, 619861.

Gaurav, Gajendra Kumar, Tariq Mehmood, Liu Cheng, Jiří Jaromír Klemeš, and Devesh Kumar Shrivastava. (2020) "Water hyacinth as a biomass: A review." Journal of Cleaner Production 277 (2020): 122214.

Gioria, M., Jarošík, V., & Pyšek, P. (2014). Impact of invasions by alien plants on soil seed bank communities: Emerging patterns. Perspectives in Plant Ecology, Evolution and Systematics, 16(3), 132-142. https://doi.org/10.1016/j.ppees.2014.03.003

Golivets, M., & Wallin, K. F. (2018). Neighbour tolerance, not suppression, provides competitive advantage to non-native plants. Ecology letters, 21(5), 745–759. https://doi.org/10.1111/ele.12934

Gomes, S. I., Merckx, V. S., & Hynson, N. A. (2018). Biological invasions increase the richness of arbuscular mycorrhizal fungi from a Hawaiian subtropical ecosystem. Biological Invasions, 20, 2421-2437.

Govaert, S., Meeussen, C., Vanneste, T., Bollmann, K., Brunet, J., O. Cousins, S. A., Diekmann, M., Graae, B. J., Hedwall, O., Heinken, T., Iacopetti, G., Lenoir, J., Lindmo, S., Orczewska, A., Perring, M. P., Ponette, Q., Plue, J., Selvi, F., Spicher, F., . . . Frenne, P. D. (2020). Edge influence on understorey plant communities depends on forest management. Journal of Vegetation Science, 31(2), 281-292. https://doi.org/10.1111/jvs.12844

Gray, A. (1879). Structural botany (Vol. 1). American Book Company.

Grove, S., Haubensak, K. A., Gehring, C., & Parker, I. M. (2017). Mycorrhizae, invasions, and the temporal dynamics of mutualism disruption. Journal of Ecology, 105(6), 1496-1508.

Gupta, S.R., Dagar, J.C., Teketay, D. (2020). Agroforestry for Rehabilitation of Degraded Landscapes: Achieving Livelihood and Environmental Security. In: Dagar, J.C., Gupta, S.R., Teketay, D. (eds) Agroforestry for Degraded Landscapes. Springer, Singapore. https://doi.org/10.1007/978-981-15-4136-0_2

Haider S, Alexander J, Dietz H, Trepl L, Edwards PJ, Kueffer C (2010) The role of bioclimatic origin, residence time and habitat context in shaping non-native plant distributions along an altitudinal gradient. Biol Invasions 12(12):4003–4018

Hale AN, Kalisz S (2012) Perspectives on allelopathic disruption of plant mutualisms: a framework for individual- and population-level fitness consequences. Plant Ecol213:1991–2006. https://doi.org/10.1007/s11258-012-0128-z

Hanspach, J., Kühn, I., Pyšek, P., Boos, E., & Klotz, S. (2008). Correlates of naturalization and occupancy of introduced ornamentals in Germany. Perspectives in Plant Ecology, Evolution and Systematics, 10(4), 241-250.

Hasanuddin, H., Hafsah, S., Erida, G., Marliah, A., Bahri, H., Bobihoe, J., & Aryani, D. S. (2021). Allelopathic potential of siam weed (Chromolaena odorata L.) extract for enhancing soybean productivity. In IOP Conference Series: Earth and Environmental Science (Vol. 922, No. 1, p. 012003). IOP Publishing.

Hasanuddin, H., Hafsah, S., Erida, G., Marliah, A., Bahri, H., Bobihoe, J., & Aryani, D. S. (2021, November). Allelopathic potential of siam weed (Chromolaena odorata L.) extract for enhancing soybean productivity. In IOP Conference Series: Earth and Environmental Science (Vol. 922, No. 1, p. 012003). IOP Publishing.

Hättenschwiler, S., & Vitousek, P. M. (2000). The role of polyphenols in terrestrial ecosystem nutrient cycling. Trends in ecology & evolution, 15(6), 238-243.

Hejda, M., Pyšek, P., & Jarošík, V. (2009). Impact of invasive plants on the species richness, diversity and composition of invaded communities. Journal of Ecology, 97(3), 393-403. https://doi.org/10.1111/j.1365-2745.2009.01480.x

Hierro, J. L., & Callaway, R. M. (2021). The ecological importance of allelopathy. Annual Review of Ecology, Evolution, and Systematics, 52, 25-45.
Hierro, J. L., & Callaway, R. M. (2021). The ecological importance of allelopathy. Annual Review of Ecology, Evolution, and Systematics, 52, 25-45.
Hulme PE (2003) Biological invasions: winning the science battles but losing the conservation war? Oryx 37(02):178–193Return to ref 2003 in article

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol 46(1):10–18

Hussain, N., Abbasi, T., & Abbasi, S. A. (2016). Vermicomposting transforms allelopathic parthenium into a benign organic fertilizer. Journal of Environmental Management, 180, 180-189.

Inderjit, and E. T. Nilsen. 2003. Bioassays and field studies for allelopathy in terrestrial plants: progress and problems. Critical Reviews in Plant Sciences 22: 221– 238.

Inderjit, Cadotte MW, Colautti RI (2005) The ecology of biological invasions:past, present and future.

Inderjit, Evans, H., Crocoll, C., Bajpai, D., Kaur, R., Feng, Y. L., ... & Callaway, R. M. (2011). Volatile chemicals from leaf litter are associated with invasiveness of a neotropical weed in Asia. Ecology, 92(2), 316-324.

Inderjit, von Dahl, C. C., & Baldwin, I. T. (2009). Use of silenced plants in allelopathy bioassays: a novel approach. Planta, 229, 569-575.India Private Limited, New Delhi. 1973.

Iqbal MF, Feng Y-L, Feng W-W, et al. (2021) Ecological impacts of the invasive plant Xanthium strumarium and the impacts of three aboveground herbivores on the invader. Ecol Indic 131:108140.

J. Giejsztowt (2020) Climate change and invasion may synergistically affect native plant reproduction Ecology (2020)

J., Kumawat, S. (2023). Degraded land rehabilitation through agroforestry in India: Achievements, current understanding, and future prospectives. Frontiers in Ecology and Evolution, 11, 1088796. https://doi.org/10.3389/fevo.2023.1088796

Jackson ML. (1973). Soil Chemical Analysis, Prentice Hall of

Jamil, M. D., Waheed, M., Akhtar, S., Bangash, N., Chaudhari, S. K., Majeed, M., Hussain, M., Ali, K., & Jones, D. A. (2021). Invasive Plants Diversity, Ecological Status, and Distribution Pattern in Relation to Edaphic Factors in Different Habitat Types of District Mandi Bahauddin, Punjab, Pakistan. Sustainability, 14(20), 13312. https://doi.org/10.3390/su142013312

Jinger, D., Kaushal, R., Kumar, R., Paramesh, V., Verma, A., Shukla, M., Chavan, S. B., Kakade, V., Dobhal, S., Uthappa, A. R., Roy, T., Singhal, V., Madegowda, M., Kumar, D., Khatri, P., Dinesh, D., Singh, G., Singh, A. K., Nath, A.

Joshi, A. A., Mudappa, D., & Raman, T. S. (2015). Invasive alien species in relation to edges and forest structure in tropical rainforest fragments of the Western Ghats. Tropical Ecology, 56(2), 233-244.

Joshi, S., Shrestha, B. B., Shrestha, L., Rashid, I., & Adkins, S. (2022). Plant invasions in mountains. In Global Plant Invasions (pp. 279-300). Cham: Springer International Publishing.

Kalisz, S., Kivlin, S. N., & Bialic-Murphy, L. (2021). Allelopathy is pervasive in invasive plants. Biological Invasions, 23, 367-371.

Kannan, R., Shackleton, C. M., & Shaanker, R. U. (2013). Playing with the forest: invasive alien plants, policy and protected areas in India. Current Science, 1159-1165.

Kannan, R., Shackleton, C. M., Krishnan, S., & Shaanker, R. U. (2016). Can local use assist in controlling invasive alien species in tropical forests? The case of Lantana camara in southern India. Forest Ecology and Management, 376, 166-173.

Kato-Noguchi, H and Kurniadie, D. Allelopathy of Lantana camara as an Invasive Plant.Plants 2021, 10, 1028. https://doi.org/10.3390/ plants10051028

Kaur, R., & Prasad, K. (2021). Technological, processing and nutritional aspects of chickpea (Cicer arietinum) - A review. Trends in Food Science & Technology, 109, 448-463. https://doi.org/10.1016/j.tifs.2021.01.044

Keane RM, Crawley MJ (2002) Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology &Evolution*. 17(4), pp.164-169.

Kennedy, T. A., Naeem, S., Howe, K. M., Knops, J. M., Tilman, D., & Reich, P. (2002). Biodiversity as a barrier to ecological invasion. Nature, 417(6889), 636-638. https://doi.org/10.1038/nature00776

Kershaw KA (1973) Quantitative and dynamic plant ecology. American Elsevier Pub.co, pp183.

Kettenring, K. M., & Adams, C. R. (2011). Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. Journal of applied ecology, 48(4), 970-979.

Khamare, Y., Chen, J., & Marble, S. C. (2022). Allelopathy and its application as a weed management tool: A review. Frontiers in Plant Science, 13, 1034649. https://doi.org/10.3389/fpls.2022.1034649

Khoddami, A., Wilkes, M. A., & Roberts, T. H. (2013). Techniques for analysis of plant phenolic compounds. Molecules, 18(2), 2328-2375.

Kim, Y. O., & Lee, E. J. (2011). Comparison of phenolic compounds and the effects of invasive and native species in East Asia: support for the novel weapons hypothesis. Ecological Research, 26, 87-94.

Kimothi, M.M., Anitha, D., Vasistha, H.B., Soni, P., and Chandola, S.K. (2010). Remote sensing to map the invasive weed,Lantana camara in forests, Tropical Ecology, 51(1): 67-74.

Kocaçalışkan, I., Talan, I. & Terzi, I. (2006). Antimicrobial Activity of Catechol and Pyrogallol as Allelochemicals. Zeitschrift für Naturforschung C, 61(9-10), 639-642. https://doi.org/10.1515/znc-2006-9-1004

Kohli, R. K. (2019). Governing the greens: Invasive Alien Plants in India. SPECIAL ISSUE ON ENVIRONMENT, 141.

Kohli, R. K., Batish, D. R., Singh, H. P., & Dogra, K. S. (2006). Status, invasiveness and environmental threats of three tropical American invasive weeds (Parthenium hysterophorus L., Ageratum conyzoides L., Lantana camara L.) in India. Biological Invasions, 8, 1501-1510.

Kohli, R. K., Dogra, K. S., Batish, D. R., & Singh, H. P. (2004). Impact of invasive plants on the structure and composition of natural vegetation of northwestern Indian Himalayas1. Weed Technology, 18(sp1), 1296-1300.

Konatowska, M. and Rutkowski, P. (2019) Phytosociology—A Useful Tool for the Assessment of Past and Future Human Impacts on Plants and Forest Ecosystems. Journal of Biosciences and Medicines, 7, 154-163. doi: 10.4236/jbm.2019.711014.

Kong CH (1998) Problems needed attention on plant allelopathy research.*Chinese Journal of Applied Ecology*,9(3):pp.332-336.

Kong, C., Hu, F., Xu, T., & Lu, Y. (1999). Allelopathic potential and chemical constituents of volatile oil from Ageratum conyzoides. Journal of Chemical Ecology, 25, 2347-2356.

Kotta, J. C., Lestari, A. B., Candrasari, D. S., & Hariono, M. (2020). Medicinal effect, in silico bioactivity prediction, and pharmaceutical formulation of Ageratum conyzoides L.: a review. Scientifica, 2020, 1-12.

Kuebbing, S. E., & Nuñez, M. A. (2015). Negative, neutral, and positive interactions among nonnative plants: patterns, processes, and management implications. Global change biology, 21(2), 926–934. https://doi.org/10.1111/gcb.12711

Kueffer, C., (2017). Plant invasions in the Anthropocene. 358 (6364), 724–725.

Kull, C. A. (2018). Critical invasion science: weeds, pests, and aliens. The Palgrave handbook of critical physical geography, 249-272.

Kumar Ashish Arya, Kamal Kant Joshi, Arachna Bachhet and Rekha rawat. (2021). Status and impact of invasive and alien species on environment, and human welfare: an Overview42(8): 49-58, 2021.Issn: 0256-971x (p)

Kumar HN, Mohana NC, Nuthan BR, Ramesha KP, Rakshith D, Geetha N, Satish S (2019) Phytomediated synthesis of zinc oxide nanoparticles using aqueous plant extract of Ocimum americanum and evaluation of its bioactivity. SN Appl Sci 1(6):651. https://doi.org/10.1007/s42452-019-0671-5

Kumar, M., Kumar, S., Verma, A. K., Joshi, R. K., & Garkoti, S. C. (2021). Invasion of Lantana camara and Ageratina adenophora alters the soil physico-chemical characteristics and microbial biomass of chir pine forests in the central Himalaya, India. CATENA, 207, 105624. https://doi.org/10.1016/j.catena.2021.105624

Kumar, M., Kundu, D. K., Ghorai, A. K., Mitra, S., & Singh, S. R. (2018). Carbon and nitrogen mineralization kinetics as influenced by diversified cropping systems and residue incorporation in Inceptisols of eastern Indo-Gangetic Plain. Soil and Tillage Research, 178, 108-117.

Kumar, S., Meena, R., Tiwari, A. K., Singh, R., Patel, S. K., & Singh, G. S. (2023). Perceptions of impacts and management of invasive alien plants: A case study from Mirzapur, India. Front Glob Change, 6, 1194076.

Kumar, T., Bishwas, A. J., Khare, P. K., & Garg, N. (2021). Invasive alien flora of tropical dry deciduous forest of Nauradehi Wildlife Sanctuary, Central India. Indian journal of Ecology, 48(1), 219-225.

Kumschick S, Gaertner M, Vilà M, Essl F, Jeschke JM, Pyšek P, Ricciardi A,Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kühn I, Mrugala A, Pergl J, Rabitsch W, Richardson DM, Sendek A,Winter M (2015). Ecological impacts of alien species: quantification, scope, caveats and recommendations. *Bioscience* 65:55–63.

Lalsangpuii, F., Rokhum, S. L., Nghakliana, F., VL Ruatpuia, J., Tochhawng, L., Trivedi, A. K., ... & Siama, Z. (2024). Mikania micrantha silver nanoparticles exhibit anticancer activities against human lung adenocarcinoma via caspase-mediated apoptotic cell death. Artificial Cells, Nanomedicine, and Biotechnology, 52(1), 186-200.

Lambers, H., Chapin, F. S., Pons, T. L., Lambers, H., Chapin, F. S., & Pons, T. L. (2008). Ecological biochemistry: allelopathy and defense against herbivores. Plant physiological ecology, 445-477.

Lamsal, P., Kumar, L., Aryal, A., & Atreya, K. (2018). Invasive alien plant species dynamics in the Himalayan region under climate change. Ambio, 47(6), 697-710.

Langmaier, M., & Lapin, K. (2020). A systematic review of the impact of invasive alien plants on forest regeneration in European temperate forests. Frontiers in Plant Science, 11, 524969.

Langmaier, M., & Lapin, K. (2020). A systematic review of the impact of invasive alien plants on forest regeneration in European temperate forests. Frontiers in Plant Science, 11, 524969.

Larson B. (2007). An alien approach to invasive species: objectivity and society in invasion biology.Biol. Invasions, 9 (8) (2007), pp. 947-956

Lattanzio, V. (2013). Phenolic compounds: introduction 50. Nat. Prod, 1543-1580.

Lázaro-Lobo, A., Alonso, Á., Fernández, R. D., Granda, E., Romero-Blanco, A., Saldaña-López, A., & Castro-Díez, P. (2023). Impacts of Plant Invasions on Ecosystem Functionality: A Perspective for Ecosystem Health and Ecosystem Services. In: (eds) Plant Invasions and Global Climate Change. Springer, Singapore. https://doi.org/10.1007/978-981-99-5910-5_2

Lee, C. E. (2002). Evolutionary genetics of invasive species. Trends in ecology & evolution, 17(8), 386-391.

Lee, M. R., Bernhardt, E. S., van Bodegom, P. M., Cornelissen, J. H. C., Kattge, J., Laughlin, D. C., ... & Wright, J. P. (2017). Invasive species' leaf traits and dissimilarity from natives shape their impact on nitrogen cycling: a meta-analysis. New Phytologist, 213(1), 128-139.

Lee, M.R.; Flory, S.L.; Phillips, R.P. (2012). Positive feedbacks to growth of an invasive grass through alteration of nitrogen cycling. Oecologia 2012, 170, 457–465.

Lekberg, Y., Gibbons, S. M., Rosendahl, S., & Ramsey, P. W. (2013). Severe plant invasions can increase mycorrhizal fungal abundance and diversity. The ISME journal, 7(7), 1424-1433.

Levin DA (1976) The Chemical Defenses of Plants to Pathogens and Herbivores.*Annual Review of Ecology and Systematics*.7,121-159.

Leyu, A. M., Debebe, S. E., Bachheti, A., Rawat, Y. S., & Bachheti, R. K. (2022). Green Synthesis of Gold and Silver Nanoparticles Using Invasive Alien Plant Parthenium hysterophorus and Their Antimicrobial and Antioxidant Activities. Sustainability, 15(12), 9456. https://doi.org/10.3390/su15129456

Li ZY, XieY (2002) Invasive alien species in China. Beijing: China Forestry Publishing House.

Li, Z. H., Wang, Q., Ruan, X., Pan, C. D., & Jiang, D. A. (2010). Phenolics and plant allelopathy. Molecules, 15(12), 8933-8952.

Liao, C., Luo, Y., Jiang, L., Zhou, X., Wu, X., Fang, C., ... & Li, B. (2007). Invasion of Spartina alterniflora enhanced ecosystem carbon and nitrogen stocks in the Yangtze Estuary, China. Ecosystems, 10, 1351-1361.

Lin, D., & Xing, B. (2007). Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. Environmental pollution, 150(2), 243-250.

Llorach, R., Martínez-Sánchez, A., Tomás-Barberán, F. A., Gil, M. I., & Ferreres, F. (2008). Characterisation of polyphenols and antioxidant properties of five lettuce varieties and escarole. Food chemistry, 108(3), 1028-1038.

Lone, P. A., Dar, J. A., Kothandaraman, S., & Khan, M. L. (2022). Invasive shrub Lantana camara L. Alters the flora and soils in tropical dry deciduous forests of Central India. Biotropica, 54(6), 1412-1427. https://doi.org/10.1111/btp.13112

Lone, P. A., Dar, J. A., Subashree, K., Raha, D., Pandey, P. K., Ray, T., ... & Khan, M. L. (2019). Impact of plant invasion on physical, chemical and biological aspects of ecosystems: A review. Tropical Plant Research, 6(3), 528-544.

Lonsdale, W. M. (1999). Global patterns of plant invasions and the concept of invasibility. Ecology, 80(5), 1522-1536.

Lorenzo, P., & Morais, M. C. (2022). Strategies for the Management of Aggressive Invasive Plant Species. Plants, 12(13), 2482. https://doi.org/10.3390/plants12132482

Lorenzo, P., Pazos-Malvido, E., Rubido-Bará, M., Reigosa, M. J., & González, L. (2012). Invasion by the leguminous tree Acacia dealbata (Mimosaceae) reduces the native understorey plant species in different communities. Australian Journal of Botany, 60(8), 669-675.

Lorenzo, P., Rodríguez-Echeverría, S., González, L., & Freitas, H. (2010). Effect of invasive Acacia dealbata Link on soil microorganisms as determined by PCR-DGGE. Applied Soil Ecology, 44(3), 245-251.

Lotina-Hennsen B, King-Diaz B, Aguilar MI, Fernendez Terrones, MG (2006) Plant secondary metabolites. Targets and mechanisms of allelopathy. Springer, Netherlands, ISBN: 978-1-4020-4279-9.

Lupini, A.; Sorgonà, A.; Princi, M.P.; Sunseri, F.; Abenavoli, M.R. Morphological and physiological effects of trans-cinnamic acid and its hydroxylated derivatives on maize root types. Plant Growth Regul. 2016, 78, 263–273.

Ma, H., Chen, Y., Chen, J., Ji, J., & He, H. (2021). Identification and comparison of allelopathic effects from leaf and flower volatiles of the invasive plants Mikania micrantha. Chemoecology, 31(6), 355-365.

Ma, J., Xie, Y., Yang, Y., Jing, C., You, X., Yang, J., ... & Li, Y. (2022). AMF colonization affects allelopathic effects of Zea mays L. root exudates and community structure of rhizosphere bacteria. Frontiers in Plant Science, 13, 1050104.

MacArthur, R. (1970). Species packing and competitive equilibrium for many species. Theoretical population biology, 1(1), 1-11.

Macías, F. A., Mejías, F. J., & Molinillo, J. M. (2019). Recent advances in allelopathy for weed control: from knowledge to applications. Pest management science, 75(9), 2413-2436.

Macías, F.A.; Mejías, F.J.R.; Molinillo, J.M.G. (2019). Recent advances in allelopathy for weed control: From knowledge to applications. Pest. Manag. Sci. 2019, 75, 2413–2436.

Mack RN. Global plant dispersal, naturalization, and invasion: pathways, modes, and circumstances. In: Ruiz GM, Carlton JT, editors. Invasive Species Vectors and Management Strategies. Island Press, Washington; 2003. p. 3–30.5.

Mack, R., & Smith, M. (2011). Invasive plants as catalysts for the spread of human parasites. NeoBiota, 9, 13-29.

Mahé, I., Chauvel, B., Colbach, N., Cordeau, S., Gfeller, A., Reiss, A., & Moreau, D. (2022). Deciphering field-based evidences for crop allelopathy in weed regulation. A review. Agronomy for Sustainable Development, 42(3), 50.

Majewska, M. L., Rola, K., Stefanowicz, A. M., Nobis, M., Błaszkowski, J., & Zubek, S. (2018). Do the impacts of alien invasive plants differ from expansive native ones? An experimental study on arbuscular mycorrhizal fungi communities. Biology and fertility of soils, 54, 631-643.

Mallik, A.U., Pellissier, F. Effects of Vaccinium myrtillus on Spruce Regeneration: Testing the Notion of Coevolutionary Significance of Allelopathy. J Chem Ecol 26, 2197–2209 (2000). https://doi.org/10.1023/A:1005528701927

Mandal, G. and Joshi, S.P. (2014). Analysis of vegetation dynamics and phytodiversity from three dry deciduous forests of Doon Valley, Western Himalaya, India. Journal of Asia-Pacific Biodiversity, 7(3), 292-304.

Mangla, S., Inderjit, & Callaway, R. M. (2008). Exotic invasive plant accumulates native soil pathogens which inhibit native plants. Journal of Ecology, 96(1), 58-67.

Manzoor, S. A., Griffiths, G., & Lukac, M. (2020). Land use and climate change interaction triggers contrasting trajectories of biological invasion. Ecological Indicators, 120, 106936. https://doi.org/10.1016/j.ecolind.2020.106936

Marshall, N. A., Friedel, M., van Klinken, R. D., & Grice, A. C. (2011). Considering the social dimension of invasive species: the case of buffel grass. Environmental science & policy, 14(3), 327-338.

McFadyen RC (2002) Chromolaena in Asia and the Pacific: spreads continues but control prospects improve. In: Zachariades C, Muniappan R, Strathie LW (eds) Proceedings of the Fifth InternationalWorkshop on Biological Control and Management of Chromolaena odorata. Durban, South Africa, 23–25 October 2000, pp 13–18

McGaw, L. J., Omokhua-Uyi, A. G., Finnie, J. F., & Van Staden, J. (2022). Invasive alien plants and weeds in South Africa: A review of their applications in traditional medicine and potential pharmaceutical properties. Journal of Ethnopharmacology, 283, 114564.

Medina-Lozano, I., Bertolín, J. R., & Díaz, A. (2021). Nutritional value of commercial and traditional lettuce (*Lactuca sativa* L.) and wild relatives: Vitamin C and anthocyanin content. Food Chemistry, 359, 129864. https://doi.org/10.1016/j.foodchem.2021.129864

Min, K., & Suseela, V. (2020). Plant invasion alters the Michaelis–Menten kinetics of microbial extracellular enzymes and soil organic matter chemistry along soil depth. Biogeochemistry, 150(2), 181-196.

Misra R (1968) Ecology workbook.Oxford and IBH publishing company, Calcutta,India. Pp244.

Mollot, G., Pantel, J. H., & Romanuk, T. N. (2017). The effects of invasive species on the decline in species richness: a global meta-analysis. In Advances in ecological research (Vol. 56, pp. 61-83). Academic Press.

Montagnini, F. (2020). The contribution of agroforestry to restoration and conservation: biodiversity islands in degraded landscapes. Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges-Vol. 1, 445-479.

Mueller-Dombois, D. (1982). Ellenberg. H. 1974. Aims and methods of vegetation ecology. New York.

Muller, C. H. (1969) Allelopathy as a factor in ecological process. Vegetation 18, 348–357.

Mungi, N. A., Qureshi, Q., & Jhala, Y. V. (2021). Role of species richness and human impacts in resisting invasive species in tropical forests. Journal of Ecology, 109(9), 3308-3321.

Murali, K.S. and Setty S. R. (2001). Effects of weeds *Lantana camara* and *Chromolaena odorata* growth on the species diversity, regeneration and stem density of tree and shrub layer in BRT sanctuary. Current Science, 80:675-678

Mushtaq W, Shakeel A, Mehdizadeh M, Alghamdi S. A, Hakeem K. R. (2019) Impact of Plant Invasions on Local Vegetation: An Indian Perspective. Biosci Biotech Res Asia 2019;16(4).

Mushtaq, W., Siddiqui, M. B., & Hakeem, K. R. (2020). Allelopathy. Springer International Publishing.

Muzzo, B. I., Mwilawa, A. J., Maleko, D. D., & Mtengeti, E. J. (2018). Allelopathic effect of Chromolaena odorata aqueous leaf extracts on seed germination and seedling growth of selected crop and pasture species in Tanzania. International Journal of Botany Studies, 3(5), 41-48.

Mwangi, E., & Swallow, B. (2008). Prosopis juliflora invasion and rural livelihoods in the Lake Baringo area of Kenya. Conservation and Society, 6(2), 130-140.

Myers N (1993) Environmental refugees in a globally warmed world. Bioscience 43(11):752–761

Nair, P. R., Kumar, B. M., Nair, V. D., Nair, P. R., Kumar, B. M., & Nair, V. D. (2021). Agroforestry for Biodiversity Conservation. An Introduction to Agroforestry: Four Decades of Scientific Developments, 539-562.

Negi A, Batish DR, Singh HP, Kohli RK (2016) Allelopathic Effect of Leaves of Invasive tree *Broussonetia papyrifera* against some crop plants. *Annals of Plant Sciences* 5.1: 1261-1264.

Negi VS, Pathak R, Rawal RS, Bhatt ID, Sharma S (2019) Long-term ecological monitoring on forest ecosystems in Indian Himalayan Region: criteria and indicator approach. Ecol Indic 102:374–381

Negi, P. S. (2013). Ecological manifestation of slope instability, its application in identification of areas of potential hill slope movement in Indian Himalaya. Ecological indicators, 25, 85-91.

Nguyen, D. T. C., Tran, T. V., Nguyen, T. T. T., Nguyen, D. H., Alhassan, M., & Lee, T. (2023). New frontiers of invasive plants for biosynthesis of nanoparticles towards biomedical applications: A review. Science of The Total Environment, 857, 159278. https://doi.org/10.1016/j.scitotenv.2022.159278

Nguyen, N. T. T., Nguyen, L. M., Nguyen, T. T. T., Liew, R. K., Nguyen, D. T. C., & Van Tran, T. (2022). Recent advances on botanical biosynthesis of nanoparticles for catalytic, water treatment and agricultural applications: A review. Science of the Total Environment, 827, 154160.

NI, G. (2023). Effects of Exotic Plant Invasions on Terrestrial Ecosystems Carbon Cycling. Ecology and Environment, 32(7), 1325.

Ni, M., Deane, D. C., Li, S., Wu, Y., Sui, X., Xu, H., ... & Fang, S. (2021). Invasion success and impacts depend on different characteristics in non-native plants. Diversity and Distributions, 27(7), 1194-1207.

Nongtri, E. S., Lallianpuii, S., & Rai, P. K. (2022). Microcosm Study to Assess Allelochemical Potential of Lantana camara on Lactuca sativa. Indian Journal of Ecology, 49(6), 2163-2166.

Norton, D. A. (2009). Species invasions and the limits to restoration: learning from the New Zealand experience. Science, 325(5940), 569-571.

Noumedem, J., Djeussi, D., Hritcu, L., Mihasan, M., & Kuete, V. (2016). Lactuca sativa. Medicinal Spices and Vegetables from Africa, 437-449. https://doi.org/10.1016/B978-0-12-809286-6.00020-0

Obehi, O. T. (2020). Remediation of a heavy metal polluted soil using weedy species; Ageratum conyzoides L. and Chromolaena odorata (L.) RM King & H. Robinson.

Oh, D., Shim, D., Song, S., Oh, J., Hong, S., & Shim, S. (2015). Effects of soil moisture condition and shading on growth of invasive plant Burcucumber (Sicyos angulatus L.). Weed & Turfgrass Science, 4(4), 315-320.

Ojija, F., Arnold, S. E., & Treydte, A. C. (2019). Impacts of alien invasive Parthenium hysterophorus on flower visitation by insects to co-flowering plants. Arthropod-Plant Interactions, 13, 719-734.

Omokhua, A. G., Madikizela, B., Aro, A., Uyi, O. O., Van Staden, J., & McGaw, L. J. (2018). Noxious to ecosystems, but relevant to pharmacology: four South African alien invasive plants with pharmacological potential. South African journal of botany, 117, 41-49.

Orbán, I., Szitár, K., Kalapos, T. (2021). The role of disturbance in invasive plant establishment in a changing climate: insights from a drought experiment. Biol Invasions 23, 1877–1890 (2021).

Ordonez, A.; Wright, I.J.; Olff, H. Functional differences between native and alien species: A global-scale comparison. Funct. Ecol. 2010, 24, 1353–1361.

Osuri, A. M., Mudappa, D., Kasinathan, S., & Shankar Raman, T. R. (2022). Canopy cover and ecological restoration increase natural regeneration of rainforest trees in the Western Ghats, India. Restoration Ecology, 30(5), e13558. https://doi.org/10.1111/rec.13558

Otusanya, O. O., Ogunwole, A. A., & Tijani, M. O. (2015). Allelopathic effect of Tithonia diversifolia and Chromolaena odorata on the germination, growth and chlorophyll accumulation of Hibiscus sabdariffa (L.). International Journal of Botany and Research, 5(3), 1-14.

Padalia, H., Srivastava, V., & Kushwaha, S. P. S. (2014). Modeling potential invasion range of alien invasive species, Hyptis suaveolens (L.) Poit. in India: Comparison of MaxEnt and GARP. Ecological informatics, 22, 36-43.

Palni LMS, Rawal RS (2013) The himalayan biodiversity: richness, representativeness, uniqueness and life-support values. G. B. Pant Institute of Himalayan Environment and Development (GBPIHED), Almora, p 84

Pancholi, R., Choudhary, S., Prajapati, A., & Sharma, A. (2023). Agroforestry's contribution to environmental sustainability.

Panda, R.M., Behera, M.D. (2019). Assessing harmony in distribution patterns of plant invasions: a case study of two invasive alien species in India. Biodivers Conserv 28, 2245–2258 (2019). https://doi.org/10.1007/s10531-018-1640-9

Pandey A, Sharma GP (2013) Plant invasion researches in India: how long do we have to wait for appropriate management options? Curr Sci 104(4):408–409

Parniske M (2008) Arbuscular mycorrhiza: the mother of plant root endosymbioses. Nat Rev Microbiol 6:763–775.https://doi.org/10.1038/nrmicro1987

Pathak. R, V.S. Negi, R.S. Rawal, I.D. Bhatt. (2019). Alien plant invasion in the Indian Himalayan Region: state of knowledge and research priorities Biod. Con., 28 (12) (2019), pp. 3073-3102

Paul, S., Datta, B. K., Ratnaparkhe, M. B., & Dholakia, B. B. (2022). Turning waste into beneficial resource: Implication of Ageratum conyzoides L. In sustainable agriculture, environment and biopharma sectors. Molecular Biotechnology, 64(3), 221-244.

Pergl, J., Vítková, M., Hejda, M., Kutlvašr, J., Petřík, P., Sádlo, J., Vojík, M., Dvořáčková, Š., Fleischhans, R., Lučanová, A., & Pyšek, P. (2023). Plant-soil interactions in the communities dominated by alien and native plants. Perspectives in Plant Ecology, Evolution and Systematics, 59, 125721. https://doi.org/10.1016/j.ppees.2023.125721

Pergl, J., Vítková, M., Hejda, M., Kutlvašr, J., Petřík, P., Sádlo, J., ... & Pyšek, P. (2023). Plant-soil interactions in the communities dominated by alien and native plants. Perspectives in Plant Ecology, Evolution and Systematics, 59, 125721.

Pernas, M., & Gómez, L. (2020). An Updated Overview on the Regulation of Seed Germination. Plants, 9(6), 703. https://doi.org/10.3390/plants9060703

Pink, d., & Keane, E. M. (1992). Lettuce: Lactuca sativa L. Genetic Improvement of Vegetable Crops, 543-571. https://doi.org/10.1016/B978-0-08-040826-2.50044-8

Potgieter, L. J., Gaertner, M., Kueffer, C., Larson, B. M., Livingstone, S. W., O'Farrell,P. J., et al. (2017). Alien plants as mediators of ecosystem services and disservices in urban systems: A global review. Biol. Invas. 19, 3571–3588. doi: 10.1007/s10530-017-1589-8

Powell, K. I., Chase, J. M., & Knight, T. M. (2013). Invasive plants have scale-dependent effects on diversity by altering species-area relationships. science, 339(6117), 316-318.

Prabakaran, K., Li, J., Anandkumar, A., Leng, Z., Zou, C. B., & Du, D. (2019). Managing environmental contamination through phytoremediation by invasive plants: A review. Ecological Engineering, 138, 28-37.

Prior, K. M., Adams, D. C., Klepzig, K. D., & Hulcr, J. (2018). When does invasive species removal lead to ecological recovery? Implications for management success. Biological Invasions, 20, 267-283.

Puig, C. G., Gonçalves, R. F., Valentão, P., Andrade, P. B., Reigosa, M. J., & Pedrol, N. (2018). The Consistency Between Phytotoxic Effects and the Dynamics of Allelochemicals Release from Eucalyptus globulus Leaves Used as Bioherbicide Green Manure. Journal of chemical ecology, 44(7-8), 658–670. https://doi.org/10.1007/s10886-018-0983-8

Pyšek, P., Hulme, P. E., Simberloff, D., Bacher, S., Blackburn, T. M., Carlton, J. T., Dawson, W., Essl, F., Foxcroft, L. C., Genovesi, P., Jeschke, J. M., Kühn, I., Liebhold, A. M., Mandrak, N. E., Meyerson, L. A., Pauchard, A., Pergl, J., Roy, H. E., Seebens, H., . . . Richardson, D. M. (2020). Scientists' warning on invasive alien species. Biological Reviews, 95(6), 1511-1534. https://doi.org/10.1111/brv.12627

Pyšek, P., Hulme, P. E., Simberloff, D., Bacher, S., Blackburn, T. M., Carlton, J. T., (2020). Scientists’ warning on invasive alien species. Biol. Rev. 95, 1511–1534.doi: 10.1111/brv.12627

Pyšek, P., Hulme, P. E., Simberloff, D., Bacher, S., Blackburn, T. M., Carlton, J. T., Dawson, W., Essl, F., Foxcroft, L. C., Genovesi, P., Jeschke, J. M., Kühn, I., Liebhold, A. M., Mandrak, N. E., Meyerson, L. A., Pauchard, A., Pergl, J., Roy, H. E., Seebens, H., . . . Richardson, D. M. (2020). Scientists' warning on invasive alien species. Biological Reviews, 95(6), 1511-1534. https://doi.org/10.1111/brv.12627

Pyšek, P., Richardson, D. M., Pergl, J., Jarošík, V., Sixtová, Z., & Weber, E. (2008). Geographical and taxonomic biases in invasion ecology. Trends in ecology & evolution, 23(5), 237-244.

Qu, T., Du, X., Peng, Y., Guo, W., Zhao, C., & Losapio, G. (2021). Invasive species allelopathy decreases plant growth and soil microbial activity. PloS one, 16(2), e0246685.

Qu, T., Du, X., Peng, Y., Guo, W., Zhao, C., & Losapio, G. (2021). Invasive species allelopathy decreases plant growth and soil microbial activity. PLoS ONE, 16(2). https://doi.org/10.1371/journal.pone.0246685

Qu, T., Du, X., Peng, Y., Guo, W., Zhao, C., & Losapio, G. (2021). Invasive species allelopathy decreases plant growth and soil microbial activity. PLOS ONE, 16(2), e0246685. https://doi.org/10.1371/journal.pone.0246685

Rabotnov, T. A. 1982. Importance of the evolutionary approach to the study of allelopathy. Sov. J. Ecol. 12:127–130.

Rabotnov, Y. N., Tupolev, A. A., Kut'inov, V. F., Kogaev, V. P., Berezin, A. Sulimenkov, V. V. (1982). Use of carbon fiber-reinforced plastics in aircraft construction. Mechanics of Composite Materials, 17, 455-465.

Raghubanshi A.S., A. Tripathi. (2009) Effect of disturbance, habitat fragmentation and alien invasive plants on floral diversity in dry tropical forests of Vindhyan highland: a review Trop. Ecol., 50 (1) (2009), p. 57

Rahel FJ (2002) Homogenization of freshwater faunas. *Annual Review of Ecology and Systematics* 33: 291–315.

Rai PK (2012) An Eco-sustainable Green Approach for Heavy metals Management:Two Case Studies of Developing Industrial Region. *Environmental Monitoring and Assessment*, 184: 421-448.

Rai PK (2013) Plant Invasion Ecology: Impacts and Sustainable Management.Nova Science Publisher, New York, USA.

Rai PK (2015) What makes the plant invasion possible? Paradigm of invasion mechanisms, theories and attributes. *Environmental Skeptics and Critics*, 4(2): 36-66.

Rai PK, Lalramnghinglova H. (2011). Ethnomedicinal plant resources of Mizoram, India: Implication of traditional knowledge in health care system. Ethnobot Leafl. 2010; 3:6.

Rai, P. K. (2018). Heavy metal phyto-technologies from Ramsar wetland plants: green approach. Chemistry and Ecology, 34(8), 786-796.

Rai, P. K. (2022). Environmental Degradation by Invasive Alien Plants in the Anthropocene: Challenges and Prospects for Sustainable Restoration. Anthropocene Science, 1(1), 5-28. https://doi.org/10.1007/s44177-021-00004-y

Rai, P. K., & Kim, H. (2020). Invasive alien plants and environmental remediation: A new paradigm for sustainable restoration ecology. Restoration Ecology, 28(1), 3-7. https://doi.org/10.1111/rec.13058

Rai, P. K., & Lalramnghinglova, H. (2010). Ethnomedicinal plant resources of Mizoram, India: Implication of traditional knowledge in health care system. Ethnobotanical Leaflets, 2010(3), 6.

Rai, P. K., & Singh, J. S. (2020). Invasive alien plant species: Their impact on environment, ecosystem services and human health. Ecological indicators, 111, 106020.

Rai, P. K., & Singh, J. S. (2024). Ecological insights and environmental threats of invasive alien plant Chromolaena odorata: Prospects for sustainable management. Weed Biology and Management, 24(1), 15-37. https://doi.org/10.1111/wbm.12286

Rai, P. K., & Singh, M. M. (2015). Lantana camara invasion in urban forests of an Indo–Burma hotspot region and its ecosustainable management implication through biomonitoring of particulate matter. Journal of Asia-Pacific Biodiversity, 8(4), 375-381. https://doi.org/10.1016/j.japb.2015.09.003

Rai, P. K., Lee, S. S., Bhardwaj, N., & Kim, K. H. (2023). The environmental, socio-economic, and health effects of invasive alien plants: Review on Tithonia diversifolia (Hemsl.) A. Gray in Asteraceae. South African journal of botany, 162, 461-480.

Rai, P.K. (2022). Environmental Degradation by Invasive Alien Plants in the Anthropocene: Challenges and Prospects for Sustainable Restoration. Anthr. Sci. 1, 5–28 (2022). https://doi.org/10.1007/s44177-021-00004-y

Rai, P.K., Singh, J.S. (2021) Plant invasion in protected areas, the Indian Himalayan region, and the North East India: progress and prospects. Proc.Indian Natl. Sci. Acad. 87, 19–35 (2021). https://doi.org/10.1007/s43538-021-00013-w

Rai, V. P. K. (2021). The impact of Tithonia diversifolia (Hemsl.) A. Gray on phytosociology and native plants diversity of Aizawl, Mizoram, North East India.

Rai.P. K., & Singh, M. M. (2015). Lantana camara invasion in urban forests of an Indo–Burma hotspot region and its Eco sustainable management implication through biomonitoring of particulate matter. Journal of Asia-Pacific Biodiversity, 8(4), 375-381. https://doi.org/10.1016/j.japb.2015.09.003

Raturi, G.P. 2012. Forest community structure along an altitudinal gradient of district Rudraprayag of Garhwal Himalaya, India. Ecologia, 2(3): 76-84.

Ray, D., Behera, M.D. & Jacob, J. (2019). Comparing invasiveness of native and non-native species under changing climate in North-East India: ecological niche modelling with plant types differing in biogeographic origin. Environ Monit Assess 191 (Suppl 3), 793 (2019). https://doi.org/10.1007/s10661-019-7685-8

Reddy, C. S. (2008). Catalogue of invasive alien flora of India. Life science journal, 5(2), 84-89.

Reza MS, Ahmed A, Caesarendra W, Bakar MSA, Shams S, Saidur R, Aslfattahi N, Azad AK (2019) Acacia holosericea: an invasive species for bio-char, bio-oil, and biogas production. Bioengineering 6(2):33. https://doi.org/10.3390/bioengineering6020033

Ricciardi, A.; Iacarella, J.C.; Aldridge, D.C.; Blackburn, T.M.; Carlton, J.T.; Catford, J.A.; Dick, J.T.A.; Hulme, P.; Jeschke, J.M.; Liebhold, A.M.; et al. Four priority areas to advance invasion science in the face of rapid environmental change. Environ. Rev. 2021, 29, 119–141

Rice EL (1984) Allelopathy,Academic Press,Orlando,Fl.

Richardson DM, Pysek P, Rejmanek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: concepts and definitions. *Diversity and Distributions* (2000) 6, 93–107.

Richardson DM, Ricciardi A. (2013). Misleading criticisms of invasion science: a field guide. Diversity and Distributions 2013; 19:1461–7.

Ridenour WM, Vivanco JM, Feng Y, Horiuchi J, Callaway RM (2008) No evidence for tradeoffs: Centaurea plants from America are better competitors and defenders than plants from the native range. *Ecological Monographs*, 78, 369–386.

Ridenour, W. M. and Callaway, R. M. (2001) The relative importance of allelopathy in interference: the effects of an invasive weed on a native bunchgrass. Oecologia 126, 444–450

Robert Bartz1,2, Ingo Kowarik1,2

Rodrigues, A. C., de Santana, H. S., Baumgartner, M. T., & Gomes, L. C. (2018). Coexistence between native and nonnative species: the invasion process and adjustments in distribution through time for congeneric piranhas in a Neotropical floodplain. Hydrobiologia, 817, 279-291.

Rodrigues, P.M.S., Schaefer, C.E.G.R., de Oliveira Silva, J., Ferreira Júnior, W.G., dos Santos, R.M. and Neri, A.V. (2018). The influence of soil on vegetation structure and plant diversity in different tropical savannic and forest habitats. Journal of Plant Ecology, 11(2), 226-236.

Roger, V. L., Boerwinkle, E., & Crapo, J. D. (2015). Respond to "future of population studies". American Journal of Epidemiology, 15, 181(6), 372–373.

Roxburgh, S. H., Shea, K., & Wilson, J. B. (2004). THE INTERMEDIATE DISTURBANCE HYPOTHESIS: PATCH DYNAMICS AND MECHANISMS OF SPECIES COEXISTENCE. Ecology, 85(2), 359-371. https://doi.org/10.1890/03-0266

Ruwanza, S., & Shackleton, C. M. (2016). Effects of the invasive shrub, Lantana camara, on soil properties in the Eastern Cape, South Africa. Weed Biology and Management, 16(2), 67-79. https://doi.org/10.1111/wbm.12094

S.U., S. L., Singh, D., & Shojaei Baghini, M. (2014). A critical review of soil moisture measurement. Measurement, 54, 92-105. https://doi.org/10.1016/j.measurement.2014.04.007

Sagar, R. & Raghubanshi, Akhilesh & Singh, J S. (2003). Tree species composition, dispersion and diversity along a disturbance gradient in a dry tropical forest region of India. Forest Ecology and Management. 186. 61-71. 10.1016/s0378-1127(03)00235-4

Saikia, S., Tamuli, K. J., Narzary, B., Banik, D., & Bordoloi, M. (2020). Chemical characterization, antimicrobial activity, and cytotoxic activity of Mikania micrantha Kunth flower essential oil from North East India. Chemical Papers, 74, 2515-2528.

Sakachep, Z. K., & Rai, P. K. (2021). Influence of invasive alien plants on vegetation of Hailakandi district, Assam, North-East, India. Indian Journal of Ecology, 48(1), 261-266.

Santos, M., Cajaiba, R. L., Bastos, R., Gonzalez, D., Petrescu Bakış, A. L., Ferreira, D., ... & Mosquera-Losada, M. R. (2022). Why do agroforestry systems enhance biodiversity? Evidence from habitat amount hypothesis predictions. Frontiers in Ecology and Evolution, 9, 630151.

Sardans, J.; Bartrons, M.; Margalef, O.; Gargallo-Garriga, A.; Janssens, I.A.; Ciais, P.; Obersteiner, M.; Sigurdsson, B.D.; Chen, H.Y.H.; Penuelas, J. (2017). Plant invasion is associated with higher plant-soil nutrient concentrations in nutrient-poor environments. Glob. Change Biol. 2017, 23, 1282–1291.

Saxena KG. (1991) Biological invasions in the Indian subcontinent: Review of invasion by plants. In:Ramakrishnan PS. (ed.) Ecology of BiologicalInvasions in the Tropics. 1991;53–73.

Saxena, S., Rawat, D. S., & Rao, P. B. (2020). Malvastrum coromandelianum (L.) Garcke: An invasive weed with multiple ethnopharmacological properties. Int. J. Pharmacog. Phytochem. Res, 12, 16-22.

Schuster, M. J., Wragg, P. D., Williams, L. J., Butler, E. E., Stefanski, A., & Reich, P. B. (2020). Phenology matters: Extended spring and autumn canopy cover increases biotic resistance of forests to invasion by common buckthorn (Rhamnus cathartica). Forest ecology and management, 464, 118067.

Seebens, H., Bacher, S., Blackburn, T. M., Capinha, C., Dawson, W., Dullinger, S., ... & Essl, F. (2021). Projecting the continental accumulation of alien species through to 2050. Global Change Biology, 27(5), 970-982.

Sekar, K. C. (2012). Invasive alien plants of Indian Himalayan region—diversity and implication. American journal of plant sciences, 3(2), 177-184.

Sengupta, R., & Dash, S. S. (2020). A comprehensive inventory and ecological assessment of alien plant invasion in Mizoram, India. Indonesian Journal of Forestry Research, 7(2), 135-154.

Sengupta, R., Kundu, A., Dhara, B., Mitra, A. K., & Dash, S. S. (2023). antimicrobial activity and phytoconstituents screening of noxious invasive alien plants, ageratina adenophora and chromolaena odorata from mizoram, a part of indo-burma biodiversity hotspot in India. exploratory Animal and Medical Research, 13(Ethnomedicine Special), 133-140.

Shackleton, R. T., Adriaens, T., Brundu, G., Dehnen-Schmutz, K., Estévez, R. A., Fried, J., ... & Richardson, D. M. (2019). Stakeholder engagement in the study and management of invasive alien species. Journal of environmental management, 229, 88-101.

Shackleton, R. T., Biggs, R., Richardson, D. M., & Larson, B. M. (2018). Social-ecological drivers and impacts of invasion-related regime shifts: consequences for ecosystem services and human wellbeing. Environmental Science & Policy, 89, 300-314.

Shah, M.A. and Reshi, Z.A. (2011). Invasion by alien macrophytes in freshwater ecosystems of India. In: Invasive alien plants an ecological appraisal for the Indian subcontinent (Bhatt, J. R., Singh, J. S., Singh, S. P., Tripathi, R. S., and Kohli, R. K. Eds.), Cabi, pp.199-213

Sharma E, Molden D, Wester P, Shrestha RM (2016) The Hindu Kush Himalayan monitoring and assessment programme: action to sustain a global asset. Mt Res Dev 36(2):236–240

Sharma GAP, Singh JS, Raghubanshi AS. (2011) Plant invasions: Emerging trends and future implications. Current Science. 2005; 88:726–734.

Sharma, G. P., & Raghubanshi, A. S. (2012). Invasive species: ecology and impact of Lantana camara. Invasive alien plants: an ecological appraisal for the Indian subcontinent, 19-42.

Sharma, J., Singh, R., Garai, S., Rahaman, S. M., Khatun, M., Ranjan, A., Mishra, S. N., & Tiwari, S. (2022). Climate change and dispersion dynamics of the invasive plant species Chromolaena odorata and Lantana camara in parts of the central and eastern India. Ecological Informatics, 72, 101824. https://doi.org/10.1016/j.ecoinf.2022.101824

Sharma, J., Singh, R., Garai, S., Rahaman, S. M., Khatun, M., Ranjan, A., Mishra, S. N., & Tiwari, S. (2022). Climate change and dispersion dynamics of the invasive plant species Chromolaena odorata and Lantana camara in parts of the central and eastern India. Ecological Informatics, 72, 101824. https://doi.org/10.1016/j.ecoinf.2022.101824

Sharma, J., Singh, R., Garai, S., Rahaman, S. M., Khatun, M., Ranjan, A., ... & Tiwari, S. (2022). Climate change and dispersion dynamics of the invasive plant species Chromolaena odorata and Lantana camara in parts of the central and eastern India. Ecological Informatics, 72, 101824.

Shrestha B.B., U.B. Shrestha, K.P. Sharma, R.B. Thapa-Parajulic, A. Devkota, M. Siwakoti. (2019). Community perception and prioritization of invasive alien plants in Chitwan-Annapurna Landscape, Nepal.J. Env. Manage., 229 (2019), pp. 38-47, 10.1016/j.jenvman.2018.06.034

Shrestha, U. B., & Shrestha, B. B. (2019). Climate change amplifies plant invasion hotspots in Nepal. Diversity and Distributions, 25(10), 1599-1612.

Shrestha, U. B., Sharma, K. P., Devkota, A., Siwakoti, M., & Shrestha, B. B. (2018). Potential impact of climate change on the distribution of six invasive alien plants in Nepal. Ecological Indicators, 95, 99-107.

Siddiqui S, Bhardwaj S, Khan S S, Meghvanshi M K (2009) Allelopathic effect of different concentration of water extract of Prosopsis juliflora leaf on seed germination and radicle length of wheat (Triticum aestivum Var-Lok-1). American Eurasian Journal of Scientific Research, 4(2), 81-84.

Singh KP. (2005). Invasive alien species and biodiversity in India. Current Science. 2005;88(4):539.

Singh SP (2014) Attributes of Himalayan Forest ecosystems: they are not temperate forests. Proc Indian Natl Sci Acad 80(2):221–233

Singh, A. K. (2021). Allelopathic effect of Ageratum conyzoides L. on seed germination and growth of pea varieties. International Journal of Biological Innovations, 3(1), 194-198.

Singh, A. K. (2021). Allelopathic effect of Ageratum conyzoides L. on seed germination and growth of pea varieties. International Journal of Biological Innovations, 3(1), 194-198.

Singh, H. P., Batish, D. R., & Kohli, R. K. (2001). Allelopathy in agroecosystems: an overview. Journal of Crop production, 4(2), 1-41.

Singh, K., Byun, C., & Bux, F. (2022). Ecological restoration of degraded ecosystems in India: Science and practices. Ecological Engineering, 182, 106708. https://doi.org/10.1016/j.ecoleng.2022.106708

Singh, M., Kumar, A., & Sharma, M. (2021). Conservation of plant diversity in agroforestry systems in a biodiversity hotspot region of northeast India. Agricultural Research, 10(4), 569-581.

Singh, S., Jaiswal, D. K., Krishna, R., Mukherjee, A., & Verma, J. P. (2020). Restoration of degraded lands through bioenergy plantations. Restoration Ecology, 28(2), 263-266. https://doi.org/10.1111/rec.13095

Sisodia S, Siddiqui MB (2010) Allelopathic effect by aqueous extracts of different parts of Croton bonplandianum Baill On some crop and weed palnts. *Journal of Agriculture Extension and Rural Development.*2:22-28.

Skripnikov, A. (2023). Bioassays for Identifying and Characterizing Plant Regulatory Peptides. Biomolecules, 13(12), 1795. https://doi.org/10.3390/biom13121795

Sorte, C. (2016). Invasive Species, Evolution and. Encyclopedia of Evolutionary Biology, 282-287. https://doi.org/10.1016/B978-0-12-800049-6.003036

Soti, P.G., Purcell, M. & Jayachandran, K. (2020). Soil biotic and abiotic conditions negate invasive species performance in native habitat. Ecol Process 9, 18. https://doi.org/10.1186/s13717-020-00220-1

Soudzilovskaia ND, Vaessen S, Barcelo M, He J, Rahimlou S, Abarenkov K, Brundrett MC, Gomes SIF, Merckx V, Tedersoo L (2020) FungalRoot: global online database of plant mycorrhizal associations. New Phytol. https://doi.org/10.1111/nph.16569

Soumya, K. V., Shackleton, C. M., & Setty, S. R. (2019). Impacts of gum-resin harvest and Lantana camara invasion on the population structure and dynamics of Boswellia serrata in the Western Ghats, India. Forest ecology and management, 453, 117618.

Souza A.O. (2018). Local ecological knowledge concerning the invasion of Amerindian lands in the northern Brazilian Amazon by Acacia mangium (Willd.) J. Ethnobiol. Ethnomed. 2018; 14:33.Springer.

Sreelatha, S., & Padma, P. R. (2009). Antioxidant activity and total phenolic content of Moringa oleifera leaves in two stages of maturity. Plant foods for human nutrition, 64, 303-311.

Stabenau, N., Zehnsdorf, A., Rönicke, H., Wedwitschka, H., Moeller, L., Ibrahim, B., & Stinner, W. (2018). A potential phosphorous fertilizer for organic farming: recovery of phosphorous resources in the course of bioenergy production through anaerobic digestion of aquatic macrophytes. Energy, Sustainability and Society, 8, 1-10.

Stefanowicz, A. M., Majewska, M. L., Stanek, M., Nobis, M., & Zubek, S. (2018). Differential influence of four invasive plant species on soil physicochemical properties in a pot experiment. Journal of soils and sediments, 18, 1409-1423.

Steinmaus, S. J., Prather, T. S., & Holt, J. S. (2000). Estimation of base temperatures for nine weed species. Journal of Experimental Botany, 51(343), 275-286.

Stockwell, C. A., Hendry, A. P., & Kinnison, M. T. (2003). Contemporary evolution meets conservation biology. Trends in Ecology & Evolution, 18(2), 94-101.

Subedi, A., Adhikari, A., Tiwari, A., & Shrestha, B. B. (2024). Canopy gaps facilitate establishment of invasive plants in a subtropical broadleaved forest of central Nepal. Ecological Frontiers. https://doi.org/10.1016/j.ecofro.2024.02.009

Sun, S., Chen, J., Feng, W., Zhang, C., Huang, K., Guan, M., ... & Feng, Y. (2021). Plant strategies for nitrogen acquisition and their effects on exotic plant invasions. Biodiversity Science, 29(1), 72.

Sundarapandian, S. M., & Subashree, K. (2017). Status of invasive plants in Tamil Nadu, India: their impact and significance. Plant biodiversity: monitoring, assessment and conservation, 371-387.

Svensson, J. R., Nylund, G. M., Cervin, G., Toth, G. B., & Pavia, H. (2013). Novel chemical weapon of an exotic macroalga inhibits recruitment of native competitors in the invaded range. Journal of Ecology, 101(1), 140-148.

Swain T, Hillis WE (1959) "The phenolic constituents of *Prunus domestica*. I.-The quantitative analysis of phenolic constituents." *Journal of the Science of Food and Agriculture* 10.1: 63-68.

Syed, S., Xu, M., Wang, Z., Yu, C., & Lian, B. (2021). Invasive Spartina alterniflora in controlled cultivation: environmental implications of converging future technologies. Ecological Indicators, 130, 108027.

Syngkli, R. B., Lallianpuii, S., & Rai, P. K. (2022). Microcosm investigation on the allelochemic potential of Ageratum conyzoides on selected food crop. Eco. Environ. Cons., 28, S298-S304.

Syngkli, R. B., Lallianpuii, S., & Rai, P. K. (2022). Microcosm investigation on the allelochemical potential of Mikania micrantha to the selected food crop. INTERNATIONAL JOURNAL OF PLANT AND ENVIRONMENT, 8(02), 137-142.

Terekhova, V.A.(2011). Soil bioassay: Problems and approaches. Eurasian Soil Sc. 44, 173–179 (2011). https://doi.org/10.1134/S1064229311020141

Thompson, K., Hodgson, J. G., Grime, J. P., & Burke, M. J. (2001). Plant traits and temporal scale: evidence from a 5-year invasion experiment using native species. Journal of Ecology, 89(6), 1054-1060.

Tilman D (1999) The ecological consequences of changes in biodiversity: a search for general principles. Ecology 80(5):1455–1474

Toberman, H., Laiho, R., Evans, C. D., Artz, R. R. E., Fenner, N., Straková, P., & Freeman, C. (2010). Long-term drainage for forestry inhibits extracellular phenol oxidase activity in Finnish boreal mire peat. European Journal of Soil Science, 61(6), 950-957.

Tollington S, Turbe A, Rabitsch W, Groombridge JJ, Scalera R, Essl F, Shwartz A (2015): Making the EU legislation on invasive species a conservation success. Conservation Letters 10: 112–120. https://doi.org/10.1111/conl.12214

Tripathi, A. K., Pandey, P. C., Sharma, J. K., Triantakonstantis, D., & Srivastava, P. K. (2022). Climate change and its impact on forest of Indian Himalayan region: A review. Climate Change: Impacts, Responses and Sustainability in the Indian Himalaya, 207-222.

Turbelin, A.J., Diagne, C., Hudgins, E.J. et al. Introduction pathways of economically costly invasive alien species. Biol Invasions 24, 2061–2079 (2022). https://doi.org/10.1007/s10530-022-02796-5

Udawatta, R. P., Rankoth, L. M., & Jose, S. (2021). Agroforestry for biodiversity conservation. Agroforestry and ecosystem services, 245-274.

Uddin, M. N., & Robinson, R. W. (2018). Can nutrient enrichment influence the invasion of Phragmites australis? Science of the Total Environment, 613, 1449-1459.

UN Decade on Ecosystem Restoration. (2023, December 31). In Wikipedia. https://en.wikipedia.org/wiki/UN_Decade_on_Ecosystem_Restoration

Van der Putten, W. H. (2010). Impacts of soil microbial communities on exotic plant invasions. Trends in Ecology & Evolution, 25(9), 512-519.

Van Kleunen M, Dawson W, Essl F (2015) Global exchange and accumulation of non-native plants. *Nature*. Sep 3; 525(7567):100-3.

Van Kleunen, M., Essl, F., Pergl, J., Brundu, G., Carboni, M., Dullinger, S., ... & Dehnen-Schmutz, K. (2018). The changing role of ornamental horticulture in alien plant invasions. Biological Reviews, 93(3), 1421-1437.

Van Meerbeek, K., Muys, B., & Hermy, M. (2019). Lignocellulosic biomass for bioenergy beyond intensive cropland and forests. Renewable and Sustainable Energy Reviews, 102, 139-149.

Vanlalruati, R. P. (2021). The impact of Tithonia diversifolia (Hemsl.) A. Gray on phytosociology and native plants diversity of Aizawl, Mizoram, North East India. Ecology, Environment and Conservation, 27, S211-S216.

Vaughn S F and Berhow M A 1999 Allelochemicals isolated from tissues of the invasive weed garlic mustard (Alliaria petiolata). J.Chem. Ecol. 25, 2495–2504

Vellend, M., Baeten, L., Becker-Scarpitta, A., Boucher-Lalonde, V., McCune, J. L., Messier, J., Myers-Smith, I. H., & Sax, D. F. (2017). Plant Biodiversity Change Across Scales During the Anthropocene. https://doi.org/10.1146/annurev-arplant-042916-040949

Vila M, Espinar JL, Hejda M (2011) Ecological impacts of invasive alien plants:a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters*,14, 702–708.
Vila M, Espinar JL, Hejda M (2011) Ecological impacts of invasive alien plants:a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters*,14, 702–708.

Vilà, M., Espinar, J. L., Hejda, M., Hulme, P. E., Jarošík, V., Maron, J. L., ... & Pyšek, P. (2011). Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecology letters, 14(7), 702-708.

Vivanco JM,Bais HP,Stermitz FR,Thelen GC,Callaway RM(2004) Biogeographical variation in community response to root allelochemistry: novel weapons and exotic invasion. *Ecology Letters,* 7: 285-292.

Wagner, V., Antunes, P. M., Irvine, M., & Nelson, C. R. (2017). Herbicide usage for invasive non-native plant management in wildland areas of North America. Journal of Applied Ecology, 54(1), 198-204.

Walker, L.R., Smith, S.D. (1997). Impacts of Invasive Plants on Community and Ecosystem Properties. In: Luken, J.O., Thieret, J.W. (eds) Assessment and Management of Plant Invasions. Springer Series on Environmental Management. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-1926-2_7

Walther GR, Roques A, Hulme PE, Sykes MT, Pyšek P, Kühn I, Zobel M, Bacher S, Botta-Dukat Z, Bugmann H, Czucz B (2009) Alien species in a warmer world: risks and opportunities. Trends Ecol Evol 24(12):686–693

Walther, G. (2010). Community and ecosystem responses to recent climate change. Philos Trans R Soc Biol Sci., 365(1549), 2019–2024.

Wamelink, W., Van Dobben, H. F., Goedhart, P. W., & Jones-Walters, L. M. (2018). The role of abiotic soil parameters as a factor in the success of invasive plant species. Emerging Science Journal, 2(6), 308-365.

Wang, C., Cheng, H., Wu, B., Jiang, K., Wang, S., Wei, M., & Du, D. (2021). The functional diversity of native ecosystems increases during the major invasion by the invasive alien species, Conyza canadensis. Ecological Engineering, 159, 106093. https://doi.org/10.1016/j.ecoleng.2020.106093

Wang, C., Xiao, H., Zhao, L., Liu, J., Wang, L., Zhang, F., ... & Du, D. (2016). The allelopathic effects of invasive plant Solidago canadensis on seed germination and growth of Lactuca sativa enhanced by different types of acid deposition. Ecotoxicology, 25, 555-562.

Wang, J., Li, Y., Li, A., Liu, R. H., Gao, X., Li, D., Kou, X., & Xue, Z. (2021). Nutritional constituent and health benefits of chickpea (Cicer arietinum L.): A review. Food Research International, 150, 110790. https://doi.org/10.1016/j.foodres.2021.110790

Wang, Y., Tan, W., Li, B., Wen, L., & Lei, G. (2021). Habitat alteration facilitates the dominance of invasive species through disrupting niche partitioning in floodplain wetlands. Diversity and Distributions, 27(9), 1861-1871.

Wang, Z., Chen, F., Li, X., Cao, H., Ding, M., Zhang, C., ... & Liu, Y. (2016). Arabidopsis seed germination speed is controlled by SNL histone deacetylase-binding factor-mediated regulation of AUX1. Nature communications, 7(1), 13412.

Wani, M. S., Tantray, Y. R., Jan, I., Singhal, V. K., & Gupta, R. C. (2020). Lactuca L.: world distribution and importance.

Wardani, D. K., Darmanti, S., & Budihastuti, R. (2018, May). Allelochemical effect of Ageratum conyzoides L. leaf extract on Soybean [Glycine max (L.) Merr. cv Grobogan] growth. In Journal of Physics: Conference Series (Vol. 1025, No. 1, p. 012044). IOP Publishing.

Wei, H., Huang, M., Quan, G., Zhang, J., Liu, Z., & Ma, R. (2018). Turn bane into a boon: Application of invasive plant species to remedy soil cadmium contamination. Chemosphere, 210, 1013-1020.

Weidlich A., E. W., Flórido, F. G., Sorrini, T. B., & S. Brancalion, P. H. (2020). Controlling invasive plant species in ecological restoration: A global review. Journal of Applied Ecology, 57(9), 1806-1817. https://doi.org/10.1111/1365-2664.13656

Weir TL,Bais HP,VivancoJ.M (2003) Intraspecific and interspecific interactions mediated by a phytotoxin, (±)-catechin, secreted by the roots of *Centaurea maculosa* (spotted knapweed). *Journal of Chemical Ecology* 29:2379–2393.

Wijeratne.V. (2015). Socio-economic Impact of Invasive Alien Species on Human lives: Case Study at Bellanvila-Attidiya marsh, Sri Lanka Department of Forestry, University of Sri Jayawardhanapura, p. 101

Williams, J. H. (1956). PROCEEDINGS. American Economic Review, 46(2).

Williamson, M. (1996). Biological invasions. Springer Science & Business Media.

Willig, M., & Presley, S. (2017). Biodiversity and Disturbance. Encyclopedia of the Anthropocene, 45-51. https://doi.org/10.1016/B978-0-12-809665-9.09813-X

Willis RJ (2010) *The History of Allelopathy*. Dordrecht, The Netherlands:

Woch, M. W., Kapusta, P., Stanek, M., Zubek, S., & Stefanowicz, A. M. (2021). Functional traits predict resident plant response to Reynoutria japonica invasion in riparian and fallow communities in southern Poland. AoB Plants, 13(4), plab035.

Wu, P., Song, Z., Wang, X., Li, Y., Li, Y., Cui, J., ... & Guo, Y. (2020). Bioactive triterpenoids from Lantana camara showing anti-inflammatory activities in vitro and in vivo. Bioorganic Chemistry, 101, 104004.

Xu, H., Liu, Q., Wang, S., Yang, G., & Xue, S. (2022). A global meta-analysis of the impacts of exotic plant species invasion on plant diversity and soil properties. Science of The Total Environment, 810, 152286. https://doi.org/10.1016/j.scitotenv.2021.152286

Yang Q, Weigelt P, Fristoe TS, et al. (2021) The global loss of floristic uniqueness. Nat Commun 12:7290.

Yang, Bin & Miao, Cui & Ren, Guang-Qian & Li, Jian & Wang, Congyan & Li, Guanlin & Dai, Zhi-Cong & Rutherford, Susan & Wan, Justin & Du, Dao-Lin. (2022). Influence of multiple global change drivers on plant invasion: Additive effects are uncommon. Frontiers in Plant Science. 13. 1020621. 10.3389/fpls.2022.1020621.

Yang, R. Y., Mei, L. X., Tang, J. J., & Chen, X. (2007). Allelopathic effects of invasive Solidago canadensis L. on germination and growth of native Chinese plant species. Allelopathy Journal, 19(1), 241-248.

Yazaki, K.; Arimura, G.; Ohnishi, T. (2017) “Hidden” terpenoids in plants: Their biosynthesis, localization and ecological roles. Plant Cell Physiol. 2017, 58, 1615–1621.

Ye, G., Chen, J., Yang, P., Hu, H. W., He, Z. Y., Wang, D., ... & Lin, Y. (2023). Non-native plant species invasion increases the importance of deterministic processes in fungal community assembly in a coastal wetland. Microbial Ecology, 86(2), 1120-1131.

Yuan, L., Li, J. M., Yu, F. H., Oduor, A. M., & van Kleunen, M. (2021). Allelopathic and competitive interactions between native and alien plants. Biological Invasions, 23(10), 3077-3090.

Yuan, Y., Wang, B., Zhang, S., Tang, J., Tu, C., Hu, S., ... & Chen, X. (2013). Enhanced allelopathy and competitive ability of invasive plant Solidago canadensis in its introduced range. Journal of Plant Ecology, 6(3), 253-263.

Zenni RD, Essl F, García-Berthou E, McDermott SM (2021) The economic costs of biological invasions around the world.NeoBiota 67: 1-9. https://doi.org/10.3897/neobiota.67.69971

Zhang P, Li B, Wu J, Hu S (2019) Invasive plants differentially affect soil biota through litter and rhizosphere pathways: a meta-analysis. Ecol Lett 22:200–210

Zhang Z, Liu Y, Yuan L, Weber E, van Kleunen M (2020) Effect of allelopathy on plant performance. bioRxiv preprint. https://doi.org/10.1101/2020.05.14.095190

Zhang, Y., Leng, Z., Wu, Y., Jia, H., Yan, C., Wang, X., Ren, G., Wu, G., & Li, J. (2021). Interaction between Nitrogen, Phosphorus, and Invasive Alien Plants. Sustainability, 14(2), 746. https://doi.org/10.3390/su14020746

Zhao M (2003) Integrated Control and Countermeasure of External Invasion Biology.Agro-environment and Deveopment: pp38-39.

Ziska LH (2003) Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. J Exp Bot 54(381):395–404

Zohmachhuana, A., Tlaisun, M., Mathipi, V., Khawlhring, L., & Priya, J. S. (2022). Suppression of the RAGE gene expression in RAW 264.7 murine leukemia cell line by ethyl acetate extract of Mikania micrantha (L.) Kunth. Journal of Applied Biology and Biotechnology, 10(5), 107-114.

Zuppinger-Dingley D,Schmid B, Petermann JS,Yadav V,DeDeyn GB, Flynn DFB(2016) Plant selection and soil legacy enhance long term biodiversity effects. *Ecology*, 97(4), 2016, pp. 918–928.

List of Publications

1. Syngkli, R. B., Lallianpuii, S., & Rai, P. K. (2022). Microcosm investigation on the allelochemic potential of Ageratum conyzoides on selected food crop. Eco. Environ. Cons., 28, S298-S304.

2. Syngkli, R. B., Lallianpuii, S., & Rai, P. K. (2022). Microcosm investigation on the allelochemical potential of Mikania micrantha to the selected food crop. INTERNATIONAL JOURNAL OF PLANT AND ENVIRONMENT, 8(02), 137-142.

3. Nongtri, E. S., Lallianpuii, S., & Rai, P. K. (2022). Microcosm Study to Assess Allelochemical Potential of Lantana camara on Lactuca sativa. Indian Journal of Ecology, 49(6), 2163-2166.

4. Lallianpuii,S and Rai, P.K. (2023).Allelopathic effects of invasive alien plant Lantana camara on seed germination and growth of chickpea (Cicer arietinum). Landuse and bioresource management for sustainable livelihood (p.143).

List of presentation presented in conferences

1. 'Allelopathic effects of *Lantana camara* on seed germination and growth of chickpea (Cicer arietinum)' in National seminar on Land Use and Bioresource Management for Sustainable Livelihood, jointly organized by Department of Environmental science, Mizoram University, Mizoram science, technology and innovation council (MISTIC) & National Bank for Agriculture and Rural Development (NABARD) on 27th-28th March, 2023.
2. 'Evaluation of allelopathic potential of *Mikania micrantha* on *Cicer arietinum* using Pot bioassay' in National seminar on environmental management: issues and challenges in North east India (NSEMICNEI, 2023) organized by the Department of Environmental science, Pachhunga University college, Aizawl and funded by Mizoram University, Mizoram on 1st-2nd June, 2023.
3. 'Effects of invasive alien plants on soil nutrient compositions in Aizawl, Mizoram, NE India' in National conference on "sustainable solutions: Navigating climate change and Natural resources", organized by the Department of Environmental Science, School of Earth Science and Natural Resources Management (SES&NRM) on 19th-20th June, 2024

BIO-DATA OF THE CANDIDATE

NAME : SARAH LALLIANPUII

Father's Name : K. Lalnuntluanga

Mother's Name : Dr. Zoramthangi

SEX : Female

Category : Scheduled Tribe

Address : Serkawn, Lunglei, Mizoram Pin: 796691

Contact no. : 8132841020

Email ID : sarahklianpuii@gmail.com

Educational Qualifications

YEAR	EXAMINATION	BOARD
2006	HSLC	MBSE
2008	HSSLC	MBSE
2014	Bachelor of science (Environmental science)	Delhi University
2015	Diploma in Dietetics, Health and Nutrition	VLCC Institute
2018	Master of science (Environmental science)	Mizoram University
2018	Certificate in Computer Application	MSCTE
2018	NET	UGC

PARTICULARS OF THE CANDIDATE

NAME OF CANDIDATE	:	SARAH LALLIANPUII
DEGREE	:	Doctor of Philosophy
DEPARTMENT	:	Environmental Science
TITLE OF THESIS	:	Ecological studies on impacts of invasive alien plant species on vegetation and their soil allelopathic interactions in Aizawl, Mizoram, India
DATE OF ADMISSION	:	01/08/2018
APPROVAL OF RESEARCH PROPOSAL		
1. DRC	:	29/03/2019
2. BOS	:	04/04/2019
3. SCHOOL BOARD	:	26/04/2019
MZU REGISTRATION NO.	:	1600700
Ph. D. REGISTRATION NO. & DATE	:	MZU/Ph.D./ 1193 of 01.08.2018

EXTENSION (IF ANY): NA

Head

Department of Environmental Science

ABSTRACT

ECOLOGICAL STUDIES ON IMPACTS OF INVASIVE ALIEN PLANT SPECIES ON VEGETATION AND THEIR SOIL ALLELOPATHIC INTERACTIONS IN AIZAWL, MIZORAM, INDIA

AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

SARAH LALLIANPUII

MZU REGISTRATION NO.: 1600700

Ph.D. REGISTRATION NO.: MZU/Ph.D./ 1193 of 01.08.2018

DEPARTMENT OF ENVIRONMENTAL SCIENCE

SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES MANAGEMENT

OCTOBER, 2024

ABSTRACT

ECOLOGICAL STUDIES ON IMPACTS OF INVASIVE ALIEN PLANT SPECIES ON VEGETATION AND THEIR SOIL ALLELOPATHIC INTERACTIONS IN AIZAWL, MIZORAM, INDIA

BY

SARAH LALLIANPUII
Department of Environmental Science

Under the supervision of

Prof. P.K. RAI

Submitted
In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Environmental Science of Mizoram University, Aizawl

Abstract

India is well known for its rich plant diversity, which is highly influenced by the country's diverse topography, climate, and ecosystems. It has a rich flora with a high number of endemic plant species found within the hotspot regions and is also home to a large number of ethnobotanical plant species.

One of the greatest scientific challenges of today involves the spread of invasive alien plant species (IAPS). IAPS is defined by the International Union for Conservation of Nature and Natural Resources "as species that become established in natural or semi-natural ecosystems or habitats, acting as a change agent that threatens native biological diversity".

India is also home to a number of invasive alien plant species that have colonized the global landscapes and are now posing a serious threat by altering socioeconomic conditions, fragmenting habitats, and contributing to climate change as well as biodiversity loss. Understanding which alien species will naturalize and increase or which alien species will adversely impact biodiversity or other resources is, therefore, one of the main challenges associated with invasion biology. Biological invasions are increasing as a result of global connectivity and human population growth, with complex effects on biogeographic realms, native species abundance, extinction risk, and genetic composition that are often only apparent when IAPS are well-established and abundant.

Biological invasions have been known to cause biodiversity loss, impacting services and ecosystems in many regions of the world, and invasive species are growing in both numbers and distribution. IAPS has seriously threatened the Indian subcontinent's ecosystems, including both terrestrial (forest and agricultural) and aquatic, thereby affecting their normal functioning and disrupting the native vegetation

Mechanisms of Plant Invasion and Novel Weapon Hypothesis (NWH)

The invasion pathway is a sequential process by which invasions occur through the use of an introduction vector, non-native species are brought to new areas, leading to

colonization. The introduced species is regarded as established if they thrive and reproduce within their non-native range.

According to the NWH, invasive plant species are effective due to their ability to produce toxic biochemicals, such as allelopathic antimicrobial root exudates, that obstruct plant growth and soil microbial activity. Molish (1937) proposed allelopathy as a mechanism of invasion for the first time. It is the interaction between plants and microorganisms, which can exert either inhibitory or stimulatory effects.

It is often considered that the tough geographical terrains (e.g., biodiversity-rich mountain ecosystems) are resistant to invasive alien plants, however, complex ecological mechanisms linked with these plants lead to their success in such landscapes. There exists scanty research on the invasion ecology of NE India, especially, Mizoram, an integral part of the Indo-Burma hotspot. Therefore, identifying the mechanisms which help the highly noxious plant invaders to succeed is important for conceptual issues in ecology and for ecosystem management.

The study focused on Aizawl district, Mizoram, focusing on highly disturbed sites, Maubawk and moderately disturbed sites, Chawlhhmun. Mission vengthlang area was the site with negligible invasion i.e., undisturbed site. The light intensity at these sites was measured using a lux meter, with high intensity indicating less forest crown cover.

Vegetation analysis

Vegetation analysis from the three sites viz. disturbed, moderately disturbed, and undisturbed was recorded during the study period. A total of 24 plant species were identified and recorded at the disturbed site, 19 plant species at the moderately disturbed site, and 16 plant species at the undisturbed site respectively.

The study on phytosociological attributes of all species at the three sites revealed the varying degrees of dispersion and species with low important value index indicated that they were of rare occurrence at the selected study sites. In the present study, the number of individuals of different species was recorded maximum at the moderately disturbed site which was in accordance with the 'Intermediate Disturbance Hypothesis' (IDH) which states that a moderate level of disturbance gives an equal opportunity for each and every plant individual to flourish. Whereas, the undisturbed site provides opportunities to few dominant plant individuals therefore they have recorded lesser number of individuals compared to disturbed sites.

Invasive alien plants such as *L. camara, A. conyzoides, C. odorata,* and *M. micrantha* were dominant at the disturbed site. The moderately disturbed site has a high species of plants like *S. media, C. accrescens, K. brevofolia* and *G. parvviflora*. The undisturbed site has a lower density of plant species such as *C. vialis and K. bervifolia* while it has sparse distribution of invasive alien plants.

Invasive plants such as *L. camara, A. conyzoides, C. odorata, M. micrantha, B. biternate, S. alata G. parviflora, S. media,* and *C. accrescens* were abundantly present at both the disturbed and moderately disturbed sites while they were sparsely distributed at the undisturbed site. Plants such as *C. accrescens, P. conjugatum, I. cylindrica, K. brevifolia, A. conizoides, C. odorata, M. micrantha, and L. camara* were found in large abundance at the disturbed site as well as moderately disturbed sites. The undisturbed site on the other has a dispersed collection of plant species such as *A. conzyoides, C. odorata, C. accrescens, and C. vialis.*

Importance Value Index (IVI)

The estimation of the importance value index is ecologically relevant as it helps in assessing the most dominant and important plant species present at the study sites. It is estimated by calculating the total values of relative density, relative abundance, and relative frequency obtained from the quadrat analysis.

The vegetation analysis from the disturbed site recorded a total of 595 plant individuals belonging to different species with IVI ranging from 2.09 to 31.38. The vegetation analysis from the moderately disturbed site recorded a total of 1158 plant individuals belonging to different species with IVI ranging from 1.60 to 32.16. The vegetation analysis from the undisturbed site recorded a total of 146 plant individuals belonging to different species with IVI ranging from 36.53 to 7.89.

The IVI for the three sites was found to be high in plants like *G. parviflora, C. vialis, S. media, C. accrescens C. odorata,* and *A. conizoides* with IVI ranging from 23.00 to 36.53. On the other hand, plant species such as *G. bicolor, C. glandulosum, U. lobata, C. infortunatum, L. camara L. leucocephala,* and *S. torvum* were plants having lower values of IVI ranging from 1.60 to 2.49.

Diversity indices

The difference in species diversity between communities generally results from variations in site quality (Denslow, 1980). The maximum diversity index using Shannon-Weiner diversity index was observed at the disturbed site (2.54), followed by the moderately disturbed site (2.47) and the undisturbed site showed the lowest diversity index (2.42). Shannon-Weiner diversity index was calculated with almost similar values at the sites along the disturbance gradient. The species richness is one of the major criteria and reflect the number of individuals belonging to a particular species, thereby recognizing its dominance and hence important for conservation priorities. The Margalef's index-based species richness was highest at the undisturbed site (4.62), followed by the disturbed site (3.6) and the moderately disturbed site (3.2) has the lowest species richness. The evenness index was higher in the undisturbed site showing that the species are evenly distributed whereas the lesser values in weed-infested regions showed patchiness in the distribution of plant species.

Soil pH

The pH values represent the degree of acidity or alkalinity and is governed by various factors like the nature of the substratum, type of parent rock, precipitation, and microbial activity in the environment.

The pH of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during monsoon season. Particularly in *L. camara*-invaded soil recorded the highest pH value (6.1) whereas the lowest (5.1) was observed in *M. micrantha* invaded soil.

The pH of the soil samples from the moderately disturbed site was recorded lowest in the post-monsoon season while it was observed highest during the monsoon season. Particularly in *L. camara-invaded* soil which recorded the highest pH value (6.02) whereas the lowest (5.4) was observed in *A. conyzoides* and *M. micrantha* invaded soil.

The pH of the soil samples from the undisturbed site was recorded lowest in the post-monsoon season while it was observed highest during the monsoon season. Particularly in *C. odorata*-invaded soil, highest pH value (6.0) was recorded whereas the lowest (5.7) was observed in *A. conyzoides* and *L. camara* invaded soil.

The soil biota, nutrient availability, and plant-soil interactions influence the processes of naturalization and invasions and these causes changes in ecosystems Significant changes in soil properties caused by invasive alien plants have the potential to increase invasions and to displace native species by impeding their natural regeneration

Soil Moisture Content

The soil moisture content of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly, *L. camara* invaded soil recorded a high soil moisture content (29.85%) whereas the lowest value (23.1%) was observed in *C. odorata* invaded soil.

The soil moisture content of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly, *L. camara* invaded soil recorded a high soil moisture content (29.85%) whereas the lowest value (23.1%) was observed in *C. odorata* invaded soil.

The soil moisture content of the soil samples from the undisturbed study site was recorded lowest in the pre- monsoon season while it was observed highest during the monsoon season. Particularly, *C. odorata* invaded soil recorded a highest soil moisture content of (32.66%) whereas the lowest value (20.22%) was recorded in *A. conyzoides* invaded soil.

Soil Organic Carbon

The soil organic carbon content of the soil samples from the disturbed study site was recorded lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly, *C. odorata* invaded soil recorded a high soil organic carbon content (0.93%) whereas the lowest value (0.03%) was recorded in *L. camara* invaded soil.

The soil organic carbon content of the soil samples from the moderately disturbed study site was recorded lowest in the pre- monsoon season while it was observed highest during the monsoon season. Particularly in *A. conyzoides* invaded soil which recorded a high (0.77%) soil organic carbon content of whereas the lowest (0.03%) was observed in *C. odorata* invaded soil.

The soil organic carbon content of the soil samples from the undisturbed study site showed that the soil organic carbon content was lowest in the pre-monsoon season while it was observed highest during the monsoon season. Particularly in *L. camara* invaded soil which recorded highest (1.29 %) soil organic carbon content whereas the lowest (0.03%) was recorded in *A. conyzoides* and *C. odorata* invaded soil.

Soil nutrient impacted by invasive alien plants

Total nitrogen content

The total nitrogen content of the soil samples from the disturbed study site showed that the total nitrogen content was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly *C. odorata* invaded soil recorded the highest (260.90 Kg/ha) whereas the lowest value (148.05 Kg/ha) was recorded in *A. conyzoides* invaded soil.

The total nitrogen content of the soil samples from the moderately disturbed study site shows that the total nitrogen content was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly *C.*

odorata invaded soil recorded the highest (496.3 Kg/ha) total nitrogen content whereas the lowest value (135.7 Kg/ha) was recorded in *M. micrantha* invaded soil.

The total nitrogen content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *L. camara* invaded soil which recorded the highest (388.0 Kg/ha) total nitrogen content whereas the lowest (206.91 Kg/ha) was recorded in *C. odorata* invaded soil.

Available Phosphorous content

The available phosphorous content of the soil samples from the disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *L. camara* invaded soil which recorded the highest (72.4 Kg/ha) available phosphorous content whereas the lowest (7.3 Kg/ha) was recorded in *M. micrantha* invaded soil.

The available phosphorous content of the soil samples from the moderately disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly *M. micrantha* invaded soil recorded the highest (173.1 Kg/ha) available phosphorous content whereas the lowest value (4.065 Kg/ha) was recorded in *C. odorata* invaded soil.

The available phosphorous content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly *M. micrantha invaded* soil recorded the highest (34.3 Kg/ha) available phosphorous content whereas the lowest value (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

Available Potassium

The available potassium content of the soil samples from the disturbed study site was observed highest during the pre- monsoon season. Particularly in *M. micrantha* invaded soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available potassium content of the soil samples from the moderately disturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre- monsoon season. Particularly in *M. micrantha invaded* soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The available potassium content of the soil samples from the undisturbed study site was recorded lowest in the monsoon season while it was observed highest during the pre-monsoon season. Particularly in *M. micrantha invaded* soil which recorded the highest (34.3 Kg/ha) available potassium content whereas the lowest (3.33 Kg/ha) was recorded in *C. odorata* invaded soil.

The primary factors that cause changes in the characteristics of soil are biological processes that are facilitated by invasive alien plants. Therefore, greater nutrient availability at investigated sites offers competitive advantage to invasive alien plants over natives which subsequently accelerate their spread.

Plant debris-soil Bioassay

Bioassay is an experimental technique which is used to assess the possible effects and risks associated with a specific chemical component of the abiotic environment. For the test of bioassay, soil and plant debris from four selected invasive alien plants *Ageratum conyzoides*, *Lantana camara*, *Chromolaena odorata,* and *Mikania micrantha* were tested against two food crops *Lactuca sativa* and *Cicer arietinum* respectively.

In the case of *L. sativa*, the highest number of germinations was observed on the third day and seventh day was from the healthy/control non-invaded soil. This shows that the germination of the seed was not affected by the plant debris. Meanwhile, the highest number of germinations of *C. arietinum* on the third and seventh day was from the plant soil bio-debris of *C. odorata*, *M. micrantha* and *A. conyzoides* invaded soils.

In the case of *L. sativa,* the highest seedling height was observed in *L. camara* invaded soil and the lowest in *M. micrantha* invaded soil. Whereas in another food crop i.e. *C. arietinum,* the highest seedling height was observed in case of *C.odorata* invaded soil whereas the lowest was in *M. micrantha* invaded soil. Root length and shoot length which indicates the seedling's competitive ability for nutrition was found higher in the pot bio-assay of the selected invasive alien plants than the healthy/control soil for both the selected food crops. The seedling biomass which shows the seedling’s growth and competitiveness was also higher in the pot bio-assay of selected invasive plants *A. conyzoides* and *C. odorata*. This higher seedling biomass values indicated that the soils in the experimental pots are more fertile than the pot containing healthy/control non-invaded soil.

The germination percentage and germination potential of the plants indicate the germination ability and viability of seeds which were found higher in the healthy/control soil for *L. sativa* but for *C. arietinum* it was found higher in case of the invaded soils. The germination index, germination rate index, and vigor index indicate the germination speed and the vitality of seeds and these indices were found higher in the healthy/control soil for *L. sativa* but in case of *C. arietinum* it was found higher in the invaded soils. Among the dominant invasive alien plants, the maximum inhibitory effects on growth parameters of bioassay food crops were observed in case of *M. micrantha* invaded soil. In general, the effects of other invasive alien plants contaminated soil on bioassay food crops were rather stimulatory.

Total Phenolic Contents (TPC)

The total phenolic contents of both the soil and leaf extracts were tested by catechol standard and gallic acid at different wavelengths. The TPC assessment of the soil by catechol standard revealed the highest concentration (0.915mg/ml) in *C. odorata* invaded soil whereas, gallic acid recorded the highest i.e., 0.038mg/mL in *L. camara* invaded soil. The presence of these phenolic contents in the soil rhizosphere reveals that these plants can emit allelochemicals in the soil which have the potential to influence their neighboring crops and plants. The TPC of the leaves by catechol standard revealed the highest concentration (12.38 mg/ml) in *L. camara* invaded soil whereas gallic acid recorded the highest (0.070 mg/ml) in *C. odorata* invaded soil.

Canopy Openness, Leaf Area Index (LAI), And Light Intensity

The canopy openness was highest at the disturbed site (87.42%) while it was lowest at the moderately disturbed site (25.92%). The incoming PAR, which is the total incoming solar radiation received by the area above the forest canopy, was highest at the moderately disturbed site at 1355.6±195.93 $\mu\ mol\ m^{-2}\ s^{-1}$ whereas, the diffused PAR, which is the total solar radiation received by the area under forest canopy was highest at the disturbed study site 562.6±368.38 $\mu\ mol\ m^{-2}\ s^{-1}$. The highest LAI, which is the leaf area index of a particular site was observed at the undisturbed study site (4.36±0.43) and lowest (1.65±1.30) at the disturbed site. The invasive alien plants at the moderately disturbed study site showed a highly significant negative relation between LAI and incoming PAR (r= -0.95) as well as LAI and diffused PAR (r= - 0.99). Whereas a positive and significant correlation was obtained between canopy openness and diffused PAR (r= 0.51), while a highly significant positive relation was obtained between diffused PAR and incoming PAR (r= 0.96).

The invasion of alien plants at the undisturbed study site revealed a highly significant negative relation between LAI and incoming PAR (r= -0.90), LAI and diffused PAR (r= -0.95) and canopy openness and LAI (r= -0.93). Whereas a highly significant positive relation was obtained between diffused PAR and incoming PAR (r= 0.98), canopy openness and incoming PAR (r= 0.90), canopy openness and Diffused PAR r= 0.93).

Management of invasive alien plants

The impacts of invasive alien plants play a major role in the decline of biodiversity threatening natural habitats worldwide. Controlling invasive alien plants is an important restoration intervention because it prevents native plant communities from growing in degraded areas. Invasive plant management can prevent native vegetation from recolonizing an area, aiding in ecological restoration and providing benefits to both native vegetation restoration and invasive plant management.

Maintaining intact forest canopy

In the present study the canopy gaps were more pronounced at the disturbed habitats when compared with undisturbed habitats. The canopy gaps were tightly associated with light intensity which was recorded highest at the disturbed site when compared with moderately disturbed and undisturbed sites. The distinct pattern in light intensity values along the disturbance gradients reflect the larger canopy gaps at the disturbed site which allow more penetration of photosynthetically active radiation. Therefore, efforts in maintaining the intact canopy by increasing native plant species richness can regulate the spread of invasive alien plants.