

**EFFECTS OF *TITHONIA DIVERSIFOLIA* (HEMSL.) A. GRAY
INVASION ON THE VEGETATION, SOIL CHEMISTRY AND
THE SOCIO-ECONOMY OF AIZAWL DISTRICT, MIZORAM**

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

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MZU REGISTRATION NO.: 1700472

Ph.D. REGISTRATION NO.: MZU/Ph.D./2018 of 23.08.2022



**DEPARTMENT OF ENVIRONMENTAL SCIENCE
SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES
MANAGEMENT
NOVEMBER, 2025**

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OF AIZAWL DISTRICT, MIZORAM**

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Submitted

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

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CERTIFICATE FROM SUPERVISOR

This is to certify that the Thesis entitled, “Effects of *Tithonia diversifolia* (Hemsl.) A. Gray invasion on the vegetation, soil chemistry and the socio-economy of Aizawl district, Mizoram”, is a bonafide work assigned to Vanlalruati (Regn. No. MZU/Ph.D./ 2018 of 23.08.2022), Department of Environmental Science, for partial fulfillment of the requirement for the degree of Doctor of Philosophy under Mizoram University.

The report submitted by the candidate is her own study and carried out by her and result embodied in the Thesis have not been submitted for award of degree or any other elsewhere. It is recommended that this dissertation be placed before the examiners for the award of the degree of Doctor of Philosophy.

Place: Tanhril

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DECLARATION
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NOVEMBER, 2025

I **VANLALRUATI**, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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ACKNOWLEDGEMENT

First and foremost, I extend my deepest thanks to the Almighty God for His unwavering love, blessings, and guidance throughout the journey of completing my research.

I am profoundly thankful to my supervisor, Prof. P.K. Rai, for his constant support, patient mentorship, and dedicated involvement throughout the duration of my study. His extensive knowledge and thoughtful guidance have significantly shaped my learning and academic growth. I would also like to sincerely acknowledge my fellow research scholar, Roger Bruce Syngkli, for his genuine moral support during this time.

My gratitude extends to the faculty members of the Department of Environmental Science, Mizoram University, for providing me the opportunity to undertake this research and for their contributions that enabled the successful submission of my thesis.

I am also thankful to the Ministry of Tribal Affairs for the renewal of the National Fellowship for Scheduled Tribe (NFST), which provided me the financial assistance in the procurement of several research materials.

Lastly, I express heartfelt appreciation to my family for their unwavering prayers, encouragement, and emotional support. Their belief in me gave me the strength and confidence to complete this academic journey. This thesis is a culmination of the collective support and contributions of all those acknowledged above.

‘To God be the Glory’

Vanlalruati

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LIST OF ABBREVEATION

%	: Percentage
°	: Degree
BM	: Biomass
BOD	: Biological oxygen demand
C	: Celsius
CABI	: Centre for Agriculture and Bioscience International
CBD	: Convention on Biological Diversity
Cd	: Concentration of Dominance
cm	: Centimeter
Cu	: Copper
D	: Dominance or Disturbed
E	: East
<i>et al.</i>	: et alii, and others
Fe	: Iron
FLE	: Fresh leaves aqueous extracts
g	: Gram (s)
GAE	: Gallic acid equivalents
GI	: Germination index
GISD	: Global invasive species database
GLA	: Gap light analyzer
GPe	: Germination percentage

GPo	: Germination potential
GPS	: Global positioning system
GRI	: Germination rate index
H'	: Shannon-Weiner diversity index
H ₂ SO ₄	: Sulfuric acid
ha	: Hectare (s)
HCL	: Hydrochloric acid
i.e.	: id est, that is
IDH	: Intermediate Disturbance Hypothesis
ISFR	: Indian state forest report
IVI	: Important value index
K	: Potassium
Kg	: Kilogram (s)
Km	: Kilometer (s)
KMnO ₄	: Potassium permanganate
LAI	: Leaf area index
m	: Metre (s)
MD	: Moderately disturbed
Mg	: Magnesium
ml	: Milliliter (s)
mm	: Millimeter (s)
Mn	: Manganese
N	: North or Nitrogen or Normality

Na ₂ CO ₃	: Sodium carbonate
NaOH	: Sodium hydroxide
NE	: Northeast
NOAA	: National oceanic and atmospheric administration
NWH	: Novel weapon hypothesis
P	: Phosphorus
PAR	: Photosynthetically active radiation
pH	: Power of Hydrogen
RA	: Relative abundance
RD	: Relative density
RF	: Relative frequency
RL	: Root length
RPM	: Revolutions per minute
SH	: Seedling height
SL	: Shoot length
SOC	: Soil Organic Carbon
SOM	: Soil Organic Matter
sq	: Square
TPC	: Total phenolic content
VI	: Vigor index
WHC	: Water Holding Capacity
Zn	: Zinc
β	: Beta or Sorenson's similarity index

μg	: Microgram
Σ	: Summation, sigma

CHAPTER-1

INTRODUCTION

1. INTRODUCTION

Conservation on biological diversity is important for maintaining healthy ecosystems (da Silva *et al.*, 2025). The increasing environmental threats deteriorates the functioning ecosystem thereby effecting human health and ecosystem services (Bobul'ská *et al.*, 2025). Plant invasions are one of the most significant attempts to alter the biodiversity and nutrient cycling of terrestrial ecosystems (Duenas *et al.*, 2021; Bobul'ská *et al.*, 2025). The invasive alien plants are widely distributed in global landscapes and adversely influence environment, native vegetation, and socio-economy (Rai, 2020).

Invasive species are defined as an alien species which becomes established in natural or semi-natural ecosystem or habitat, is an agent of change, and threatens native biological diversity (International Union for Conservation of Nature, 2000). The Convention on Biological Diversity (1992) has been recognized invasive species as the second worst threat after habitat destruction. The plant invasion process involves different ecological stages such as transportation, colonization, establishment and landscape spread (Theoharides and Dukes, 2007). However, the vast majority of biological factors driving the spread of invasive alien plant species remain largely unexplored (Chengxu *et al.*, 2011). The majority of invasive alien plant developed a huge quantity of light seeds, allowing them to move long distances by wind or by other modes of transportation like animals and people (Dogra *et al.*, 2009). For their survival, development, growth, and ability to adapt to a variety of environmental situations, invasive plants have a robust vegetative reproductive capability to expand quickly (Wang, 1990; Zhao, 2003; Sage, 2004).

The most essential factors in the success of invasive alien plants are considered to be the presence of allelochemicals which are considered as novel weapons (Linked with “Novel weapon hypothesis”) (Callaway and Ridenour, 2004; Chengxu *et al.*, 2011; Syed *et al.*, 2021). These allelochemicals are the secondary metabolites produced into the environment by organisms or a plant invader which has the ability to suppress native indigenous plants and edible crops (Callaway and Ridenour, 2004; Syngkli and Rai, 2024). This process of interaction is known as

allelopathy (Perveen *et al.*, 2020). The allelopathy influences plants invasiveness and associated with naturalization and establishment of invasive species in non-native introduced habitat ranges (Kato-Noguchi, 2020). This affects other organisms within the same community in terms of germination, growth, survival, and reproduction (Manivel *et al.*, 2023).

Allelopathy is broadly classified into direct and indirect allelopathy based on the involvement of intermediate organism (Manivel *et al.*, 2023). There are substantial differences in these phytotoxins chemical makeup, mode of action, and effects on plants which could be either inhibitory or stimulatory (Kaur *et al.*, 2012; Syngkli *et al.*, 2022a). Allelochemicals act as important component of both managed and natural ecosystems, allelochemicals released by invasive alien plants also offers biological defence against plant diseases and pathogens, thereby facilitating their invasive spread (Syngkli *et al.*, 2022b). The biological properties highly affected the successful spread of invasive alien plant species (Rai and Singh, 2020). Transportation infrastructures (such as roads or railways) also facilitate the abrupt spread of invasive alien plant s (Callaway and Ridenour, 2004). To this end, the allelochemic compounds in invasive plants in fact act as novel weapons which facilitate the invasive spread of *T. diversifolia* in introduced landscapes (Blumenthal *et al.*, 2003).

The dissemination of invasive plant species is facilitated by a range of biotic and abiotic vectors, including humans, animals, wind, and rainfall, either through intentional or inadvertent actions (Divakara *et al.*, 2013; Banerjee *et al.*, 2021). Anthropogenic activities, particularly the introduction of agricultural crops, forage species, ornamental plants, and the operation of transport systems are among the primary drivers of this spread (Dogra *et al.*, 2009). Nonetheless, the ecological mechanisms underlying the successful establishment and expansion of invasive alien plant species remain insufficiently understood (Chengxu *et al.*, 2011; Dudenhoeffer and Hodge, 2018). Many invasive taxa exhibit prolific seed production, often generating large quantities of lightweight seeds capable of long-distance dispersal via wind, fauna, or human-mediated transport. Furthermore, these species typically

possess robust vegetative traits that enhance their capacity for invasive proliferation (Nielsen *et al.*, 2020).

Plant invasion plays an important role in the development and modulation/shaping of forest ecosystems because of its substantial impact (Woch *et al.*, 2021). In this respect, the impacts are linked with multitude of invasive plant traits and ecological mechanism (Callaway and Ridenour, 2004). The invasiveness of alien plants may be increased by anthropogenic-mediated disturbances, such as fluctuations in nutrients caused by excessive emissions of various soil nutrients (Vitousek *et al.*, 1987). The ability of invasive plants to respond appropriately to nutrient availability is of fundamental importance for colonization and adaptation to the environment as soil nutrients are critical elements for plant growth and productivity (Schoenfelder *et al.*, 2010). It is widely observed in forest, agroforestry and agriculture system that changes the soil properties which could last for a longer period even after invasive plants is removed (Raizada *et al.*, 2008). This is because the invasive alien plant possesses plasticity in nature which helps them to adapt in high and low resources availability which 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 (Burke *et al.*, 2013; Funk, 2013; Sardans *et al.*, 2017; Knauf, 2021). It has been widely been demonstrated that plant invaders introduced in a new habitat altered the soil properties of the native soil and make the soil less suitable for other plants species to grow (Zavaleta, 2000; Sharma *et al.*, 2013). The impact on soil environment due to invasive alien plants may differ depending on the species of invasive plants (Stefanowicz *et al.*, 2018). Thus, resource availability provided directly support the resource hypothesis by increasing the invasion of alien plant species (Blumenthal, 2006).

1.1. Management of invasive alien plants

Invasive alien plant poses significant threats to biodiversity, agricultural productivity, and ecosystem stability worldwide (Rai and Singh, 2020). Management of invasive alien plant species is facilitated by knowing their origin, distribution pattern,

landscape spread, habitation and mode of introduction are necessary (Sengupta and Dash, 2020). In general, there are three common methods for the control and management of invasive alien plant species such as mechanical, chemical, and biological methods (Van-Wilgen *et al.*, 2001). Among the various management strategies, mechanical control remains one of the most widely practiced methods due to its immediate effectiveness in physically removing unwanted vegetation (Falade *et al.*, 2019). This practice is widely adapted by marginal farmers in agriculture and agroforestry systems (Aboyeji., 2022). This technique encompasses the use of tools such as ploughs, hoes, scythes, mowers, cultivators, and rotary weeders to uproot or suppress invasive plants (Ehi-Eromosele *et al.*, 2013; Falade *et al.*, 2019). Additionally, advanced mechanical methods include the application of heat, force, or suffocating layers of UV-stabilized plastic sheets to inhibit photosynthesis and destroy seedling growth (Ayodele and Aluk, 2017; State of the World's Plants, 2017). Despite its advantages, mechanical control is labour-intensive, requires complete removal of root systems, and poses the risk of site disturbance that can eventually lead to rapid reinvasion, if not properly managed (Hussner *et al.*, 2017). Furthermore, this method is often proved to be ineffective in large-scale infestations and challenging terrains (Syrett *et al.*, 2000; Anthony *et al.*, 2013).

In addition to physical/mechanical methods, chemical methods are widely practised for management of invasive alien plants (Hussner *et al.*, 2017). For broader context, chemical control through herbicides such as glyphosate and triclopyr offers selective or non-selective suppression but raises concerns over environmental safety and non-target effects (Ayodele and Aluk, 2017; Kughur, 2012). Similarly, biological control using natural enemies like insects, fungi, bacteria, and nematodes is ecologically sustainable but limited by environmental conditions and low chances of complete eradication (Ehi-Eromosele *et al.*, 2013; State of the World's Plants, 2017). The control of invasive alien plants through integrated management approaches tailored to specific ecological settings for effective long-term control of invasive species (Witt *et al.*, 2019).

Apart from physical/mechanical, chemical, and biological method, analysing canopy openness, light intensity i.e., photosynthetically active radiation (PAR), and

leaf area index (LAI) are important for the management prospect. Canopy openness has profound impact on the light and heat reaching the ground as well as soil nutrient and soil moisture content that are accessible to plants (Shrestha *et al.*, 2018). Canopy openness may occur due to loss of vegetation and due to intense disruption such as fires and windstorms (Keram *et al.*, 2019). However, this canopy gaps formed can facilitate invasive alien plants colonization and on the other hand canopy gaps can promote the regeneration of native plant species that can compete with or suppress invasives (Subedi *et al.*, 2024). Restoring native plant species helps re-establish ecological balance and resistance to further invasion (Shrestha *et al.*, 2018; Brokaw and Busing, 2020).

A related metric, such as leaf area index (LAI), and photosynthetically active radiation (PAR) serves as an effective tool for managing invasive alien plant species by helping to assess invasion risk, shape canopy and planting strategies, monitor ecological restoration, and inform ecological modelling (Beeles *et al.*, 2022). By controlling or understanding light availability, restoration ecologist can more effectively suppress invasive plants spread and conserve native biodiversity (Crawford *et al.*, 2020). To accurately describe the light conditions in forest understories, direct measurements of solar radiation especially PAR are considered the most reliable. PAR is commonly measured both above and below the forest canopy and is divided into two components i.e., incoming PAR, which refers to the direct sunlight received at the canopy level, and diffused PAR, which is in fact the scattered light that passes through the canopy and reaches the forest floor (Syngkli and Rai, 2024).

1.2. *Tithonia diversifolia* (Hemsl.) A. Gray as invasive alien plant

T. diversifolia belongs to the Asteraceae family and is known to be originated from Central America, it is widely distributed throughout the world (Fasuyi and Ibitayo, 2011). India is also one of the countries where *T. diversifolia* is widely distributed, especially in Northeast India (Agboola and Muoghalu, 2014). In context of origin, almost 80% of invasive alien plant species were introduced from South and Central American region (Omolola, 2020; Boral and Moktan, 2022). In terms of taxonomy,

T. diversifolia was named after the botanist Rene Destontaines. The name ‘Tithonus’ was taken from the Greek word meaning ‘Aurora’, while ‘Diversus’ denotes Latin word which means ‘divergent’ and ‘folium’ means ‘leaf’ (Desfontaines, 1802; Alex *et al.*, 2018). *T. diversifolia* is commonly referred to as Mexican sunflower or tree marigold (Kawlani *et al.*, 2017; Juswardi *et al.*, 2024).

T. diversifolia is a perennial or annual shrub that can grow up to 3 meters in height (Omolola, 2020). The flowers heads are solitary on a peduncle 6-13cm in length, display attractive yellowish to orange coloured with luxuriant flowering during winter (Omolola, 2019; Kato-Noguchi and Kato, 2025). The leaves are simple, arranged alternately, lobed with attenuate or decurrent bases, and about 5-15cm long and 3.5-6cm broad. Leaves are dark green, toothed and wedged shaped at the base (Akobundu and Agyakwa, 1987; Ajao and Moteetee, 2017; Omolola, 2019).

Mostly, propagation of *T. diversifolia* is by seeds, they germinate naturally under its canopy or by transplanted elsewhere (Sihai *et al.*, 2004). The seed is quadrangular, spirally-ridged, pubescent below and glabrous above (John-Dewole, and Oni, 2013). The germination rates ranging from 18 to 56% at 25°C (Jama *et al.*, 2000). The dispersal of seed in relation to *T. diversifolia* is carried out by humans, livestock, and water currents (Ajao and Moteetee, 2017).

It has been widely accepted that *T. diversifolia* becomes an emerging invasive plant due to aggressive growth rate and high seed production (Muoghalu and Chuba, 2005; Zachariades *et al.*, 2009; Otusanya *et al.*, 2015). They are known to have secondary metabolites such as sesquiterpenoids, terpenoids, flavonoids, tannins and saponins (Zhou *et al.*, 2013; Kato-Noguchi, 2020 and Omolola, 2020). They are also known to exhibit allelopathy which means they may exert both stimulatory and inhibitory phytotoxic plant attributes (Akobundu and Agyakwa 1987; Taiwo and Makinde, 2005; Ayeni *et al.*, 2008). This enables to increase their population in the newly invaded environment by hindering or restricting the growth and development of native plants (Chengxu *et al.*, 2011; Meiners *et al.*, 2012).

The decomposition of *T. diversifolia* biomass enhances the soil nutrients, organic matter content, and crop productivity (Agbede, 2025). The leaves and the

stem of *T. diversifolia* is rich in nitrogen (N), phosphorus (P), and potassium (K) (Farni *et al.*, 2022; Aboyeji, 2022; Robinson *et al.*, 2024). *T. diversifolia* can be harvested at various growth stages, and the biomass can be incorporated into the soil. The decomposition rate is faster thereby, helps in maintaining and improving the physical, chemical and biological properties of the soil (Chagas-Paula *et al.*, 2012; Ewane *et al.*, 2020). The leaves also have high magnesium (Mg) content and smaller amount of iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) which helps in the treatment of various diseases in human (Omolola, 2020).

1.3. Global perception on *T. diversifolia*

T. diversifolia, originally introduced to Africa as an ornamental plant, has become widely naturalized due to its strong ecological adaptability, allowing *T. diversifolia* to thrive in diverse habitats such as forests, farmlands, roadsides, and waste areas (Ajao and Moteetee, 2017). *T. diversifolia* spread has significantly impacted native biodiversity, as observed in southwestern Nigeria, where invaded areas showed reduced species diversity and productivity (Witt *et al.*, 2019). In Asia, particularly South, East, and Southeast Asia where there are rich in biodiversity, *T. diversifolia* has established itself extensively, aided by anthropogenic disturbances like climate change, land-use change, and wildfires (Merrill 1922; Weber *et al.*, 2008). For instance, in China, *T. diversifolia* is currently prevalent in southern Yunnan, a region known for its rich biodiversity (Dai *et al.*, 2021). Salient ecological attributes of *T. diversifolia* such as formation of monodominant stands and the release of allelochemicals have been shown to suppress the germination and early growth of native plant species, thereby leading to significant negative impacts on both biodiversity and agricultural productivity (Li and Wang, 2015). Moreover, its high genetic variability presents a major obstacle to effective control and management strategies (Yang *et al.*, 2012). In India, despite the harmful ecological impact, *T. diversifolia* has also been used for certain beneficial prospects such as potential dust capturer, suggesting the plantation of *T. diversifolia* in and around industrial area to ameliorate the particulate air pollution (Nitesh *et al.*, 2016).

1.4. Scope of the study

The northeast (NE) India is immensely rich in native and endemic biodiversity and this region of paramount ecological significance which underlie in an Indo-Burma (presently name as Myanmar) biodiversity hotspot. To this end, Mizoram is an integral landscape of this hotspot having high number of endemic plants and animal species in this region (Rai and Singh, 2024; Solanki *et al.*, 2024). Past studies significantly contributed to the documentation, exploration, and ecological investigation on this region on various aspects in relation to the biodiversity conservation. The native and indigenous biodiversity of Mizoram is greatly being disturbed by the introduction, colonization, and subsequent landscape spread of invasive alien plants. Majority of the studies on ecology of *T. diversifolia* belong to the African countries and some parts of Asian countries, but the scientific study and information is very scant in India especially NE, India despite its aggressive spread. Some of these plant invaders are listed among the list of top 100 harmful global biotic invader. In light of this, past studies in Indian context prioritized these global invasive alien plant species such as *Parthenium hysterophorus* L., *Chromolaena odorata* L., *Mikania micrantha* Kunth, and *Ageratum conyzoides* L. However, the emerging alien invasive plant species *T. diversifolia* was largely unnoticed which is now widely invasive, especially in context of Aizawl, Mizoram. Literary evidences confirmed that *T. diversifolia* has been listed among 163 alien invasive plant species in Mizoram. Furthermore, *T. diversifolia* gradually became a new potential invasive alien plant species in protected areas of Mizoram such as Phawngpui National Park and Lengteng Wildlife Sanctuary. It was reported that *T. diversifolia* infest the agricultural land and forest in Mizoram causing hindrance to local farmers while harvesting their crop plants and also pose a threat to the native plants. The success of this invasive alien plants from Asteraceae is linked with several plant traits and ecological mechanisms. The establishment and spread of invasive plant species in forest ecosystems tied up with the canopy openness, leaf area index (LAI), and photosynthetically active radiation (PAR). They are essential variables in forest ecology as they collectively influence light availability, thereby shaping the microclimate and influencing understory plant growth, seedling survival, and species

composition. On the other hand, the benefits of *T. diversifolia* in agriculture, medicine, and environmental management, *T. diversifolia* remains underutilized in many communities and country due to limited awareness, poor extension services, and negative perceptions. This knowledge gap hinders its potential to support sustainable farming and healthcare practices. Since the urbanized landscapes such as those belonging to Aizawl, Mizoram are ideal for studying the effects of *T. diversifolia*, due to presence of distinct disturbance gradient, this ecological investigation selected urban forest of this capital state of Mizoram. In this respect, effects of *T. diversifolia* on native vegetation was analysed in differentially disturbed sites of Aizawl by analysing its phytosociology and community characteristics. Further, the present study aimed to validate the ‘novel weapon hypothesis (NWH)’ by characterizing soil physico-chemical properties and the allelochemical activity. Moreover, the socio-economic implications and management option were conducted in order to mitigate the spread of *T. diversifolia* and provide information on the best option how to utilise, manage and control the aggressive spread of *T. diversifolia*.

The above-mentioned ecological investigation on *T. diversifolia* in Aizawl, Mizoram was planned with the following objectives-

1.5. OBJECTIVES

1. To study the effects of *T. diversifolia* on plant community characteristics.
2. To study the effects of *T. diversifolia* on soil physico-chemical properties.
3. To study the allelochemic attributes of *T. diversifolia*.
4. To study the socio-economic implications and management options of *T. diversifolia*.

CHAPTER-2

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

2.1. Global aspects on the invasion of *T. diversifolia*

Global Invasive Species Database (GISD) (2020) and Center for Agriculture and Bioscience International (CABI) (2020) identified *T. diversifolia* as an invasive alien plant species worldwide. Specifically, *T. diversifolia* is originating from Central America, its native range includes Belize, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, and Panama (CABI 2020; Boral and Moktan, 2022). Also, several countries like Burundi (Bamps and Farron 1967), Congo (Bamps and Farron 1967), China (Wang *et al.*, 2004), Philippines (Merrill 1922), India (Moktan and Das 2013; Sankaran *et al.*, 2014; Sengupta and Dash, 2020), Indonesia, Laos, Timor-Leste, Malaysia, Myanmar, Thailand, Vietnam, and Nepal (CABI 2020) reported *T. diversifolia* as an invasive alien plant species in their country (Boral and Moktan, 2022).

Initially, *T. diversifolia* introduced to Africa as ornamental plants, however, historical evidences indicated that it has become widespread in this region (Ajao and Moteetee, 2017). These species are commonly found in various habitats, including forests, farmlands, waste or marginal areas, plantations, gardens, and along roadsides of forestry/agroforestry patches (Lowry *et al.*, 2020). The strong ecological adaptability of *T. diversifolia* in introduced region plays a major role in their expansion and contributing to the decline of biodiversity (Witt *et al.*, 2019). Several studies assessed the effects of *T. diversifolia* on native plant diversity (Jama *et al.*, 2000). In this respect, Oludare and Moughalu (2014) studied the impact of *T. diversifolia* on the invaded and uninvaded habitats in south western Nigeria. The study showed that the invaded habitats of *T. diversifolia* decreased the diversity indices (such as Shanon-Weiner diversity, abundant species, and evenness index) and the productivity when compared with non-invaded habitats. This is due to the allelopathic interaction in development and growth process as it affects all development and growth aspects like proteins, hormones, and chlorophyll synthesis (Vilà *et al.*, 2011). Further, the socio-economic assessments in Zambia reported *T. diversifolia* has negatively affected native plant communities, restricts access to

agricultural lands, reduces water availability, reduces crop productivity, and impacts livestock health (Witt *et al.*, 2019).

On the other hand, *T. diversifolia* acted as a potential source of nutrients for improved resilience of soil/terrestrial ecosystems and enhanced productive capacity and crop yields (Ajao and Moteetee, 2017). For instance, it has been reported in Kenya that the biomass had a higher macronutrient content than commonly used leguminous mulch species, and adding *T. diversifolia* mulch to phosphorus deficient soil subsequently increased microbial activity, soil phosphorus availability and crop phosphorus uptake by agriculture crops (Jama *et al.*, 2000). Also, in Costa Rica, mulching beans (*Phaseolus vulgaris* L.) with *T. diversifolia* biomass in agroforestry soil resulted in increased root nodules and improved shoot and root characteristics due to enhanced soil phosphorus availability (Mustonen *et al.* 2014). Despite its invasive ecological attribute, *T. diversifolia* is valued for its high nutrient and mineral content, making its plant residues useful as green manure for improving soil fertility and as fodder for livestock (Witt *et al.*, 2019).

It has been demonstrated that the quality of leaf material of *T. diversifolia* determined the rate of decomposition and nutrient enrichment (Partey, 2010). This further caused positive modulation in physico-chemical properties of soil (such as pH, organic carbon, P, N, and exchangeable cation), hence improved the soil fertility (Agboola and Moughalu, 2014). In Ghana, *T. diversifolia* leaves exhibited a greater rate of decomposition and nutrient release when compared to leaves from leguminous trees (Partey *et al.*, 2011). Furthermore, the dry leave matter dispersed over the soil and get buried underground to boost soil fertility, mineral availability, and crop output (Jama *et al.*, 2000; Kaho *et al.*, 2011, van Sao *et al.*, 2010). Thus, farmers from Uganda and Kenya who have limited affordability and limited availability of inorganic fertilizers used the leaves of *T. diversifolia* as biopesticides and for biofertilizers in order to replace hazardous and expensive synthetic pesticides (Mwine *et al.*, 2011; Jama *et al.*, 2000).

In Asian perspective, *T. diversifolia* has become one of the several “New-World” plant species especially in South Asia (Merrill 1922; Weber *et al.*, 2008).

They are concentrated towards Southern China in which *T. diversifolia* was known to be transported from South America (Boral and Moktan, 2022). In accordance with Critical Ecosystem Partnership Fund (CEPF), the South Asia, East Asia, and South East Asia are the zones of rich biodiversity where six of the world's thirty-six biodiversity hotspots are located (CEPF, 2020). Potential anthropogenic global changes such as climate change, alterations in land use patterns, and several threats like wildfires, facilitated invasive alien plant species which has reduced 40% of the Southeast Asian indigenous biodiversity (Sodhi *et al.*, 2004). These activities make such ecologically relevant high biodiversity zone no longer to act as potential buffer against invasive flora (Peh, 2010). The increased presence of mutualistic partners also facilitated the successful establishment of many invasive plants (Dutta, 2018). Furthermore, Sun *et al.* (2001) studied the distribution, plant communities, growth patterns, and chromosome structure of *T. diversifolia*, which reveal its ability to reproduce both vegetatively and reproductively via seeds, consequently playing a major role in its invasiveness in introduced region. *T. diversifolia* therefore this invasive alien plant equips with invasive traits of its family i.e., Asteraceae has now become widespread across forestry, agroforestry, and agricultural landscapes in certain Asian countries and Indian biodiversity hotspots especially in Mizoram, underline in Indo-Burma hotspot (Banerjee *et al.*, 2021).

Historical evidences suggested that the introduction of invasive alien plants species in Asia, including India, began during European colonization in the 15th century, initially for food and later for ornamental and economic purposes (Lockwood *et al.*, 2009; Callaway, 2022; Lenzner *et al.*, 2022). In India, most of invasive alien plants were introduced as garden ornamentals (Hiremath and Sundaram; 2013). The information on spread of invasive alien plant species and their potential threats is very limited in NE states of India, particularly from Mizoram (Sengupta and Dash, 2020). The common ecological studies on invasive alien plants were conducted mainly on *Ageratum conyzoides*, *Parthenium hysterophorus* and *Lantana camara* (Kohli *et al.*, 2006). In this regard, Reddy (2008) found 173 invasive alien plant species in India between 2003 and 2007, belonging to 117 genera and 44 families. Tropical America was the source of the majority of the invasive

species, followed by tropical Africa and others (Reddy, 2008). In Kashmir Himalayas of India, 571 invasive alien plants were enumerated (Khuroo *et al.*, 2012). Whereas, about 190 invasive alien plants identified from Indian Himalayan region (Sekar *et al.*, 2012) while 497 invasive alien plants were documented from Himachal Pradesh (Jaryan *et al.*, 2013). Most of the invasive alien plants in these studies belonged to herbaceous plants followed by shrubs, climbers and trees. Further, Asteraceae was observed to be the most dominant family in context of invasive alien plants (CABI, 2019).

2.2. Plants invasion studies in Mizoram

Mizoram, a mountainous state in northeastern (NE) India, is part of the Indo-Myanmar biodiversity hotspot, known for its rich variety of plant and animal life, including numerous endemics and threatened plant species (Vanlalruati and Rai, 2021; Sengupta and Dash, 2022). The vulnerability to alien plant invasions in Mizoram is heightened by several factors, including its unique topography, geographical position, and changing climate (Tlanhlui *et al.*, 2023). Bordered by Myanmar to the east and Bangladesh to the west, the state is exposed to the spread of invasive species via both human-mediated and natural dispersal (India State Forest Report (ISFR), 2021). The region has rugged terrain and climatic diversity that create a wide range of microhabitats by invasive species to be exploited (Nikhil and Aneesh, 2025). Additionally, traditional agricultural practices like "Jhum" or shifting cultivation generate open, disturbed, or fallow areas. These conditions offer ideal environments for invasive species to establish themselves and spread into adjacent natural forests (Sati, 2020). However, when non-native plant species are introduced and become naturalized, some turn invasive especially in anthropogenically disturbed habitat by human activity thereby posing a threat to the native flora (Syngkli *et al.*, 2025). Studying these invasive alien plants are vital, as they often outcompete native plants for essential abiotic resources like sunlight, water, and nutrients, leading to reduced biodiversity and altered ecosystem dynamics (Nikhil and Aneesh, 2025). Understanding their ecological effects is essential for developing effective management strategies (Rai and Vanlalruati, 2022; Tlanhlui *et al.*, 2023; Syngkli *et al.*, 2025).

During World War II, when the Indian subcontinent, including present-day Mizoram (formerly Lushai Hills), was under British rule, several invasive alien plants were introduced (Shankar *et al.*, 2011). Herbarium records showed early occurrences of species like *Chromolaena odorata* (L.) R.M. King & H. Rob. (1938), *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. (1931), and *Mikania micrantha* Kunth (1956), the latter likely introduced for use in tea plantations and military camouflage (Sengupta and Dash, 2020). These plants may have spread into Mizoram through the Khasia-Jaintia Hills–Silchar-Aizawl–Lushai Hills route, eventually invading the state disturbed landscapes of this biodiversity rich states (Sengupta and Dash, 2020).

In the latest ISFR (2023), *C. odorata*, *Saccharum spontaneum* L., *M. micrantha*, *Ipomoea carnea* Jacq., and *A. adenophora* were listed as major invasive species in the state inside the reserve forest area. In this context, Sengupta and Dash (2020) recorded 163 alien plant species belonging to 135 genera and 51 families in Mizoram. The 57.66% of the alien species reported from Mizoram were of American origin followed by 11.65 % from African, 7.36% from Mexican, and 5.52% from Australian origin. In Reiek forest, Lalzarzovi and Lalnuntluanga (2015), identified 6 species as alien invasive species. Those were *Ageratum conyzoides* (L.) L., *Bidens Pilosa* L., *Cyperus rotundus* L., *Imperata cylindrical* (L.) P.Beauv., *Ipomoea hederifolia* L., and *Urena lobate* L. Whereas, according to CABI (2020), there are 27 plant species which were reported to be invasive in Mizoram. However, the ecological process and causes of invasion in Mizoram need to elucidated for biodiversity conservation and formulating concrete forest management policies (Sengupta and Dash, 2020).

However, despite *T. diversifolia* being known invasive alien plants, there has not been any empirical or pragmatic research into its current and future potential habitat in India, particularly in Mizoram NE India.

2.3. Phytochemicals constituents of *T. diversifolia*

T. diversifolia contains a diverse array of phytochemicals, which are responsible for its pharmacological, agricultural, and ecological activities (Banerjee *et al.*, 2021; Misrahanum, 2022). These substances are found in leaves, stems, flowers, and roots, among other places (John-Dewole and Oni, 2013; Olayinka *et al.*, 2015; Agboola *et al.*, 2016; Tagne *et al.*, 2018). Sesquiterpene lactones, flavonoids, diterpenoids, saponins, tannins, alkaloids, phenolics, and essential oils are the main categories of secondary metabolites that have been found in *T. diversifolia* (Christopher, 2025; da Silva Júnior *et al.*, 2025).

2.3.1. Sesquiterpene Lactones

Among the most well-studied constituents of *T. diversifolia* are sesquiterpene lactones, particularly tagitinin A, B, C, and D (Tagne *et al.*, 2018). These compounds exhibit a broad range of biological activities, including antimalarial, anti-inflammatory, anticancer, and antibacterial effects (Chagas-Paula *et al.*, 2012; Heinrich *et al.*, 1998). Tagitinin C, in particular, has been shown to possess potent cytotoxic properties against several cancer cell lines (Lalremruata, *et al.*, 2025).

2.3.2. Flavonoids and Phenolic Compounds

Flavonoids such as quercetin, luteolin, and apigenin derivatives are also present in the plant, they are mainly found in the leaves and flowers (Dias *et al.*, 2021). These compounds are known for their antioxidant, anti-inflammatory, and antimicrobial effects (Olayinka *et al.*, 2015). Total phenolic content contributes significantly to the *T. diversifolia* of antioxidant activity, which plays a vital role in disease prevention and immune modulation (Miura *et al.*, 2005).

2.3.3. Terpenoids and Diterpenes

Plant invader from Asteraceae especially, *T. diversifolia* produces various terpenoids, including kaurenoic acid and other ent-kaurene derivatives, which are associated with anti-inflammatory and hepatoprotective effects (Olayinka *et al.*, 2015; Pimentel *et al.*, 2024). These diterpenoids may also contribute to traditional use of *T.*

diversifolia in treating liver disorders and infectious diseases (Wahyuningsih *et al.*, 2015).

2.3.4. Saponins, Tannins, and Alkaloids

Qualitative phytochemical screening of *T. diversifolia* revealed the presence of saponins, which may contribute to the antidiabetic and hypocholesterolemic activities (Olukunle *et al.*, 2014; Omolola, 2020). Tannins are responsible for astringent properties and may support the use of *T. diversifolia* plant in treating diarrhoea and wound healing (Olayinka *et al.*, 2015). Alkaloids, although present in smaller quantities, have been associated with various neuroactive and antimicrobial effects (Ajao and Moteetee, 2017; Olukunle *et al.*, 2014).

2.3.5. Nutritional and Mineral Content

In addition to phytochemicals, *T. diversifolia* contains essential minerals and nutrients such as calcium, phosphorus, potassium, magnesium, and crude proteins, particularly in its leaves (Jama *et al.*, 2000). This composition makes it a valuable fodder crop for livestock (Osuga *et al.*, 2012). The high protein and mineral content support its use in animal feed to enhance growth, productivity, and livelihood (Buragohain, 2016).

2.4. Ethnomedicinal usage of *T. diversifolia*

Globally, *T. diversifolia* is widely used in traditional medicine by many ethnic groups. In countries like the United States and Venezuela, oral extracts from its stems and leaves are traditionally used to treat abscesses, bruises, and muscle cramps (Frei *et al.*, 1998; Játem-Lászer *et al.*, 1998). In both Mexico and Nigeria, the plant is consumed for its antimalarial properties (Heinrich *et al.*, 1998; Ajaiyeoba *et al.*, 2006). In Costa Rica, dried leaves are applied externally to heal wounds, while in India, toasted leaf powder is commonly used to treat skin conditions such as bruises, infections, and wounds (Kuo and Chen, 1997; Frei *et al.*, 1998; Heinrich, 2000). In African countries such as Uganda, the plant is either ingested or used topically to address microbial infections in the genital area (Kamatenesi-Mugisha *et al.*, 2008). Similarly, in Kenya, its leaves are used in the treatment of gastrointestinal issues and

also used as a remedy for snakebites and other traditional veterinary practices to manage ecto-parasites (Owuor *et al.*, 2005; Njoroge and Bussmann, 2006; Tagne *et al.*, 2018). Taiwanese traditional medicine uses leaf infusions to effectively manage diabetes and hepatitis (Miura *et al.*, 2005; Ajao and Moteetee, 2017). While in Indonesia, the plant is utilized to treat a range of ailments including diabetes, diarrhoea, liver disorders, stomach pain, and wounds (Wahyuningsih *et al.*, 2015).

Various parts of *T. diversifolia* are also used in the treatment of measles (Ajao and Moteetee, 2017), type II diabetes (Anthoney *et al.*, 2016), bacterial infections (Olukunle *et al.*, 2014; Omolola, 2020), as well as for their insecticidal (Anthoney *et al.*, 2016) and anti-inflammatory (Olukunle *et al.*, 2014) properties. Additionally, several studies have reported the potential of *T. diversifolia* to inhibit the growth of cancer cells (Chagas-Paula *et al.*, 2012; Ajao and Moteetee, 2017; Kawlani *et al.*, 2017; Tagne *et al.*, 2018; Lalremruata, *et al.*, 2025)

2.5. Beneficial uses of *T. diversifolia*

T. diversifolia has been widely studied for its various practical applications, including its use as an ornamental plant, fuelwood (with dry stems commonly burned for fire), fodder, green manure, biopesticide, living fence, and for marking boundaries (Ng'inja *et al.*, 1998; Otuma *et al.*, 1998). The leaves and flowers of *T. diversifolia* have been reported for high nutritional value, suggesting their potential as animal feed for livestock such as chickens, fish, goats, and cattle (Pathoummalangsy and Preston, 2008; Osuga *et al.*, 2012). While using *T. diversifolia* as cattle feed, the plant not only promotes weight gain but also enhances milk production (Premartane *et al.*, 1998; Wambui *et al.*, 2006; Buragohain, 2016; Katongole *et al.*, 2016; Wambui *et al.*, 2006). Interestingly, both fresh leaves and ash from *T. diversifolia* are applied to fields to repel pests like termites (Adoyo *et al.*, 1997). As green manure, however, *T. diversifolia* requires substantial labour input, making it more suitable for use in cultivating high-value crops such as tomatoes, kale, carrots, and maize (Jama *et al.*, 2000). Furthermore, the plant can form dense thickets that help reduce the impact of rainfall on the soil, thereby minimizing erosion (Ng'inja *et al.*, 1998).

While *T. diversifolia* offers numerous positive effects such as improving soil fertility, providing medicinal value, and supporting environmental sustainability its negative impacts, including potential invasiveness and competition with native species, cannot be ignored. However, these drawbacks should be carefully managed rather than used to dismiss its use, as the significant benefits of *T. diversifolia* can make it a valuable resource for livelihood either when properly controlled or in its initial phase of invasion (van Wilgen *et al.*, 2001). Present study is an ecological and socio-economic approach in relation to *T. diversifolia* belonging to disturbed urban forests of Aizawl, Mizoram, NE India.

CHAPTER – 3

METHODOLOGY

3. METHODOLOGY

STUDY AREA

Aizawl district, Mizoram, Northeast (NE) India was selected as a study area (Fig.1). Aizawl falls between 92°3' - 92°60' E and 21°58' - 24°85' N with the elevation varies from 800 m to 1188 m above the mean sea level (Kumar and Verma, 2009). This area lies in the Tropic of Cancer in northern part of Mizoram and is situated at the ridge 1132 meters (3715 ft) above sea level, with the Tlawng river valley to its west and the Tuirial river valley to its east. Further, Aizawl is bounded on the North by Kolasib District on the west by the Mamit District and on the East by Champhai District. The geographical area is 3576.31 sq.kms. The area has a mild climate with an average annual temperature 20.6⁰C and average annual rainfall 2560 mm (Colney and Nautiyal, 2013; Lodrick, 2022). The soils are young, immature and sandy, the texture of soil varies from sandy loam and clayey loam to clay (Kalita *et al.*, 2023). The state total forest cover is 17990.46 sq.kms which is 85.34% of the total geographical area (ISFR, 2023). The study area falls underlie Indo-Burma global biodiversity hotspot which is also falls in NE states of India (Syngkli *et al.*, 2024). This hotspot has number of species restricted in a particular area which are rare or threatened species that provide unique and irreplaceable roles within the ecosystem (Myers, 2000).

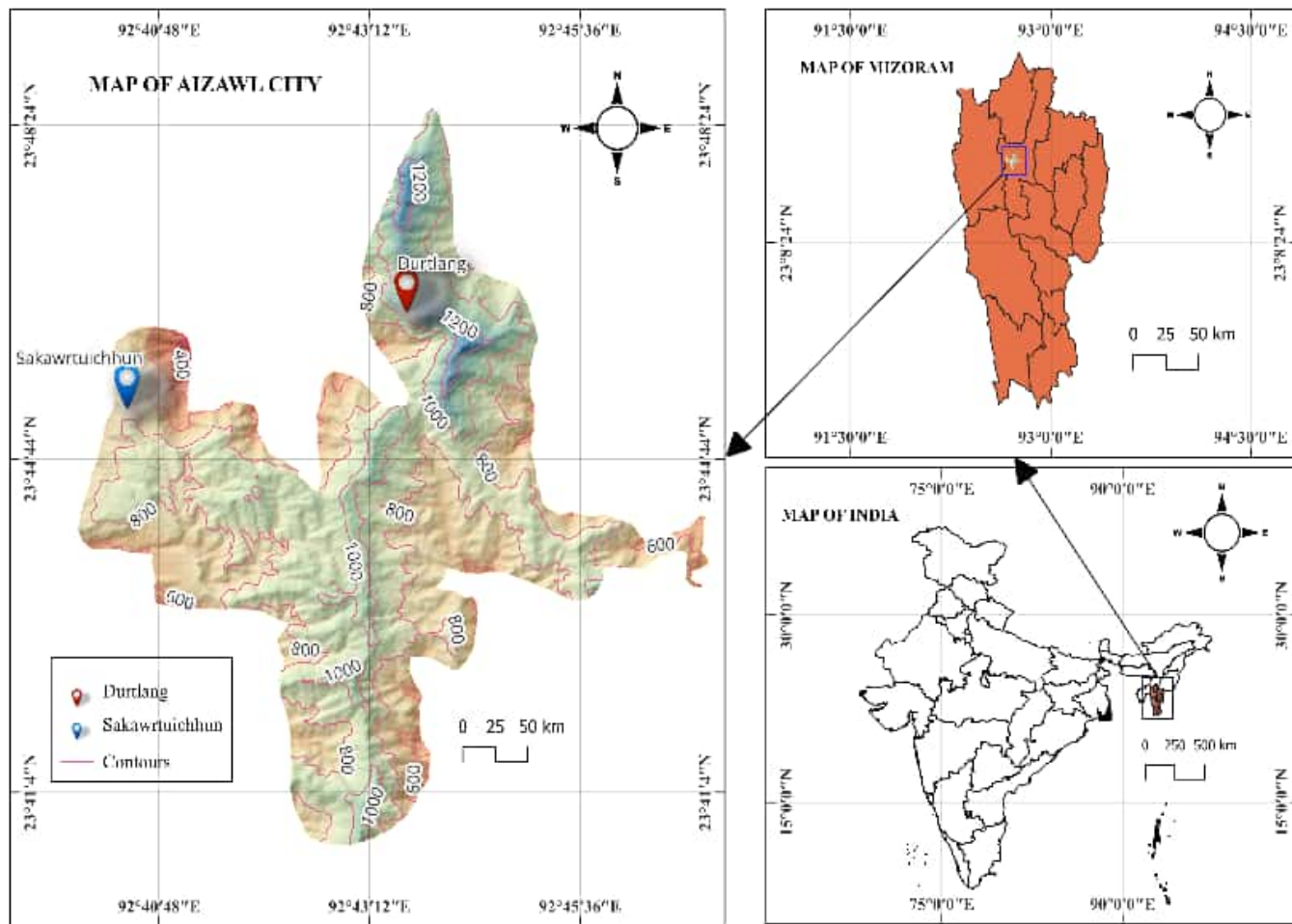


Fig. 1: Map of study site Aizawl, Mizoram, Northeast (NE) India, an Indo-Myanmar biodiversity hotspot region.

Rationale for site selection

For sampling, two different sites were chosen based on the varying disturbance intensity (i.e., disturbed and moderately disturbed site) which were evaluated in terms of assigning impact factors (Sagar *et al.*, 2003). The intensity of disturbances was measured in terms of natural and anthropogenic activities. Pertaining to the disturbed site, 0.96 sq.kms of Sakawrtuichhun was selected due to heavy anthropogenic activities like road construction, recreational centre, industries, factories, stone quarries, agricultural activities, and human habitation. The light intensity measured using a lux meter at this site was 115.67 ± 69.58 LUX. The temperature recorded at this site was $28 \pm 1^{\circ}\text{C}$. Preliminary spot testing of soil at selected sites was done, especially in the context of soil texture. In this respect, the results revealed that the texture of the disturbed soil was identified as loamy, consisting of 42.6% sand, 43.6% silt, and 13.8% clay.

Whereas, 1.36 sq.kms of Durtlang was selected as moderately disturbed site as human disturbance was less and there was more natural/undisturbed forest intact canopy. The light intensity measured using a lux meter at this site was 88.33 ± 13.58 LUX. The temperature recorded at this site was $25 \pm 3^{\circ}\text{C}$. The texture of the moderately disturbed soil was also classified as loamy, consisting of 38.4% sand, 45.2% silt, and 16.4% clay. Therefore, in relation to soil texture spot testing revealed slight differences which may also be linked to differential success of invasive alien plants. In this respect, the soil at disturbed site seems to be more porous due to high sand and low clay content, when compared with soil of moderately disturbed site. Henceforth, the disturbed site may be more ideal for storage and dispersal of soil seed bank of specific invasive alien plants.

Conversely, uninvaded site was not included in the study due to the highly urbanized nature of the sampling locations, which were subject to multiple anthropogenic disturbances such as road construction, traditional shifting cultivation (jhum), dense urban settlements, grazing, and stone quarrying. Based on the field observation, selected sites were ranked according to the degree of disturbance they experience from multiple anthropogenic perturbations (such as road, habitation,

agricultural land, stone quarries, recreational centre, industries, factories, and rockiness). Disturbance intensities were given impact factor ranged from 1 to 3 on each site in which impact factor 3 being the highest impact and 1 being the lowest. The field observations represent the entire range of conditions. For example, an impact factor of value 1 was assigned to the site that was farthest from the road, agricultural/mining land, market, and human settlements. The impact factor for the other sites was calculated based on their distance from the site with the lower impact factor. Additional implications were assessed through visual estimation (Table 1).

Table 1: Intensity of impact on disturbed and moderately disturbed site.

Source of impact	Relative impact	
	Disturbed site	Moderately disturbed site
Road	3	1
Agricultural land	3	1
Habitation	3	2
Stone quarries	3	1
Recreational centre	3	0
Industries	3	0
Factories	3	0
Rockiness	3	3
Total	24	8

3.1. Plant community characteristics

The interactions between invasive and native plant species in disturbed and moderately disturbed sites have been studied through methodologies which were frequently prescribed for vegetation analysis (Misra, 1968). In both the study site, 10 quadrats each of 5m x 5m and 1m x 1m for shrubs and herbs species respectively were laid out randomly with adequate caution to include common invasive and ruderal plants (Sakachep and Rai, 2025). In this context, quantitative/phytosociological parameters such as the percentage, frequency, density, and abundance of each species present in quadrats have been recorded and analysed 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.

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

a) Frequency (%): This term refers to the degree of dispersion of individual species in an area and usually expressed in terms of percentage occurrence. Frequency was studied by sampling the study area at several places at random and recorded the name of the species that occurred in each sampling units.

$$\text{Frequency (\%)} = \frac{\text{Number of quadrats in which species occurred}}{\text{Total number of quadrats studied}} \times 100$$

g) 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 place 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:

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

h) 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;

$$\text{Relative Density (RD)} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100$$

- i) **Relative Frequency:** The degree of dispersion of individual species in an area in relation to the number of all the species occurred.

$$\text{Relative Frequency (RF)} = \frac{\text{Frequency of a species}}{\text{Total frequency of all the species}} \times 100$$

- j) **Relative Abundance:** The number of individuals of different species in the community per unit area.

$$\text{Relative Abundance (RA)} = \frac{\text{Abundance of a species}}{\text{Total abundance of all the species}} \times 100$$

- k) **Importance Value Index (IVI):** IVI was used to express the dominance and ecological succession of any species. Species IVI will be computed by adding the figures of relative density, relative frequency and relative abundance for that species.

$$\text{IVI} = \text{Relative density (RD)} + \text{Relative frequency (RF)} + \text{Relative abundance (RA)}.$$

3.1.1. Measurement of diversity indices

- a) **Simpson Index of Dominance, D**

$$Cd = \sum_{i=0}^n p_i^2$$

Where,

p_i = proportion of individual in the i^{th} species.

As the Simpson's index values decreases, diversity increases. Simpson diversity index is therefore usually expressed as "1-D" (Simpson, 1949).

b) Sorenson's similarity index, β

$$\beta = \frac{2c}{S_1 + S_2}$$

Where,

S_1 = number of species in community 1.

S_2 = number of species in community 2.

c = number of species common to both communities (Sorensen, 1948).

c) Shannon-Weiner diversity index, H'

$$H' = - \sum_{i=1}^s p_i \ln p_i$$

Where,

H' = the Shannon-Weiner diversity index

P_i = the proportion of individuals in the i^{th} species i.e. n_i/N (Shannon and Weaver, 1949).

3.2. Analysis of physico-chemical properties of soil

For the analysis of soil physico-chemical properties, soil samples were collected for two years (i.e., 2023 and 2024) from disturbed and moderately disturbed sites at the depth of 0-15 cm where *T. diversifolia* was prevalent. With the help of tweezers and a gentle shake, rhizosphere dirt was extracted from the soil that was still attached to live roots (Hauchhum and Tripathi, 2019; Momin *et al.*, 2021). The bulk soil, which was not attached to roots and located in the central core, was collected separately for physicochemical analysis. The fresh soil samples were taken for analysing physicochemical (pH and soil moisture content) attributes. For other parameters (water holding capacity, soil organic carbon, soil organic matter, available nitrogen, available phosphorus, and available potassium), the soil samples were air-dried at room temperature (25-30 °C) and sieved with a 2 mm and 0.5 mm sieve (Kaur *et al.*, 2022; Kanjana *et al.*, 2024). Soil sampling was conducted across three seasons—

pre-monsoon, monsoon, and post-monsoon to assess seasonal or temporal changes in soil physicochemical properties. The temperature recorded at the disturbed site was ranged between 23-29°C while at moderately disturbed site it was recorded between 22-28°C, the soil samples were analyzed in triplicates for various physio-chemical parameters thereby revealing less variation. With the absence of a completely uninvaded site, moderately disturbed site was taken as a control or reference site for comparison since it has the less anthropogenic activities and invasive alien plants are mostly in establishment or early successional stages, unlike disturbed site.

3.2.1. Physical properties of soil

a) Soil moisture content

The moisture content of soil was determined by ‘oven dry method (Anderson and Ingram, 1994). For this, 10 g of freshly collected soil samples was kept in a hot air oven 105°C for 24 hours. The air-dried soils were then weighted and recorded. The percentage moisture content was calculated by the following formula.

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where,

W_1 = initial weight

W_2 = final weight

b) Water holding capacity (WHC)

Water holding capacity was determined by placing filter paper in a keen-box (perforated with holes of 0.75 mm diameter at the bottom) so as to cover the whole bottom of the box. The weight of the filter paper and the box were taken and designated as W_1 . 10g of the crushed dried soil sample were transferred inside the box and weight again designated as W_2 . The box containing soil was then placed in a petridish containing water and kept for overnight. The weight of the saturated soil was then weighted which was designated as W_3 . The Water Holding Capacity (WHC) was calculated using the formula:

$$\text{Water holding capacity (\%)} = \frac{W_3 - W_2}{W_2 - W_1} \times 100$$

Where,

W_1 = weight of box and filter paper

W_2 = weight of box, filter paper and soil

W_3 = weight of water absorbed

$W_2 - W_1$ = weight of soil

3.2.2. Chemical properties of soil

c) Soil pH

Soil pH was measured by mixing 10g of freshly soil sample and 50mL of distilled water and stirred for 20 minutes in a 100mL beaker using a magnetic stirrer. The solution was then kept overnight and the pH readings were taken using electronic digital pH meter.

d) Soil organic carbon (SOC)

Soil organic carbon was determined by rapid dichromate oxidation technique (Walkley and Black Method, 1934). The dried soil was grounded completely and sieved through 0.2mm (80 mesh) and 0.5g of the soil sample was taken in a dry conical flask. 10mL of 1N potassium dichromate solution was added, then 20mL concentrated sulphuric acid was added carefully and swirled for 2 - 3 times. The flask was allowed to stand for 30 minutes. 200mL of distilled water and 10mL ortho-phosphoric acid was added to get a sharper end point of the titration. After the addition of 1mL diphenylamine indicator, the content was titrated with 0.5N ferrous ammonium sulphate solutions till the colour flashes from blue-violet to green. Simultaneously, a blank was run without soil. The soil organic carbon is calculated by the following formula and expressed in percentage.

$$\text{a) Organic carbon (\%)} = \frac{10 (B-T)}{B} \times 0.003 \times \frac{100}{S}$$

Where,

B = Volume of ferrous ammonium sulphate required for blank titration in mL

T = Volume of ferrous ammonium sulphate needed for soil sample in mL

S = Weight of soil in gram

$$\text{b) Organic matter (\%)} = \% \text{ Organic carbon} \times 1.724$$

e) Available nitrogen

The available Nitrogen was determined by Kjeldahl method (Kjeldahl, 1883). For the analysis, 5g of air-dried soil sample was weighed and transfer to the digestion tube. The tube was loaded in distillation unit and on the other side 25mL of 0.32% KMnO_4 and 25mL of 2.5 % NaOH was added. 25mL of 2.5% boric acid was taken in a 250mL conical flask and kept in the receiver end of the machine. The collected distillate was then titrated against 0.02N H_2SO_4 till the colour turns pink. Blank titration (without soil) reaction was made for the final calculation. The burette readings were noted down and calculate the available Nitrogen by the following formula:

$$\text{Available Nitrogen} \left(\frac{\text{Kg}}{\text{ha}} \right) = \frac{14 \times N \times T \times 2.24 \times 10^6}{W \times 1000}$$

Where,

T= Titrant value burette reading

N= Normality of acid (0.02N H_2SO_4)

W= Weight of soil (g)

f) Available phosphorus

Available phosphorus was determined Oslen's method (Olsen *et al.*, 1954). The extract was prepared by “adding 2.5g of dried soil and 0.5g of Darco G-60 activated charcoal in 50mL of sodium bicarbonate solution in a flask was mixed and shake for 30 minutes with a suitable shaker. The suspension was filtered through Whatman filter paper No.40 to obtain clear filtrate. 5mL aliquot of the extract was taken in a

25mL volumetric flask and acidified with 5N H₂SO₄. A small quantity of distilled water was added to it and added 4mL of reagent B. The intensity of the blue colour is read on spectrophotometer at 660nm wavelengths after 10 minutes.

$$\text{Available phosphorus } \left(\frac{\text{Kg}}{\text{ha}} \right) = R \times \frac{V}{v} \times \frac{1}{S} \times \frac{(2.24 \times 10^6)}{10^6}$$

Where,

V = total volume of extractant (mL)

v = volume of aliquot taken for analysis (mL)

S = weight of soil (g)

R = weight of phosphorus in the aliquot in µg (from standard graph)

g) Available potassium

For available potassium, method devised by Biswas and Mukerjee (1985) was used. For analysis, 5g of dried soil was mixed with 25mL of neutral ammonium acetate solution (1:5) in 250mL conical flask. The solution containing soil was shaken in a beaker for 5 minutes and filtered immediately through a Whatman filter paper No.1. The first few drops of the filtrate was rejected. The potassium concentration in the extract was determined by flame photometer at K-filter and calculated according to the following formula:

$$\text{Available Potassium } \left(\frac{\text{Kg}}{\text{ha}} \right) = R \times \frac{V}{W} \times \frac{2.24 \times 10^6}{10^6}$$

Where,

V = Volume of the soil extract in mL

W = Weight of dry sample taken for extraction in gram

R = ppm of K in the extract (obtained from standard graph)

3.3. Allelochemic attributes of *T. diversifolia*

3.3.1. Plant debris-soil bioassay

The method adopted by Singh *et al.*, (2014) was adapted for plant debris-soil bioassay of *T. diversifolia*. Invaded soil of *T. diversifolia* was collected from disturbed and moderately disturbed sites. The experiment was conducted seasonally (i.e., pre-monsoon, monsoon, and post-monsoon) during the year 2023. The soil samples taken from disturbed and moderately disturbed sites were indicated as experimental pot 1 and 2 respectively while another control pot experiment was filled with healthy forest soil. The most commonly grown crop *P. sativum* L. (pea) was chosen for bioassay experiment due to its fast-growing attribute, simultaneous germination, and the seed homogeneity. A total of thirty seeds were sown (10 seeds in each pot) on control and in experimental pot 1 and 2. All the pots were provided with the same amount of sunlight and water. The number of seed germination was noted on the 3rd and 7th day of the pot experiment. All the plants were carefully examined at different time intervals in order to note the changes in morphology. 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 (SH)

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 7th days of incubation multiplied by 100 (Wang *et al.*, 2016).

$$GPe = \frac{\text{Number of seeds germinated on the 7}^{\text{th}} \text{ day}}{\text{Total number of seeds}} \times 100$$

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.

$$GPo = \frac{\text{Number of seeds germinated on the 3}^{\text{rd}} \text{ day}}{\text{Total number of seeds}}$$

f) Germination Index (GI)

It indicates the germination speed and vitality of seeds. It is calculated using the formula:

$$GI = \frac{\sum Gi}{I}$$

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 (Steinmaus *et al.*, 2000):

$$GRI = GPe \times GI$$

h) Vigor Index (VI)

It also indicates the germination speed and vitality of seeds. It is determined using the formula (Abdul-Baki and Anderson, 1973):

$$VI = GI \times BM$$

3.3.2. Analysis of allelopathic effects through fresh leaves aqueous extracts (FLE)

Collection of plant material

T. diversifolia is an invasive plant that grows in all parts of Mizoram (Rai and Vanlalruati, 2022). The leaves of *T. diversifolia* were collected from the roadside of invaded region and washed with clean water to remove dust. The clean fresh leaves were measured and prepared for aqueous extract using standard methodologies as per Syngkli and Rai (2024).

Preparation of fresh leaves aqueous extracts (FLE) of *T. diversifolia*

The method adopted by Ismail and Chong (2002) was adapted for the preparation of aqueous leaf extract of *T. diversifolia* with slight modification. The freshly collected leaves from the site were cut into small chips of about 4 cm length and soaked in conical flask containing 100 mL distilled water and agitated in a rotary shaker (Rotary Flask Shaker, Scientech, Science Enterprises, Delhi, India) at 140-150 RPM for 18 h at 27°C. The aqueous extract was then filtered through 2 layers of filter papers (Whatman No. 41) to remove solid materials and maintained it eventually into 4 concentrations (i.e., 50 mg/L, 37.5 mg/L, 25 mg/L, and 12.5 mg/L). Besides these concentrations of aqueous extracts, a control (distilled water) was used to compare the results.

Germination experiment

In this study, *P. sativum* (pea) was selected as a model assay crop to evaluate the allelopathic effects of *T. diversifolia* on soil. *P. sativum* is a popular crop and widely cultivated in both agricultural fields and home gardens across Mizoram due to its short growth cycle of 50–70 days. This characteristic makes it a preferred species for plant bioassay and ecotoxicological research (Kim *et al.*, 2022; Mobley *et al.*, 2022). Henceforth, the primary aim of this study was to examine the allelopathic influence of *T. diversifolia*-invaded soils on the growth performance of *P. sativum*, with potential implications for sustaining crop productivity in agricultural systems.

Ten seeds of *P. sativum* L. were kept in petri dishes containing 5 mL of different extract concentrations and control were added in petri dishes and covered with the filter papers. All experiments were done in triplicate. The petri dishes were covered and incubated B.O.D Incubator, at 30° C for 4 days. Ten seeds of test crop i.e., *P. sativum* were randomly selected and placed in each of oven dried petri dishes (90 x 15 mm) which have been lined with Whatman No. 41 filter paper. The filter paper served as an absorbent for fresh leaves aqueous extracts (FLE) or distilled water so as to keep the seed moistened always and avoid the imposition of water stress. Twelve petri dishes were moistened with 5 mL of different extract concentrations and three petri dishes were moistened with 5 mL distilled water which in fact served as a control. The petri dishes were incubated (in B.O.D Incubator), at 30° C for a time frame of 4 days. Emergence of 1 mm radicle was marked as the criterion for germination. The seed germination percentage, radicle length, plumule length, and biomass of the test crops were measured to compare the effects of *P. sativum* based leaf extracts in comparison to control.

3.3.3. Allelochemical analysis

a) Sample extractions

Allelochemical compounds from the leaves and flowers of *T. diversifolia* were extracted using a modified version of the traditional cold maceration solvent extraction technique, based on the method described by Handa *et al.*, (2008). The extraction was performed using a sample-to-solvent ratio of 10:100 (w/v). Specifically, 10 grams of fresh plant material were placed in a 250 mL stoppered Erlenmeyer flask containing 100 mL of 95% methanol. The mixture was kept at room temperature for 72 hours with intermittent stirring. After the maceration period, the solution was filtered through Whatman No. 1 filter paper (125 mm), and the filtrate was concentrated using a rotary evaporator (BUCHI Rotavapor R-300) to remove the solvent. This process yielded crude extracts from both the leaves and flowers.

b) Quantification of allelochemicals

i. Total phenolic content (TPC)

The total phenolic content was determined by using the Folin-Ciocalteu colorimetric method adopted by Ainsworth and Gillespie, (2007). Herein, 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. Spectrophotometer was used to determine the optical densities of the sample and standard solutions at 765 nm in a spectrophotometer. The phenol concentration was measured in terms of gallic acid equivalents (GAE) per gram of extracts, with gallic acid concentrations (10, 20, 40, 80, and 100 $\mu\text{g/mL}$) being selected as standard.

ii. Tannins

The total tannin content of the crude extract of *T. diversifolia* was determined by Folin-Ciocalteu method by Lahare *et al.*, (2021). The stock solution was prepared by adding 20 mL of methanol in 20 mg of crude extract. 0.1 mL of crude extract was taken out from the stock solution and dissolved by 7.5 mL of distilled water. 0.5 mL of Folin reagent and 1 mL of 35% (Na_2CO_3) were added to the mixture and diluted again with 10 mL of distilled water. The mixture is kept at room temperature for half an hour after being thoroughly mixed. Spectrophotometer was used to determine the optical densities of the sample and standard solutions at 725 nm. The tannin concentration was measured in terms of gallic acid equivalents (GAE) per gram of extracts, with gallic acid concentrations (10, 20, 40, 80, and 100 $\mu\text{g/mL}$) being selected as standard.

3.4. Socio-economic implications and management options of *T. diversifolia*

3.4.1. Socio-economic implication of *T. diversifolia*

The evaluation of the environmental and socio-economic impacts of *T. diversifolia* invasions, a field-based survey was conducted involving direct interactions with local communities. A total of 100 individuals were interviewed using semi-structured questionnaires, which allowed for both guided inquiry and the flexibility to explore emerging themes in respondent's answers. The study focused on understanding the perspectives of rural and indigenous people across selected districts of Mizoram, including Aizawl, Kolasib, Siahla, Serchhip, Saitual, Lawngtlai, Champhai, Hnahthial, Mamit, Lunglei, and Khawzawl. While the primary focus was on the periurban and urban forests of Aizawl, the capital district of Mizoram. However, capturing the socio-economic effects of *T. diversifolia* required the involvement of rural residents and farmers besides urban region of Aizawl. Therefore, this was the rationale behind extending the study area to adequately gather the societal perception of rural, periurban and urban people on the effects of *T. diversifolia*, especially in environmental and socio-economic (livelihood) sector.

During the interviews, respondents provided detailed insights into their perceptions and experiences regarding the presence and spread of *T. diversifolia*. The interviews captured information on a range of themes, including ecological changes, land use alterations, impacts on agriculture, local biodiversity, and effects on human and animal health. Socio-economic dimensions such as changes in livelihood, income, and resource availability were also explored. The responses were meticulously recorded in pre-designed questionnaire formats, enabling systematic data collection.

Following data collection, the recorded information was carefully reviewed, summarized, and processed for analysis and reference. Patterns, recurring concerns, and emerging narratives were identified to understand how the invasive species is influencing both the environment and the socio-economic fabric of affected communities.

This form of participatory research using community-based surveys proved to be an effective approach for capturing nuanced and localized knowledge. It offered valuable insights into the direct and indirect consequences of *T. diversifolia* invasion, highlighting the interconnectedness of ecological degradation and socio-economic vulnerability. As supported by previous researches, such qualitative and participatory assessments are essential for informing management strategies, raising awareness, and designing context-specific interventions to mitigate the impacts of invasive alien plants (Mukherjee, 2003; Witt *et al.*, 2019).

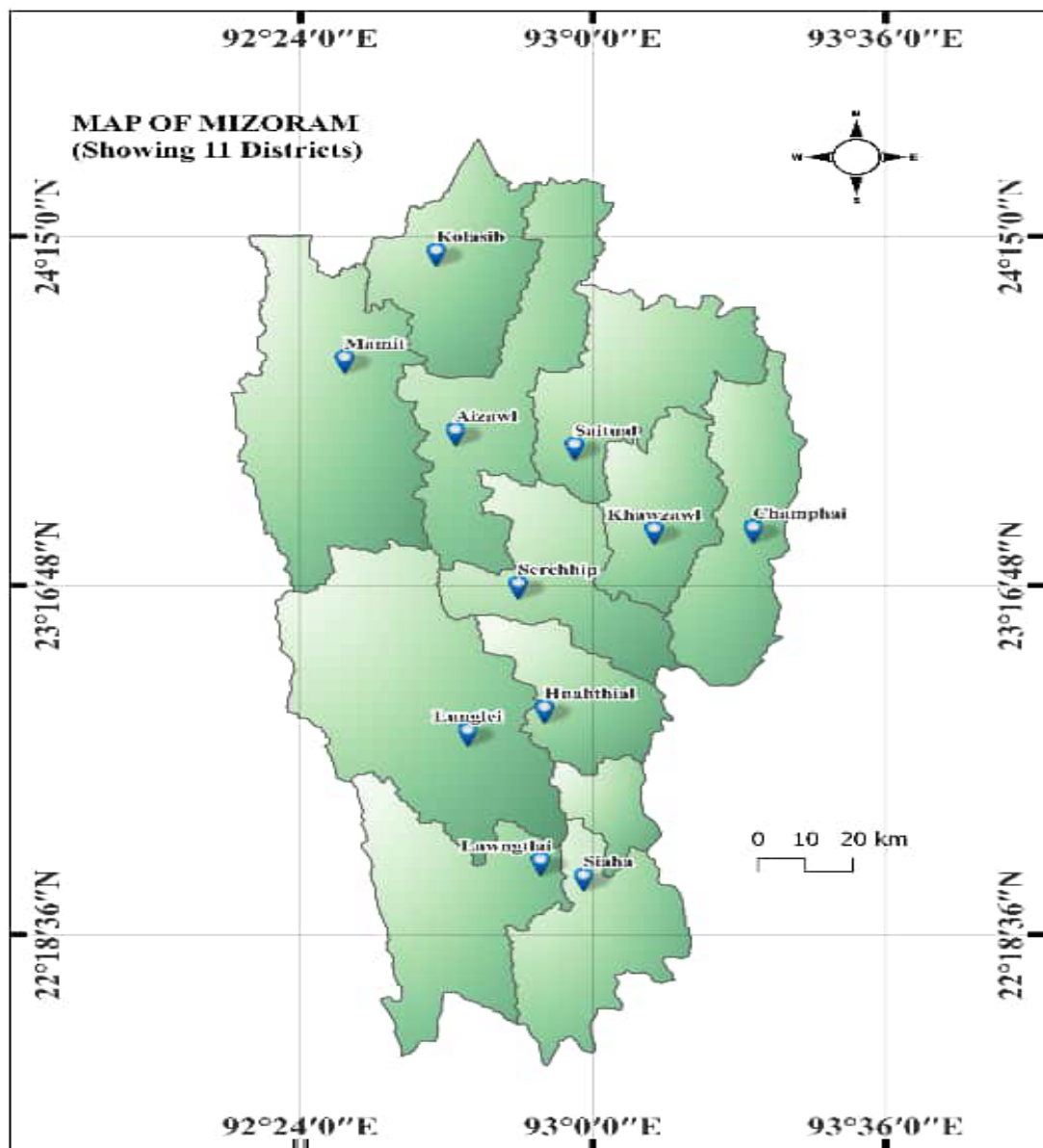


Fig. 2: Map showing questionnaire survey site in different districts of Mizoram.

3.4.2. Management implication of *T. diversifolia*

Canopy openness, leaf area index (LAI), and photosynthetically active radiation (PAR)

Canopy openness at the selected study sites were assessed using hemispherical photography combined with analysis through Gap Light Analyzer (GLA) software method, as devised by Sooraj *et al.*, (2020). In this respect, photographs were captured facing upward and perpendicular to the ground using a fisheye lens (Skyvik Signi One 10mm) attached to a smartphone. For each of ten designated areas, three replicate photos were taken on a cloudy day, with the best image from each set chosen for GLA analysis. Site coordinates and elevation data were recorded using a GPS device (Garmin GPSMAP 64s). The canopy openness (the gap in the foliar portion of canopy structure) was then evaluated using the selected images within the GLA software. Magnetic declination values required for configuration were obtained from the National Oceanic and Atmospheric Administration (NOAA) website. In addition, light intensity i.e., photosynthetically active radiation (PAR) (the solar radiation which serves as the primary energy source for biomass by regulating the photosynthetic rate and influencing plant growth) and leaf area index (LAI) (which is the total surface area of leaves per unit of ground area) were measured using a plant canopy analyzer (Integration of handheld and Software by Kaizen Imperial, and Quantum Sensors from Apogee Instruments, USA) at ten randomly chosen points per site. This canopy gap analysis aimed to understand habitat ecology and explore how such openings in the canopy might influence the proliferation of invasive alien plant species, potentially enhancing their allelopathic effects. The invasion rate was categorized as low, moderate, or high based on the level of canopy openness in the area. A low invasion rate ranged from 0 to 33.33%, moderate from 33.34% to 66.66%, and high from 66.67% to 100%.

CHAPTER – 4

RESULTS AND DISCUSSIONS

4. RESULTS

4.1. Plant community characteristics: The vegetative analysis during the study period documented 40 plant species at the disturbed site and 57 plant species at the moderately disturbed site. Both the study sites (i.e., disturbed and moderately disturbed sites) documented 55 herbs (i.e., 74%) and 19 shrubs (i.e., 26%) which belonged to 30 families (Fig. 3). To this end, Asteraceae was the most dominant family recorded from the study sites, followed by the family Poaceae (Fig. 4). Most of the species have a native place in Mexico, North, and South America. Out of 74 species documented from the study sites, 16 were among those invasive alien plants which were earlier listed by Sengupta and Dash (2020) in context of Mizoram Northeast (NE) India. These species were *Ageratina adenophora* (Spreng.) R.M.King & H.Rob., *Ageratum conyzoides* (L.) L., *Amaranthus spinosus* L., *Bidens pilosa* L., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Cosmos bipinnatus* Cav., *Crassocephalum crepidioides* (Benth.) S. Moore, *Erigeron canadensis* L., *Imperata cylindrica* (L.) P.Beauv, *Ipomoea cairica* (L.) Sweet, *Manihot esculenta* Crantz, *Mikania micrantha* Kunth, *Solanum torvum* Sw., *Spilanthes acmella* (L.) L., *Tithonia diversifolia* (Hemsl.) A. Gray, and *Urena lobata* L (Table. 2).

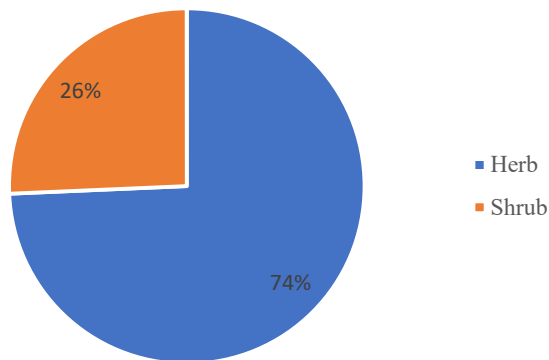


Fig. 3: Habitat composition of plants in percentage

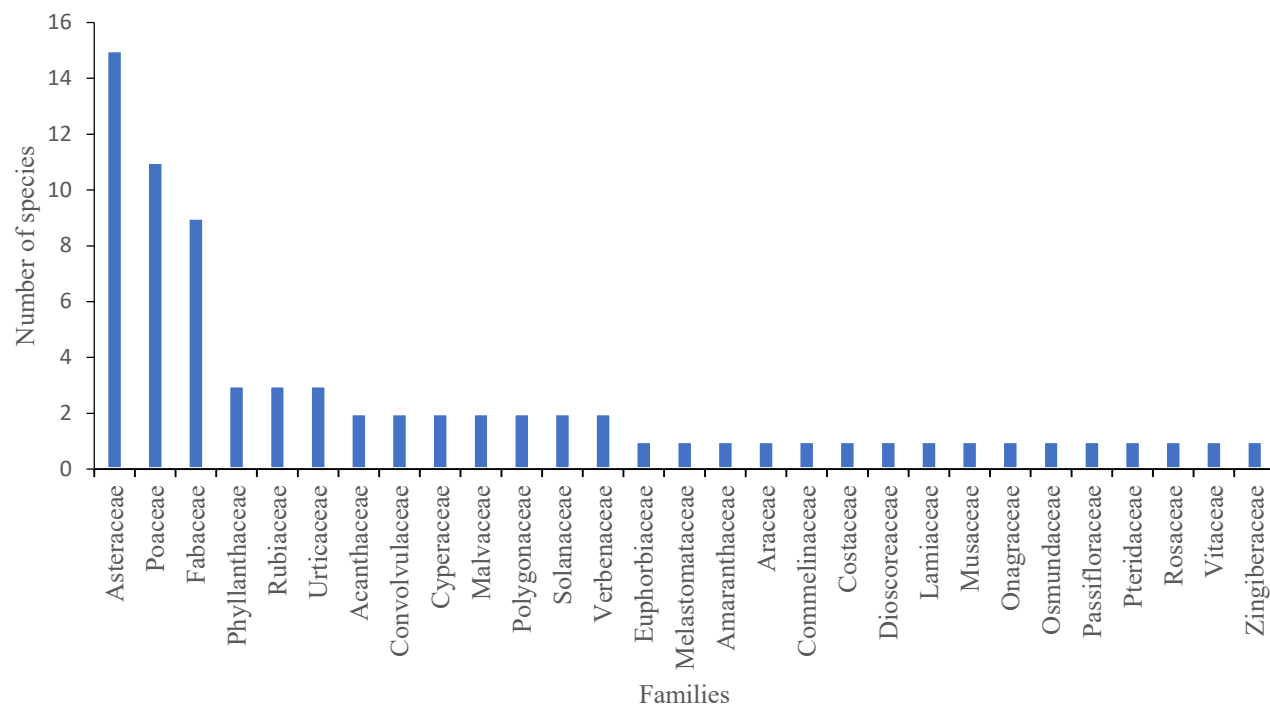


Fig. 4: Dominant families and their species composition in the study area i.e., Aizawl, Mizoram, Northeast (NE) India.

Table 2: List of the plant species in the study sites (i.e., Aizawl, Mizoram, Northeast (NE) India.) along with their family, habitat, and origin.

Sl No.	Name of species	Family	Habitat	Origin
1	<i>Adiantum pedatum</i> L.	Pteridaceae	Herb	North America (Chandrappa <i>et al.</i> , 2011)
2	<i>Ageratina adenophora</i> (Spreng.) R.M.King & H. Rob. *	Asteraceae	Herb	Mexico & Central America (Poudel <i>et al.</i> , 2020)
3	<i>Ageratum conyzoides</i> (L.) L. *	Asteraceae	Herb	Mexico, Central and North America (Wang <i>et al.</i> , 2024)
4	<i>Amaranthus spinosus</i> L. *	Amaranthaceae	Herb	Tropical America (Rengarajan <i>et al.</i> , 2025)
5	<i>Bidens pilosa</i> L. *	Asteraceae	Herb	Tropical America (Kato-Noguchi and Kurniadie, 2024)
6	<i>Boehmeria virgata</i> (G.Forst.) Guill.	Urticaceae	Herb	Tropical Africa and Asia (Arsul <i>et al.</i> , 2021)
7	<i>Bridelia tomentosa</i> Blume	Phyllanthaceae	Shrub	South China and South Asian countries (Chen <i>et al.</i> , 2021)
8	<i>Calliandra houstoniana</i> (Mill.) Standl.	Fabaceae	Shrub	Mexico and Central America (Arias and Macqueen, 1996)
9	<i>Calopogonium mucunoides</i> Desv.	Fabaceae	Herb	South America (Pizarro and Carvalho, 1997)
10	<i>Centratherum punctatum</i> Cass.	Asteraceae	Herb	Australia, Central and South America and West Indies (Talan <i>et al.</i> , 2023)
11	<i>Cheilocostus speciosus</i> (J.Konig) C.Specht	Costaceae	Herb	Southeast Asia (Benelli <i>et al.</i> , 2018)
12	<i>Chloris gayana</i> Kunth	Poaceae	Herb	Africa (Andama <i>et al.</i> , 2019)
13	<i>Chromolaena odorata</i> (L.) R.M. King & H. Rob. *	Asteraceae	Shrub	South and Central America (Akinmoladun <i>et al.</i> , 2007)
14	<i>Circaea lutetiana</i> L.	Onagraceae	Herb	Asia, Europe, and Africa (Iskakova <i>et al.</i> , 2025)

15	<i>Cissus discolor</i> Blume	Vitaceae	Herb	Tropical Asia (Joseph, 2020)
16	<i>Clerodendrum infortunatum</i> L.	Lamiaceae	Shrub	India, Thailand, Malaysia, Bangladesh and Sri Lanka (Prashith Kekuda <i>et al.</i> , 2019)
17	<i>Colocasia esculenta</i> (L.) Schott	Araceae	Herb	Southeast Asia (Guzzon <i>et al.</i> , 2025)
18	<i>Commelina benghalensis</i> L.	Commelinaceae	Herb	Asia and Africa (Kansagara and Pandya, 2019)
19	<i>Cosmos bipinnatus</i> Cav. *	Asteraceae	Herb	Mexico and Tropical America (Lutz and Piątek, 2016)
20	<i>Crassocephalum crepidioides</i> (Benth.) S. Moore*	Asteraceae	Herb	Tropical Africa (Schramm <i>et al.</i> , 2021)
21	<i>Curcuma longa</i> L.	Zingiberaceae	Herb	Tropical Asia (Aggarwal <i>et al.</i> , 2005)
22	<i>Cyperus rotundus</i> L.	Cyperaceae	Herb	India (Sivapalan, 2013)
23	<i>Cyperus strigosus</i> L.	Cyperaceae	Herb	North America (Stevanović <i>et al.</i> , 2004)
24	<i>Debregeasia longifolia</i> (Burm.f.) Wedd.	Urticaceae	Shrub	Southeast Asia (Almubayedh and Ahmad, 2019)
25	<i>Dendrolobium triangulare</i> Muell.Arg	Fabaceae	Shrub	Tropical Asia (Lock and Heald, 1994)
26	<i>Digitaria sanguinalis</i> (L.) Scop.	Poaceae	Herb	Europe (Jones <i>et al.</i> , 2021)
27	<i>Dioscorea bulbifera</i> L.	Dioscoreaceae	Herb	Tropical Asia and Sub-Saharan Africa (Niyas, 2015)
28	<i>Erechtites minimus</i> (Poir.)	Asteraceae	Herb	America and Australia (Coleman <i>et al.</i> , 2003)

29	<i>Erigeron canadensis</i> L.*	Asteraceae	Herb	North America (Beres <i>et al.</i> , 2018)
30	<i>Flueggea virosa</i> (Roxb. ex Willd.) Royle	Phyllanthaceae	Shrub	Africa, Asia and Australia (Bailly, 2024)
31	<i>Galinsoga parviflora</i> (Cav.)	Asteraceae	Herb	Central America (Damalas, 2008)
32	<i>Hypoestes phyllostachya</i> Baker	Acanthaceae	Shrub	South Africa, Madagascar and South East Asia (Rai <i>et al.</i> , 2022)
33	<i>Imperata cylindrica</i> (L.) P.Beauv.*	Poaceae	Herb	Southeast Asia and East Africa (Kato-Noguchi, 2022)
34	<i>Ipomoea cairica</i> (L.) Sweet*	Convolvulaceae	Herb	Tropical Asia and Africa (Choudhury <i>et al.</i> , 2015)
35	<i>Ipomoea hederifolia</i> L.	Convolvulaceae	Herb	Tropical America (Rao <i>et al.</i> , 2016)
36	<i>Koenigia polystachya</i> (Wall. ex Meisn.) T.M.Schust. &Reveal	Polygonaceae	Herb	Asia (Łazarski and Pliszko, 2023)
37	<i>Lantana camara</i> L.	Verbenaceae	Shrub	Central America (Rao <i>et al.</i> , 2016)
38	<i>Laportea canadensis</i> (L.) Wedd.	Urticaceae	Herb	North America (Sinville <i>et al.</i> , 2022)
39	<i>Leucaena leucocephala</i> (Lam.) de Wit	Fabaceae	Shrub	Mexico and Central America (Sharma <i>et al.</i> , 2022)
40	<i>Lolium perenne</i> L.	Poaceae	Herb	Europe, Middle East and North Africa (Hew <i>et al.</i> , 2020)
41	<i>Manihot esculenta</i> Crantz*	Euphorbiaceae	Shrub	Mexico and Central America (Hughes, 1998)
42	<i>Miconia crenata</i> (Vahl) Michelang	Melastomataceae	Shrub	Tropical America (Kumar and Rajendraprasad, 2025)
43	<i>Mikania micrantha</i> Kunth*	Asteraceae	Herb	South America (Sengupta and Dash, 2020)
44	<i>Mimosa pudica</i> L.	Fabaceae	Herb	Brazil (Muhammad <i>et al.</i> , 2016)

45	<i>Musa paradisiaca</i> L.	Musaceae	Herb	South East Asia (Vega-Rojas <i>et al.</i> , 2021)
46	<i>Mussaenda pubescens</i> Dryand	Rubiaceae	Shrub	China (Li <i>et al.</i> , 2010)
47	<i>Oplismenus hirtellus</i> (L.) P.Beauv	Poaceae	Herb	Southern Mexico, West Indies and South America (Hitchcock, 1920)
48	<i>Osmundastrum cinnamomeum</i> (L.) C.Persl	Osmundaceae	Herb	East Asia and America (Yu and Kim, 2024)
49	<i>Pachyrrhizus erosus</i> (L.) Urb.	Fabaceae	Herb	Mexico and Central America (Pati <i>et al.</i> , 2025)
50	<i>Paederia foetida</i> L.	Rubiaceae	Herb	India and Southeast Asia (Tan <i>et al.</i> , 2019)
51	<i>Panicum philadelphicum</i> Bernh. ex Trin.	Poaceae	Herb	North America (Steyermark and Schmoll, 1939)
52	<i>Panicum virgatum</i> L.	Poaceae	Herb	North America (Triplett <i>et al.</i> , 2012)
53	<i>Passiflora foetida</i> L.	Passifloraceae	Herb	Central and South America (Hopley <i>et al.</i> , 2021)
54	<i>Pennisetum purpureum</i> Schum.	Poaceae	Herb	Tropical Africa (Rao <i>et al.</i> , 2016)
55	<i>Persicaria lapathifolia</i> (L.) Delarbre	Polygonaceae	Herb	North Africa (Ayman <i>et al.</i> , 2024)
56	<i>Phyllanthus recticulatus</i> Poir.	Phyllanthaceae	Shrub	Tropical Asia (Hiremath <i>et al.</i> , 2024)
57	<i>Pueraria montana</i> (Lour.) Merr	Fabaceae	Herb	Tropical Asia (Heider <i>et al.</i> , 2007)
58	<i>Rubus moluccanus</i> L.	Rosaceae	Shrub	Asia and Australia (Ansari <i>et al.</i> , 2024)

59	<i>Setaria palmifolia</i> (J.Koenig) Stapf	Poaceae	Herb	Tropical Asia (Rao <i>et al.</i> , 2016)
60	<i>Sida rhombifolia</i> L.	Malvaceae	Shrub	Africa, India, and Southeast Asia (Rao <i>et al.</i> , 2016)
61	<i>Solanum nigrum</i> L.	Solanaceae	Herb	Southeast Asia (Chen <i>et al.</i> , 2022)
62	<i>Solanum torvum</i> Sw. *	Solanaceae	Shrub	West Indies (Rao <i>et al.</i> , 2016)
63	<i>Sorghum halepense</i> (L.) Pers.	Poaceae	Herb	Asia (Paterson <i>et al.</i> , 2020)
64	<i>Spermacoce latifolia</i> Aubl.	Rubiaceae	Herb	Tropical America (Rao <i>et al.</i> , 2016)
65	<i>Spilanthes acmella</i> (L.) L. *	Asteraceae	Herb	Brazil (Tiwari <i>et al.</i> , 2011)
66	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	Verbenaceae	Herb	Tropical and Subtropical America (Schapoval <i>et al.</i> , 1998)
67	<i>Strobilanthes capitata</i> (Nees) T.Anderson	Acanthaceae	Herb	India, Bhutan, Nepal, Myanmar, China, Thailand (Kladwong and Chantaranothai, 2024)
68	<i>Tagetes erecta</i> L.	Asteraceae	Herb	Mexico and Central America (Castillo-Pérez <i>et al.</i> , 2023)
69	<i>Tagetes patula</i> L.	Asteraceae	Herb	Mexico and Guatemala (New York Botanical Garden, 1905)
70	<i>Thysanolaena maxima</i> (Roxb. ex Hornem.) Honda	Poaceae	Herb	India, Pakistan, South-east Asia (Rao <i>et al.</i> , 2016)
71	<i>Tithonia diversifolia</i> (Hemsl.) A. Gray *	Asteraceae	Shrub	Mexico, Central and South America (Vanlalruati and Rai, 2021)
72	<i>Trifolium repens</i> L.	Fabaceae	Herb	Southeastern Europe and Southern Asia (Wang <i>et al.</i> , 2023)
73	<i>Urena lobata</i> L. *	Malvaceae	Shrub	Tropical Africa (Sengupta and Dash, 2020)
74	<i>Vigna unguiculata</i> L. Walp	Fabaceae	Herb	India (Rao <i>et al.</i> , 2016)

*= Listed among invasive alien plants in Mizoram (Source: Sengupta and Dash, 2020)

Density: The density at the disturbed site was calculated to be the highest in *T. diversifolia* (93.40) while least (i.e., 0.10) was calculated in case of several plants such as *C. crepidioides*, *D. longifolia*, and *M. pubescens* (Table 3). Whereas, at moderately disturbed site, the highest density was calculated in *T. diversifolia* (61.40) while least (i.e., 0.10) was calculated in case of several plants such as *C. discolor*, *C. speciosus*, *L. leucocephala*, *M. esculenta*, and *S. cayennensis* (Table 4).

Frequency: The frequency at the disturbed site, was calculated to be highest (i.e., 100%) in *T. diversifolia* and *M. micrantha* while least value (i.e., 10%) was calculated in case of several plants such as *C. mucunoides*, *C. punctatum*, *C. crepidioides*, *D. longifolia*, *G. parviflora*, *K. polystachya*, *L. camara*, *M. pubescens*, *P. erosus*, *P. foetida*, *P. lapathifolia*, *P. reticulatus*, *S. palmifolia*, *S. nigrum*, and *T. erecta* (Table 3). Whereas, at moderately disturbed site, the highest frequency was calculated in *T. diversifolia* (100%) while least (i.e., 10%) was calculated in case of several plants such as *A. pedatum*, *C. gayana*, *C. lutetiana*, *C. discolor*, *C. bipinnatus*, *C. longa*, *C. speciosus*, *I. cairica*, *L. canadensis*, *L. leucocephala*, *M. esculenta*, *M. pudica*, *M. paradisiaca*, *P. philadelphicum*, *P. virgatum*, *P. montana*, *S. cayennensis*, *S. capitata*, and *T. repens* (Table 4).

Abundance: The abundance at the disturbed site was calculated to be highest in *T. diversifolia* (93.40) while least (i.e., 1) was calculated in case of several plants such as *C. crepidioides*, *D. longifolia*, and *M. pubescens* (Table 3). Whereas, at moderately disturbed site, the highest abundance was calculated in case of *T. diversifolia* (61.40) while least (i.e., 1) was calculated in case of several plants such as *C. discolor*, *C. infortunatum*, *C. speciosus*, *L. leucocephala*, *M. esculenta*, and *S. cayennensis* (Table 4).

Relative Density: The relative density at the disturbed site was observed to be the highest in *T. diversifolia* (37.51) while least (i.e., 0.04) was calculated in case of several plants such as *C. crepidioides*, *D. longifolia*, and *M. pubescens* (Table 3). Whereas, at the moderately disturbed site, the highest relative density was calculated in case of *T. diversifolia* (23.93) while least (i.e., 0.04) was calculated in case of

several plants such as *C. discolor*, *C. speciosus*, *L. leucocephala*, *M. esculenta*, and *S. cayennensis* (Table 4).

Relative Frequency: The relative frequency at the disturbed site, was calculated to be the highest in *T. diversifolia* (8.33%) and *M. micrantha* (8.33%) while least (i.e., 0.83%) was calculated in case of several plants such as *C. mucunoides*, *C. punctatum*, *C. crepidioides*, *D. longifolia*, *G. parviflora*, *K. polystachya*, *L. camara*, *M. pubescens*, *P. erosus*, *P. foetida*, *P. lapathifolia*, *P. reticulatus*, *S. palmifolia*, *S. nigrum*, and *T. erecta* (Table 3). Whereas, at moderately disturbed site, the highest relative frequency was calculated in *T. diversifolia* (5.88%) while least (i.e., 0.59%) was calculated in case of several plants such as *A. pedatum*, *C. gayana*, *C. lutetiana*, *C. discolor*, *C. bipinnatus*, *C. longa*, *C. speciosus*, *I. cairica*, *L. canadensis*, *L. leucocephala*, *M. esculenta*, *M. pudica*, *M. paradisiaca*, *P. philadelphicum*, *P. virgatum*, *P. montana*, *S. cayennensis*, *S. capitata*, and *T. repens* (Table 4).

Relative Abundance: The relative abundance at the disturbed site, was calculated to be highest in *T. diversifolia* (17.77) while least (i.e., 0.19) was calculated in case of several plants such as *C. crepidioides*, *D. longifolia*, and *M. pubescens* (Table 3). Whereas, the highest relative abundance at moderately disturbed site, was calculated in *T. diversifolia* (7.57) while least (i.e., 0.12) was calculated in case of several plant such as *C. discolor*, *C. infortunatum*, *C. speciosus*, *L. leucocephala*, *M. esculenta*, and *S. cayennensis* (Table 4).

Importance Value Index (IVI): The highest IVI at the disturbed site was calculated in *T. diversifolia* (63.61) followed by *O. hirtellus* (24.66), and *M. micrantha* (24.37), while least (i.e., 1.06) was calculated in case of several plants such as *C. crepidioides*, *D. longifolia*, and *M. pubescens* (Table 3). Whereas, the highest IVI at moderately disturbed site was calculated in *T. diversifolia* (37.38) followed by *C. odorata* (14.55), and *M. micrantha* (14.19) while least (0.75) was calculated in case of several plant such as *C. discolor*, *C. speciosus*, *L. leucocephala*, *M. esculenta*, and *S. cayennensis*. Thus, the IVI of *T. diversifolia* was highest in both disturbed (63.61) and moderately disturbed site (37.38). The moderately disturbed site has higher IVI of *T. diversifolia* than the disturbed site (Table 4).

Previous studies also observed the influence of *T. diversifolia* on phytosociology of plants. For example, in assessing the diversity, abundance, and distribution of the Asteraceae family on Mount Lawu, *T. diversifolia* was reported to adversely impact on the IVI of native plants, thereby, marking it as one of the dominant species within the plant community (Sunarto *et al.*, 2016). Whereas, the ecological assessment of invasive alien plants in protected areas in Mizoram recorded the IVI of *T. diversifolia* to be 33.41% and 26.24% in Phawngpui national park and Lengteng wildlife sanctuary, respectively (Sengupta and Dash, 2020). Similarly, the present study found the IVI of *T. diversifolia* to be higher at both study sites than the IVI recorded in the protected area in Mizoram (Sengupta and Dash, 2020), but less than the IVI recorded in Mount Lawu (Sunarto *et al.*, 2016). Thus, in present vegetation analysis, *T. diversifolia* was observed to play a significant role in shaping plant community structure at both the study sites.

4.1.1 Diversity Indices

***Simpson Index of Dominance (D)*:** The Simpson index of dominance was higher in disturbed ($D = 0.17$) site than the moderately disturbed ($D = 0.08$) site. Whereas, Simpson diversity index was calculated by subtracting the dominance index from 1. The calculation showed that the moderately disturbed site (0.92) has higher diversity than the disturbed site (0.83). Thus, this result depicted the trend that as the Simpson dominance index values decreases, diversity increases (Table 5).

***Shannon-Weiner diversity index (H')*:** From the calculation, it was shown that the moderately disturbed site ($H' = 3.22$) has more plant diversity than disturbed site ($H' = 2.46$). As per the classification proposed by Fernando (1998), the Shannon-Weiner diversity index at both the sites were considered to be under low to high diversity ranged (Table 5). Thus, this index provides a measure of the level of species diversity within the studied area.

Sorenson's similarity index (β): It measures the similarity between plant communities at disturbed and moderately disturbed site. The value of Sorenson's similarity index between disturbed and moderately disturbed sites was $\beta= 0.47$ (Table 5). This Sorenson's similarity index highlights the changes in biodiversity patterns associated with disturbance intensity and emphasizes the importance of monitoring and managing anthropogenic impacts on plant communities (Kim *et al.*, 2025).

Table 3: Vegetative analysis at the disturbed site, Aizawl, Mizoram, Northeast (NE), India.

Sl No.	Name of species	Density	Frequency	Abundance	Relative density	Relative frequency	Relative abundance	IVI
1	<i>Tithonia diversifolia</i> (Hemsl.) A. Gray	93.40	100	93.40	37.51	8.33	17.77	63.61
2	<i>Ageratum conyzoides</i> (L.) L.	4.00	40	10.00	1.61	3.33	1.90	6.84
3	<i>Bidens pilosa</i> L.	2.90	30	9.67	1.16	2.50	1.84	5.50
4	<i>Calopogonium mucunoides</i> Desv.	2.50	10	25.00	1.00	0.83	4.76	6.59
5	<i>Centratherum punctatum</i> Cass.	0.20	10	2.00	0.08	0.83	0.38	1.29
6	<i>Chromolaena odorata</i> (L.) R.M. King & H. Rob.	12.30	80	15.38	4.94	6.67	2.92	14.53
7	<i>Commelina benghalensis</i> L.	1.60	30	5.33	0.64	2.50	1.01	4.16
8	<i>Crassocephalum crepidioides</i> (Benth.) S. Moore	0.10	10	1.00	0.04	0.83	0.19	1.06
9	<i>Debregeasia longifolia</i> (Burm.f.) Wedd.	0.10	10	1.00	0.04	0.83	0.19	1.06
10	<i>Dendrolobium triangulare</i> Muell.Arg	0.40	20	2.00	0.16	1.67	0.38	2.21
11	<i>Digitaria sanguinalis</i> (L.) Scop.	6.60	40	16.50	2.65	3.33	3.14	9.12
12	<i>Flueggea virosa</i> (Roxb. ex Willd.) Royle	1.40	40	3.50	0.56	3.33	0.67	4.56
13	<i>Galinsoga parviflora</i> (Cav.)	1.00	10	10.00	0.40	0.83	1.90	3.14
14	<i>Imperata cylindrica</i> (L.) P.Beauv.	2.40	30	8.00	0.96	2.50	1.52	4.99
15	<i>Ipomoea cairica</i> (L.) Sweet	7.70	30	25.67	3.09	2.50	4.88	10.47
16	<i>Koenigia polystachya</i> (Wall. ex Meisn.) T.M.Schust. &Reveal	1.00	10	10.00	0.40	0.83	1.90	3.14
17	<i>Lantana camara</i> L.	0.20	10	2.00	0.08	0.83	0.38	1.29
18	<i>Lolium perenne</i> L.	11.60	60	19.33	4.7	5.00	3.68	13.34
19	<i>Leucaena leucocephala</i> (Lam.) de Wit	1.00	40	2.50	0.40	3.33	0.48	4.21
20	<i>Mikania micrantha</i> Kunth	27.10	100	27.10	10.88	8.33	5.16	24.37
21	<i>Mimosa pudica</i> L.	8.30	70	11.86	3.33	5.83	2.26	11.42
22	<i>Mussaenda pubescens</i> Dryand	0.10	10	1.00	0.04	0.83	0.19	1.06

23	<i>Oplismenus hirtellus</i> (L.) P.Beauv	26.20	50	52.40	10.52	4.17	9.97	24.66
24	<i>Osmundastrum cinnamomeum</i> (L.) C.Persl	0.50	20	2.50	0.20	1.67	0.48	2.34
25	<i>Pachyrrhizus erosus</i> (L.) Urb.	1.30	10	13.00	0.52	0.83	2.47	3.83
26	<i>Paederia foetida</i> L.	0.40	10	4.00	0.16	0.83	0.76	1.75
27	<i>Panicum virgatum</i> L.	4.80	20	24.00	1.93	1.67	4.57	8.16
28	<i>Persicaria lapathifolia</i> (L.) Delarbre	0.50	10	5.00	0.20	0.83	0.95	1.99
29	<i>Passiflora foetida</i> L.	0.70	20	3.50	0.28	1.67	0.67	2.61
30	<i>Phyllanthus reticulatus</i> Poir.	1.00	10	10.00	0.40	0.83	1.90	3.14
31	<i>Pueraria montana</i> (Lour.) Merr	9.00	40	22.50	3.61	3.33	4.28	11.23
32	<i>Rubus moluccanus</i> L.	0.60	20	3.00	0.24	1.67	0.57	2.48
33	<i>Setaria palmifolia</i> (J.Koenig) Stapf	1.00	10	10.00	0.40	0.83	1.90	3.14
34	<i>Solanum nigrum</i> L.	0.20	10	2.00	0.08	0.83	0.38	1.29
35	<i>Solanum torvum</i> Sw.	1.50	30	5.00	0.60	2.50	0.95	4.05
36	<i>Sorghum halepense</i> (L.) Pers.	1.40	30	4.67	0.56	2.50	0.89	3.95
37	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	3.40	40	8.50	1.37	3.33	1.62	6.32
38	<i>Tagetes erecta</i> L.	2.00	10	20.00	0.80	0.83	3.80	5.44
39	<i>Thysanolaena maxima</i> (Roxb. ex Hornem.) Honda	5.40	20	27.00	2.17	1.67	5.14	8.97
40	<i>Urena lobata</i> L.	3.20	50	6.40	1.29	4.17	1.22	6.67

Table 4: Vegetative analysis at the moderately disturbed site, Aizawl, Mizoram, Northeast (NE), India.

SI No.	Name of species	Density	Frequency	Abundance	Relative density	Relative frequency	Relative abundance	IVI
1	<i>Tithonia diversifolia</i> (Hemsl.) A. Gray	61.40	100	61.40	23.93	5.88	7.57	37.38
2	<i>Adiantum pedatum</i> L.	2.00	10	20.00	0.78	0.59	2.46	3.83
3	<i>Ageratina adenophora</i> (Spreng.) R.M.King & H.Rob.	7.70	50	15.40	3.00	2.94	1.90	7.84
4	<i>Ageratum conyzoides</i> (L.) L.	7.10	50	14.20	2.77	2.94	1.75	7.46
5	<i>Amaranthus spinosus</i> L.	1.00	30	3.33	0.39	1.76	0.41	2.57
6	<i>Bidens pilosa</i> L.	12.00	70	17.14	4.68	4.12	2.11	10.91
7	<i>Boehmeria virgata</i> (G.Forst.) Guill.	3.50	30	11.67	1.36	1.76	1.44	4.57
8	<i>Bridelia tomentosa</i> Blume	0.30	20	1.50	0.12	1.18	0.18	1.48
9	<i>Calliandra houstoniana</i> (Mill.)Standl.	0.30	20	1.50	0.12	1.18	0.18	1.48
10	<i>Chloris gayana</i> Kunth	4.20	10	42.00	1.64	0.59	5.18	7.40
11	<i>Chromolaena odorata</i> (L.) R.M. King & H. Rob.	18.10	80	22.63	7.05	4.71	2.79	14.55
12	<i>Circaea lutetiana</i> L.	0.50	10	5.00	0.19	0.59	0.62	1.40
13	<i>Cissus discolor</i> Blume	0.10	10	1.00	0.04	0.59	0.12	0.75
14	<i>Clerodendrum infortunatum</i> L.	0.40	40	1.00	0.16	2.35	0.12	2.63
15	<i>Colocasia esculenta</i> (L.) Schott	0.40	30	1.33	0.16	1.76	0.16	2.08
16	<i>Commelina benghalensis</i> L.	3.20	50	6.40	1.25	2.94	0.79	4.98
17	<i>Cosmos bipinnatus</i> Cav.	4.80	10	48.00	1.87	0.59	5.92	8.37
18	<i>Curcuma longa</i> L.	0.60	10	6.00	0.23	0.59	0.74	1.56
19	<i>Cyperus rotundus</i> L.	9.00	40	22.50	3.51	2.35	2.77	8.63
20	<i>Cyperus strigosus</i> L.	2.40	40	6.00	0.94	2.35	0.74	4.03
21	<i>Dioscorea bulbifera</i> L.	1.20	20	6.00	0.47	1.18	0.74	2.38
22	<i>Erechtites minimus</i> (Poir.)	1.60	40	4.00	0.62	2.35	0.49	3.47

23	<i>Erigeron canadensis</i> L.	1.50	30	5.00	0.58	1.76	0.62	2.97
24	<i>Flueggea virosa</i> (Roxb. ex Willd.) Royle	1.20	20	6.00	0.47	1.18	0.74	2.38
25	<i>Galinsoga parviflora</i> (Cav.)	9.20	40	23.00	3.59	2.35	2.83	8.77
26	<i>Cheilocostus speciosus</i> (J.Konig) C.Specht	0.10	10	1.00	0.04	0.59	0.12	0.75
27	<i>Hypoestes phyllostachya</i> Baker	8.50	20	42.50	3.31	1.18	5.24	9.73
28	<i>Ipomoea cairica</i> (L.) Sweet	4.00	10	40.00	1.56	0.59	4.93	7.08
29	<i>Ipomoea hederifolia</i> L.	9.50	50	19.00	3.70	2.94	2.34	8.99
30	<i>Lantana camara</i> L.	1.90	20	9.50	0.74	1.18	1.17	3.09
31	<i>Laportea canadensis</i> (L.) Wedd.	4.80	10	48.00	1.87	0.59	5.92	8.37
32	<i>Leucaena leucocephala</i> (Lam.) de Wit	0.10	10	1.00	0.04	0.59	0.12	0.75
33	<i>Manihot esculenta</i> Crantz	0.10	10	1.00	0.04	0.59	0.12	0.75
34	<i>Miconia crenata</i> (Vahl) Michelang	4.90	40	12.25	1.91	2.35	1.51	5.77
35	<i>Mikania micrantha</i> Kunth	16.90	90	18.78	6.59	5.29	2.31	14.19
36	<i>Mimosa pudica</i> L.	2.60	10	26.00	1.01	0.59	3.20	4.81
37	<i>Musa paradisiaca</i> L.	0.20	10	2.00	0.08	0.59	0.25	0.91
38	<i>Oplismenus hirtellus</i> (L.) P.Beauv	3.40	20	17.00	1.33	1.18	2.10	4.60
39	<i>Osmundastrum cinnamomeum</i> (L.) C.Persl	2.30	40	5.75	0.90	2.35	0.71	3.96
40	<i>Panicum philadelphicum</i> Bernh. ex Trin.	4.40	10	44.00	1.71	0.59	5.42	7.73
41	<i>Panicum virgatum</i> L.	1.10	10	11.00	0.43	0.59	1.36	2.37
42	<i>Pennisetum purpureum</i> Schum.	2.20	30	7.33	0.86	1.76	0.90	3.53
43	<i>Pueraria montana</i> (Lour.) Merr	1.00	10	10.00	0.39	0.59	1.23	2.21
44	<i>Setaria palmifolia</i> (J.Koenig) Stapf	4.40	40	11.00	1.71	2.35	1.36	5.42
45	<i>Sida rhombifolia</i> L.	5.00	30	16.67	1.95	1.76	2.05	5.77
46	<i>Solanum nigrum</i> L.	0.50	30	1.67	0.19	1.76	0.21	2.16
47	<i>Solanum torvum</i> Sw.	0.70	20	3.50	0.27	1.18	0.43	1.88
48	<i>Sorghum halepense</i> (L.) Pers.	3.80	30	12.67	1.48	1.76	1.56	4.81
49	<i>Spermacoce latifolia</i> Aubl.	4.50	30	15.00	1.75	1.76	1.85	5.37

50	<i>Spilanthes acmella</i> (L.) L.	0.90	30	3.00	0.35	1.76	0.37	2.49
51	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	0.10	10	1.00	0.04	0.59	0.12	0.75
52	<i>Strobilanthes capitata</i> (Nees) T.Anderson	1.00	10	10.00	0.39	0.59	1.23	2.21
53	<i>Tagetes patula</i> L.	1.60	40	4.00	0.62	2.35	0.49	3.47
54	<i>Thysanolaena maxima</i> (Roxb. ex Hornem.) Honda	3.00	50	6.00	1.17	2.94	0.74	4.85
55	<i>Trifolium repens</i> L.	5.00	10	50.00	1.95	0.59	6.16	8.70
56	<i>Urena lobata</i> L.	3.10	50	6.20	1.21	2.94	0.76	4.91
57	<i>Vigna unguiculata</i> L. Walp	1.30	50	2.60	0.51	2.94	0.32	3.77

Table 5: Simpson Index of Dominance, Simpson Diversity Index, Shannon- Weiner diversity index, and Sorenson's similarity index in disturbed, and moderately disturbed sites, Aizawl, Mizoram, Northeast (NE), India.

Sites	Disturbed	Moderately Disturbed
Simpson Index of Dominance	0.17	0.08
Simpson Diversity Index	0.83	0.92
Shannon-Weiner diversity index	2.46	3.22
Sorenson's similarity index	0.47	

4.2. Soil analysis

Soil moisture content: Soil moisture content at the disturbed site ranged from 4.93 ± 0.19 % to 17.86 ± 2.36 % whereas at the moderately disturbed site, the value of soil moisture content in soil ranged from 8.50 ± 0.36 % to 26.90 ± 4.42 % (Table 6). During monsoon, both the disturbed and moderately disturbed site has highest soil moisture content, as compared to the other seasons (Fig. 5). In another study conducted by Agbede *et al.*, (2013) soil moisture content of *T. diversifolia* was recorded between the ranged of 12.6% to 14.8%. Thus, the present study aligns with is past study performed by Agbede *et al.*, (2013).

At the disturbed site, the moisture content demonstrated highly positive significant correlation with available phosphorus ($r= 0.830$) (Appendix III). Meanwhile, at the moderately disturbed site, soil moisture content demonstrated positive significant correlation with SOC ($r= 0.541$) and SOM ($r= 0.540$), whereas, negative significant correlation with pH ($r= -0.691$) and available nitrogen ($r= -0.522$) (Appendix IV). Further, the two-way ANOVA revealed that soil moisture content recorded to have significant variation between the seasons ($F_{1,11}= 14.42985$; $p< 0.012646$) (Appendix V).

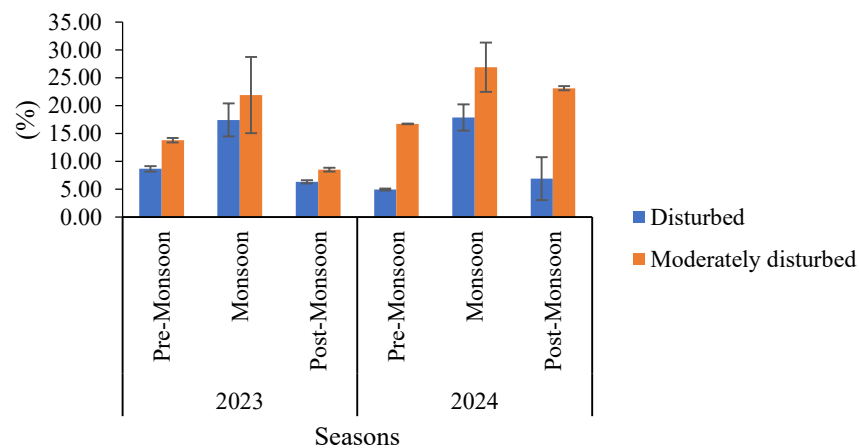


Fig. 5: Seasonal variation of soil moisture (%) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Water holding capacity (WHC): The percentage of WHC of soil at the disturbed site ranged from 49.10 ± 9.64 % to 71.37 ± 1.71 % whereas at moderately disturbed site the value of WHC ranged from 51.03 ± 2.91 % to 90.73 ± 2.95 % (Table 6). Mostly, during monsoon season, the soil WHC was more and there was a slight increase at moderately disturbed site even during pre-monsoon (i.e. 90.73 ± 2.95 %) (Fig. 6). According to Hafifah *et al.* (2016), the recorded WHC was 39.80 % which was lower as compared to the findings of the current study. This difference may be attributed to variations in soil texture, organic matter content, or land management practices between the two study sites.

At the disturbed site, the WHC has demonstrated negative significant correlation with SOC ($r = -0.704$), SOM ($r = -0.662$) and available nitrogen ($r = -0.576$) (Appendix III). Further, the two-way ANOVA revealed that WHC has significant variation between the seasons ($F_{1,11} = 9.054858$; $p < 0.029785$) and the sites ($F_{5,11} = 5.4396058$; $p < 0.0433$) (Appendix VI).

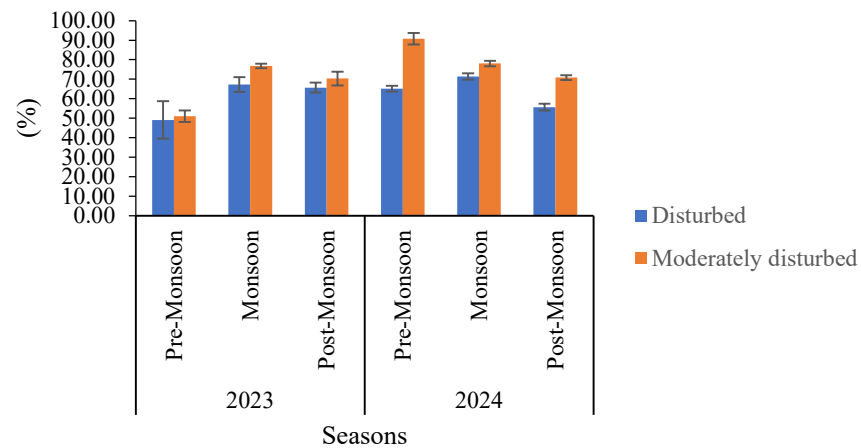


Fig. 6: Seasonal variation of soil water holding capacity (%) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

In addition to WHC, preliminary spot testing of soil at selected sites was done, especially in the context of soil texture. However, due to site specific constraints, such as the abundance of invasive alien plants at rock-soil/sediments boundaries, it was difficult to analyse texture, porosity, and bulk density in long term. Moreover, the present work was focused more towards the chemical parameters, therefore major parameters were selected from this corner to describe the soil chemistry. In respect of spot testing of physical characteristics, the results revealed that the texture of the disturbed soil was identified as loamy, consisting of 42.6% sand, 43.6% silt, and 13.8% clay.

The texture at the moderately disturbed soil was also classified as loamy, consisting of 38.4% sand, 45.2% silt, and 16.4% clay. Therefore, in relation to soil texture, spot testing revealed slight differences, which may also be linked to differential success of invasive alien plants. In this respect, the soil at disturbed site seems to be more porous due to high sand and low clay content, when compared with soil of moderately disturbed site. Henceforth, the disturbed site may be more ideal for storage and dispersal of soil seed bank of specific invasive alien plants including *T. diversifolia*

Soil pH: Soil samples at both the study sites were mostly observed acidic in nature. At the disturbed site, the pH of the soil ranged from 6.17 ± 0.04 to 6.84 ± 0.05 whereas, at moderately disturbed site, the pH of the soil ranged from 6.02 ± 0.74 to 6.78 ± 0.04 (Table 6). The soil pH generally decreased during post-monsoon season (Fig. 7). This may be attributed to leaching of basic nutrients caused by heavy rainfall during monsoon. Other findings also found pH of *T. diversifolia* soil to be 7.44 at invaded site and 5.42 at uninvaded site (Oludare and Muoghalu, 2014).

At the disturbed site, pH demonstrated highly negative significant correlation with available potassium ($r = -0.890$) (Appendix III). Meanwhile, at the moderately disturbed site, pH demonstrated highly negative significant correlation with SOC ($r = -0.879$) and SOM ($r = -0.880$). Also, pH has negative significant correlation with soil moisture ($r = -0.691$) (Appendix IV).

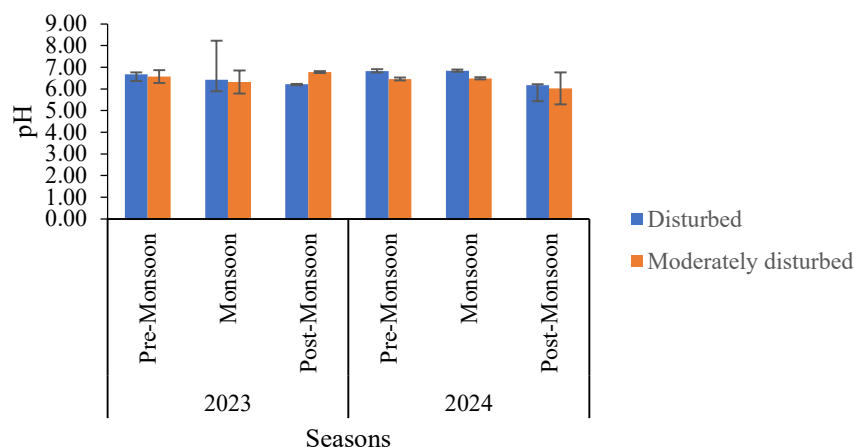


Fig. 7: Seasonal variation of soil pH along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Soil organic carbon (SOC): The SOC content at the disturbed site ranged from 0.14 ± 0.02 % to 1.35 ± 0.49 % whereas, at moderately disturbed site SOC ranged from 0.62 ± 0.52 % to 3.48 ± 1.42 % (Table 6). In 2023, the SOC content was highest during pre-monsoon season in both the sites. On the contrary, in 2024, the SOC content was highest during post-monsoon season at both the selected sites (Fig. 8). This may be due to abundant organic input, slow decomposition, and management practices at the study sites along the disturbance. In the study conducted by Agbede (2025), the SOC recorded was found to be 0.96 % which was at the same ranged of the SOC recorded on the present study.

At the disturbed site SOC demonstrated highly positive significant correlation with SOM ($r= 0.993$), positive significant correlation with available nitrogen ($r= 0.617$) while negative significant correlation WHC ($r= -0.704$) (Appendix III). Meanwhile, at the moderately disturbed site, SOC demonstrated highly positive significant correlation with SOM ($r= 1.000$) while highly negative significant correlation with pH ($r= -0.879$) (Appendix IV). Further, the two-way ANOVA revealed that SOC has recorded to have significant variation between the seasons ($F_{1,11}= 11.35477; p< 0.019897$) (Appendix VIII).

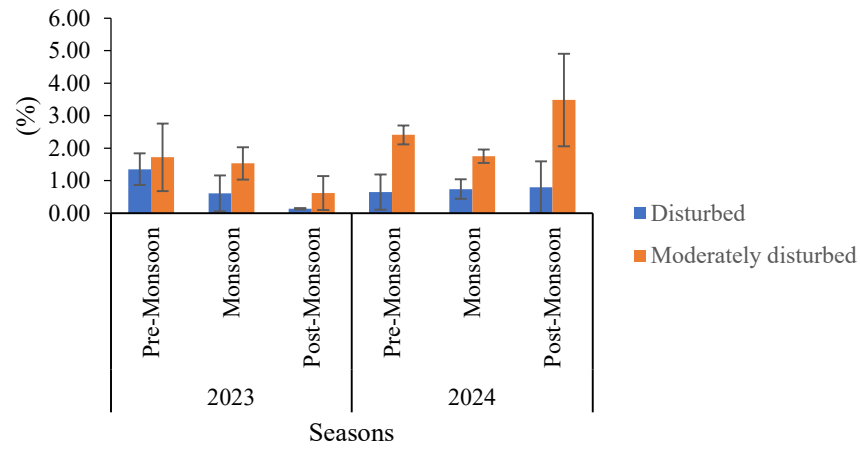


Fig. 8: Seasonal variation of soil organic carbon (%) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Soil organic matter (SOM): The SOM at the disturbed site was ranged from 0.24 ± 0.02 % to 2.33 ± 0.49 % whereas, at moderately disturbed site SOM ranged from 1.07 ± 0.52 % to 6.00 ± 1.42 % (Table 6). In 2023, the SOM was highest during pre-monsoon season in both the sites. Contrastingly, in 2024, the SOM was highest during post-monsoon season at both the sites (Fig. 9).

At the disturbed site, SOM has significant correlation with available nitrogen ($r = 0.666$) and highly positive significant correlation with SOC ($r = 0.993$) while negative significant correlation with WHC ($r = -0.662$) (Appendix III). Meanwhile, at the moderately disturbed site, SOM demonstrated highly positive significant correlation with SOC ($r = 1.000$), while highly negative significant correlation with pH ($r = -0.880$) and significant correlation with soil moisture content ($r = 0.540$) (Appendix IV). Further, the two-way ANOVA revealed that SOM has recorded to have significant variation between the seasons ($F_{1,11} = 10.75673$; $p < 0.021961$) (Appendix IX).

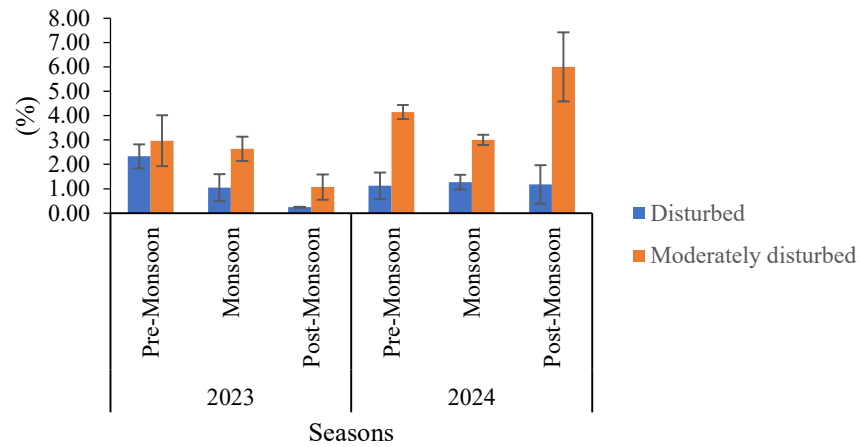


Fig. 9: Seasonal variation of soil organic matter (%) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Available nitrogen: The available nitrogen of soil at the disturbed site ranged from 99.93 ± 36.21 kg/ha to 289 ± 0.00 kg/ha. Whereas, at moderately disturbed site available nitrogen ranged from 16.31 ± 0.00 kg/ha to 398 ± 25 kg/ha (Table 6). As per the soil fertility rating adopted by Satish *et al.* (2018), the available nitrogen found in both the study sites was under low to moderate range. In 2024, the available nitrogen during monsoon season was quite low at both disturbed (99.93 ± 36.21 kg/ha) and moderately disturbed (16.31 ± 0.00 kg/ha) site (Fig. 10).

Previous study in Kenya showed that when *T. diversifolia* was used as a green manure, the available nitrogen was found to 32 kg/ha (Jama *et al.*, 2000). Comparing this outcome with the present study revealed that the available nitrogen was much higher than that in Kenya. This may be due to several environmental and biological factors that affect *T. diversifolia* presence and mobility in the soil.

At the disturbed site, available nitrogen demonstrated positive significant correlation with SOC ($r = 0.617$) and SOM ($r = 0.666$) while negative significant correlation with WHC ($r = -0.576$) (Appendix III). Meanwhile, at the moderately disturbed site, available nitrogen demonstrated negative significant correlation with soil moisture content ($r = -0.522$) (Appendix IV). Further, the two-way ANOVA revealed that available nitrogen has recorded to have significant variation between the sites ($F_{5,11} = 6.540776; p < 0.029977$) (Appendix X).

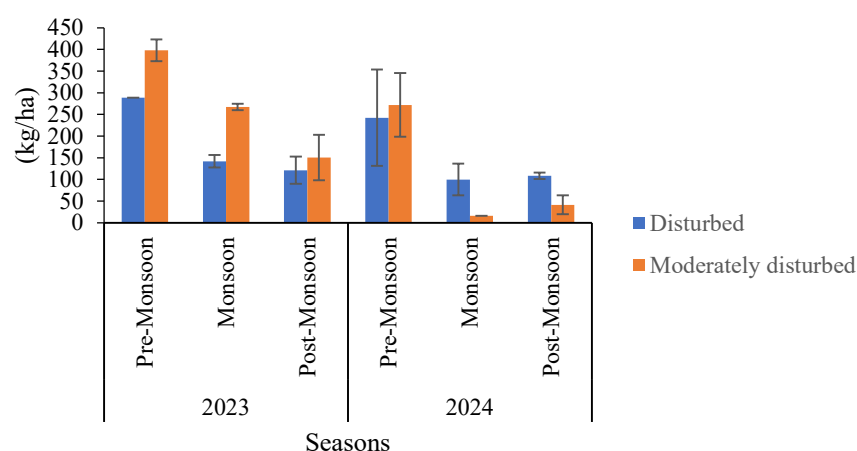


Fig. 10: Seasonal variation of available soil nitrogen (kg/ha) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Available Phosphorus: The soil available phosphorus at the disturbed site ranged from 9.42 ± 1.41 kg/ha to 29.97 ± 3.92 kg/ha. Whereas, moderately disturbed site available phosphorus ranged from 11.11 ± 3.39 kg/ha to 34.22 ± 4.10 kg/ha (Table 6). As per the soil fertility rating adopted by Satish *et al.* (2018), the available phosphorus found in both the study sites underlie in the lower range. Although, available phosphorus was low at both the sites, the moderately disturbed site has recorded more available phosphorus content than the disturbed site (Fig. 11). Mostly, the available phosphorus content of *T. diversifolia* was low which align with the findings of the study conducted by Hafifah *et al.* (2016) when *T. diversifolia* was used as green manure for improving soil.

At the disturbed site available phosphorus has demonstrated highly positive significant correlation with soil moisture content ($r= 0.830$) (Appendix III). Meanwhile, at the moderately disturbed site, available phosphorus demonstrated negative significant correlation with available potassium ($r= -0.703$) (Appendix IV). Further, the two-way ANOVA revealed that available phosphorus has recorded to have significant variation between the seasons ($F_{1,11}= 6.665269$; $p< 0.049329$) (Appendix XI).

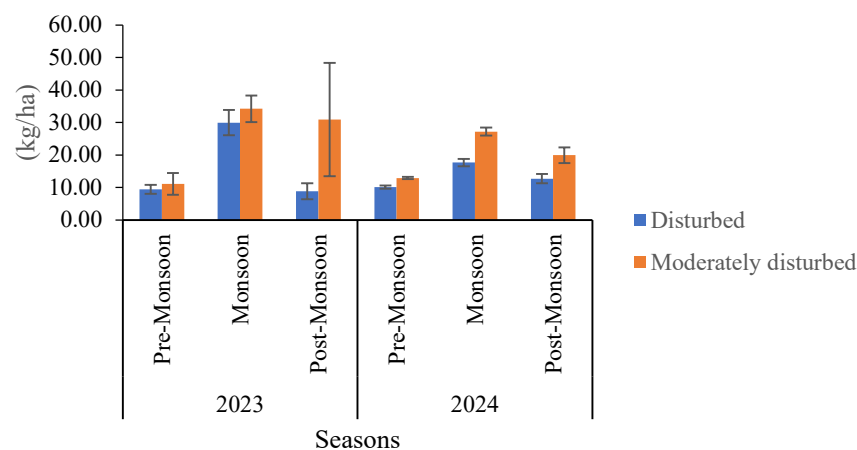


Fig. 11: Seasonal variation of soil available phosphorus (kg/ha) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Available potassium: The soil available potassium at the disturbed site ranged from 51.73 ± 4.14 kg/ha to 320.67 ± 50.06 kg/ha. Whereas, at moderately disturbed site available potassium ranged from 221.33 ± 18.88 kg/ha to 518.93 ± 17.11 kg/ha (Table 6). Although, there was an abrupt decline in potassium content at disturbed site during monsoon season (i.e., in 2024), the rest was noted under moderate to high range at both the sites (Satish *et al.*, 2018). The moderately disturbed site has more soil available potassium than the disturbed site (Fig. 12). Also, another study by Agbede *et al.* (2013), recorded available potassium of *T. diversifolia* in the range of 98.87 kg/ha to 213.49 kg/ha, which is lower than the present results.

At the disturbed site, available potassium has demonstrated highly negative significant correlation with soil pH ($r = -0.890$) (Appendix III). Meanwhile, at the moderately disturbed site, available potassium demonstrated highly negative significant correlation with available phosphorus ($r = -0.703$) (Appendix IV). Further, the two-way ANOVA revealed that available potassium has recorded to have significant variation between the seasons ($F_{1,11} = 13.06169$; $p < 0.015314$) (Appendix XII).

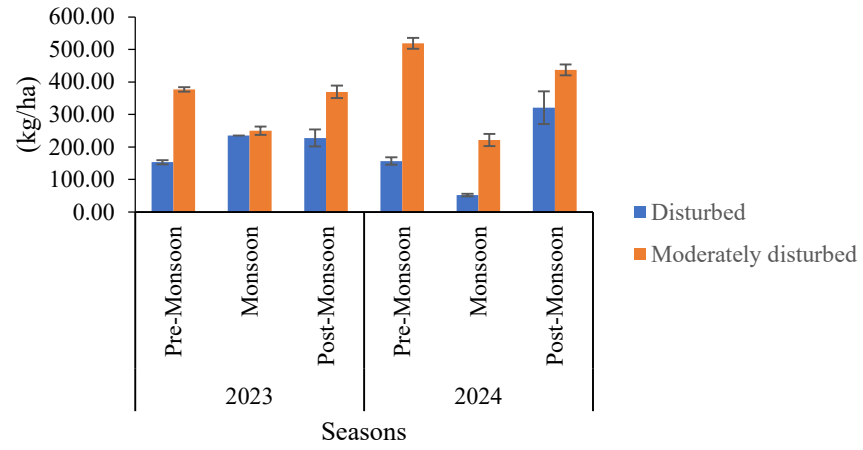


Fig. 12: Seasonal variation of soil available potassium (kg/ha) along the disturbance gradient, Aizawl, Mizoram, Northeast (NE), India.

Table 6: The overall seasonal variation of soil parameters along the disturbance gradient (2023-2024) in Aizawl, Mizoram, Northeast (NE), India.

Sl. No	Parameters	Sites	2023			2024		
			Pre-Monsoon	Monsoon	Post-Monsoon	Pre-Monsoon	Monsoon	Post-Monsoon
1	Soil moisture content (%)	Disturbed	8.66 ± 0.49	17.42 ± 2.96	6.31 ± 0.28	4.93 ± 0.19	17.86 ± 2.36	6.89 ± 3.84
		Moderately disturbed	13.77 ± 0.39	21.87 ± 6.82	8.50 ± 0.36	16.73 ± 0.06	26.90 ± 4.42	23.10 ± 0.38
2	WHC (%)	Disturbed	49.10 ± 9.64	67.27 ± 3.76	65.70 ± 2.51	65.20 ± 1.47	71.37 ± 1.71	55.67 ± 1.68
		Moderately disturbed	51.03 ± 2.91	76.80 ± 1.10	70.33 ± 3.52	90.73 ± 2.95	78.07 ± 1.40	70.83 ± 1.21
3	pH	Disturbed	6.67 ± 0.09	6.42 ± 1.81	6.22 ± 0.01	6.83 ± 0.08	6.84 ± 0.05	6.17 ± 0.04
		Moderately disturbed	6.57 ± 0.30	6.32 ± 0.53	6.78 ± 0.04	6.46 ± 0.07	6.49 ± 0.05	6.02 ± 0.74
4	Soil organic carbon (%)	Disturbed	1.35 ± 0.49	0.61 ± 0.55	0.14 ± 0.02	0.65 ± 0.54	0.74 ± 0.30	0.80 ± 0.79
		Moderately disturbed	1.72 ± 1.04	1.53 ± 0.50	0.62 ± 0.52	2.41 ± 0.29	1.75 ± 0.21	3.48 ± 1.42
5	Soil organic matter (%)	Disturbed	2.33 ± 0.49	1.05 ± 0.55	0.24 ± 0.02	1.12 ± 0.54	1.27 ± 0.30	1.18 ± 0.79
		Moderately disturbed	2.97 ± 1.04	2.64 ± 0.50	1.07 ± 0.52	4.15 ± 0.29	3.01 ± 0.21	6.00 ± 1.42
6	Available Nitrogen (kg/ha)	Disturbed	289 ± 0.00	142 ± 14.73	121.26 ± 31.57	242.52 ± 111.49	99.93 ± 36.21	108.30 ± 7.24
		Moderately disturbed	398 ± 25	267.33 ± 7.51	150.53 ± 52.22	271.79 ± 73.50	16.31 ± 0.00	41.40 ± 21.73
7	Available Phosphorus (kg/ha)	Disturbed	9.42 ± 1.41	29.97 ± 3.92	8.84 ± 2.50	10.16 ± 0.49	17.68 ± 1.14	12.72 ± 1.42
		Moderately disturbed	11.11 ± 3.39	34.22 ± 4.10	30.92 ± 17.41	12.93 ± 0.37	27.19 ± 1.21	19.94 ± 2.41
8	Available Potassium (kg/ha)	Disturbed	153.07 ± 6.47	235.2 ± 0.00	227.73 ± 25.87	156.80 ± 11.20	51.73 ± 4.14	320.67 ± 50.06
		Moderately disturbed	377.07 ± 6.47	250.13 ± 12.93	369.60 ± 19.40	518.93 ± 17.11	221.33 ± 18.88	437.00 ± 17.09

4.3. Allelochemic attributes of *T. diversifolia*

4.3.1. Plant debris-soil bioassay

Seeds germination and germination percentage (GPe): During all the seasons, the germination was observed to increase from the 3rd day to the 7th day in most of the pots but there was less germination on the 7th day in experimental pot 2 during pre-monsoon (Fig. 13). During post-monsoon, the invaded soil of *T. diversifolia* enhanced the rate of germination of *P. sativum* when compared with other seasons. Mostly, the experimental pot 1 has lower rate of germination than experimental pot 2 (Fig. 14). The invaded soil of experimental pot 1 which was taken from disturbed site clearly showed that *T. diversifolia* invaded soil at the disturbed site showed least potential as a medium to grow crop at the initial stage than the moderately disturbed soil thereby showing the sign of allelopathy. Previous studies have already confirmed that the allelochemic compounds released into the soil by root/rhizosphere exudates of living plant tissues and those emitted through decomposition of plant residue of invasive alien plants inhibit germination, seedling establishment, and plant growth (Belz, 2007; Bais, *et al.*, 2006; Bonanomi, *et al.*, 2006;). Thus, *T. diversifolia* has shown remarkable allelopathic influence on the germination and growth of *P. sativum*. Such inhibitory effects on seed germination were also reported on other plant species or edible crops such as *Tridax procumbens* L., *Brassica oleracea* L., *Avena sativa* L., *Allium cepa* L., *Solanum lycopersicum* L., *Triticum aestivum* L., and *Amaranthus viridis* L. (Ademiluyi, 2013; Kato-Noguchi, 2020).

The seed germination at the 3rd day has positive significant correlation with germination at the 7rd day ($r = 0.654$), germination percentage ($r = 0.654$), germination potential ($r = 0.795$), germination index ($r = 0.799$), germination rate index ($r = 0.754$), vigor index ($r = 0.682$) (Appendix XXV). The germination percentage has highly positive significant correlation with seed germination at the 7th day ($r = 1.000$), and positive significant correlation with seed germination at the 3th day ($r = 0.654$), germination potential ($r = 0.764$), germination index ($r = 0.767$), germination rate index ($r = 0.719$), vigor index ($r = 0.737$) (Appendix XXV).

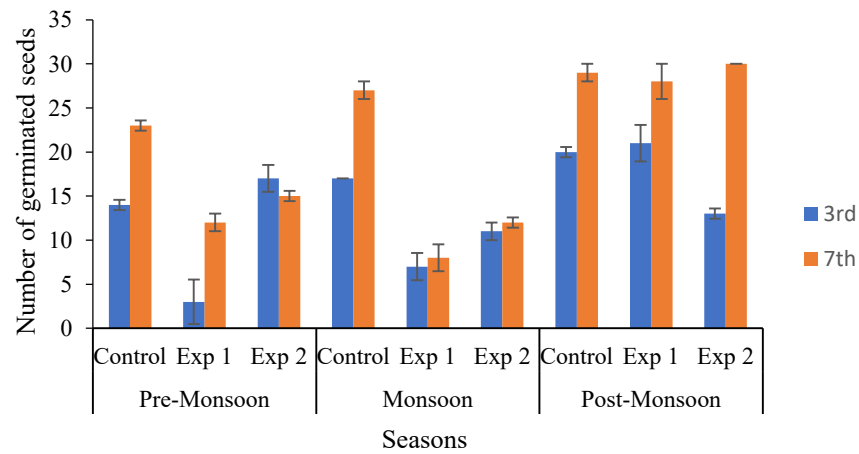


Fig. 13: Average number of germinated seeds in different experimental pots in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023, at Aizawl, Mizoram, Northeast (NE), India.

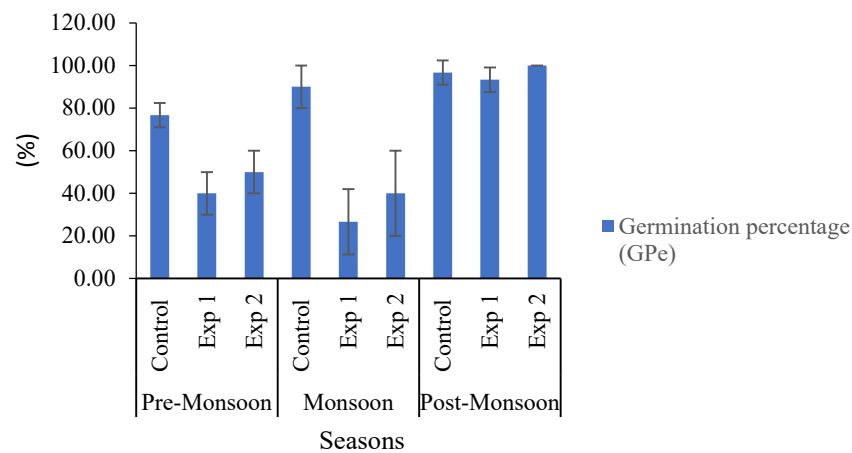


Fig. 14: Germination percentage (GPe) of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

Seedling height, root length and shoot length: During monsoon and post-monsoon, the seedling height of *P. sativum* showed the signed of stimulatory effect whereas, during pre-monsoon, the seedling height of the experimental pots was found to be lower than the control pots (Fig. 15). The seedling height has highly positive significant correlation with root length ($r= 0.967$), shoot length ($r= 0.999$), vigor

index ($r= 0.840$) and positive significant correlation with seedling biomass ($r= 0.799$), germination potential ($r= 0.755$), germination index ($r= 0.752$), germination rate index ($r= 0.664$) (Appendix XXV).

In all the seasons, the root length in the experimental pots were lower when compared with the control pot. The average root length observed during the present study ranged from 4.18 cm to 9.58 cm. The root length has recorded to have highly positive significant correlation with shoot length ($r= 0.952$), seedling biomass ($r= 0.857$), seedling height ($r= 0.967$) and positive significant correlation with vigor index ($r= 0.730$) (Appendix XXV). The one-way ANOVA revealed that the root length has recorded to have significant variation between the seasons ($F_{2,8}= 8.539373; p< 0.036011$) and between the sites ($F_{2,8}= 43.7662; p< 0.00191$) (Appendix XV). As compared to the effect of *Nicotiana plumbaginifolia* rhizosphere on *P. sativum* (i.e. 24.07 cm) the root lengths were extremely low in all the pots (Mushtag, *et al.*, 2021). Thus, the present study revealed the allelopathic effects of *T. diversifolia* on *P. sativum* which was even stronger than *N. plumbaginifolia* where the root length showed the sign of inhibitory effect (Mushtag, *et al.*, 2021).

In the present study, the shoot length in monsoon and post-monsoon showed longer shoot length than the control whereas, pre-monsoon showed slight decline in the length of the shoot of *P. sativum*. The average root length observed during the present study ranged from 15.69 cm to 35.35 cm. The shoot length has highly positive significant correlation with seedling height ($r= 0.999$), root length ($r= 0.952$), vigor index ($r= 0.856$) and positive significant correlation with seedling biomass ($r= 0.779$), germination potential ($r= 0.786$), germination index ($r= 0.783$), and germination rate index ($r= 0.702$) (Appendix XXV). The one-way ANOVA revealed that the shoot length has recorded to have significant variation between the sites ($F_{2,8}= 7.529324; p< 0.044049$) (Appendix XVI). In this respect, the experiment conducted by Musyimi *et al.* (2015) found that the shoot length of *P. sativum* was between 53 cm to 57 cm which was even more than the shoot length found in the present experiment (Fig. 15).

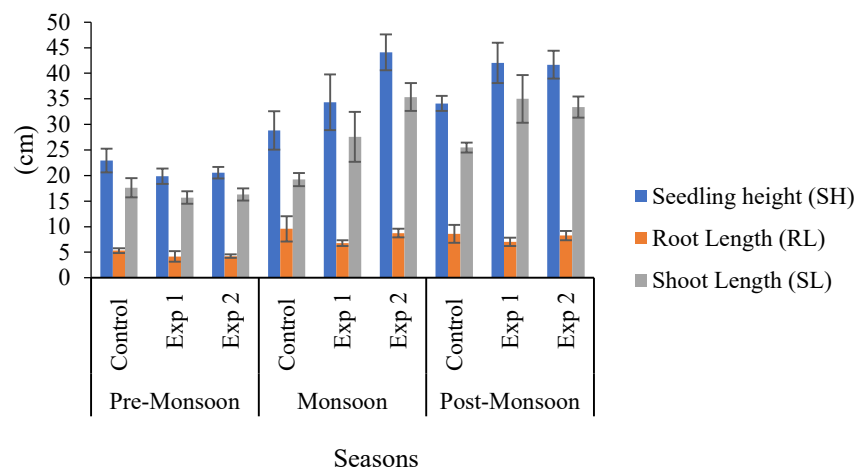


Fig. 15: Seedling height, root length and shoot height of *P. sativum* at different experimental pots in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

Seedling biomass: Biomass production and distribution is an important mechanism through which plant species can survive under environmental stress (Musyimi *et al.*, 2015). A greater leaf area could result in a larger surface area for light harvesting, which would enhance photosynthesis, biomass gain, and shoot growth (Bano *et al.*, 2012). According to the findings, the experimental pot 2 during monsoon has the highest seedling biomass (1.39 ± 0.17) which was greater than that of the control (0.71 ± 0.09) and experimental pot 1 during pre-monsoon (0.6 ± 0.05) with the lowest seedling biomass (Fig. 16). In line with our observation, another study by Oluwafemi and Olumide (2013) reported that control pot has the lowest biomass as compared to the other pots which showed the signs of stimulatory effects on growth and development of *P. sativum*.

The seedling biomass of the plant has highly positive significant correlation with root length ($r= 0.857$) and positive significant correlation with seedling height ($r= 0.799$), shoot length ($r= 0.779$), vigor index ($r= 0.745$) (Appendix XXV).

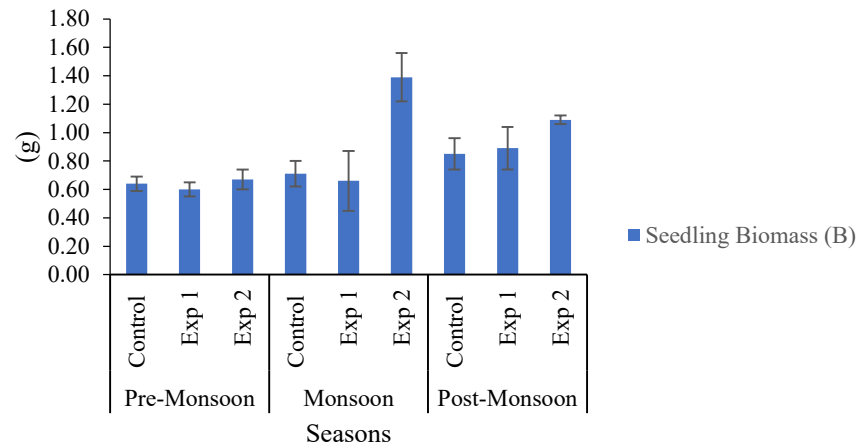


Fig. 16: Biomass of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

Germination potential (GPo), germination index (GI), germination rate index (GRI) and vigor index (VI): The germination potential, germination index and germination rate index are the measurement of the percentage and speed of germination which could be vary due to the response of temperature and light regime (Kader, 2005; Javaid, 2018). During pre-monsoon and monsoon, the germination potential, germination index and germination rate index were lower however, during post-monsoon, germination potential, germination index and germination rate index values were slightly increased (Fig. 17, 18, and 19).

Germination potential has highly positive significant correlation with germination index ($r= 1.000$), germination rate index ($r= 0.979$), vigor index ($r= 0.928$) and positive significant correlation with germination of seed at the 3rd ($r= 0.795$) and 7th ($r= 0.764$), seedling height ($r= 0.755$), shoot length ($r= 0.786$), germination percentage ($r= 0.764$) (Appendix XXV). Germination index has highly positive significant correlation with germination rate index ($r= 0.978$), vigor index ($r= 0.924$), germination potential ($r=1.000$) and positive significant correlation with germination of seed at the 3rd ($r= 0.799$) and 7th ($r= 0.767$), seedling height ($r= 0.752$), shoot length ($r= 0.783$), germination percentage ($r= 0.767$) (Appendix XXV). Germination rate index has highly positive significant correlation with vigor index ($r= 0.871$), germination potential ($r= 0.979$), germination index ($r= 0.978$), and

positive significant correlation with germination of seed at the 3rd ($r= 0.754$) and 7th ($r= 0.719$), seedling height ($r= 0.664$), shoot length ($r=0.702$), germination percentage ($r= 0.719$) (Appendix XXV).

The seed vigor index describes a seed capacity to emerge quickly, uniformly, and produce high-quality vigorous seedlings (Mangena, 2021). It is associated with many physiological characteristics, including root and shoot length, dry weight of the seedling, germination rate, radicle length, root activity, coleoptile length, mesocotyl length, germination potential, germination index, and time for attaining 50% germination (Barik *et al.*, 2022; Zhao *et al.*, 2019). During the present study, the vigor index ranged from 0.2 to 1.88. Mostly, during post-monsoon vigor index was higher which indicated that this season has potential of producing high quality seeds (Fig. 20). Vigor index has highly positive significant correlation with germination potential ($r= 0.928$), germination index ($r= 0.924$), germination rate index($r= 0.871$), shoot length ($r= 0.856$), seedling height ($r= 0.840$) and positive significant correlation with germination of seed at the 3rd ($r= 0.682$) and 7th ($r= 0.737$), root length ($r= 0.730$), seedling biomass ($r= 745$), germination percentage ($r= 0.737$) (Appendix XXV).

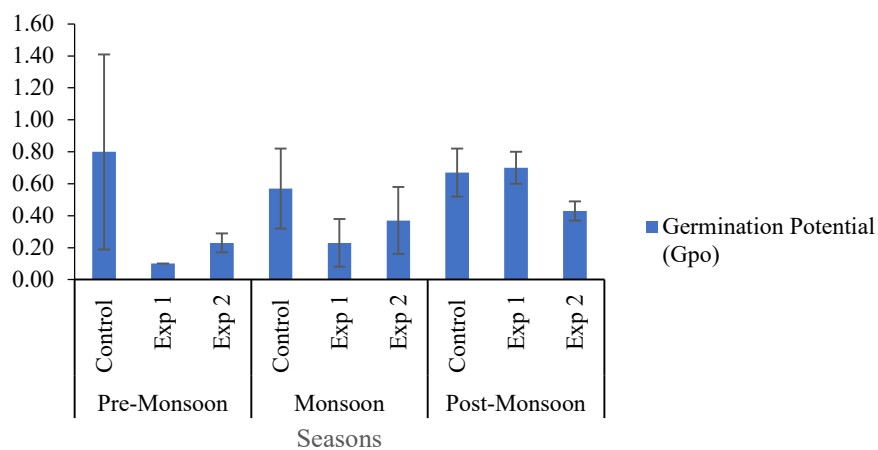


Fig. 17: Germination potential (GPo) of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

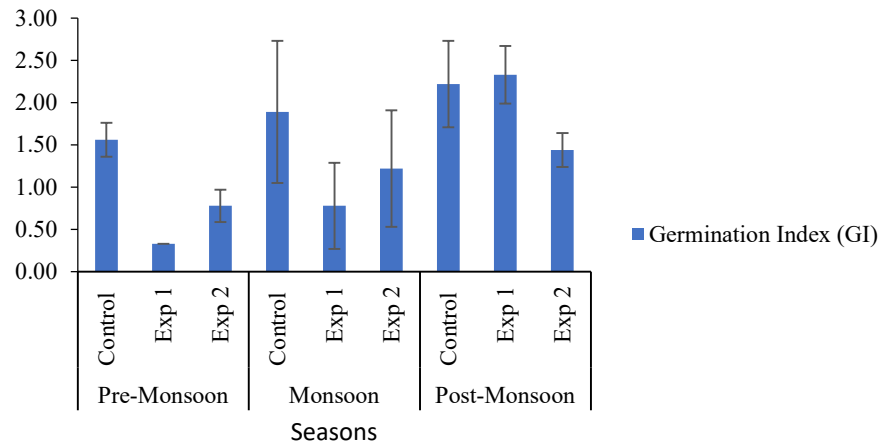


Fig. 18: Germination index (GI) of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

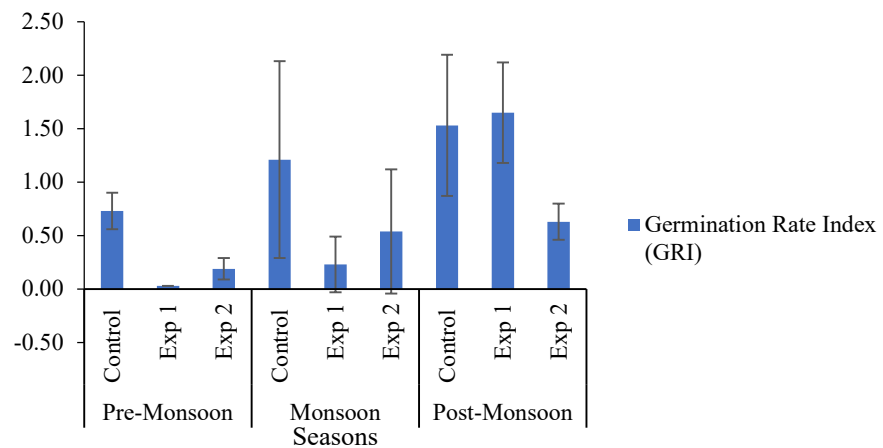


Fig. 19: Germination rate index (GRI) of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

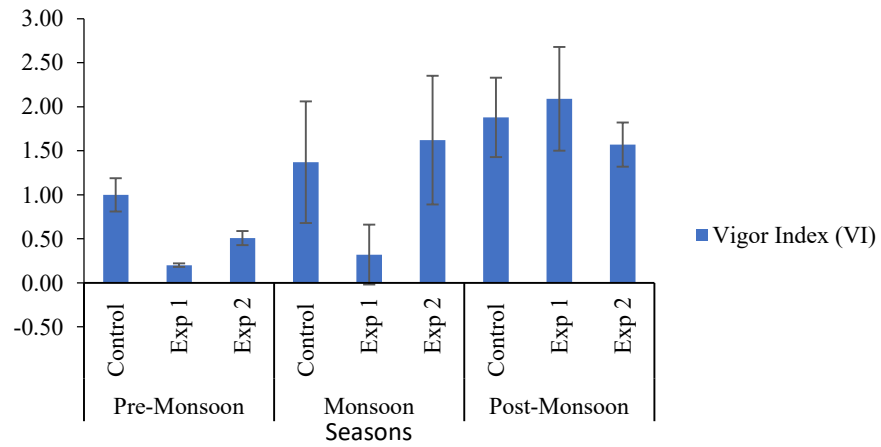


Fig. 20: Vigor index (VI) of *P. sativum* in different seasons (pre-monsoon, monsoon and post-monsoon) during the year 2023 at Aizawl, Mizoram, Northeast (NE), India.

4.3.2. Analysis of allelopathic effects through fresh leaves aqueous extracts (FLE)

Seed germination: The FLE concentration of *T. diversifolia* affected the germination in the concentration dependent manner and more inhibition was noted at higher concentrations. The highest concentration of FLE (50 mg/L) has the highest inhibition rate of germination followed by 37.5 mg/L, 25 mg/L, and 12.5 mg/L (Fig. 21). The germinated seeds have shown highly positive significant correlation with radicle length ($r= 0.914$), seedling biomass ($r= 0.921$), and plumule length ($r= 0.869$) (Appendix XXVI). This clearly showed that the FLE of *T. diversifolia* has inhibitory effects on the growth of *P. sativum* in the concentration dependent manner. Also, this showed that the aggressive growth of *T. diversifolia* in the agricultural land could inhibit the growth of crops to hamper productivity and hence food security.

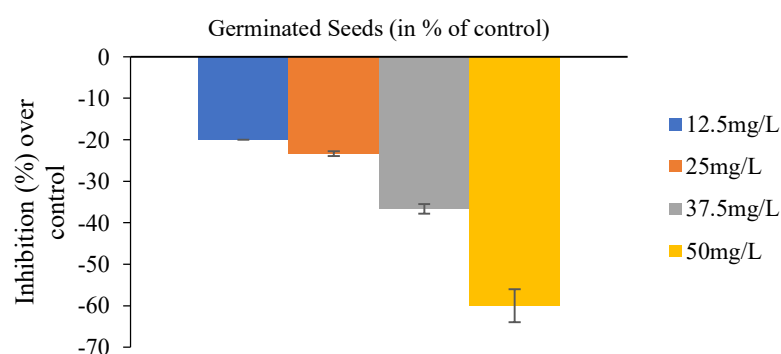


Fig. 21: Allelopathic effects of *T. diversifolia* fresh leaves aqueous extracts (FLE) on seed germination of *P. sativum*.

Seed radical: The present experiment showed that the FLE concentration inhibited the growth of radical emanating from seeds. The highest concentration of FLE (50 mg/L) has the highest inhibition rate of germination followed by 37.5 mg/L, 25 mg/L, and 12.5 mg/L. The seed radicle has shown highly positive significant correlation with seedling biomass ($r= 0.999$), seed germination ($r= 0.914$) and significant positive correlation with plumule length ($r= 0.675$) (Appendix XXVI). The One-way ANOVA for seed radical showed that there was significant variation between and within the treatments ($F_{1,7}= 12.76952$; $p< 0.011735$) (Appendix

XXVIII). Thus, the result showed that the radical length of *P. sativum* reduced with increased in the concentration (Fig. 22). Previous studies also showed that radicle is important for absorbing water from the soil, which promotes the development of the embryonic plant (Yi *et al.*, 2021). Since radical length is sensitive to phytotoxic compounds, the presence of allelochemicals may reduce cell division, which could affect the growth of seed radical (Abu *et al.*, 2010).

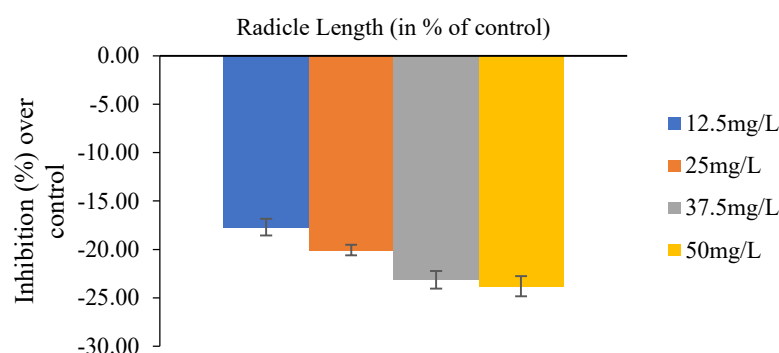


Fig. 22: Allelopathic effects of *T. diversifolia* fresh leaves aqueous extracts (FLE) on radicle length of *P. sativum*.

Seedling biomass: The present experiment showed that the biomass of *P. sativum* was affected by the FLE concentration. The highest concentration (50 mg/L) has demonstrated the highest inhibition rate while the lowest concentration (12.5 mg/L) has shown the lowest inhibition rate. The concentration 25 mg/L has higher inhibition rate than 37.5 mg/L concentration. The seedling biomass has highly positive significant correlation with radicle length ($r= 0.999$), seed germination ($r= 0.921$) and significant positive correlation with plumule length ($r= 0.700$) (Appendix XXVI). The One-way ANOVA for seedling biomass showed that there was significant variation between and within the treatments ($F_{1,7}= 14.59906$; $p< 0.008752$) (Appendix XXIX). However, seedling biomass has been observed to be affected by the increase in the concentration of FLE (Fig. 23). The present findings pertaining to concentration dependent effects on biomass was also corroborated by Fangue *et al.* (2021) who observed that an increase in concentration of FLE of *T. diversifolia* led to a significant decline in both fresh weight and root dry weight of

tomato plants. Therefore, it can be inferred from this study that the concentration of FLE had a substantial impact on the biomass of *P. sativum*.

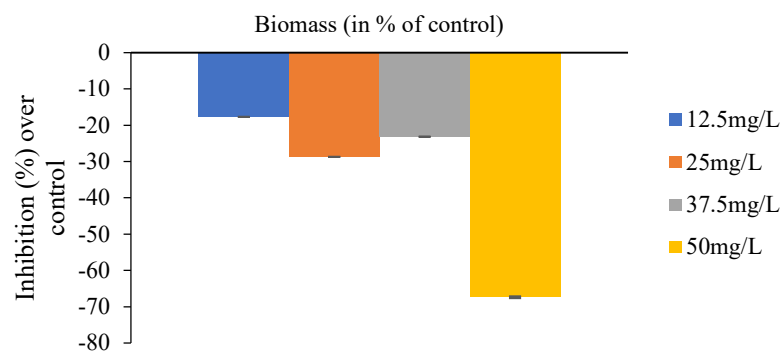


Fig. 23: Allelopathic effects of *T. diversifolia* fresh leaves aqueous extracts (FLE) on biomass of *P. sativum*.

Seed plumule: The present experiment showed that the seed plumule of *P. sativum* was affected by the FLE concentration. The highest concentration (50 mg/L) has the highest inhibition rate while the lowest concentration (12.5 mg/L) has the lowest inhibition rate. The concentration 25 mg/L has higher inhibition rate than 37.5 mg/L concentration. The seed plumule has highly positive significant correlation with seed germination ($r= 0.869$) and significant positive correlation with radicle length ($r= 0.675$) and seedling biomass ($r= 0.700$) (Appendix XXVI). The One-way ANOVA for seed plumule showed that there was significant variation between and within the treatments ($F_{1,7}= 12.85735$; $p< 0.011563$) (Appendix XXX). However, seed plumule has also been observed to be affected by the increase in concentration of FLE (Fig. 24). The similar report on plumule inhibition by invasive alien plant was observed by Abu *et al.* (2010). Recently, Zivanayi *et al.* (2024) also reported in their bioassay experiment performed on other edible crops that the aqueous extracts of *T. diversifolia* negatively affected the plumule growth in “*Zea mays* L., *Glycine max* L., *Helianthus annuus* L., *Sorghum bicolor* L., *Vigna unguiculata* L., and *Eleusine indica* L.

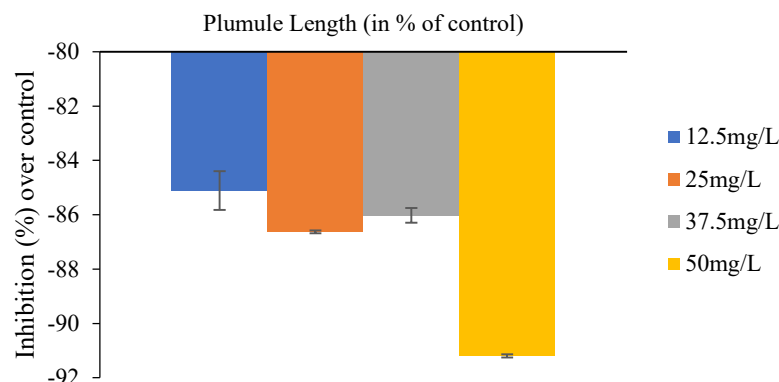


Fig. 24: Allelopathic effects of *T. diversifolia* fresh leaves aqueous extracts (FLE) on plumule length of *P. sativum*.

4.3.3. Allelochemical analysis

a) Quantification of total phenolic content

The quantification of the phytochemical compounds such as total phenol was carried out in the leaf, and flower of *T. diversifolia* using gallic acid as a standard. The results showed that the methanol extract of *T. diversifolia* flowers has the higher phenolic content ($35.26 \pm 1.02 \mu\text{g/mL}$) than the methanol extract of leaves ($12.65 \pm 0.37 \mu\text{g/mL}$) (Fig. 25) (Appendix XXXI). In allelopathy perspective, this phenolic compound might be released into the environment to inhibit the germination and growth of competing plant species, thereby influencing plant community dynamics and ecosystem composition (Inderjit and Weston, 2003). In this respect, another study by Roopa *et al.* (2020), also confirmed that methanol extract of flowers ($121.7 \mu\text{g/mL}$) has the higher half maximal inhibitory concentration (i.e. IC_{50}) of phenol than the leaves ($120.264 \mu\text{g/mL}$) of *T. diversifolia* by using ascorbic acid as a standard. Thus, the analysis of phenolic content of the *T. diversifolia* leaves and flowers confirmed that the flowers of *T. diversifolia* has the most inhibitory effect to other plant species.

b) Quantification of tannins content

The quantification of the phytochemical compounds such as total tannins was carried out in the leaf and flower of *T. diversifolia* using gallic acid as a standard. The result showed that the methanol extract of *T. diversifolia* flowers ($67.47 \pm 1.46 \mu\text{g/mL}$) has the higher tannins content than methanol extract of leaves ($16 \pm 2.18 \mu\text{g/mL}$) (Fig. 24) (Appendix XXXI). Previous studies also noted that tannins are important for regulating plant life during the interaction of plant and environment (Ucar *et al.*, 2013). They also inhibit various diseases due to their antimicrobial effects, and prevent gene mutation (Sommerauer *et al.*, 2019; Champagne *et al.*, 2020; Tong *et al.*, 2022). Thus, the presence of total tannins in leaves and flowers of *T. diversifolia* enable to adapt well in the environment and prevent them from pest and insect attack.

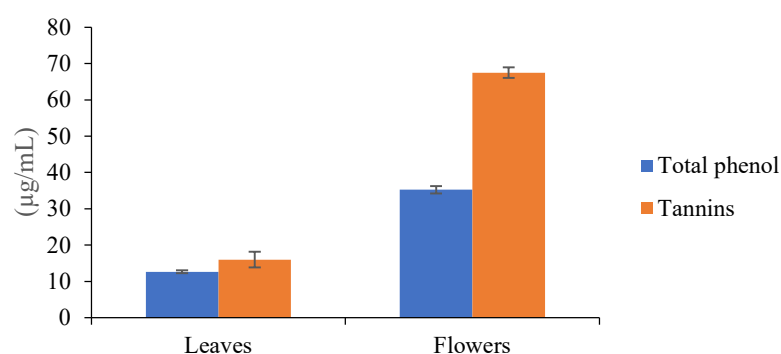


Fig. 25: Total phenolic and tannins content of *T. diversifolia* in leaves and flowers.

4.4. Socio-economic implications and management options of *T. diversifolia*

4.4.1. Socio-economic implication of *T. diversifolia*

Societal perception on T. diversifolia

To conduct the survey on socio-economy impacts of *T. diversifolia*, the present study noted the perception of rural and indigenous people in selected districts of Mizoram. These districts were Aizawl, Kolasib, Siaha, Serchhip, Saitual, Lawngtlai, Champhai, Hnahthial, Mamit, Lunglei, and Khawzawl. The present study, restricted its focus on periurban/urban forest of Aizawl, the capital district of Mizoram. However, to record

socio-economic implications of *T. diversifolia* the participation of rural people and farmers was necessary, besides urban region of Aizawl. Therefore, this was the rationale behind extending the study area to adequately gather the societal perception of rural, periurban, and urban people on the effects of *T. diversifolia*, especially in environmental and socio-economic (livelihood) sector.

Based on the responses gathered from the questionnaire, it was evident that public awareness and understanding of invasive alien plants remain limited. While a majority of respondents indicated that they were familiar with the term "Invasive alien plant,"(45%) their acquired knowledge did not extend to the broader ecological impacts that *T. diversifolia* can exhibit, particularly their harmful effects on native plant populations (55%). Specifically, although many respondents (87%) recognized the species *T. diversifolia*, there were still individuals who were quite unaware (13%) of its presence, despite the plant growing in close proximity to their homes or communities. In the context of Mizoram, *T. diversifolia* is widely acknowledged as a non-native species (55%), believed to have been introduced into the region via various means of transportation while some acknowledge (45%) it as a native species. However, most respondents were unaware (58%) that *T. diversifolia* is classified as an invasive alien plant. Only a small portion of the population (42%) demonstrated awareness of its invasive nature and the potential ecological threat it poses to invaded ecosystems (Table 7).

Table 7: Societal perception on different variables of *T. diversifolia*

Variables	Respondents positive response (%) (n= 100)	Respondents negative response (%) (n= 100)
Basic knowledge on invasive alien plants	55	45
Recognition of the name <i>T. diversifolia</i>	87	13
<i>T. diversifolia</i> as a native species in Mizoram	45	55
<i>T. diversifolia</i> as invasive species	42	58
Soil fertility	20	80
Impact on forest and wildlife	26	74
As troublesome weed to the agriculturists/ local farmers	21	79
Invasion in agricultural systems	21	79
Other invasive alien plants	36	64
The need of control and manage for future aspects	28	72

Introduction and the spread of T. diversifolia in Mizoram

According to the information gathered from the respondents, the earliest known establishment of *T. diversifolia* in the region dates back to around the year 1945. A significant number of participants reported that they have been familiar with this plant since their early childhood (16%), indicating its long-standing presence in their surroundings. Despite its early introduction, it was mostly between the years 2013 and 2023 that the plant began to gain noticeable attention, possibly due to its increasing spread and visible dominance in certain areas. However, there were also some respondents who were unable to recall (25%) exactly when they first became aware of the plant, suggesting that *T. diversifolia* has become so integrated into the landscape that its origin or introduction was not easy to recall (Fig. 26). In this respect, another study by Shankar *et al.* (2011) clearly stated that invasive alien plant species were introduced during World War II, when the Indian subcontinent, including present-day Mizoram (formerly known as the Lushai Hills) was under British colonial rule, primarily for use in tea plantations and military camouflage.

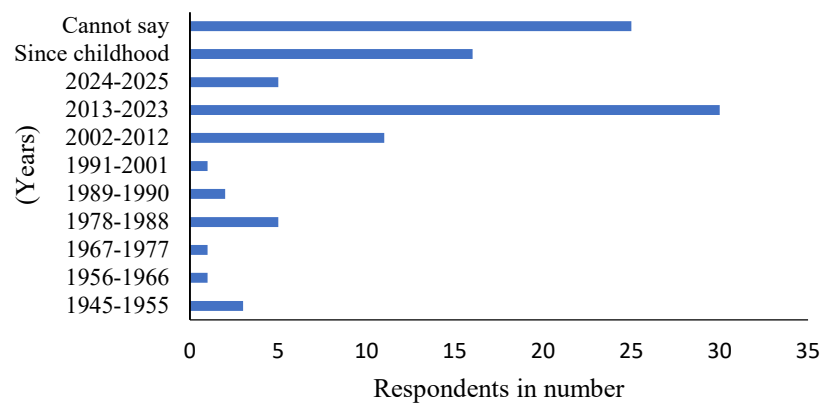


Fig. 26: Respondents opinion (n= 100) on the introduction of *T. diversifolia*.

Pertaining to societal responses on the mechanisms by which *T. diversifolia* spreads, most respondents believed that the primary mode of dispersal was through seeds carried by the wind (72%). This was followed by other contributing factors such as the movement of wild animals (27%), the closure or disturbance of forest areas (22%), changes in climate conditions (18%), inadequate management or

control measures (12%), and various human activities (12%). These insights reflect a general understanding among the community of the multiple and complex ways through which invasive species like *T. diversifolia* can proliferate and establish themselves in novel introduced environments (Fig. 27). A similar finding was reported in the study by Chukwuka *et al.* (2007), which noted that seed dispersal can occur through natural agents like wind and insects, as well as through human activities, including the importation of food crops.

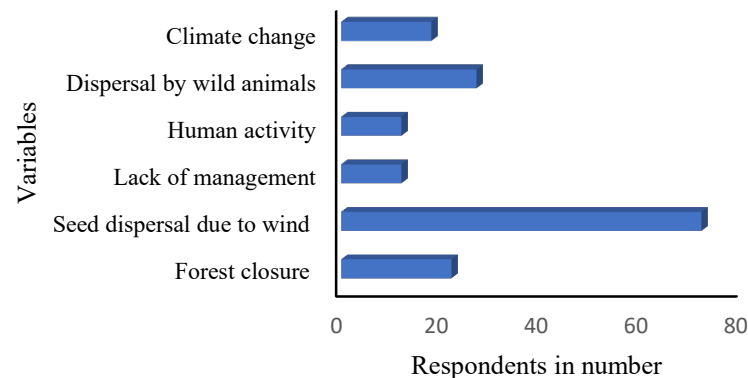


Fig. 27: Respondents (n=100) opinion on the spread of *T. diversifolia*.

Economic and social impact of T. diversifolia

In general, most people did not utilize *T. diversifolia* for economic purposes (98%). From an economic standpoint, many respondents believed that *T. diversifolia* lacks significant value, primarily because *T. diversifolia* was not considered to possess notable nutritional benefits and was not seen as a viable option for sustainable or long-term commercial ventures. However, a few (10%) respondents did mention that the plant has potential as livestock feed, particularly for pigs, due to its availability and ease of growth (Table 8). In another research study conducted by Ribeiro *et al.* (2016) demonstrated that *T. diversifolia* can effectively replace forage and concentrates in dairy cow diets, without negatively impacting performance or methane emissions. Similarly, Mauricio *et al.* (2017) observed that when *T. diversifolia* grown alongside grasses in integrated silvopastoral systems, as it

contributes to increased meat and milk production per hectare and also improves milk quality. These findings highlight *T. diversifolia* potential for economically beneficial use.

Additionally, *T. diversifolia* was appreciated by some for its ornamental value (34%). Its bright yellow flowers were visually appealing, and many people noted that they make attractive decorations. The flowers were often used in making bouquets, and in recent times, local florists have started incorporating them into their floral arrangements, indicating some small-scale commercial use in the decorative plant sector (Table 8).

Beyond its decorative uses, *T. diversifolia* has also been used for traditional medicinal purposes (12%). Some respondents reported that *T. diversifolia* leaves were applied to treat stomach issues and healing fresh wounds. In such cases, the raw leaves were crushed into a paste and applied directly to the affected area over several days, which was believed to aid in the healing process (Table 8). Supporting this traditional use, Daka *et al.* (2024) demonstrated that an aqueous extract of *T. diversifolia* resulted in a greater rate of wound healing by the 14th day of treatment compared to an ethanol-based extract.

In daily life, especially in tribal areas, the dry stems of *T. diversifolia* were noted for their common use as firewood (15%). Bonfires were a cultural practice in many communities, and the stems of this plant were valued for their flammability, making them a convenient source of fuel (Table 8).

With respect to pest and weed control, the majority of respondents did not view *T. diversifolia* as an effective or suitable biocontrol option (97%). Most participants lacked knowledge or understanding of how *T. diversifolia* might function in controlling pests or suppressing weed growth. However, a small number of respondents (3%) did believe that *T. diversifolia* could potentially aid in weed control by blocking sunlight with its dense understorey canopy of foliage, thereby limiting the light available for weeds to thrive with normal growth and development (Table 8).

Moreover, the plant serves practical purposes in land management. Since *T. diversifolia* often grows along the edges of forests, it naturally acts as a boundary or informal fence for agricultural land. Similarly, in Nigeria, *T. diversifolia* commonly grows along roadsides, farmlands, and lawns, where it is also used to mark or delineate land boundaries (Chukwuka *et al.*, 2007). This border-like growth helps prevent soil erosion, offering an ecological benefit to local farmers (21%). Additionally, the plant fallen leaves decompose on the ground and contribute to the soil fertility (16%). These natural residues function as a form of compost, enriching the soil and supporting sustainable agriculture practices without the need for artificial fertilizers (Table 8).

In conclusion, the general socio-economic perception of *T. diversifolia* among the respondents were mixed rather than offering an explicit conclusion. Only a small portion of approximately 12% viewed the plant as having a positive impact on their socio-economic community or environment. On the other hand, about 10% of the respondents believed that *T. diversifolia* has a negative impact, possibly due to its invasive nature, competition with native vegetation, or lack of significant economic usefulness. A significant majority of respondents, i.e., around 57%, expressed that *T. diversifolia* has both positive and negative effects. This group recognized the plant potential utility in certain areas, while also acknowledging the ecological and economic challenges it may pose. Meanwhile, 21% of the respondents admitted that they had no clear understanding of the plant's overall impact (Fig. 28).

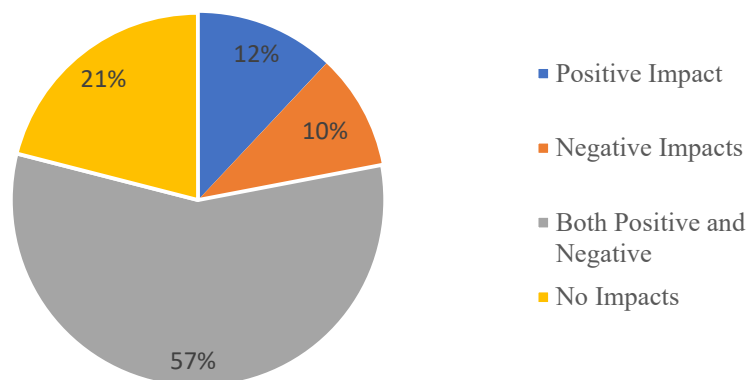


Fig. 28: Respondents (n=100) opinion on the general positive and negative impact on *T. diversifolia*.

Table 8: Respondents (n=100) opinion on the purposes and uses of *T. diversifolia*.

Variables	Percentage of respondents who consider positive effect (%)	Percentage of respondents who consider negative effect (%)
Economic	2	98
Fodder for livestock	10	90
Ornamental/decoration	34	66
Medicinal	12	88
For firing	15	85
Pest and weed control	3	97
Soil erosion control	21	79
Manure/compose	16	84

Growth distribution of T. diversifolia in the affected area

Based on the opinions of the respondents, perceptions about the current growth status of *T. diversifolia* since they first became aware of the plant vary significantly. A large portion of the respondents (41%) were uncertain and could not clearly comment on the current extent or spread of *T. diversifolia*. Some respondents (31%) believed that the growth and spread of *T. diversifolia* have remained relatively unchanged over the years, suggesting a stable presence in their surroundings. Others, however, felt that the plant growth has been increasing steadily (22%), with *T. diversifolia* becoming more widespread and invasive over time. This group may have noticed its expansion into new areas or an increase in its dominance over native vegetation. On the contrary, a smaller number of respondents (6%) observed a decline in the plant presence, possibly due to human intervention, environmental factors, or natural competition with other plant species (Fig. 29).

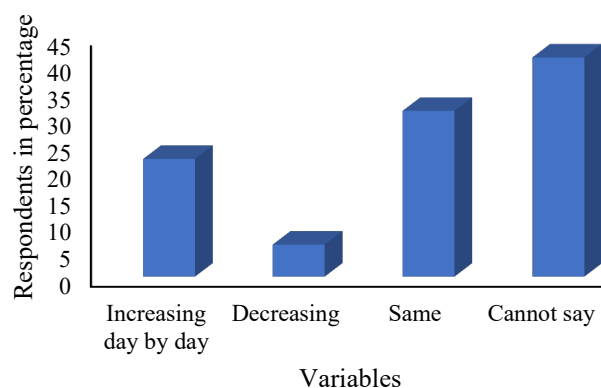


Fig. 29: Respondents (n=100) opinion on the growth distribution on *T. diversifolia* in the affected area.

Impact of T. diversifolia on soil fertility, forest, wildlife and agricultural crops

The majority of respondents (80%) did not consider *T. diversifolia* to be an effective fertilizer for crop production. Most people felt that the plant lacks the necessary properties to significantly enhance soil fertility or support crop yield when used directly. However, a few individuals (20%) noted that *T. diversifolia* could be beneficial when its biomass is burned and the resulting ash or residue is spread onto crop beds. This method was believed to add some nutrients to the soil. Additionally, some respondents mentioned using *T. diversifolia* as mulch, wherein the leaves and stems were left on the surface of the soil to decompose slowly, thereby enriching the soil organically. Others believed that simply growing crops in soil where *T. diversifolia* leaves have naturally decomposed over time can improve soil quality, suggesting passive use of the plant as a natural compost material (Table 7). Supporting present survey, another study by Jama *et al.* (2000) reported that the fresh leaf biomass of *T. diversifolia* is nutrient-rich and decomposes quickly when applied to soil, providing around 3.5% N, 0.37% P and 4.1% K on a dry matter basis.

When asked about its effects on forests and wildlife, most respondents (74%) did not believe that *T. diversifolia* has a major impact. They viewed *T. diversifolia* as just another wild-growing plant, with no noticeable threat to local ecosystems. However, a smaller group of respondents (26%) expressed concern about potential negative effects. They speculated that the plant might be harmful to certain wildlife

species, possibly causing allergic reactions or toxicity in animals that frequently come into contact with or often consume it. Additionally, these respondents noted that if *T. diversifolia* spread is unchecked within forested areas, especially in the absence of active monitoring it could quickly outcompete native vegetation. Due to its fast growth and aggressive spread, they were afraid that *T. diversifolia* could dominate forest undergrowth and reduce biodiversity in a relatively short period of time (Table 7).

A large number of respondents (79%) reported that *T. diversifolia* has been a persistent problem for agriculture over the years. Because of its tall growth and ability to spread over large areas, *T. diversifolia* requires significant effort to clear the land before planting crops. Although some respondents (21%) acknowledged its usefulness as a natural fence or boundary marker due to its growth along field edges, they also pointed out that its aggressive spread which meant that the farmers need to continuously monitor and manage it to prevent overgrowth. On the other hand, a few respondents referred *T. diversifolia* as "the farmer's friend," appreciating its ability to control soil erosion, demarcate land boundaries, and enhance soil quality through leaf litter and decomposition. This reflects a divided view among some community members who see both the challenges and benefits of the plant (Table 7).

The majority of respondents (79%) strongly believed that *T. diversifolia* poses a significant threat to agricultural crops. In Mizoram, where homestead gardening was a common agricultural practice, respondents reported that *T. diversifolia* often invades cultivated areas, including those near human settlements. Its ability to survive in various environments makes it particularly problematic. Several respondents shared specific examples of crops that have been negatively affected by the presence of *T. diversifolia*. These include a wide range of vegetables and tubers commonly grown in the region, such as: *Brassica juncea* (L.) Czern. (Antram), *Solanum nigrum* L. (Anhling), *Colocasia* species (Dawl), *Solanum tuberosum* L. (potato or Alu), *Phaseolus vulgaris* L. (French bean), *Zingiber officinale* Roscoe. (Ginger or Sawhthing), *Pisum sativum* L. (green pea or Chana hring), *Musa* species (Banana or Balhla, Tumbu, Saisu), *Dioscorea* species (yam– Bal, Bahra), *Solanum* species (Tomato, Trawkte, Tawkpui), *Zea mays* L. (Maize or Vaimim), *Cajanus cajan*

(L.) Huth (Pigeon pea or Behliang), and *Alocasia fornicata* (Kunth) Schott (Baibing). These crops are vital for local consumption and livelihoods, so the spread of *T. diversifolia* into cultivated spaces is seen as a serious issue by most farmers. Only a small number of respondents (21%) believed that *T. diversifolia* does not impact agricultural production, indicating a broad consensus about its harmful effects on farming or ethno-agricultural systems of shifting cultivation or ‘Jhum’ in the region (Table 7).

Potential controlling and coping measures for T. diversifolia invasion

According to the data collected, the majority of respondents (72%) did not believe that *T. diversifolia* requires active control or management for future environmental or ecological concerns. Their reasoning was largely rooted in the perception that the plant has been present for generations dating back to the time of their forefathers and that it grows naturally without causing any immediate or visible harm. As long as *T. diversifolia* does not lead to significant negative impacts on agriculture, biodiversity, and human activities, many felt there was no urgent need to implement control measures (Table 7).

In contrast, a smaller but concerned portion of the respondents (28%) rather opined a different view (Table 7). They emphasized the importance of monitoring and managing *T. diversifolia*, before it potentially becomes a serious threat to native plant species and the local ecosystem. This group advocated for proactive measures to prevent future ecological imbalances caused by unchecked spread of the invasive *T. diversifolia*.

With respects to the control strategies, most respondents (53%) favoured physical methods as the primary approach. These include manual techniques such as cutting, ploughing, burning (firing), and uprooting or extracting the plant roots. Physical control was seen as the most accessible and familiar method, particularly in rural and tribal communities where such practices are commonly used. Following physical control, chemical (27%) and biological (9%) methods were less frequently suggested but still recognized. Common chemicals mentioned for use in managing *T. diversifolia* included substances like Glycel (a glyphosate-based herbicide) and DDT

(dichloro-diphenyl-trichloroethane). Biological control was the least cited, with few respondents mentioning methods such as preventing seed dispersal as a means to control the plant spread. Interestingly, 6% of the respondents believed that an integrated approach combining physical, chemical, and biological methods would be the most effective strategy for managing the invasion of *T. diversifolia*. A small number of individuals (5%) also admitted of having no knowledge on control mechanisms at all, thereby highlighting a gap in public awareness and education regarding this invasive alien plants management (Fig.30). In this respect, a rare study by Kaplan *et al.* (2017) emphasized that those invasive alien plants which are widespread and abundant are best addressed through integrated management approaches. This approach involved a combination of manual, chemical, and biological control methods tailored to local conditions, followed strategies for attaining ecological restoration (Kaplan *et al.*, 2017).

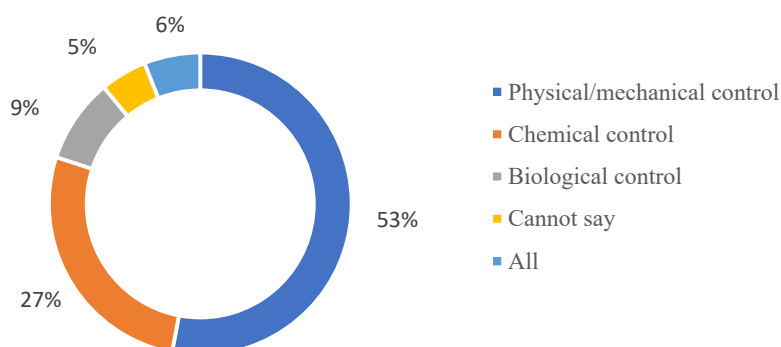


Fig. 30: Respondents (n=100) opinion on the control measures of *T. diversifolia*.

Awareness of other invasive alien plants

During the survey, when asked about their knowledge of other invasive alien plants besides *T. diversifolia*, only a small number of respondents (36%) were able to name additional species. The majority of participants (64%) could not identify any other invasive alien plants, which clearly indicates a general lack of awareness or concern regarding the broader issue of invasive alien plants within the community. This limited knowledge of local people suggests that the presence and impact of invasive

alien plants are not well recognized or prioritized in local environmental discussions (Table 7). Among those who could identify other invasive alien plants, the most commonly mentioned species included: *L. camara*, *M. micrantha* (japan hlo), *A. Adenophora*, *C. odorata* (tlangsam), *A. conyzoides* (vailen hlo), *B. pilosa* (vawipuithal/chabet), *Blumea lanceolaria* (buar), *M. pudica* (hlo nuar), *Ipomoea* species, *Cosmos* species (hnaahsin). Among the listed invasive alien plants some (such as *L. camara*, *M. micrantha*, *A. Adenophora*, *C. odorata*, and *B. pilosa*) are under global recognition as top 100 harmful biotic invaders (Lowe *et al.*, 2000; Yadav *et al.*, 2024). This reflects the limited yet valuable local knowledge of invasive alien plants, mostly based on personal experience or traditional understanding. However, the overall low level of awareness among the majority of respondents highlights a need for increased environmental education and outreach programs regarding the identification, impact, and management of invasive alien plants. Raising awareness at the community level could play a crucial role in early detection and control of invasive alien plants before they cause further harm to native ecosystems and agricultural productivity (Table 7).

4.4.2. Management option on the spread of *T. diversifolia*

4.4.2.1. Sustenance of intact canopy can control/contain invasive alien plants.

Disturbed site canopy openness, leaf area index (LAI) and photosynthetically active radiation (PAR)

Forest canopy openness was analysed across ten plots at a disturbed site where *T. diversifolia* infestation was notably high. Among the plots, the largest canopy openness was recorded at D9 (98.73%), while the smallest canopy openness was at D5 (28.71%) (Table 9). This canopy openness allowed varying amounts of sunlight to penetrate the forest floor, potentially favouring the growth and spread of *T. diversifolia*, which may directly influence on the intensity and impact of field-level allelopathy. The correlation analysis between various light parameters revealed that diffused PAR, which is the scattered sunlight that penetrates below the canopy has a highly positive significant correlation with incoming PAR ($r = 0.92497$) (Table 10). This indicates that areas receiving more direct solar radiation also tend to have higher levels of diffused light under the canopy. Such light availability likely contributes to the proliferation of *T. diversifolia* by supporting its photosynthetic activity even beneath partially covered canopy areas. Measurements of LAI, which reflected that the leaf density of vegetation, ranged from a low of 0.05 ± 0.03 to a high of 2.17 ± 0.50 (Table 9). In this context, LAI showed a positive significant correlation with incoming PAR ($r = 0.72796$), suggesting that greater solar radiation is associated with more vegetative growth, possibly including *T. diversifolia* itself or plant communities it dominates (Table 10). Additionally, canopy openness was found to have a positive significant correlation with elevation ($r = 0.71741$) (Table 10). The invasion rate which was categorized based on the canopy openness showed that at the disturbed site, large canopy openness facilitates the invasion rate of *T. diversifolia* and support less diverse vegetation or reduced species diversity, attributed to sparser canopies, allowing greater light penetration. this greater light penetration was also observed through LUX meter values recorded at the disturbed sites, while defining the habitat ecology of selected study sites.

Table 9: Analysis of canopy openness, LAI and PAR at the disturbed site (i.e., Aizawl, Mizoram, Northeast (NE), India) of *T. diversifolia*.

Plot	GPS Coordinates (DMS)	Elevation	Photosynthetically Active Radiation (PAR)		Leaf Area Index (LAI)	Canopy Openness (%)	Invasion Rate
			Incoming PAR $\mu\text{ mol m}^{-2} \text{ s}^{-1}$	Diffused PAR $\mu\text{ mol m}^{-2} \text{ s}^{-1}$			
D1	N23°45'25.44" E092°39'59.52"	686	1110.67±19.40	308.67±81.08	2.17±0.50	49.1	Moderate
D2	N23°45'27.97" E092°40'01.19"	692	195.33±2.52	131.00±10.58	0.67±0.15	29.45	Low
D3	N23°45'31.12" E092°39'57.14"	665	748.33±10.50	477.33±199.79	0.87±0.81	33.2	Low
D4	N23°45'31.27" E092°40'01.35"	676	458.33±4.04	258.33±41.88	0.97±0.28	35.67	Moderate
D5	N23°45'32.88" E092°40'07.28"	703	65±1.73	35.67±12.06	1.07±0.60	28.71	Low
D6	N23°45'33.61" E092°40'09.13"	708	80±0.00	77.67±1.53	0.05±0.03	59.24	Moderate
D7	N23°45'29.22" E092°39'49.33"	652	250.67±1.53	178.67±7.37	0.56±0.08	63.64	Moderate
D8	N23°45'26.14" E092°39'50.52"	649	307.33±0.58	141±13.75	1.30±0.16	48.97	Moderate
D9	N23°45'18.98" E092°40'16.34"	768	1620±517.94	821±841.93	1.63±1.48	98.73	High
D10	N23°45'19.39" E092°40'16.97"	784	342.67±6.66	239±19.67	0.60±0.13	90.14	High

Table 10: Pearson correlation coefficient (r) values between elevation, incoming PAR, diffused PAR, LAI and Canopy openness at disturbed site (i.e., Aizawl, Mizoram, Northeast (NE), India).

	<i>Elevation</i>	<i>Incoming PAR</i>	<i>Diffused PAR</i>	<i>LAI</i>	<i>Canopy Openness</i>
Elevation	1				
Incoming PAR	0.32320	1			
Diffused PAR	0.38982	0.92497**	1		
LAI	-0.00401	0.72796*	0.47154	1	
Canopy Openness	0.71741*	0.46523	0.52960	0.05108	1

*Correlation is significant at the 0.05 level **Correlation is significant at 0.01 level

Moderately disturbed site canopy openness, leaf area index and photosynthetically active radiation (PAR)

Forest canopy openness was assessed across ten plots within a moderately disturbed site, where infestation by *T. diversifolia* was prominent. The percentage of canopy openness varied among the plots, with the largest canopy openness recorded at MD4 (25.85%), and the smallest at MD6 (10.71%) (Table 11). This relatively low canopy openness suggested partial disturbance, which lower the invasion rate but still influence the growth and spread of *T. diversifolia* due to low light availability under the canopy. Correlation analysis of environmental parameters revealed notable patterns. The LAI, acted as an indicator of vegetation density and canopy cover, which exhibited a significant negative correlation with elevation ($r = -0.69379$) (Table 12). Furthermore, diffused PAR and incoming PAR showed a highly positive correlation with each other ($r = 0.88609$), confirming that as direct sunlight increases, more light is scattered beneath the canopy (Table 12). This relationship suggests that even in moderately disturbed sites, light availability under the canopy is closely linked to overall sunlight penetration, which can impact understory growth and regeneration. The LAI values at this site ranged from 0.71 ± 0.67 to 5.32 ± 1.80 , indicating variability in vegetative density across the plots (Table 11). However, despite this variation, LAI did not show a significant relationship with elevation in the moderately disturbed site. This suggests that other local factors such as microclimate, soil conditions, or canopy structure may play a more influential role in determining leaf area than elevation alone. Generally, the invasion rate at moderately

disturbed sites were low due to limited light penetration/availability while less canopy openness supported diverse vegetation with higher species diversity, when compared with a disturbed site. Together this factors, tends to lower the invasion rate at moderately disturbed sites.

Table 11: Analysis of canopy openness, LAI and PAR at the moderately disturbed site (i.e., Aizawl, Mizoram, Northeast (NE), India) of *T. diversifolia*.

Plot	GPS Coordinates (DMS)	Elevation	Photosynthetically Active Radiation (PAR)		Leaf Area Index (LAI)	Canopy Openness (%)	Invasion rate
			Incoming PAR $\mu \text{ mol m}^{-2} \text{ s}^{-1}$	Diffused PAR $\mu \text{ mol m}^{-2} \text{ s}^{-1}$			
MD1	N 23°47'33.02" E 092°44'06.01"	1060	1158±75.23	409.67±320.91	2.04±1.24	13.14	Low
MD2	N 23°47'33.97" E 092°44'05.72"	1057	129.33±12.10	44.33±27.06	2.00±0.90	18.39	Low
MD3	N 23°47'33.97" E 092°44'05.72"	1057	210±18.38	41±2.83	2.72±0.03	19.6	Low
MD4	N 23°47'56.24" E 092°44'02.77"	1075	61±1.00	29.33±6.03	1.24±0.34	25.85	Low
MD5	N 23°47'56.31" E 092°44'02.11"	1067	67±1.00	21.00±9.85	2.05±0.74	16.08	Low
MD6	N 23°47'54.73" E 092°44'12.44"	938	604.33±1.53	33.33±24.34	5.32±1.80	10.71	Low
MD7	N 23°47'54.21" E 092°44'09.10"	994	150.67±3.21	90.33±21.55	0.88±0.44	22.03	Low
MD8	N 23°47'39.93" E 092°44'00.90"	1139	15±0.00	6±0.82	1.54±0.23	16.63	Low
MD9	N 23°47'41.04" E 092°43'59.74"	1138	24.33±0.58	12.33±6.43	1.35±1.10	11.38	Low
MD10	N 23°47'41.39" E 092°44'59.47"	1143	29.33±2.52	20±6.93	0.71±0.67	13.31	Low

Table 12: Pearson correlation coefficient (r) values between elevation, incoming PAR, diffused PAR, LAI and Canopy openness at moderately disturbed site (i.e., Aizawl, Mizoram, Northeast (NE), India).

	<i>Elevation</i>	<i>Incoming PAR</i>	<i>Diffused PAR</i>	<i>LAI</i>	<i>Canopy Openness</i>
Elevation	1				
Incoming PAR	-0.44066	1			
Diffused PAR	-0.16016	0.88609**	1		
LAI	-0.69379*	0.45390	0.00568	1	
Canopy Openness	-0.07177	-0.36696	-0.16399	-0.39942	1

*Correlation is significant at the 0.05 level

**Correlation is significant at 0.01 level

The observed variation in light intensity values across different disturbance gradients clearly reflects the impact of canopy structure on light penetration. In the disturbed sites, where canopy openness was larger and more frequent, there was a noticeable increase in the penetration of incoming PAR to the forest floor. These elevated light levels create favourable microclimatic conditions for the establishment and rapid growth of light-demanding invasive alien plants, such as *T. diversifolia*. In contrast, moderately disturbed canopy areas limit light availability beneath the canopy, naturally suppressing the growth of *T. diversifolia* that rely on high light conditions to thrive. This suggests a strong ecological link between canopy openness and invasion risk, where increased light serves as a catalyst for the spread of aggressive, non-native/invasive vegetation.

Therefore, effective forest management and restoration strategies should prioritize the maintenance and enhancement of dense canopy cover. One of the most sustainable approaches to achieving this is through increasing the richness and diversity of native plant species, especially those of shade-tolerant and fast-growing native trees and understory species. A diverse native plant community not only contributes to canopy closure over time but also enhances ecosystem resilience, outcompeting invasives for resources such as light, space, and nutrients (Singh *et al.*, 2022). In conclusion, preserving an intact forest canopy and promoting native biodiversity are key strategies in regulating light availability and thus limiting the

spread of *T. diversifolia*. These actions can play a significant role in restoring ecological balance in disturbed forest ecosystems.

4.4.2.2. Management Strategies of *T. diversifolia* as per societal perceptions.

The sustainable management of *T. diversifolia* can be achieved by balancing its ornamental and ecological benefits while actively addressing its invasive potential. Based on public opinion from the questionnaire survey, around 28% of respondents recommended early intervention or control methods/ecological strategies to prevent future ecological disruptions caused by the unchecked spread of *T. diversifolia*. Due to the topography of Mizoram, physical control methods are considered the most suitable by locals and farmers. Techniques such as cutting, ploughing, and controlled burning are widely preferred, provided they are executed systematically to avoid harming native vegetation. The community views timely and repeated harvesting as an important early management strategy. According to recent findings (Nuwarapaksha, 2024), harvesting the plant every three months yields high-quality biomass suitable for green manure. This practice not only enhances soil fertility but also inhibits seed production, effectively curbing its invasive managing spread.

From a biological control perspective, respondents supported the integration of native and economically significant plant species such as *Mesua ferrea* L., *Artocarpus chaplasha* Buch-Ham., *Aquilaria agallocha* Roxb., *Acacia pennata* (L.) Willd., *Clerodendrum colebrookianum* Walp., *Parkia roxburghii*, *Moringa oleifera* Lam. and *Podocarpus neriifolius* D. Don and understory plants such as *Amomum dealbatum* (Roxb.) Kuntze, *Canavalia cathartica* Thouars, *Colocasia esculanta* L., *Gnetum gnemon* Linn, *Hibiscus sabdariffa* L. These plants are traditionally valued in Mizoram and are supposed to suppress the proliferation of *T. diversifolia* while simultaneously benefiting local livelihoods through their food, medicinal, or cultural uses.

With regards to chemical control, the use of herbicides or weedicides is acceptable to the public, but only under expert guidance to prevent ecological harm. There is a recognized need for public awareness, as some individuals have reportedly used ecologically damaging or banned substances like DDT. Education on safe

practices and expert consultation are therefore crucial components of any chemical control strategy.

While some people appreciate *T. diversifolia* for its ornamental value particularly its vibrant, sunflower-like blooms, many remain concerned about its rapid growth and invasive behavior. To mitigate these concerns, society supports the idea of restricting its cultivation for ornamental use, only in controlled/regulated settings. Also, in this respect, the findings adopted by Kriticos and Kriticos (2021), suggested the same idea to cultivate *T. diversifolia* where environment conditions are unsuitable for its natural persistence and spread.

Moreover, in recent findings *T. diversifolia* has shown potential in integrated pest management, a concept that resonates positively with various stakeholders including farmers. Further in this respect, *T. diversifolia* hedgerows have been observed to host numerous natural pest predators, contributing to significant reductions in pests like the yellow sugarcane aphid (*Sipha flava*), thus reducing the over-reliance on chemical pesticides (Macé and Goebel, 2024). This aligns well with local aspirations for ecological farming and eco-friendly pest control.

Therefore, societal perception in Mizoram reflects a strong preference for multi-pronged and locally adapted management approaches of *T. diversifolia*. By combining early detection with physical, biological, and regulated chemical methods with judicious use in agriculture and landscaping, the community envisions a model that promotes sustainable utilization, while preserving ecological balance of this integral landscape of an Indo-Burma biodiversity hotspot region.

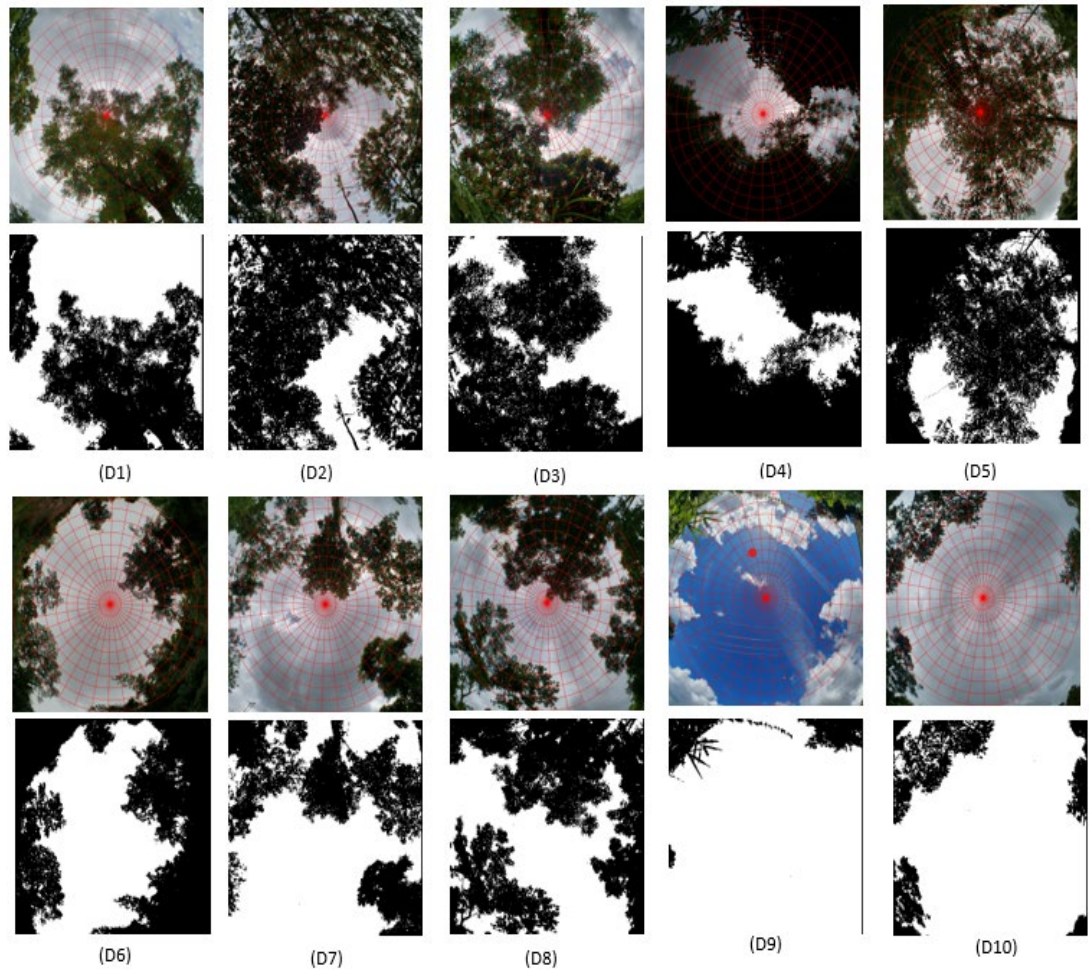


Fig. 31: Hemispherical photos taken on different plots to estimate the canopy openness on the disturbed area of *T. diversifolia*. The canopy openness analyzed by Gap Light Analyzer (GLA) are shown in colour (original) and monochromatic (processed photo after adjusting) photograph.

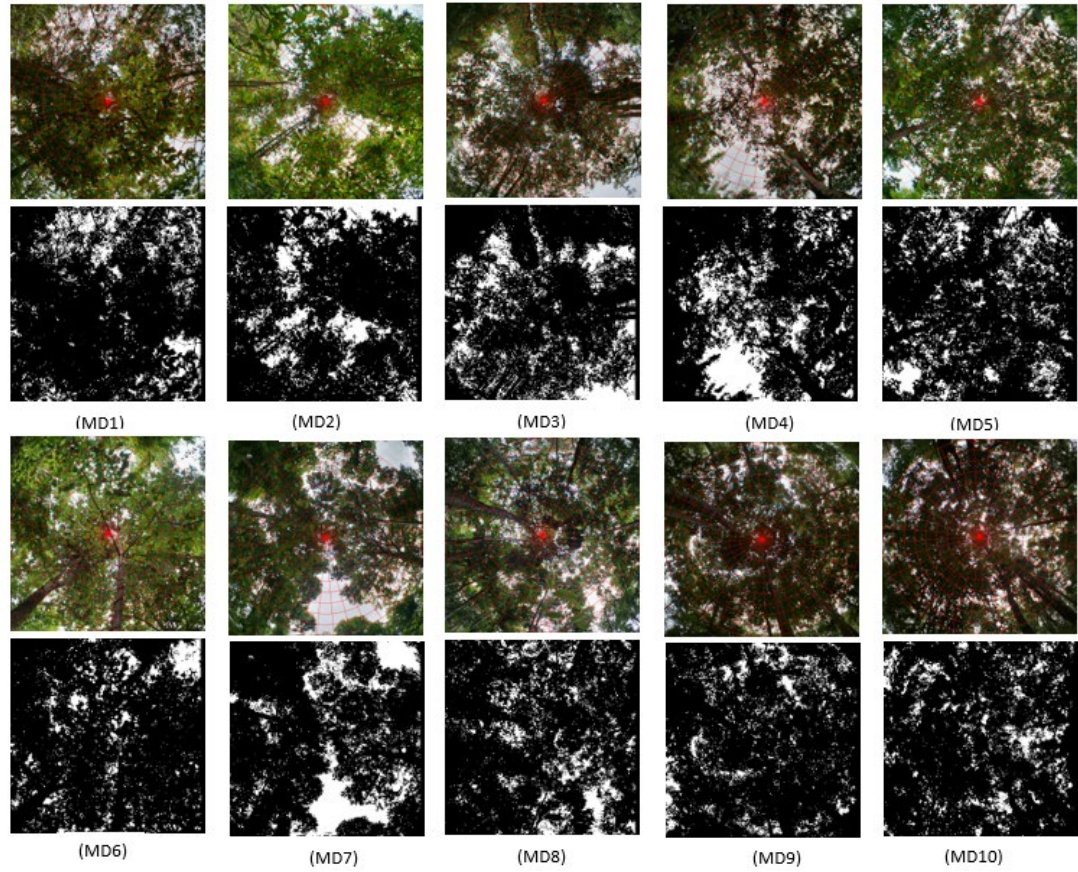


Fig. 32: Hemispherical photos taken on different plots to estimate the canopy openness on the moderately disturbed area of *T. diversifolia*. The canopy openness analyzed by Gap Light Analyzer (GLA) are shown in colour (original) and monochromatic (processed photo after adjusting) photograph.

CHAPTER-5

CONCLUSION

5. CONCLUSION

The study was conducted in Aizawl District, located in Mizoram, Northeast (NE) India. This region lies along the Tropic of Cancer in the northern part of the state and underlie in an Indo-Burma global biodiversity hotspot, which extends across several northeastern states of India. The hotspot is recognized for a home of numerous rare and threatened species that are restricted to specific areas and play unique, irreplaceable roles in the ecosystem. For sampling purposes, two sites were selected based on differences in disturbance intensity such as disturbed and moderately disturbed areas. Disturbance intensity was evaluated in relation to both natural and human-induced factors. An uninvaded site could not be included because the study locations were highly urbanized and exposed to multiple anthropogenic pressures such as road construction, traditional shifting cultivation (jhum), dense settlements, grazing, and stone quarrying.

Present study explicitly elucidated that *T. diversifolia* invasion can have substantial impacts on phytosociology, diversity, and distribution of neighbouring plants. In addition to its impact on ecological attributes this study further evidenced that invasive spread of *T. diversifolia* is potentially related with soil physico-chemical characteristics. The invasion of *T. diversifolia* has profound impact on agriculture systems, especially edible crops which was corroborated with pot experiments, with the help of *P. sativum* as model bioassay plant. Moreover, the societal perception of rural and urban people was recorded through socio-economic survey of selected districts of Mizoram.

The results of present study concluded that *T. diversifolia* is ecologically an enigma and threat of this invasive alien plants where widely observed in the selected study area of Indo-Burma hotspot region. The threats of *T. diversifolia* were manifested through their influence on the soil health, especially in terms of soil physico-chemical characteristics. Also, the adverse influence of *T. diversifolia* was realised through their negative impacts on phytosociology and biodiversity indices of native plants. The leaf leachates of *T. diversifolia* have negatively impacted the growth of the agricultural crop and food security. For the effective management,

community education, sustainable control strategies, and safeguarding/maintaining native biodiversity through limiting forest canopy are essential to restore ecological balance.

Studying the characteristics of plant communities within the study area is important for understanding the paradigm shift in plant populations dynamics. In this respect, the effects of selected invasive alien plants i.e., *T. diversifolia* can have a remarkable impact on ecological attributes, diversity and distributions of native plants, and soil chemistry. The research emphasized that the that the plant traits of Asteraceae family also extend to *T. diversifolia* which significantly affects plant community structure, influencing species dispersal, environmental tolerance, and response to altered disturbance regimes. The overall findings pertaining to ecological effects of *T. diversifolia* at differential disturbance regimes (moderately disturbed and disturbed) in fact support the 'Intermediate Disturbance Hypothesis' (IDH) adopted Connell (1978) which predicts that species diversity is maximized at intermediate levels of disturbance. In this sense, the moderately disturbed site recorded 57 plant species which was notably higher than the 40 species observed at the highly disturbed site, during the selected study period (2022-2024). This suggests that at moderate or intermediate disturbance levels, equitably balance or trade-off between competitive exclusion by existing dominant species and the harsh conditions caused by intense disturbance, which can rather impose adverse influence on plant diversity and distribution. At intermediate disturbance level, enough ecological space and resources are available to allow a wider variety of species to establish and co-exist, whereas in the highly disturbed site, environmental stress or physical disruption likely limited species colonization and survival.

Quantitative analysis using the Importance Value Index (IVI) demonstrated that *T. diversifolia* dominated both the disturbed (63.61) and moderately disturbed (37.38) sites, with a notably higher IVI in the disturbed area. This trend indicated its strong competitive ability, particularly under high disturbance conditions. Further, at the disturbed site, *O. hirtellus* (24.66) and *M. micrantha* (24.37) emerged as co-dominant species, reflecting their adaptability to frequent disturbance. Conversely, at the moderately disturbed site, *C. odorata* (14.55) and *M. micrantha* (14.19) co-

dominated with *T. diversifolia*, suggesting a paradigm shift in species composition with changing disturbance intensity. These patterns underscore how disturbance levels influence not only species dominance, but also the overall structure of plant communities.

The ecological indices further support the influence of disturbance intensity on plant community structure. The Simpson Index of Dominance was higher at the disturbed site (0.17), compared to the moderately disturbed site (0.08), indicating that a few species dominated the community under more intense disturbance. In contrast, the Shannon-Wiener Diversity Index revealed greater species diversity at the moderately disturbed site (3.22) than the disturbed site (2.46), aligning with the IDH. These findings suggest that moderate levels of disturbance create conditions favorable for a more balanced and diverse plant community, while high disturbance promotes dominance by a few opportunistic species, such as *T. diversifolia*. Overall, the study highlights the critical role of disturbance intensity in shaping species composition, dominance patterns, and biodiversity. The comparative analysis using Sorenson's similarity index indicates that the plant communities in the disturbed and moderately disturbed sites share limited overlap in species composition. This low similarity suggests that disturbance intensity plays a significant role in shaping plant community structure, thereby favouring different sets of species under varying environmental conditions. The findings further highlighted that even moderate changes in disturbance levels can lead to distinct ecological assemblages, underlining the importance of disturbance regimes in biodiversity management and conservation planning.

The seasonal variation in soil physico-chemical parameters across the disturbance gradient showed clear distinctions between disturbed and moderately disturbed sites. Higher soil moisture levels in moderately disturbed areas indicated better water retention, while greater water holding capacity (WHC) reflects improved soil structure and porosity. In addition to WHC, preliminary spot testing of soil at selected sites was done, especially in the context of soil texture. However, due to site specific constraints, such as the abundance of invasive alien plants at rock-soil/sediments boundaries, it was difficult to analyse texture, porosity, and bulk

density in long term. Moreover, the present work was focused more towards the chemical parameters, therefore major parameters were selected from this corner to describe the soil chemistry. In respect of spot testing of physical characteristics, the results revealed that the texture of the disturbed soil was identified as loamy, consisting of 42.6% sand, 43.6% silt, and 13.8% clay.

The texture at the moderately disturbed soil was also classified as loamy, consisting of 38.4% sand, 45.2% silt, and 16.4% clay. Therefore, in relation to soil texture, spot testing revealed slight differences, which may also be linked to differential success of invasive alien plants. In this respect, the soil at disturbed site seems to be more porous due to high sand and low clay content, when compared with soil of moderately disturbed site. Henceforth, the disturbed site may be more ideal for storage and dispersal of soil seed bank of specific invasive alien plants including *T. diversifolia*.

Although soil pH remained relatively stable across both sites, the disturbed site tended to be slightly more acidic, particularly post-monsoon periods. In relation to nutrients, 'soil organic carbon' (SOC) and 'soil organic matter' (SOM) were consistently higher at moderately disturbed sites. This suggested greater accumulation of organic material and more efficient nutrient cycling in areas with lower disturbance intensity. Available nitrogen levels fluctuated seasonally, which were generally observed higher at moderately disturbed sites, particularly during the pre-monsoon season, indicating better nutrient availability for plant growth. Similarly, available phosphorus and potassium levels were consistently greater at the moderately disturbed site, thereby confirming the enhanced nutrient retention and overall soil fertility. Both the disturbed and moderately disturbed sites soils were classified as loamy soil which make it suitable for the invasive alien plants like *T. diversifolia* to established well and penetrate the roots to the soil. The diversity indices showed that moderately disturbed site has higher diversity which may be attributed due to better soils health in terms of nutrients enrichment, when compared with heavily disturbed sites. The improved soil moisture, organic matter, and nutrient availability in moderately disturbed environments result to higher plant diversity and productivity, thereby validating the IDH. The disturbed site which has lower nutrient

availability could not support other plants to established well. Overall, results on the physico-chemical properties of soil results emphasize the ecological significance of maintaining moderate disturbance regimes to preserve soil health and biodiversity, besides for managing the spread of invasive alien plants.

The present study confirmed that the *T. diversifolia* remarkably influenced the growth parameters such as germination, plumule, radical, and biomass accumulation of *P. sativum* in plant debris soil bioassay, which was in fact dependent on fresh leaves aqueous extract (FLE) concentration. Seasonal soil bioassays using plant debris revealed that crop growth tends to improve during the post-monsoon period when *T. diversifolia* is in blooming stage and less plant debris accumulates in the soil, however it is suppressed during the pre-monsoon season, especially when decomposing debris is absorbed into the soil, thereby resulting in inhibition of crop development. The FLE experiment also demonstrated that *T. diversifolia* exhibits allelopathic properties, hence negatively impacting the bioassay plant i.e., *P. sativum*, when the concentration FLE is increased. The flowers of *T. diversifolia* were known to have higher allelochemicals especially phenols and tannins compared to the leaves. This suggested that the presence of *T. diversifolia* in the farmland and using leaves leachate of *T. diversifolia* as a biofertilizer in farms and agricultural systems could disrupt nutrient uptake in nearby crops, ultimately reducing growth, yield, and threatening food security. Therefore, farmers should exercise adequate caution when considering the use of *T. diversifolia* leaf leachates in agricultural systems. Overall, the findings support the role of ‘novel weapon hypothesis’ (NWH) as a key mechanism behind the invasive success of *T. diversifolia* in the Aizawl, Mizoram, Northeast (NE), India.

The questionnaire results reveal that public awareness and understanding of invasive alien plants remain generally low. Although most respondents claimed familiarity with the term "Invasive alien plant," their understanding did not extend to the wider ecological consequences, particularly the negative impacts these species can have on native vegetation. Some local people including marginal farmers consider *T. diversifolia* to be beneficial often referred to as “the farmer’s friend” while others fail to see any advantages, reflecting in fact a complex and mixed

societal perception on this plant invader. This variations in opinion showed limited awareness or close observation of how local plant life has changed over time. These contrasting views highlight the subjective nature of local perceptions and emphasize the need for more systematic ecological monitoring to accurately track the spread and impact of *T. diversifolia*. Moreover, the fact that most participants could not name any other invasive species points to a broader lack of awareness or concern about the issue of invasive alien plants within the community. This limited understanding suggests that invasive species are not widely recognized or discussed in local environmental conversations. In terms of control methods, some respondents reported using banned chemical i.e., DDT, however its use was not frequent. Further, this chemical is banned in many countries due to its serious environmental and health risks, indicating a gap in knowledge regarding safe and approved pest and weed control options. This highlights the need for community education to raise awareness about the ecological threats posed by invasive alien plants and to promote safe, and effective management strategies.

Effective management of *T. diversifolia* can be achieved by enhancing the species richness and diversity of native vegetation, particularly by introducing fast-growing, shade-tolerant native trees (*Mesua ferrea* L., *Artocarpus chaplasha* Buch-Ham., *Aquilaria agallocha*, *Acacia pennata*, *Clerodendrum colebrookianum* Walp., *Parkia roxburghii* G. Don, *Moringa oleifera* Lam. and *Podocarpus neriifolius* D.Don) and understory plants (*Amomum dealbatum* (Roxb.) Kuntze, *Canavalia cathartica* Thouars, *Colocasia esculanta* (L.), *Gnetum gnemon* Linn, *Hibiscus sabdariffa* L.). A diverse, dense, and intact native plant community helps close the forest canopy over time and strengthens the ecosystem ability to resist invasions by competing more effectively for essential resources like light, space, and nutrients. Ultimately, maintaining a healthy, continuous forest canopy and supporting native biodiversity are crucial strategies for controlling light penetration, thereby restricting the spread of *T. diversifolia*. These measures are vital for ecological restoration in urban fragmented forested landscape of Aizawl, Mizoram, Northeast (NE), India.

APPENDICES

Appendix I: Vegetative analysis at the disturbed site, Aizawl, Mizoram, Northeast (NE), India.

SI No.	Name of species	Quadrats										No. of individuals
		I	II	III	IV	V	VI	VII	VIII	IX	X	
1	<i>Tithonia diversifolia</i> (Hemsl.) A. Gray	40	75	167	177	109	90	51	90	54	81	934
2	<i>Ageratum conyzoides</i> (L.) L.	0	0	8	8	22	0	0	2	0	0	40
3	<i>Bidens pilosa</i> L.	4	0	0	0	0	15	0	0	0	10	29
4	<i>Calopogonium mucunoides</i> Desv.	0	25	0	0	0	0	0	0	0	0	25
5	<i>Centratherum punctatum</i> Cass.	0	0	0	0	0	0	0	2	0	0	2
6	<i>Chromolaena odorata</i> (L.) R.M. King & H. Rob.	21	0	11	13	7	4	10	42	15	0	123
7	<i>Commelina benghalensis</i> L.	0	0	0	0	0	3	0	3	10	0	16
8	<i>Crassocephalum crepidioides</i> (Benth.) S. Moore	0	0	0	1	0	0	0	0	0	0	1
9	<i>Debregeasia longifolia</i> (Burm.f.) Wedd.	1	0	0	0	0	0	0	0	0	0	1
10	<i>Dendrolobium triangulare</i> Muell.Arg	0	0	0	0	1	3	0	0	0	0	4
11	<i>Digitaria sanguinalis</i> (L.) Scop.	35	0	6	0	18	0	0	0	0	7	66
12	<i>Flueggea virosa</i> (Roxb. ex Willd.) Royle	0	0	0	0	0	3	5	2	4	0	14
13	<i>Galinsoga parviflora</i> (Cav.)	0	0	0	0	0	0	10	0	0	0	10
14	<i>Imperata cylindrica</i> (L.) P.Beauv.	0	5	0	0	7	0	0	12	0	0	24
15	<i>Ipomoea cairica</i> (L.) Sweet	0	4	0	0	17	0	0	0	0	56	77
16	<i>Koenigia polystachya</i> (Wall. ex Meisn.) T.M.Schust. &Reveal	0	0	0	0	0	0	0	0	10	0	10
17	<i>Lantana camara</i> L.	2	0	0	0	0	0	0	0	0	0	2
18	<i>Lolium perenne</i> L.	17	8	0	11	0	0	23	0	27	30	116
19	<i>Leucaena leucocephala</i> (Lam.) de Wit	1	0	3	5	1	0	0	0	0	0	10
20	<i>Mikania micrantha</i> Kunth	18	42	79	9	27	15	6	17	38	20	271
21	<i>Mimosa pudica</i> L.	0	13	10	29	5	1	10	15	0	0	83

22	<i>Mussaenda pubescens</i> Dryand	1	0	0	0	0	0	0	0	0	0	1
23	<i>Oplismenus hirtellus</i> (L.) P.Beauv	0	0	21	158	71	0	0	5	7	0	262
24	<i>Osmundastrum cinnamomeum</i> (L.) C.Persl	0	0	2	0	3	0	0	0	0	0	5
25	<i>Pachyrrhizus erosus</i> (L.) Urb.	0	0	13	0	0	0	0	0	0	0	13
26	<i>Paederia foetida</i> L.	0	0	0	0	0	4	0	0	0	0	4
27	<i>Panicum virgatum</i> L.	10	38	0	0	0	0	0	0	0	0	48
28	<i>Persicaria lapathifolia</i> (L.) Delarbre	0	0	0	0	0	0	0	0	5	0	5
29	<i>Passiflora foetida</i> L.	0	3	0	4	0	0	0	0	0	0	7
30	<i>Phyllanthus recticulatus</i> Poir.	10	0	0	0	0	0	0	0	0	0	10
31	<i>Pueraria montana</i> (Lour.) Merr	0	0	12	0	0	23	0	0	45	10	90
32	<i>Rubus moluccanus</i> L.	1	0	5	0	0	0	0	0	0	0	6
33	<i>Setaria palmifolia</i> (J.Koenig) Stapf	0	0	0	0	0	0	0	0	0	10	10
34	<i>Solanum nigrum</i> L.	0	0	0	0	0	0	0	2	0	0	2
35	<i>Solanum torvum</i> Sw.	0	0	4	2	0	0	0	9	0	0	15
36	<i>Sorghum halepense</i> (L.) Pers.	0	3	0	0	0	6	0	0	0	5	14
37	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	2	0	0	0	0	11	15	6	0	0	34
38	<i>Tagetes erecta</i> L.	0	0	0	0	0	20	0	0	0	0	20
39	<i>Thysanolaena maxima</i> (Roxb. ex Hornem.) Honda	0	0	0	0	0	30	24	0	0	0	54
40	<i>Urena lobata</i> L.	2	3	19	6	2	0	0	0	0	0	32

Appendix II: Vegetative analysis at the moderately disturbed site, Aizawl, Mizoram, Northeast (NE), India.

SI No.	Name of species	Quadrats										No. of individuals
		I	II	III	IV	V	VI	VII	VIII	IX	X	
1	<i>Tithonia diversifolia</i> (Hemsl.) A. Gray	62	75	93	130	112	79	68	96	56	66	614
2	<i>Adiantum pedatum</i> L.	0	0	0	0	0	0	0	20	0	0	20
3	<i>Ageratina adenophora</i> (Spreng.) R.M.King & H.Rob.	0	4	7	8	50	8	0	0	0	0	77
4	<i>Ageratum conyzoides</i> (L.) L.	18	22	21	2	0	0	8	0	0	0	71
5	<i>Amaranthus spinosus</i> L.	0	3	2	0	0	0	5	0	0	0	10
6	<i>Bidens pilosa</i> L.	23	0	3	8	8	35	30	0	13	0	120
7	<i>Boehmeria virgata</i> (G.Forst.) Guill.	0	3	0	0	0	0	20	12	0	0	35
8	<i>Bridelia tomentosa</i> Blume	0	0	2	1	0	0	0	0	0	0	3
9	<i>Calliandra houstoniana</i> (Mill.) Standl.	0	2	0	0	0	0	1	0	0	0	3
10	<i>Chloris gayana</i> Kunth	42	0	0	0	0	0	0	0	0	0	42
11	<i>Chromolaena odorata</i> (L.) R.M. King & H. Rob.	0	0	17	12	11	8	23	15	60	35	181
12	<i>Circaea lutetiana</i> L.	0	0	0	5	0	0	0	0	0	0	5
13	<i>Cissus discolor</i> Blume	0	1	0	0	0	0	0	0	0	0	1
14	<i>Clerodendrum infortunatum</i> L.	0	0	1	0	0	0	3	0	0	0	4
15	<i>Colocasia esculenta</i> (L.) Schott	0	0	0	1	0	0	1	0	0	2	4
16	<i>Commelina benghalensis</i> L.	4	0	6	3	5	0	0	14	0	0	32
17	<i>Cosmos bipinnatus</i> Cav.	0	0	0	0	0	0	48	0	0	0	48
18	<i>Curcuma longa</i> L.	0	6	0	0	0	0	0	0	0	0	6
19	<i>Cyperus rotundus</i> L.	0	4	0	24	0	0	0	50	12	0	90
20	<i>Cyperus strigosus</i> L.	1	0	0	7	0	0	10	0	6	0	24
21	<i>Dioscorea bulbifera</i> L.	9	0	0	3	0	0	0	0	0	0	12
22	<i>Erechtites minimus</i> (Poir.)	0	0	0	4	2	1	0	0	0	9	16
23	<i>Erigeron canadensis</i> L.	3	0	0	6	0	0	6	0	0	0	15

24	<i>Flueggea virosa</i> (Roxb. ex Willd.) Royle	0	0	0	0	7	0	0	5	0	0	12
25	<i>Galinsoga parviflora</i> (Cav.)	0	0	0	12	48	20	12	0	0	0	92
26	<i>Cheilocostus speciosus</i> (J.Konig) C.Specht	0	0	0	0	0	0	0	0	1	0	1
27	<i>Hypoestes phyllostachya</i> Baker	0	0	0	0	55	0	0	30	0	0	85
28	<i>Ipomoea cairica</i> (L.) Sweet	0	0	0	0	0	0	40	0	0	0	40
29	<i>Ipomoea hederifolia</i> L.	0	6	0	22	0	0	12	15	0	40	95
30	<i>Lantana camara</i> L.	0	0	0	0	0	3	16	0	0	0	19
31	<i>Laportea canadensis</i> (L.) Wedd.	0	0	0	0	0	0	0	0	48	0	48
32	<i>Leucaena leucocephala</i> (Lam.) de Wit	0	0	0	0	1	0	0	0	0	0	1
33	<i>Manihot esculenta</i> Crantz	0	0	0	0	0	0	0	1	0	0	1
34	<i>Miconia crenata</i> (Vahl) Michelang	0	16	0	2	11	0	0	20	0	0	49
35	<i>Mikania micrantha</i> Kunth	51	22	13	28	5	10	0	8	17	15	169
36	<i>Mimosa pudica</i> L.	26	0	0	0	0	0	0	0	0	0	26
37	<i>Musa paradisiaca</i> L.	0	0	0	0	2	0	0	0	0	0	2
38	<i>Oplismenus hirtellus</i> (L.) P.Beauv	0	16	18	0	0	0	0	0	0	0	34
39	<i>Osmundastrum cinnamomeum</i> (L.) C.Persl	4	12	0	0	0	0	0	3	0	4	23
40	<i>Panicum philadelphicum</i> Bernh. ex Trin.	0	0	0	44	0	0	0	0	0	0	44
41	<i>Panicum virgatum</i> L.	11	0	0	0	0	0	0	0	0	0	11
42	<i>Pennisetum purpureum</i> Schum.	0	4	0	0	6	0	0	0	12	0	22
43	<i>Pueraria montana</i> (Lour.) Merr	0	0	0	0	10	0	0	0	0	0	10
44	<i>Setaria palmifolia</i> (J.Koenig) Stapf	0	0	1	0	0	0	0	20	19	4	44
45	<i>Sida rhombifolia</i> L.	33	0	0	0	0	0	15	2	0	0	50
46	<i>Solanum nigrum</i> L.	0	1	0	0	2	0	0	2	0	0	5
47	<i>Solanum torvum</i> Sw.	2	0	0	0	5	0	0	0	0	0	7
48	<i>Sorghum halepense</i> (L.) Pers.	30	4	0	4	0	0	0	0	0	0	38
49	<i>Spermacoce latifolia</i> Aubl.	0	5	0	0	0	0	10	0	0	30	45
50	<i>Spilanthes acmella</i> (L.) L.	1	0	0	3	5	0	0	0	0	0	9

51	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	1	0	0	0	0	0	0	0	0	0	1
52	<i>Strobilanthes capitata</i> (Nees) T.Anderson	0	0	0	10	0	0	0	0	0	0	10
53	<i>Tagetes patula</i> L.	2	0	0	0	4	6	0	0	4	0	16
54	<i>Thysanolaena maxima</i> (Roxb. ex Hornem.) Honda	0	1	0	2	5	0	12	10	0	0	30
55	<i>Trifolium repens</i> L.	0	0	0	0	0	0	50	0	0	0	50
56	<i>Urena lobata</i> L.	0	5	0	2	0	0	1	0	18	5	31
57	<i>Vigna unguiculata</i> L. Walp	1	0	1	0	0	4	0	0	3	4	13

Appendix III: Pearson correlation coefficient (r) values between soil parameters for two years data at disturbed site, Aizawl, Mizoram, Northeast (NE), India.

	<i>Soil moisture content</i>	<i>WHC</i>	<i>pH</i>	<i>SOC</i>	<i>SOM</i>	<i>Available Nitrogen</i>	<i>Available Phosphorus</i>	<i>Available Potassium</i>
Soil moisture content	1							
WHC	0.496	1						
pH	0.254	0.212	1					
SOC	0.067	-0.704*	0.408	1				
SOM	0.100	-0.662*	0.480	0.993**	1			
Available Nitrogen	-0.398	-0.576*	0.484	0.617*	0.666*	1		
Available Phosphorus	0.830**	0.453	-0.027	-0.088	-0.075	-0.370	1	
Available Potassium	-0.408	-0.361	-0.890**	-0.224	-0.308	-0.228	0.039	1

* Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level

Appendix IV: Pearson correlation coefficient (r) values between soil parameters for two years data at moderately disturbed site, Aizawl, Mizoram, Northeast (NE), India.

	<i>Soil moisture content</i>	<i>WHC</i>	<i>pH</i>	<i>SOC</i>	<i>SOM</i>	<i>Available Nitrogen</i>	<i>Available Phosphorus</i>	<i>Available Potassium</i>
Soil moisture content	1							
WHC	0.328	1						
pH	-0.691*	-0.162	1					
SOC	0.541*	0.173	-0.879**	1				
SOM	0.540*	0.172	-0.880**	1.000**	1			
Available Nitrogen	-0.522*	-0.340	0.316	-0.258	-0.256	1		
Available Phosphorus	0.166	0.212	0.090	-0.496	-0.496	-0.425	1	
Available Potassium	-0.432	0.155	-0.122	0.463	0.463	0.245	-0.703*	1

* Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level

Appendix V: Two-way ANOVA for soil moisture content as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	198.4533	1	198.4533	14.42985	0.012646	6.607891
Between sites	326.7256	5	65.34511	4.751344	0.056166	5.050329
Error	68.76487	5	13.75297			
Total	593.9438	11				

Appendix VI: Two-way ANOVA for WHC of soil as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	335.8092	1	335.8092	9.054858	0.029785	6.607891
Between sites	1008.6681	5	201.7336	5.439605	0.0433	5.050329
Error	185.4304	5	37.08608			
Total	1529.9077	11				

Appendix VII: Two-way ANOVA for pH of soil as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	0.021675	1	0.021675	0.378834	0.565161	6.607891
Between sites	0.483475	5	0.096695	1.690029	0.289357	5.050329
Error	0.286075	5	0.057215			
Total	0.791225	11				

Appendix VIII: Two-way ANOVA for SOC as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	4.344033	1	4.344033	11.35477	0.019897	6.607891
Between sites	3.428767	5	0.685753	1.792476	0.268694	5.050329
Error	1.912867	5	0.382573			
Total	9.685667	11				

Appendix IX: Two-way ANOVA for soil organic matter as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	13.33521	1	13.33521	10.75673	0.021961	6.607891
Between sites	9.647875	5	1.929575	1.556475	0.31958	5.050329
Error	6.198542	5	1.239708			
Total	29.18163	11				

Appendix X: Two-way ANOVA for soil available nitrogen as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	1688.627	1	1688.627	0.451592	0.531376	6.607891
Between sites	122288.8	5	24457.75	6.540776	0.029977	5.050329
Error	18696.37	5	3739.274			
Total	142673.8	11				

Appendix XI: Two-way ANOVA for soil available phosphorus as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	188.1792	1	188.1792	6.665269	0.049329	6.607891
Between sites	645.4168	5	129.0834	4.572106	0.06038	5.050329
Error	141.164	5	28.2328			
Total	974.76	11				

Appendix XII: Two-way ANOVA for soil available potassium as a function of variation between different seasons and variation among different sites.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	88212.74	1	88212.74	13.06169	0.015314	6.607891
Between sites	71192.78	5	14238.56	2.108307	0.216207	5.050329
Error	33767.74	5	6753.548			
Total	193173.3	11				

Appendix XIII: Two-way ANOVA for seed germination as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	169.5556	2	84.77778	3.468182	0.133775	6.944272
Between sites	330.8889	2	165.4444	6.768182	0.052028	6.944272
Error	97.77778	4	24.44444			
Total	598.2222	8				

Appendix XIV: Two-way ANOVA for seedling height as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	83.150288	2	41.575144	0.46443	0.658608	6.944272
Between sites	176.729688	2	88.364844	0.987111	0.448288	6.944272
Error	358.074777	4	89.518694			2
Total	617.954755	8				

Appendix XV: Two-way ANOVA for root length as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	5.060622	2	2.530311	8.539373	0.03601	6.944272
Between sites	25.93682	2	12.96841	43.7662	1	6.944272
Error	1.185244	4	0.296311		0.00191	2
Total	32.18269	8				

Appendix XVI: Two-way ANOVA for shoot length as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	90.462022	2	45.231011	1.941313	0.2575	6.944272
Between sites	350.854155	2	175.427077	7.529324	0.044049	6.944272
Error	93.196711	4	23.299177			

Total	534.5128889	8
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Appendix XVII: Two-way ANOVA for seedling biomass as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	0.211667	2	0.105833	2.705582	0.180648	6.944272
Between sites	0.174867	2	0.087433	2.235194	0.223004	6.944272
Error	0.156467	4	0.039117			
Total	0.543	8				

Appendix XVIII: Two-way ANOVA for germination percentage as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	1884.212356	2	942.106177	3.469523	0.133709	6.944272
Between sites	3676.353089	2	1838.17654	6.769508	0.052013	6.944272
Error	1086.150644	4	271.537661			
Total	6646.716089	8				

Appendix XIX: Two-way ANOVA for germination potential as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	0.226689	2	0.113344	2.967564	0.162096	6.944272
Between sites	0.094156	2	0.047078	1.232582	0.38279	6.944272
Error	0.152778	4	0.038194			
Total	0.473622	8				

Appendix XX: Two-way ANOVA for germination index as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	1.105088	2	0.552544	2.888198	0.167403	6.944272
Between sites	1.880088	2	0.940044	4.913694	0.083683	6.944272
Error	0.765244	4	0.191311			

Total	3.750422	8
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Appendix XXI: Two-way ANOVA for germination rate index as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	0.798689	2	0.399344	2.690195	0.181835	6.944272
Between sites	1.398822	2	0.699411	4.711602	0.088799	6.944272
Error	0.593778	4	0.148444			
Total	2.791289	8				

Appendix XXII: Two-way ANOVA for vigor index as a function of variation between different seasons and variation among different treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between seasons	0.2196	2	0.1098	0.252723	0.798261	19
Between sites	0.828816	1	0.828816	1.907664	0.301297	18.51282
Error	0.868933	2	0.434466			
Total	1.91735	5				

Appendix XXIII: Allelopathic effects of *T. diversifolia* debris-soil bioassay on different growth parameters of *P. sativum*.

Parameters		Control			Experimental pot 1			Experimental pot 2		
		Pre-Monsoon	Monsoon	Post-Monsoon	Pre-Monsoon	Monsoon	Post-Monsoon	Pre-Monsoon	Monsoon	Post-Monsoon
Germination	3rd	14±0.58	17±2.52	20±1.53	3±0.00	7±1.53	21±1.00	17±0.58	11±2.08	13±0.58
	7th	23±0.58	27±1.00	29±0.58	12±1.00	8±1.53	28±0.58	15±1.00	12±2.00	30±0.00
Seedling height (SH)		22.94±2.33	28.81±3.74	34.08±1.47	19.87±1.52	34.35±5.44	42.02±3.93	20.54±1.12	44.08±3.52	41.67±2.73
Root Length (RL)		5.32±0.48	9.58±2.47	8.58±1.76	4.18±1.04	6.8±0.57	7.02±0.83	4.24±0.34	8.73±0.85	8.27±0.9
Shoot Length (SL)		17.62±1.87	19.23±1.28	25.5±0.97	15.69±1.23	27.55±4.88	35.00±4.65	16.3±1.18	35.35±2.73	33.40±2.06
Seedling Biomass (B)		0.64±0.05	0.71±0.09	0.85±0.11	0.6±0.05	0.66±0.21	0.89±0.15	0.67±0.07	1.39±0.17	1.09±0.03
Germination percentage (GPe)		76.67±5.77	90±10	96.67±5.77	40±10.00	26.67±15.28	93.33±5.77	50±10.00	40±20	100.00±0.00
Germination Potential (Gpo)		0.80±0.61	0.57±0.25	0.67±0.15	0.1±0.00	0.23±0.15	0.70±0.10	0.23±0.06	0.37±0.21	0.43±0.06
Germination Index (GI)		1.56±0.20	1.89±0.84	2.22±0.51	0.33±0.00	0.78±0.51	2.33±0.34	0.78±0.19	1.22±0.69	1.44±0.20
Germination Rate Index (GRI)		0.73±0.17	1.21±0.92	1.53±0.66	0.03±0.00	0.23±0.26	1.65±0.47	0.19±0.10	0.54±0.58	0.63±0.17
Vigor Index (VI)		1±0.19	1.37±0.69	1.88±0.45	0.2±0.02	0.32±0.34	2.09±0.59	0.51±0.08	1.62±0.73	1.57±0.25

Appendix XXIV: Allelopathic effects of *T. diversifolia* fresh leaves aqueous extracts (FLE) on different growth parameters of *P. sativum*.

Concentration	Germinated Seeds (in % of control)	Radicle Length (in % of control)	Biomass (in % of control)	Plumule Length (in % of control)
Control	100±0	100±00.50	100±2.81	100±0±0.06
12.5g/L-1	-20±0	-17.69±0.87	-17.68±0.07	-85.11±0.71
25g/L-1	-23.33±0.58	-20.07±0.54	-28.73±0.02	-86.63±0.05
37.5g/L-1	-36.67±1.15	-23.13±0.90	-23.2±0.04	-86.02±0.27
50g/L-1	-60±4	-23.81±1.04	-67.4±0.25	-91.19±0.06

Appendix XXV: Pearson correlation coefficient (r) values between growth parameters for plant soil-debris bioassay.

	<i>Germination 3rd</i>	<i>Germination 7th</i>	<i>Seedling height (SH)</i>	<i>Root Length (RL)</i>	<i>Shoot Length (SL)</i>	<i>Seedling Biomass (B)</i>	<i>Germination percentage (GPe)</i>	<i>Germination Potential (GPo)</i>	<i>Germination Index (GI)</i>	<i>Germination Rate Index (GRI)</i>	<i>Vigor Index (VI)</i>
Germination 3rd	1										
Germination 7th	0.654*	1									
Seedling height (SH)	0.355	0.460	1								
Root Length (RL)	0.193	0.345	0.967**	1							
Shoot Length (SL)	0.387	0.480	0.999**	0.952**	1						
Seedling Biomass (B)	0.234	0.288	0.799*	0.857**	0.779*	1					
Germination percentage (GPe)	0.654*	1.000**	0.460	0.345	0.480	0.288	1				
Germination Potential (GPo)	0.795*	0.764*	0.755*	0.580	0.786*	0.471	0.764*	1			
Germination Index (GI)	0.799*	0.767*	0.752*	0.577	0.783*	0.463	0.767*	1.000**	1		
Germination Rate Index (GRI)	0.754*	0.719*	0.664*	0.459	0.702*	0.348	0.719*	0.979**	0.978**	1	
Vigor Index (VI)	0.682*	0.737*	0.840**	0.730*	0.856**	0.745*	0.737*	0.928**	0.924**	0.871**	1

* Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level

Appendix XXVI: Pearson correlation coefficient (r) values between growth parameters for plant leave aqueous extract (FLE).

	<i>Concentration (mg/L)</i>	<i>No. of germinated seeds</i>	<i>Radicle length (cm)</i>	<i>Seedling biomass (g)</i>	<i>Plumule length (cm)</i>
Concentration(mg/L)	1				
No. of germinated seeds	-0.948**	1			
Radicle length (cm)	-0.822**	0.914**	1		
Seedling biomass (g)	-0.841**	0.921**	0.999**	1	
Plumule length (cm)	-0.975**	0.869**	0.675*	0.700*	1

* Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level

Appendix XXVII: One-way ANOVA for seed germination as a function of variation between

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between treatments	276.125	1	276.125	1.903763	0.216872	5.987378
Within treatments	870.25	6	145.0417			
Total	1146.375	7				

and within treatments.

Appendix XXVIII: One-way ANOVA for radicle length as a function of variation between
and within treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between treatments	1666.954	1	1666.954	12.76952	0.011735	5.987378
Within treatments	783.25	6	130.5417			
Total	2450.204	7				

Appendix XXIX: One-way ANOVA for seedling biomass as a function of variation between
and within treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between treatments	1900.978	1	1900.978	14.59906	0.008752	5.987378
Within treatments	781.2738	6	130.2123			
Total	2682.252	7				

Appendix XXX: One-way ANOVA for plumule length as a function of variation between
and within treatments.

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between treatments	1674.179	1	1674.179	12.85735	0.011563	5.987378
Within treatments	781.2709	6	130.2118			
Total	2455.45	7				

Appendix XXXI: Quantitative analysis of alleochemical contents of *T. diversifolia* by Gallic acid

Parameters	Leaves	Flowers
Total phenol	12.65 ± 0.37	35.26 ± 1.02
Tannins	16 ± 2.18	67.47 ± 1.46

Appendix XXXII: Demographic profile of questionnaire respondents (n=100).

VARIABLE	CATEGORY	NUMBER OF RESPONSES	PERCENTAGE (%)
Age	≤10 years	0	0
	11-20 years	47	47
	21-30 years	28	28
	31-40 years	7	7
	41-50 years	10	10
	≥51 years	8	8
Gender	Male	45	45
	Female	55	55
Education Level	Middle school	4	4
	High school	11	11
	Higher secondary school	48	48
	Bachelor degree	12	12
	Master degree	20	20
	Others	5	5
Occupation	Students	65	65
	Farmers	14	14
	Govt. Servant	9	9
	Others*	12	12
District Wise participants	Aizawl	46	46
	Lunglei	11	11
	Siaha	14	14
	Champhai	1	1
	Kolasib	19	19
	Lawngtlai	1	1
	Mamit	3	3
	Hnahthial	1	1
	Khawzawl	1	1
	Serchhip	1	1
	Saitual	2	2

*Others include: Driver, housewife, business owner, electrician, labour, and storekeeper



Questionnaire for Socio-Economic and Livelihood Survey
Department of Environmental Science, Mizoram University

Sl. No:

Only for residents of Mizoram

Name: _____

Address with district: _____

Age: _____ Gender: _____

Occupation: _____ Education: _____

Today's Date: ____/____/____



Tithonia diversifolia

(Bawngpu par)

Instruction: Please put a tick ☒ in the given box next to the answer of your choice or write in the space provided as the case may be. *Your personal information is confidential.*

1) Have you ever come across the name *Tithonia diversifolia* (vernacular name **Bawngpu par**)? Yes ☐ No ☐

2) Since when did you start noticing *T. diversifolia* arrive in your area (year)?

3) Do you think *T. diversifolia* is a native species in Mizoram? Yes ☐ No ☐

If yes, please specify: _____

4). Do you know what is an invasive species (Species with rapid growth rates, extensive dispersal capabilities, large and rapid reproductive output, and broad environmental tolerance)? Yes ☐ No ☐

5). Do you think *T. diversifolia* is an invasive species? Yes ☐ No ☐

If Yes, what may be the potential factors (reasons) for the spread of *T. diversifolia*?

- a) Forest closure ☐
- b) Seed dispersal due to wind ☐
- c) Lack of management ☐
- d) Human activity ☐
- e) Dispersal by wild animals ☐
- f) Climate change ☐

g) Others:

6) Do you think *T. diversifolia* invasion have (**Choose only ONE**):

- a) Positive Impact ☐
- b) Negative Impacts ☐
- c) Both Positive and Negative ☐
- d) No Impacts ☐

7) Do you **use** *T. diversifolia* for: -

a) Economic purposes (monetary benefits) Yes ☐ No ☐

If yes, please specify:

b) Medicinal purposes Yes ☐ No ☐

If yes, please specify:

c) Fodder (food) for livestock Yes ☐ No ☐

If yes, which animal:

d) Soil erosion control Yes ☐ No ☐

If yes, please specify:

e) Pest and weed control Yes ☐ No ☐

If yes, please specify:

f) Manure/compose Yes ☐ No ☐

If yes, please specify:

g) Ornamental or decoration purposes Yes ☐ No ☐

If yes, please specify:

8) Do you think *T. diversifolia* it enriches the soil fertility? Yes ☐ No ☐

Please specify: _____

9) Do you think *T. diversifolia* impact forest and wildlife? Yes ☐ No ☐

10) Does *T. diversifolia* cause problems to the agriculturist? Yes ☐ No ☐

If yes, please specify: _____

11) Does *T. diversifolia* invade the agricultural crops? Yes ☐ No ☐

If yes, please specify: _____

12) What are the most effected crops in *T. diversifolia* prevalent area?

Please specify: _____

13) Which method do you use to control *T. diversifolia*?

Please specify: _____

14) From your opinion, what will be the most *suitable and sustainable option or method* control and management of *T. diversifolia*?

a) Physical/mechanical control ☐

Please specify: _____

b) Chemical control ☐

Please specify: _____

c) Biological control ☐

Please specify: _____

15) Do you think *T. diversifolia* is (**Choose only ONE**):

a) Increasing day by day ☐

b) Decreasing ☐

c) Same ☐

d) Cannot say ☐

16) Do you think *T. diversifolia* needs to control and manage for future aspects? Yes ☐
No ☐

Please specify: _____

17) Do you know any other invasive alien plants (IAPs) (*You can write in your local name*)?
Yes ☐ No ☐

If yes, please name: _____

18) Does others IAPs grow along with the *T. diversifolia* (*You can write in your local name*)?
Yes ☐ No ☐

If yes, please name: _____

Remarks _____

Thank you for your kind cooperation.

Vanlalruati

Research Scholar

Department of Environmental Science, MZU

PHOTOPLATES

1. Some photos of the plants captured during vegetative analysis



Tithonia diversifolia



Setaria palmifolia



Galinsoga parviflora



Centratherum punctatum



Mimosa pudica



Passiflora foetida



Commelina benghalensis



Ipomoea cairica



Ipomoea hederifolia



Dioscorea bulbifera



Adiantum viridimontanum



Erigeron canadensis



Oplismenus hirtellus



Stachytarpheta cayennensis



Persicaria lapathifolia



Colocasia esculenta



Hypoestes phyllostachya



Ageratina adenophora



Urena lobata



Sida rhombifolia



Solanum nigrum



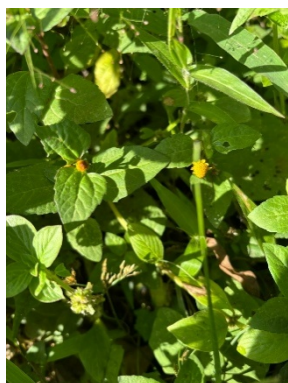
Mikania micrantha



Chromolaena odorata



Lantana camara



Spilanthes acmella



Crassocephalum crepidioides



Manihot esculenta

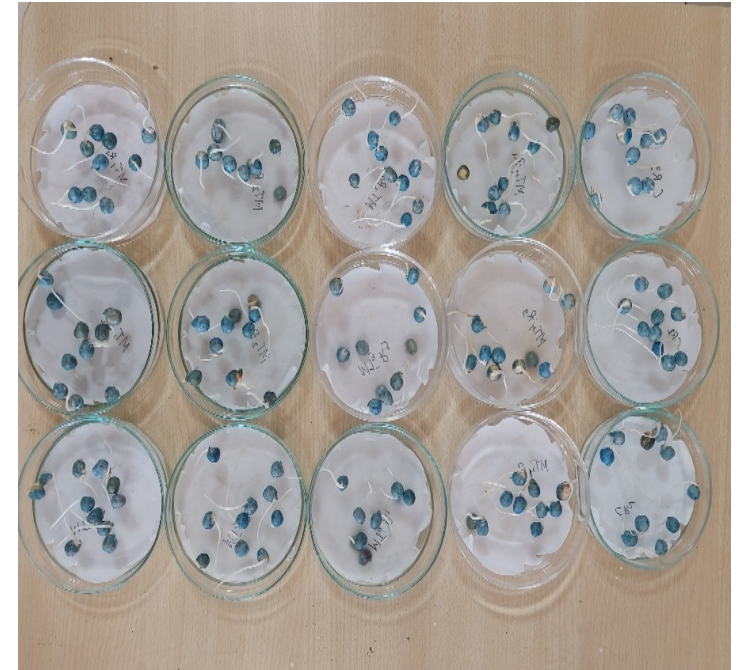
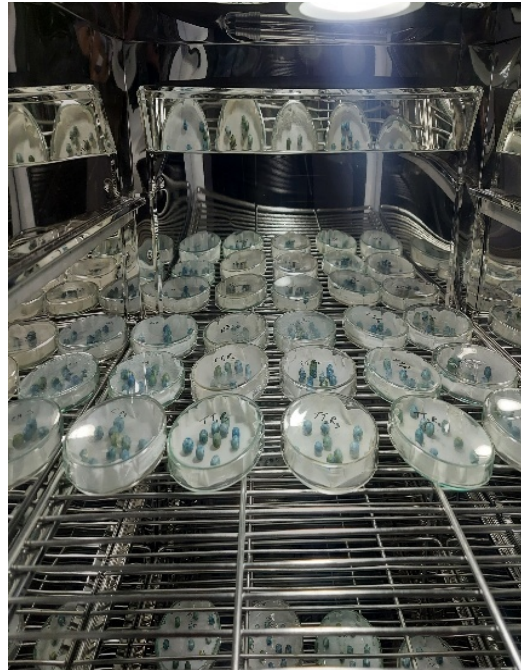


Ageratum conyzoides

2. Experimental stages during plant debris-soil bioassay



3. Various stages of aqueous leaves extract (FLE) experiment



4. Stages during allelochemical analysis: Methanol extraction with rotary evaporator and preparation of gallic acid standard



5. *T. diversifolia* distributed area in Aizawl, Mizoram



Zuangtui to Selesih road



Durtlang



Zuangtui



Durtlang leitan



Thuampui

6. *T. diversifolia* distributed area in different district of Mizoram



Mamit district (Photo courtesy: Rinchhani)



Siaha town (Photo courtesy: Gospel Thihlum)



Serchhip district (Photo courtesy: Awmtei)



Banana plantation in Siaha district (Photo courtesy: Hruaia Kompa)



Lunglei district (Photo courtesy: Lawmawmi)

7. Instruments used for measuring canopy openness during the study period



Garmin GPSMAP 64s



Fisheye lens (Skyvik Signi One 10mm)



Handheld instrument for measuring Leaf Area Index (LAI) from Kaizen Imperial



Handheld quantum sensors from Apogee instruments

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2	HSSLC	MBSE	2013
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4	M.Sc	MZU	2019
5	M.Phil	MZU	2022

List of Publications

- 1 Vanlalruati, Rai, P. K., Lalzarzovi, S. T., and Syngkli, R. B. (2025). Allelopathy of invasive *Tithonia diversifolia* (Hemsl.) A. Gray and its linkage with canopy gaps in a biodiversity hotspot. *Plant Science Today*, 12 (4). <https://doi.org/10.14719/pst.8615>
- 2 Vanlalruati., Rai, R. K., and Syngkli, R. B. (2025). Allelopathic Effects of Invasive Alien Plant *Tithonia divesifolia* (Hemsl.) A. Gray on *Pisum sativum* L. *International Journal of Plant and Environment*, 11(3), 623-629, <https://doi.org/10.18811/ijpen.v11i03.21>
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List of presentation presented in conferences

- 1 The positive and negative socio-economic implications of *Tithonia diversifolia* invasion in Aizawl, Mizoram on “Three days International Conference on Environmental Hazards in Mountainous Regions: Problems and Prospects” held on 21-23rd February, 2024
- 2 Societal perception on the mode of introduction and management option of *Tithonia diversifolia* invasion in Aizawl, Mizoram NE India on The International Conference on “Climate Change and Natural Resources Management for Sustainable Development” held on 13-15th March, 2024



RESEARCH ARTICLE

Allelopathy of invasive *Tithonia diversifolia* (Hemsl) A. Gray on *Pisum sativum* L. and its linkage with canopy openness in a global biodiversity hotspot

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Received: 01 March 2025; Accepted: 28 August 2025; Available online: Version 1.0: 05 November 2025

Cite this article: Vanlalruati, Prabhat KR, Lalzarzovi ST, Roger BS. Allelopathy of invasive *Tithonia diversifolia* (Hemsl) A. Gray on *Pisum sativum* L. and its linkage with canopy openness in a global biodiversity hotspot. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.8615>

Abstract

Allelochemicals are the secondary metabolites present in the leaves or other parts of the invasive alien plants that can either stimulate or inhibit the development of the native plants. To this end, an emerging invasive plant, i.e., *Tithonia diversifolia* from Asteraceae is inadequately explored in terms of allelopathy, especially in relation to its influence on the germination and growth of edible crops. Thus, the present study aims to study its allelopathic effect on common bioassay crop i.e., *Pisum sativum*, grown in Mizoram to help validate the 'novel weapon hypothesis (NWH)'. In addition, the ecological investigation was performed with respect to the canopy openness, leaf area index (LAI) and photosynthetically active radiation (PAR) as they can be inextricably linked with invasive spread and modulation of allelopathy. Results showed that with increase in the concentration of *T. diversifolia* derived fresh leaves aqueous extracts (FLE), the growth parameters (rate of seed germination, seed radicle, seed plumule and biomass) of *P. sativum* decreases, which may be ascribed to the inhibitory effect of allelochemicals. Last, the study also observed that the higher canopy openness facilitates the spread of *T. diversifolia* due to high light availability, while the lower canopy gaps restrict the growth of *T. diversifolia*. Henceforth, in control/containment perspective, the sustenance of intact canopy can sustainably manage and reduce the *T. diversifolia* infestation in agriculture systems by alleviating its field allelopathic effects on edible crops, thereby help maintain crop yield and food security.

Keywords: allelopathy; bioassay; canopy openness; edible crops; invasive alien plants; sustainable management

Introduction

In Anthropocene, ecological issues such as habitat destruction and ecological alteration can arise the introduction of invasive alien plant species into novel introduced habitats which in turn leads to biodiversity erosion, loss of ecosystem services and species extinction (1-3). Release of allelochemical *via* multiple mechanisms is one way that could affect native plants or edible crops, mediated by perturbation in physiological functions, such as growth, germination, photosynthesis, respiration, water and hormone balance of nearby edible crops (4, 5). Interestingly, allelopathy can either stimulate or inhibit the development of native plants (*Medicago sativa* L.) and agricultural crops (*Zea mays* L.) of nutritional value through the release of secondary metabolic compounds or allelochemicals (6). The allelochemicals are generally water soluble and are emitted into the environment by the process of volatilization, leaching, root exudation and decomposition of plant residues (7, 8). Invasive alien plants derived allelochemicals are produced as secondary metabolites, which remarkably modulate the chemical ecology, invasive spread and vegetation dynamics (9-11). Previous works reported that the majority of allelochemicals are found in leaves or other parts of the invasive alien plants (12). Moreover, quantification and detection of allelochemicals (minor compounds) were quite obscure due to their complex and intricate

nature (12). Therefore, previous studies recommended the use of bioassay crop plants, which are more sensitive than chemical methods and are further linked with crop yield and food security (12, 13). In this respect, model bioassay crops can manifest sensitivity in terms of morphological, physiological and biochemical changes, unlike chemical quantification (13). Moreover, the elucidation of mechanism linked with allelopathy can help achieve sustainable management of this invasive alien plant.

The Asteraceae family comprises of many invasive alien plants and weeds, which are enriched with multiple allelochemicals that can perturb ecosystem functioning and agricultural productivity (14). From this family, *Tithonia diversifolia* (Hemsl.) A. Gray is an emerging invasive plant due to its aggressive growth rate and heavy seed production, especially in an Indo Burma global biodiversity hotspot of immense ecological importance (15-17). They are known to exhibit allelopathy by exerting both stimulatory and inhibitory or phytotoxic attributes which are widely described in South African, Chinese and Indian Himalayan Region (18-21). In this respect, past studies observed that the root exudates of *T. diversifolia* is known to inhibit the germination, growth and chlorophyll accumulation of tomato; however, the impacts of leaves extracts were not elucidated (22). Further, a recent study also reported that the increase in concentration of aqueous extract of the plant parts of *T. diversifolia*

Allelopathic Effects of Invasive Alien Plant *Tithonia diversifolia* (Hemsl.) A. Gray on *Pisum sativum* L.

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DOI: 10.18811/ijpen.v11i03.21

ABSTRACT

The essential factors for the success of invasive alien plants are considered to be the presence of allelochemicals, which are considered “novel weapons”. The allelochemicals released by invasive plants interact differently with each other, especially native and endemic diversity, and also serve as a biological defense against plant diseases and pathogens. To this end, *Tithonia diversifolia* (Hemsl.) A. Gray, an emerging invasive alien plant in the northeastern (NE) Himalayas, is scantily investigated in terms of exhibiting allelopathy, despite being an aggressive weed in Mizoram, NE India. Especially, their effects on widely edible crops need to be studied because of their inextricable linkage with food productivity and rural livelihood. Thus, the present investigation was carried out on the allelopathic effects of *T. diversifolia*, based on the physical parameters such as SH, RL, SL, B, GPe, GPo, GI, GRI and VI on the selected common crop *Pisum sativum* L. through a pot bioassay experiment. In this respect, two highly invaded sites of *T. diversifolia* were selected for the collection of soil samples based on the variable disturbance factors. The present result concluded that *T. diversifolia* has strong stimulatory allelopathic effects on the growth parameters of *P. sativum* at the initial stage of the seed germination; however, it tends to normalize at the later stage of germination. The infested soil of *T. diversifolia* was observed to be suitable for growing food crops, although it may take longer to germinate due to the allelopathic effect of *T. diversifolia*. Nevertheless, wise utilization of the leaf leachates may enhance soil fertility for better production of food crops and facilitate sustainable agriculture.

Keywords: Novel weapon hypothesis, Secondary metabolites, *Pisum sativum*, Allelopathy, Seed germination.

Highlights

- The novel allelopathic compounds act as a weapon to inhibit and stimulate the growth/development of native plants or edible food crops.
- *T. diversifolia* is enriched with allelochemicals, is an emerging invasive alien plant in NE India, but with limited studies on allelopathy.
- To know the allelopathic effect of *T. diversifolia* on a crop (*Pisum sativum* L.), a pot bioassay was conducted.
- *T. diversifolia* showed strong stimulatory allelopathic effects at the initial stage on the growth of *P. sativum*.

International Journal of Plant and Environment (2025);

ISSN: 2454-1117 (Print), 2455-202X (Online)

INTRODUCTION

The lack of natural enemies, i.e., “enemy release hypothesis,” and the introduction of novel allelopathic compounds give invasive alien plants a competitive advantage to disrupt native ecosystems and crops (Blumenthal *et al.*, 2003; Lenda *et al.*, 2023). The disturbed environments, which underwent forest fire, burning through shifting cultivation and waterlogged or flooded, made agricultural ecosystems as well as urbanized habitats more susceptible to invasion (Callaway and Ridenour, 2004; Brasseur *et al.*, 2024). Transportation infrastructures (such as roads or railways) also facilitate the abrupt spread of invasive alien plants (Callaway and Ridenour, 2004; Syngkli *et al.*, 2025). The biological properties highly affected the successful spread of invasive alien plant species (Rai and Singh, 2020). To this end, the allelochemical compounds in invasive plants in fact act as novel weapons (linked with “Novel weapon hypothesis”) to suppress native indigenous plants and edible crops (Callaway and Ridenour, 2004; Syngkli and Rai, 2024).

One of the most essential factors in the success of invasive alien plants is considered to be the presence of allelochemicals, which are considered novel weapons against native plants and food crops (Chengxu *et al.*, 2011; Syed *et al.*, 2021). These

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How to cite this article: Vanlalruati, Rai, R.K., Syngkli, R.B. (2025). Allelopathic Effects of Invasive Alien Plant *Tithonia diversifolia* (Hemsl.) A. Gray on *Pisum sativum* L. *International Journal of Plant and Environment*. 11(3), 623-629.

Submitted: 27/09/2024 **Accepted:** 05/06/2025 **Published:** 30/09/2025

allelochemicals are the secondary metabolites produced in the environment by organisms or a plant invader, which can inhibit or enhance the growth of other nearby native plants or food crops (Syngkli *et al.*, 2022a) as *T. diversifolia* is known to have secondary metabolites such as sesquiterpenoids, terpenoids, flavonoids, tannins and saponins (Zhou *et al.*, 2013; Noguchi, 2020 and Omolola, 2020), their allelopathic effects need to be



RESEARCH ARTICLE

Effects of canopy openness on diversity and distribution of invasive alien plants in an Indo-Burma biodiversity hotspot region

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Received: 26 March 2025; Accepted: 11 June 2025; Available online: Version 1.0: 31 October 2025

Cite this article: Sarah L, Prabhat KR, Roger BS, Vanlalruati, Lalzarzovi ST. Effects of canopy openness on diversity and distribution of invasive alien plants in an Indo-Burma biodiversity hotspot region. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.8528>

Abstract

Invasive alien plants (IAPs) perturb the ecosystem functioning and endanger plant biodiversity, which is inadequately explored in global biodiversity hotspots. The present study, therefore, aimed to analyze the vegetation dynamics and plant diversity in the urban forest of Aizawl, Mizoram, an integral landscape of the Indo-Burma biodiversity hotspot. The study was conducted from 2020 to 2023. We evaluated the phytosociology of IAPs along the anthropogenic disturbance gradient (highly disturbed, moderately disturbed and less disturbed sites), which were distinct in the urban forest. We also investigate the ecology of IAPs in the area by determining habitat attributes such as forest canopy openness, leaf area index (LAI) and photosynthetically active radiation (PAR). LAI is the total surface area of leaves per unit of ground area ($\text{m}^2 \text{m}^{-2}$) and PAR is the portion of the electromagnetic spectrum (400-700 nm) that green plants may employ to power their photosynthesis. Moderately disturbed site recorded the highest number of plant individuals ($n = 1158$) with an importance value index (IVI) ranging from 1.60 to 32.16. Further, the disturbed site recorded a total of $n = 595$ plant individuals with IVI ranging from 2.09 to 31.38. Whereas the less disturbed site has the least plant individuals ($n = 146$) with IVI ranging from 7.89 to 36.53. Notably, IAPs such as *Ageratum conizoides* L., *Calypocarpus vialis* Less., *Chromolaena odorata* (L.) R.M. King & H. Rob. have the highest IVI at all sites. The canopy openness was more pronounced in disturbed habitats (87.42 %) when compared with moderately disturbed (25.92 %) and less disturbed (37.24 %) habitats. Maintaining the intact forest canopy by increasing native plant species richness and less human intervention on the pristine environment can result in sustainable management of IAPs. Therefore, sustenance of dense canopy regulate the invasive spread and alteration of species dynamics of biodiversity hotspot region.

Keywords: canopy openness; diversity indices; importance value index; invasive alien plants; leaf area index; photosynthetically active radiation

Introduction

Invasive alien plants (IAPs) are one of the major threats in the Anthropocene, which disrupts the homeostasis of the biosphere, perturbs environmental sustainability and jeopardizes the achievement of United Nations Sustainable Development Goals (SDGs) (1, 2). Plant invasion threatens human survival and negatively impacts ecosystem health and biodiversity in several ways (3, 4). Globalization, urbanization and population growth of humans have led to an alarming increase in biological invasions (5, 6). These invasions have complex effects on biogeographic realms, native species abundance, extinction risk and genetic composition (7). It is often noticeable only when IAPs are well-established, colonized, become abundant and attain landscape spread (8). India is well known for its rich plant diversity, which is highly influenced by the country's diverse topography, climate and ecosystems. India is also home to many IAPs 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 (6, 9). 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 (10, 11). Therefore, understanding which alien species will naturalize and increase or which alien species will adversely impact biodiversity or other resources is one of the main challenges associated with invasion ecology (12, 13).

Native ecosystems have suffered significant harm in terms of their structure and functionality as a result of plant invasions. Since IAPs can release certain secondary metabolites or chemicals that can have an allelopathic effect on the coexisting native plants, they can successfully invade specific environments (14, 15). Hence, this supports the Novel Weapon Hypothesis (NWH) and Enemy Release Hypothesis (ERH). NWH stated that IAP could gain an advantage over native species by using novel biochemical weapons, which are potential secondary metabolites (16) and ERH stated that IAP has an advantage in new regions where native species are less familiar with them (17). Therefore, it is crucial that we take measures to control the spread of IAPs in India through effective management strategies such as early detection and eradication, monitoring and surveillance programs and public awareness campaigns (18).



Original article

Societal perception on environmental and socio-economic implications of *Tithonia diversifolia* (Hemsl.) A. Gray invasion in an Indo-Burma biodiversity hotspot

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ABSTRACT

Tithonia diversifolia (Hemsl.) A. Gray is an emerging and little studied plant invader in North East India, an Indo-Burma biodiversity hotspot. Identifying the impacts of its invasiveness in terms of both harmful and economically beneficial facets is required for the formulation and implementation of sustainable management options. An environmental and socio-economic implication survey through the pragmatic questionnaire method is a useful approach to explicitly elucidate the holistic influence of *T. diversifolia* on ecosystem resilience. The interaction of *T. diversifolia* with the local people of Mizoram was assessed in this study in terms of its effects on their livelihoods, socio-economic, and ecological factors. Results of the survey in relation to agricultural implications revealed that 42.68% of the respondents opined that the dried litter of *T. diversifolia* can improve soil fertility. Also, 63.41% people during their interview perceived *T. diversifolia* as an effective tool to prevent. However, 70.73% of rural people did not consider *T. diversifolia* to be a good source of livelihood for income generation or socio-economic status. Since, the respondents were not aware of chemical and biological control measures to regulate the spread of invasive alien plant species, physical methods such as slashing (46.34%), burning (13.41%), chopping and burning (29.27%) were widely applied for the control and management of invaded areas of *T. diversifolia* at selected study sites. Thus, the survey gave a brief idea to the other local people, farmers, and agriculturists of Mizoram to control the invasive spread of *T. diversifolia* in forestry and agroforestry systems. Also, other Himalayan landscapes infested with *T. diversifolia* can generate awareness and identify the sustainable strategy for their management to conserve the indigenous biodiversity.

KEY WORDS: socio-economic, *Tithonia diversifolia*, invasive alien plant, livelihood, sustainable management

ARTICLE HISTORY: received 30 May 2022; received in revised form 23 August 2022; accepted 24 August 2022

1. Introduction

Invasive alien plant species have been introduced into a new area by human activity and become widespread, causing significant economic, ecological, and social impacts (ESCHEN ET AL., 2021). They have been spreading progressively and reported to be widely distributed in global landscapes (MURPHY ET AL., 2012). The rapid growth of invasive alien plants is usually confined to fallow lands, wastelands, roadsides, and disturbed habitats (HAYSOM & MURPHY, 2003). The increased diversity and distribution of

invasive alien plant species pose a threat to natural forest ecosystems (RAI & SINGH, 2020).

Tithonia diversifolia (Hemsl.) A. Gray commonly known as tree marigold or Mexican sunflower is a perennial shrub belonging to the Asteraceae that grows rapidly with vigorous reproductive attributes, reaching 2 to 3 m in height, it grows well at an altitude of 800-1500 m, and flowers annually in November and December (BURAGOHAIN, 2016; ROJAS-SANDOVAL ET AL., 2018). *T. diversifolia* is native to Mexico and Central America, however, in the current scenario it has a pantropical distribution and has naturalized across South America, the West Indies,

Environmental and socio-economic impacts of a Hydropower Plant in North East India: Perception of rural people

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Citation: Prabhat Kumar Rai, S. T. Lalzarzovi, Roger Bruce Syngkli, Vanlalruati, Lalnuntluanga, Lalawmpuii (2025). Environmental and socio-economic impacts of a Hydropower Plant in North East India: Perception of rural people. *Environmental Reports; an International Journal*. DOI: <https://doi.org/10.51470/ER.2025.7.1.19>

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Received 28 November 2024 | Revised 30 December 2024 | Accepted 03 January 2025 | Available Online January 30 2025

ABSTRACT

India has enormous hydropower potential, particularly in the North Eastern region, which can be tapped to meet the growing energy needs of the expanding population and mitigate climate change. This study was conducted to evaluate how the Serlui B Hydropower Project, a small hydropower plant in Mizoram, NE India (an 'Indo Burma global biodiversity hotspot region') impacts the socioeconomic, ecological, and livelihood aspects of the rural indigenous population. In this study, the questionnaire method was used to assess the societal perception of the rural population on the impact of hydroelectricity generation on the environment, climatic variables, and socio-economy. In terms of effects on the environment and wildlife, 93% of the respondents observed it to be a negative view because of extensive deforestation and land submergence. Further, 54% of the respondents observed the deterioration of water quality, ascribed to the submergence of organic matter and suspended solids. Also, the excessive spread of water hyacinths (*Eichhorniacrassipes* (Mart.) Solms) in the small hydropower plants area can degrade the water quality and aquatic biodiversity which warrants urgent attention. Pertaining to rural livelihood-linked aquaculture, 77% of the respondents informed that fisheries have improved in terms of fish quantity and size however; some original rare species of fish underwent extirpation. In terms of energy and socio-economy, the survey obtained positive results from the respondents, as the majority of the interviewed people revealed sufficient energy supply, employment opportunities, and access to commercial Areca nut plantations after the establishment of the hydropower plant. The present findings are critically compared and discussed from a global perspective to assess the impacts of hydropower projects on sustainable rural livelihood, environmental management, and climate action.

Keywords: Climate Action, Energy resilience, Natural Resources, Serlui B River, Small Hydropower Plant, Socio-economic, Sustainable Rural Livelihood

1. INTRODUCTION

Energy demand is constantly rising in emerging countries like India to accelerate industrial activity and economy [1]. Renewable energy is an integral component of a nation's economic growth, sustainable environment, and accelerating the efforts towards climate change mitigation/climate action [2-3]. In a global survey of 2016, around 14% of the world's population i.e., about 1.1 billion people are deprived of adequate access to electricity [4]. Further, these estimates, emphasized that the majority of people living in rural parts of developing countries (84 %), particularly in South Asia and sub-Saharan Africa received no electric supply [5]. In these developing nations, biomass and fossil fuels are the sources of energy for the majority of the rural population [4]. Global burning of fossil fuels accounts for 78.4% of energy consumption, while renewable sources, which are divided into several sub-categories (e.g., hydropower, biomass, biofuel, solar, and wind power) account for 19% [6-7]. However, fossil fuel reserves are depleting at a high rate and the traditional use of solid biomass for cooking which is widely practiced is detrimental to the health of humans and the environment [8]. Therefore, there exists an urgent need to shift towards cleaner alternative energy sources due to the rapidly increasing prices of fossil fuels and

pollution resulting from the continuous use of these biomass and fuels [8].

Hydropower projects are considered to have less influence on society and the environment when compared with other conventional energy sources [9-10]. About 70% of the energy generated by all renewable sources comes from hydropower plants, a versatile technology that can also have positive social and economic effects [4]. In addition to producing energy, a hydropower project can help with irrigation, flood control, and ecotourism [11]. India has a great deal of potential for small and medium-sized hydropower projects. These projects might help meet the country's rising energy needs [12]. Depending on their sizes, hydropower projects are divided into large and small hydro projects. Various nations use different size standards to categorize minor hydropower projects. Small hydropower plants (SHPs) in India are defined as those having a capacity of 25 MW or less [13]. The details of installed capacity to delineate the hydropower projects are listed in Table 1. SHPs are widely employed in rural electrification projects all over the world [14]. It has generally been perceived that rural communities benefit instantly and directly from these projects [14]. However, the perception of rural people on the establishment of SHPs should be prioritized in environmental management and policy formulation perspectives.

Study on the impact of *Mikania Micrantha* Kunth on soil chemistry, crop yields, and forest canopy in an Indo-Burma biodiversity hotspot region

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Citation: Roger Bruce Syngkli, Vanlalruati, Prabhat Kumar Rai (2024). Study on the impact of *Mikania Micrantha* Kunth on soil chemistry, crop yields, and forest canopy in an Indo-Burma biodiversity hotspot region.

Environmental Reports; an International Journal, **08 to 14**, DOI: <https://doi.org/10.51470/ER.2024.6.2.08>

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Received 19 July 2024 | Revised 22 August 2024 | Accepted 17 September 2024 | Available Online October 03 2024

ABSTRACT

Mikania Micrantha Kunth is an invasive alien plant pervasive in an Indo-Burma global biodiversity hotspot, which can exert a major impact on biodiversity, agriculture, socioeconomy, and human health. The present study attempts to evaluate the allelopathic effect of *M. micrantha* leaf aqueous extract on the germination of *Pisum sativum* L. (Pea). Major allelochemicals like total phenolic compounds (TPC) and tannins present in the leaves and flower extracts of *M. micrantha* were analyzed by spectrophotometry method. We also investigate the habitat attributes of *M. micrantha* infested site by analyzing soil physicochemical characteristics, photosynthetically active radiation (PAR), leaf area index (LAI), and canopy openness. The results showed that *M. micrantha* aqueous extract inhibits *P. sativum* germination, biomass, plumule, and radicle length at all concentrations, with the highest inhibition observed at 25gL⁻¹. The presence of allelochemicals (total phenolic content and tannins) in the extracts also demonstrates allelochemical potential of *M. micrantha*, thus, validating the 'novel weapon hypothesis (NWH)'. Further in respect of abiotic environmental components, study area with high soil temperature, soil moisture content, water holding capacity, nitrogen, and potassium facilitated the invasive spread of *M. micrantha*. This study concludes that novel disturbed habitats with increased availability of PAR, low LAI, and high canopy openness are more susceptible to invasion of *M. micrantha*. On the contrary, a pristine environment with low canopy openness and less anthropogenic disturbances are rather resistant to the invasion of *M. micrantha*. Henceforth, an integrated study comprising site characteristics, soil chemistry, and bioassay is necessary to devise sustainable management of *M. micrantha*. To this end, the sustenance of dense canopy can be the most effective management strategy to control this worst global plant invader.

Keywords: Allelochemicals, Forest Canopy Openness, Leaf Area Index, Gap Light Analyser, *Mikania micrantha*, Novel Weapon Hypothesis, *Pisum sativum*

1. INTRODUCTION

Invasive plants have a significant negative impact on crop productivity, biodiversity, and the environment [1-3]. Global food safety and agricultural stability are affected by several interrelated and tightly linked factors, including population growth, poverty, environmental deterioration, and the use of synthetic herbicides [4]. Crop yields are negatively impacted by weed competition for resources including light, nutrients, space, water, and allelopathy [5-7]. The financial burden and unsustainable nature of traditional weed management practices jeopardized farmers' livelihoods, which strained the general public and policymakers [8-9].

Mikania micrantha Kunth. ("mile-a-minute" weed) is an extremely fast-growing perennial vine belonging to the Asteraceae family and genus *Eupatorium* in the Compositae family [10] (Figure 1a). It is native to the sub-tropical regions of South, Central, and North America [11]. *M. micrantha* was known as the top 100 noxious invaders by the International Union for Conservation of Nature (IUCN) [12-13]. The flowers of *M. micrantha* produced crown hair seeds that can proliferate over a long distance and hence difficult to control [14] (Fig. 1a). Invasive spread of *M. micrantha* results in a notable decrease in the output of agricultural crops and hence endanger food security [15]. The harmful effects of *M. micrantha* are primarily caused by allelopathic effect (release of allelochemicals/secondary metabolites) which modulated the soil chemistry, microbial diversity, agricultural yield, and biodiversity in a

manner to sustain its invasive spread [16-18]. In terrestrial ecosystems, *M. micrantha* climbs and cover trees and rapidly causes the death of trees and shrubs, thereby severely impacting the native biodiversity [11]. This abrupt spread of *M. micrantha* can perturb the normal photosynthetic metabolism of native plants, enforcing their senescence and expanding the canopy gaps (Fig. 1b). In this respect, past studies also observed that *M. micrantha* compete with other neighboring plants/edible crops for nutrients and other abiotic resources by blocking the sunlight [45, 2119-20]. This above-canopy spread of *M. micrantha* significantly lowers the growth and productivity of a number of crops and has the ability to choke, suffocate, penetrate crowns, and pull over plants [21].

In this study, we investigate the allelopathic effects of *M. micrantha* on a selected food crop (i.e., *Pisum sativum* L.) of wide dietary intake and nutritional value. *P. sativum* (locally known as green pea) is a nutritious legume crop that is high in protein, vitamins, minerals, and health-promoting beneficial compounds [22-23]. Pea has been used for experiments for decades pertaining to a plethora of cytogenetics, and ecological studies as it is susceptible to broad leaf herbicides, can be used year-round, and performs well in bioassays. In this respect, the analysis of major allelochemicals present on the plant parts, allelopathy, physicochemical characterization of soil, and their linkage with the habitat attributes of *M. micrantha* (such as light intensity, canopy gap analysis, and leaf area index (LAI)) was studied which is a rather novel integrated approach in its

PARTICULARS OF THE CANDIDATE

NAME OF CANDIDATE	:	VANLALRUATI
DEGREE	:	Doctor of Philosophy
DEPARTMENT	:	Environmental Science
TITLE OF THESIS	:	Effects of <i>Tithonia diversifolia</i> (Hemsl.) A. Gray invasion on the vegetation, soil chemistry and the socio-economy of Aizawl district, Mizoram
DATE OF ADMISSION	:	23/08/2022
APPROVAL OF RESEARCH PROPOSAL		
1. DRC	:	18.10.2022
2. BOS	:	04.11.2022
3. SCHOOL BOARD	:	16.11.2022
MZU REGISTRATION NO.	:	1700472
Ph. D. REGISTRATION NO. & DATE	:	MZU/Ph.D./2018 of 23.08.2022
EXTENSION (IF ANY)	:	NA

Head

Department of Environmental Science

ABSTRACT

**EFFECTS OF *TITHONIA DIVERSIFOLIA* (HEMSL.) A. GRAY
INVASION ON THE VEGETATION, SOIL CHEMISTRY AND
THE SOCIO-ECONOMY OF AIZAWL DISTRICT, MIZORAM**

**AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY**

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Ph.D. REGISTRATION NO.: MZU/Ph.D./ 2018 of 23.08.2022



**DEPARTMENT OF ENVIRONMENTAL SCIENCE
SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES
MANAGEMENT
NOVEMBER, 2025**

ABSTRACT

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ON THE VEGETATION, SOIL CHEMISTRY AND THE SOCIO-ECONOMY
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BY

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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

Invasive plant species pose a major threat to terrestrial ecosystems by disrupting biodiversity and altering nutrient cycling processes. Among these, invasive alien plants are extensively spread across global landscapes, negatively impacting native vegetation, environmental conditions, and socio-economic systems. The invasion process typically unfolds in several ecological stages, including transportation, colonization, establishment, and eventual spread across the landscapes. A key factor contributing to the success of these invasive species is the production of allelochemicals: which are in fact secondary metabolites released into the environment that inhibit the growth and development of native plant species and agricultural crops. This chemical interaction, known as allelopathy, enhances the invasive potential of alien species by aiding their establishment and naturalization in new habitats. Allelopathic interactions often disrupt the germination, survival, and reproduction of other community organisms.

This study focuses on *Tithonia diversifolia* (Hemsl.) A. Gray, an invasive alien species belonging to the Asteraceae family, originally native to Central America. It is now naturalized in many parts of the world, including India, where it has become particularly widespread in the northeastern states. Despite its rapid expansion in Mizoram, particularly around Aizawl, scientific investigations on its ecological impacts remain limited or unexplored. Prior research in India has predominantly focused on other invasive species, overlooking the emerging threat posed by *T. diversifolia*. This lack of ecological and socio-economic data restricts the development of sustainable management strategies and hinders its potential integration into farming and health systems.

The ecological disturbance gradient present in urbanized landscapes like Aizawl, provides suitable study site to evaluate the ecological influence of *T. diversifolia*. For this, the disturbed site was selected which was faced with heavy anthropogenic activities while the moderately disturbed site has less human disturbance and more natural/undisturbed forest intact canopy. Conversely, uninvaded site was not included in the study due to the highly urbanized nature of the sampling locations, which were subject to multiple anthropogenic disturbances such

as road construction, traditional shifting cultivation (jhum), dense urban settlements, grazing, and stone quarrying. Further present study calculated vegetation attributes like plant community characteristics were analysed by using quadrats method and calculated the importance value index (IVI) and diversity indices such as Simpson Index of Dominance, Simpson diversity index, Sorenson's similarity index, Shannon-Weiner diversity index. For soil physico-chemical properties, soil samples were collected in triplicate from both the study sites and for the analysis of pH, soil moisture content, water holding capacity (WHC), soil organic carbon content (SOC), soil organic matter (SOM), available nitrogen, available phosphorus, and available potassium. The allelochemical attributes of *T. diversifolia* were studied based on the plant debris soil bioassay experiment, fresh leaves aqueous extract (FLE) of *T. diversifolia*, and analysis of the allelochemical component present in *T. diversifolia*. The socio-economic implication was done based on the semi-structured questionnaire method which included the participation of 100 individuals. For the management implications, canopy gap, photosynthetically active radiation (PAR), and leaf area index (LAI) were studied in order to control or manage the distribution and spread of *T. diversifolia*.

Vegetation analysis revealed 40 plant species at the disturbed site and 57 species at the moderately disturbed site. Across both areas, 74% were herbs and 26% were shrubs, representing 30 plant families. In present studies, Asteraceae was observed as the most dominant family, followed by Poaceae. Importance Value Index (IVI) analysis indicated that *T. diversifolia* dominated both study sites, with a significantly higher IVI at the disturbed site (63.61) when compared with the moderately disturbed site (37.38). The Simpson Index of Dominance was also greater at the disturbed area (0.17), signifying dominance by a few species under high disturbance. In contrast, the Shannon-Wiener Diversity Index was higher in the moderately disturbed area (3.22), indicating greater species diversity. Sorenson's Similarity Index showed low species overlap between the two sites, suggesting that varying disturbance levels remarkably shape different plant communities.

The analysis of physico-chemical properties of soil at the study site is important to know the interaction of *T. diversifolia* plants with the soil parameters.

The soil analysis was conducted for three seasons such as pre-monsoon, monsoon, and post-monsoon for the period of two years (i.e., 2023-2024). The soil at the moderately disturbed site has higher soil moisture content, WHC, soil SOC, SOM, available nitrogen, available phosphorus and available potassium across all the seasons. While the pH at the moderately disturbed site has remained relatively stable at both the sites, the moderately disturbed site generally has acidic soil than the disturbed site. Thus, the study concluded that moderately disturbed site has more potential to allow coexistence of different plant species as there was more nutrient retention for increased soil fertility. Whereas, at the disturbed site, due to less availability of nutrient and soil fertility there has been a declined or less diversity of plants to co-exist well with *T. diversifolia*. Therefore, disturbance regimes may preserve soil health and biodiversity in order to manage the spread of invasive alien plants.

Further, soil bioassay experiments demonstrated that *T. diversifolia* significantly affected the growth of *Pisum sativum* L. (pea), with reduced germination, plumule and radicle elongation, and biomass accumulation. Seasonal studies showed that crop growth improved during the post-monsoon phase when the plant is in full bloom and debris is minimal but was suppressed in the pre-monsoon season due to the accumulation and decomposition of plant material. The fresh leaves aqueous extract (FLE) experiment showed that as the concentration of FLE increases the seed germination, seed radicle, seed biomass, while plumule length decreases. The flower part of *T. diversifolia* was found to have higher phenol (35.26 ± 1.02 $\mu\text{g/mL}$) and tannin (67.47 ± 1.46 $\mu\text{g/mL}$) contents than the phenol (12.65 ± 0.37 $\mu\text{g/mL}$) and tannin (16 ± 2.18 $\mu\text{g/mL}$) contents found in the leave of *T. diversifolia*. Thus, these results confirmed the allelopathic nature of *T. diversifolia* and suggest their frequent use as a green manure or biofertilizer could be detrimental to nearby crops, potentially threatening agricultural productivity and food security.

This study explores community perceptions and awareness regarding invasive alien plant species, with a focus on *T. diversifolia*, in a local context. Varied responses during questionnaire of present socio-economic survey in Mizoram revealed that while many participants were familiar with the term "invasive alien

plant," their understanding of the broader ecological impacts particularly on their influence on native biodiversity was limited. Perceptions of *T. diversifolia* vary widely as some local residents, including marginal farmers, viewed it as beneficial while others see no value in the plant. These mixed views reflect a general lack of awareness and limited observation of ecological changes over time. Most respondents were unable to identify any other invasive species, suggesting that invasive plant invaders are not a prominent topic in local environmental discourse. These findings underscore the urgent need for targeted community education, along with ecological monitoring to improve understanding of invasive alien plants and thereby promote environment friendly control methods.

Ecological management emphasize preserving intact native plant communities, which can effectively reduce invasions by limiting available resources such as light, space, and nutrients. A closed forest canopy, supported by diverse and shade-tolerant native species, can limit the establishment of *T. diversifolia* and help restore ecological balance. Also, societal perception of local indigenous people can also be taken into consideration for formulating management strategies of *T. diversifolia* in selected study area. This management strategies through the study of canopy openness aimed to enhance native plant richness and density to control the spread of this invasive species.

For sustainable utilization, it is essential to balance the ornamental and ecological roles of *T. diversifolia* while mitigating its invasive potential. Its bright sunflower-like floral appearance makes it attractive for various purposes, including pollinator's attraction. Timely harvesting, particularly within three months of growth can optimize biomass for use as green manure while preventing seed formation. In agricultural systems, *T. diversifolia* may also serve in integrated pest management, aiding in natural pest control and reducing reliance on chemical pesticides, when cultivated under climate-controlled conditions, harvested at optimal stages, and integrated wisely into farming systems. However, it should not be cultivated widely, especially at disturbed sites in order to restrict its natural spread.