A CASE STUDY ON WEED MANAGEMENT AWARENESS IN KAMPAR: FARMERS' PERCEPTIONS, WEED FLORA COMPOSITION, AND EFFECT OF FERTILIZERS ON WEED GROWTH

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By

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ABSTRACT

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Tong Pei Sin

Rural farming is a prominent feature in developing countries. Weed management remains a challenge in food security and sustainable agriculture in the tropics, especially for smallholders. Smallholders contribute to 13 out of the 17 Sustainable Development Goals (SDGs) in economic, environmental and social contexts. The chemical approach has widespread use but the approach has risks on the environment and food safety. This study was motivated by the importance of agricultural activities in Kampar, Malaysia, but little is known about the essential aspects related to sustainable weed management for smallholders. This study addressed knowledge gaps in weed management by using Kampar as a case study and shedding light on developing a model for sustainable weed management for smallholders. A semi-structured questionnaire survey was designed to study and glean rural farmers' knowledge and perception of weeds, their sources of information, and their reasons for willingness or unwillingness to adopt non-chemical weed control methods. This survey was conducted from June to October 2018 and analysed using descriptive and chi-square statistics. Knowledge of weed species led to the anticipation of yield loss and exploration of potential control methods. It was found that social networking and agriculture chemical companies were the main sources of

information on weed control methods. Despite knowing the harmful effects of chemical herbicides, farmers' willingness/resistance to adopt non-chemical control methods depended on many different factors. Next, field surveys of weed on maize farms were conducted during June of 2017, 2018 and 2020 in a former tin mining land, with a total of 120 quadrats of 0.5 m x 0.5 m. Fifteen species were observed. Four species with the highest density were *Cyperus* sp., followed by *Amaranthus viridis, Eleusine indica* and *Hedyotis corymbosa.* The Shannon-Wiener diversity index (*H′*) showed low species diversity of weeds, while Pielou's evenness index and Simpson's dominance index indicated the phenomenon of non-dominating weed species on maize farms. The variation in the number of individuals in broadleaf, sedge and grass was significant between 2017 and 2018; 2018 and 2020; and 2017 and 2020. The relationship between maize, mean rainfall, mean temperature and weed species was analysed using a general linear model, and none of them affected maize yields. Based on the above information, *Amaranthus viridis,* being the second highest density weed found on the maize farms, was chosen for a study on plant responsiveness. The species had a high correlation in Pearson's correlation (r) and regression (R^2) between the number of inflorescences, the number of leaves, and plant height under treatments NPK 12:12:17, NPK 15:15:15 and in the wild respectively. Plants under NPK 12:12:17 and NPK 15:15:15 were studied with five treatments, which were control, 1 g, 2 g, 4 g and 8 g. One-way ANOVA showed that parameters of leaves and inflorescences were statistically significant at $p < 0.05$ for *A. viridis* under NPK 12:12:17, while plant height was statistically significant at $p < 0.05$ under NPK 15:15:15. Based on the data collected, a model for sustainable weed management for smallholders would involve a few components. The first component comprises rural farmers' learning on weed management through insights into weed management practices among smallholders, and challenges that demand attention and efforts towards improvement for existing weed control, which is predominantly chemical herbicides. Weed composition and crop yield need to be assessed for the impacts of weeds on crop yield for monitoring to derive informed decisions on weed management. The study of plant functional traits or weed biology providing knowledge for predicting weediness characteristics through growth and development is the third component. Each component or combined components could be used to reassess, deliberate and design weed management on farms with the objective of complementing and leveraging current weed controls for smallholders through examining the use of herbicides and fertilizers. A multidisplinary approach is recommendable for practical weed management.

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Date: 3 July 2024 ___________________

SUBMISSION OF THESIS

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This dissertation/thesis entitled **"A CASE STUDY ON WEED MANAGEMENT AWARENESS IN KAMPAR: FARMERS' PERCEPTIONS, WEED FLORA COMPOSITION, AND EFFECT OF FERTILIZERS ON WEED GROWTH"** was prepared by TONG PEI SIN and submitted as partial fulfilment of the requirements for the degree of Doctor of Philosophy in Science at Universiti Tunku Abdul Rahman.

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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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LIST OF ABBREVIATIONS

F	Frequency
GDP	Gross domestic product
ha	Hectare
IVI	Important value index
NPK	Nitrogen(N), phosphorus (P), potassium (K)
MFD	Mean field density
MOFD	Mean occurrence field density
Mt	Metric tonne
RA	Relative abundance
RD	Relative density
RF	Relative frequency
RU	Relative uniformity
SD	Standard deviation
SDG	Sustainable Development Goal
U	Uniformity
2,4-D	2,4-dichlorophenoxyacetic acid

CHAPTER 1

INTRODUCTION

Agriculture serves as the backbone of the industrial sector in many countries. In 2019, agriculture contributed 7.1% to Malaysia's GDP. Despite its relatively small share in the economy, it is recognised as one of the most important sectors that provides food and employment to rural communities in Malaysia. In general, rural farming is a prominent feature of developing countries. Weeds are recognized as the primary hindrance to crop yield, resulting in varying degrees of yield loss depending on the crop type (Gharde, et al*.,* 2018; Ziska dan Dukes, 2011). An average of 28% of yield loss caused by weeds is considered the norm (Vilà, et al., 2021). Therefore, weed management is critical to ensure food security and environmental sustainability for small-scale farmers in tropical regions (Fryer, 1981; Yaduraju and Rao, 2013).

Agriculture research has long focused on production risks, including issues related to quantity and quality (Komarek, De Pinto and Smith, 2020). Factors affecting yields include weather, pests and diseases. As weeds compete directly with crops for essential resources like water, nutrients and sunlight and their impacts on crop production are well documented. Thus, weed management is a critical component in ensuring an adequate supply of food for the world's population. Weed control methods remain farmers' decision while considering uncertainties and production probabilities (Birthisel, Clements and Gallandt, 2020).

Although weeds have been a part of agriculture since the beginning of agriculture approximately 10,000 years ago, and mechanical control methods have since existed, the discipline of Weed Science is relatively new. It emerged less than a century ago compared to other disciplines in agriculture, such as plant pathology (Radosevich, Holt and Ghersa, 1997; Timmons, 2005). The evolution of the Weed Science discipline was catalyzed by the discovery of the first synthetic herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) in 1941 by Pokorny, leading to significant emphasis of chemical control method in weed management. Both tillage and herbicides have become primary methods for weed removal and they are considered technological tools (MacLaren, et al., 2020).

The overwhelming success of herbicides has made Weed Science primarily "herbicide-based" discipline; limiting research in other relevant research areas in weed management. Chemical control is the predominant weed management method in Malaysia. In 2019, of the total 47,805 tonnes of pesticides used, 39,692 tonnes (83.0%) were herbicides (FAO, 2021). While herbicides display remarkable results, they come with environmental costs and health impairments. Environmental hazards, such as pollution and herbicide resistant weeds, have emerged. Herbicides were detected in soil as well as surface and ground water, leading to resource contamination (Allinson, et al., 2017; Sun, et al., 2017). Allinson et al. (2017) found as many as 19 different herbicides in water samples collected. As of September 2023, a total of 269 herbicide- resistant weeds have been identified (Heap, 2023). To date, weeds have developed resistance to 21 out of the known 31 herbicide sites of action and to 167 different herbicides.

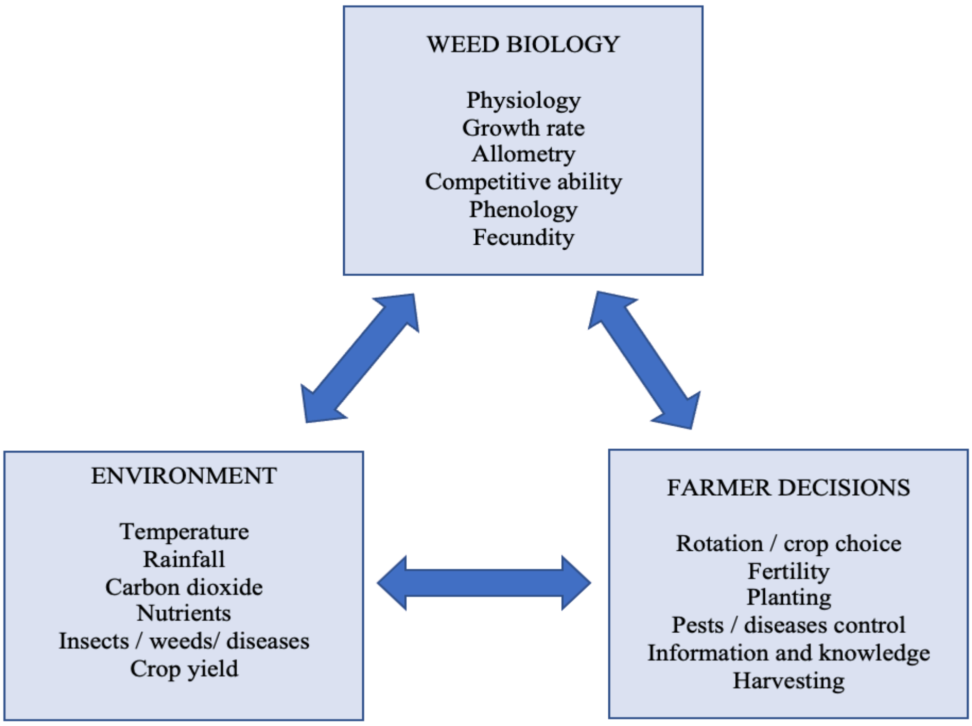
The second problem pertains to food safety issues. Numerous studies have highlighted comsumers' concerns about herbicide residues in food, especially fruits and vegetables (Amjad, et al., 2013; Matt, et al., 2013). Additionally, herbicide residues have been found in dietary supplements (Páleníková, et al., 2015). If not addressed, the issue of herbicide residues in food is expected to continue posing threats to consumers' health (Kim, Kabir and Jahan, 2017; Then and Bauer-Panskus, 2017).

The third problem involves toxicity exposure on people and non-target organisms. Kim, Kabir and Jahan (2017) argued that there are various direct and indirect routes of chemical exposure. Farmers and workers who are spraying herbicides are those directly exposed to chemical toxicity. Indirect routes may include exposure through herbicide residues in foods and drinking water. Toxicity exposure is continuously observed in both terrestrial and aquatic organisms (Diepens, et al., 2017; Herrick, 2017; Qi, et al., 2020; Salvat, Roche and Ramade, 2016). Herbicide injury to non-target organisms, such as crops, is also not uncommon (Herrick, 2017).

As a result of these dire consequences, weed scientists and practitioners have called for a paradigm shift in weed science research and management, shifting the focus from herbicides to vegetation management on farms, which includes knowledge of weed ecology, biology and genetics (Bakar, 2006; Breen and Ogasawara, 2011; Chauhan, et al., 2017; Clements, DiTommasa and Hyvonen, 2014; Davis, et al., 2009; Fernandez-Quintanilla, et al. 2008; MacLaren, et al., 2020; Varanasi and Jugulam, 2017; Wayse, 1992). There is limited understanding of many components of weed problems and their interactions (Jordan, et al., 2016). For example, the effects of fertilization on weed growth and development should receive more attention, as much remains unknown (Little, et al., 2021). This knowledge serves as a basis for different management controls, ranging from chemical (i.e., appropriate dose and herbicide resistance) to non-chemical and biological control (Mortensen, Bastiaans and Sattin, 2000).

In Malaysia, a similar call for more environmentally friendly weed management has been made, drawing from studies on paddy fields (Juraimi, et al., 2013; Karim, Man and Sahid, 2004). However, there has been little success in achieving the paradigm shift (Liebman, et al., 2016). Challenges remain in developing and implementing eco-friendly weed management systems (Liebman, et al., 2016). Therefore, doubt has arisen as to whether the focus of weed research has truly contributed to moving in that direction (Moss, 2008; Smith, Mortensen and Ryan, 2010).

Recognizing the multifaceted nature of the weed problem and its unintended harmful effects, the discipline of Weed Science has gradually shifted its focus away from herbicide centric research. The dynamic nature of the discipline has presented challenges for studies, further complicated by its interdisciplinary character (Chauhan, et al., 2017; Davis, et al., 2009; Rodgers, 1974; Ward, et al., 2014). Its significance is expected to grow concerning global food security and the increasing world population (Neve, et al., 2018). In a region where agriculture is the main economic activity, such as in Malim Nawar, Perak, where the sector remains relatively underexplored, this study aims to enhance our understanding of weed management factors. It draws inspiration from the conceptual model proposed by Birthisel, Clements and Gallandt (2020) (Figure 1.1). These factors are essential for making ecological approaches to weed management both practical and resilient at different levels, from local to regional, and required coordinated, broad-based efforts for effective solutions (Jordan, et al., 2016; MacLaren, et al., 2020). A multi-pronged approach involving weed management education and research is needed to achieve sustainable agriculture (Chauhan, et al., 2017; Fryer, 1981; Gaba, et al., 2016).



(Adapted from Birthisel, Clements and Gallandt, 2020)

Figure 1.1: Factors influencing weed management practices on farm.

1.1 Problem Statement

Weed studies in Malaysia have predominantly focused on taxonomy, leading to a lack of understanding in other weed-related research areas (Wee, Rao and Khoo, 2013). These studies have been primarily conducted in paddy fields and major plantation crops such as oil palm and rubber. Furthermore, paddy farmers have been the main subjects of surveys aimed at understanding farmers' attitudes. While the agricultural sector emphasizes the development of commercial plantations, the importance of smallholders cannot be ignored as they play a vital role in food security and sustainable agriculture, contributing towards the achievement of Sustainable Development Goals (SDGs) (Terlau, Hirsch and Blanke, 2019) (Table 1.1).

Table 1.1. The contribution of smallholders to 14 SDGs and its contexts.

Goal	Description	Contexts
1	End poverty in all its forms everywhere	Governance, social
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Economic, environment, governance, social
3	Ensure healthy lives and promote well-being for all at all ages	Social
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Environment, social
5	Achieve gender equality and empower all women and girls	Economic, social
6	Ensure availability and sustainable management of water and sanitation for all	Social
7	Ensure access to affordable, reliable, sustainable and modern energy for all	Economic, environment
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Governance
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Economic, governance
10	Reduce inequality within and among countries	Governance
11	Make cities and human settlements inclusive, safe, resilient and sustainable	Social
15	Protect, restore and promote sustainable use f terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Economic, environment, social
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	Economic, governance
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	Economic, environment

(Source: https://sdgs.un.org/goals#goals; modified from Terlau, Hirsch and Blanke, 2019)

To achieve a paradigm shift from the predominant use of chemical control to non-chemical methods, ecological weed management must include inter-related aspects, such as the farmer community, weed composition, and weed biology, fostering a comprehensive understanding. Weed management is context specific, combining the mentioned characteristics (MacLaren, et al., 2020). Providing this knowledge to policy makers and practitioners regarding the factors that hinder sustainable use of environment-friendly strategies could help overcome this obstacle, and enhance farmers' decision making in weed management. Hence, this study aims to address knowledge gaps in decision-making related to weed management among smallholders.

Perak has a total area of 21,023.50 km^2, accounting for 6.3% of Malaysia's total land area of 329,847 km^2. Agriculture occupies an approximately 36% of the state's land use as reported by the Perak State Government in 2018. Perak is the third largest state in Peninsular Malaysia for vegetable planting areas, following Pahang and Johor, according to data from the Department of Agriculture in 2018. In terms of economic contribution, agriculture, forestry and fishery constituted the fourth largest sector, contributing 1.8% to the state's Gross National Product (GNP) based on 2014 values (Unit Perancang Ekonomi Negeri Perak, 2014). Recognizing its strategic importance, agriculture is identified as a key sector for economic growth by the Perak State Government in 2018. Furthermore, the agricultural sector is pivotal in realizing the objectives outlined in the Perak Food Security Action Plan for the years 2022-2030.

The Kampar District in Perak, Malaysia, encompasses a land area of approximately 67,980 ha, with 33% dedicated to agricultural activities, as reported by the Perak State Government in 2016. These areas were formerly tin mining areas, but gradually, they have been repurposed for agriculture and diverse uses, such as crop cultivation, aquaculture, and livestock practices (Table 1.2). Agriculture plays a significant role in the local economy contributing 44.5% to the district's income, as indicated by the Kampar District Council, Perak Department of Town and Country Planning and Peninsular Malaysia Department of Town and Country Planning in 2015. Recognizing the economic importance of agriculture, there are plans to designate Malim Nawar as the primary agricultural site for vegetable crop cultivation and the development of modern, high-technology farms by 2030. This agricultural planning aims to foster intensive agricultural activities and advance weed management practices.

Table 1.2. Land use in Kampar District in 2014.

Land use	Area size (ha)	Percentage (%)
Forest area	36,484	54.5
Agriculture use	22,128	33.0
Urban development	4,577	6.8
Unused land	2,716	4.1
Water areas (e.g. rivers)	962	1.4
Recreation and park	130	0.2
Total	**66,997**	**100**

(Source: Kampar District Council, Perak Department of Town and Country Planning and Peninsular Malaysia Department of Town and Country Planning, 2015)

1.2 Hypothesis and research questions

Agriculture serves the dual purpose of feeding the world's population and ensuring environmental sustainability. Effective weed management is crucial in supporting these two roles. In light of previously identified challenges in weed management and research deficiencies in Malaysia, it is imperative to closely examine existing weed management practices through three inter-linking aspects of small farmers' attitude (i.e., social dimension), weed composition (i.e., weed thresholds) and weed biology (i.e., integrated weed management) to foster sustainable agriculture and enhance food security among smallholders (Birthisel, Clements and Gallandt, 2020; Chauhan, et al., 2017; Jordan, et al., 2016; Neve, et al., 2018; Terlau, Hirsch and Blanke, 2019). Thus prompting the research question: How can the integration of each of these weed problem characteristics contribute to ecologically friendly weed management decisions for sustainable agriculture?

1.2 Objectives

The motivation behind this research stems from the critical significance of agricultural activities in Kampar, where essential aspects related to weed management remain relatively unknown. These crucial aspects encompassing the involvement of the farmer community, the diversity of weed species on farms and the intricacy of weed biology. By selecting Malim Nawar as the case study, this investigation seeks to fill existing knowledge gaps in weed management practices, with a particular focus on promoting sustainable weed management strategies for smallholders. The primary objective is to contribute valuable insights that enhance decision-making processes related to weed management among smallholders.

The objectives of this study are:

1. To evaluate farmers' learning and knowledge on weeds and weed management;
2. To assess the relationship of weed species, weed density, mean temperature and mean rainfall, with maize yield;
3. To determine trait responsiveness at the plant level for *Amaranthus viridis* which is a dominant species on maize farms to NPK 15:15:15 and NPK 12:12:17 and wild population, and variations within the fertilized groups that may shape the species' weediness trajectory.

1.4 Research work flow

The research work proceeded in four parts. Firstly, a comprehensive literature review was conducted to understand the status of weed science research and the deficiency of smallholders studies in Malaysia. The review also covered the development of weed biology and weed management research.

Secondly, informed by Birthisel, Clements and Gallandt's (2020) conceptual model on factors influencing weed management practices and the literature review findings, an interdisciplinary approach was adopted to study rural farmers' decision on weed management, the link between weed composition and maize yield, as well as weed responses under NPK12:12:17 and NPK 15:15:15. This study provides the basis for achieving sustainable weed management by incorporating the multifaceted nature of weed science.

Thirdly, each component of small holders' knowledge and preference on weed management practices; the causal relationship between weed composition and maize yield; and functional traits of weed species responding to NPK12:12:17 and NPK 15:15:15. These components have revealed gaps, challenges and opportunities and play a complementary role for sustainable weed management.

Lastly, the study entailed presenting the results and discussing the implications, limitations and application challenges of sustainable weed management to inform users, stakeholders and policymakers in a broader context.

CHAPTER 2

LITERATURE REVIEW

2.1 What are they – the concept of smallholders and weeds?

Smallholders are recognised for their importance in agricultural production, food security and sustainable agriculture (Terlau, Hirsch and Blanke, 2019; y Paloma, Riesgo and Louhichi, 2020). Though there is no single universally accepted definition of smallholders, this group of farmers may have a few common characteristics. Okidegbe (2001) characterised smallholders are those with a maximum of crop land size of maximum 2 ha, as part of a study on rural poverty reduction. The farm area size for smallholders has subsequently been modified from 2 ha to 10 ha (Altieri and Koohafkan, 2008). However, land size alone does not define smallholders, as this may present a false impression that smallholders are a homogenous group in terms of land size (Murphy, 2012).

Smallholders are the group of farmers being marginalized in the aspects of capital, geography (i.e., rural households), farm inputs, markets, assets and information, in which they could experience in one metric or more (Murphy, 2012). Such farms are either individually operated or relying on family members for workforce (FAO, 2014; Terlau, Hirsch and Blanke, 2019). Smallholders are interchangeably used with small farmers, small-scale farmers, rural farmers, rural smallholders, family farmers and small family farmers (FAO, 2014; Laizer, Chacha and Ndakidemi, 2019; Murphy, 2012; Ndimbwa, Mwantimwa and Ndumbaro, 2022; Obidike, 2011). The context of smallholders may differ based on locality (World Bank, 2019).

In the context of Malaysia, smallholders are associated with industrial crops such as oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis*), and cocoa (*Theobrama cacao*), as well as food crops such as rice, vegetables, and fruits (World Bank, 2019; Rusli and Fatah, 2022). Smallholders from the two sectors are faced with socioeconomic and institutional issues, such as ageing farmers, low compliance to environmental standards, insecure land tenures, and limited capital, market access, and infrastructure (World Bank, 2019; Rahman, 2020). The only official definition for smallholders was under the Rubber Industry Smallholders Development Authority Act 1972 (Act 85) which carries the interpretation in Section 2(a), as follows:

"an owner or a lawful occupier of any land of an area of less than 40 hectares, a lawful representative of the owner or a lawful representative of the lawful occupier".

In nature, no plants are considered as weeds (Zimdahl, 2018). The concept of weed is as old as the history of agriculture, with an origin where the distinction between desirable and undesirable species was made in a specific location at a particular time. From the transformation of human-gatherers to the beginning of agriculture around 10,000 years ago, weeds have been part of the agricultural system. The use of the word ‘weed’ began in the 1900s in the context of plant adaptations in human-modified habitats (Harlan and deWet, 1965). Weeds have since become ubiquitous in human-modified landscapes. Weed-related research has been overlooked for its constant presence on farms, unlike sudden pest and disease outbreaks that would catch researchers’ attention.

The word ‘weed’ has been used interchangeably between negative connotations and beneficial uses in the literature, as some researchers have argued that the negative aspect should not be the ultimate criterion. Negative connotations are associated with a reduction in crop production and quality, while others have justified that weeds could be beneficial or cover crops, soil erosion control, medicinal plant uses, and have even been linked to fighting climate change. Some researchers have promoted the importance of weed diversity on farms in terms of ecological functionality with other species (Marshall, et al., 2003).

To weed scientists and weed science societies, weeds imply a group of plants that are unwanted and interfering with human activities. Weeds are viewed as an issue that needs to be managed when total elimination is impossible and unrealistic. Additionally, they share a set of weediness characteristics that distinguish them from non-weedy plants. Weeds are *r*-strategist with high fecundity, rapid growth and a short period to maturation. These adaptations enable weeds to colonize and establish a viable population on a site (Fried, et al., 2020). However, weeds in agricultural habitats are constantly undergoing evolution and adaptations resulting from disturbances in the context of farm management and agronomic practices (Lososová, Chytrý and Kühn, 2008).

Without a standard and universal definition for weeds (Baker, 1974; Holm, et al., 1991; Randall, 1997), this study will adopt the context of unwanted plants on farms and those undesirable for agricultural production, subject to an anthropocentric perspective of growers and farmers, which is a reduction factor in crop production through competing for resources such as sunlight, nutrients and water (Rijsdijk, 1986; Swanton, Nkoa and Blackshaw, 2015). Weeds are potentially the most severe yield reduction factor on farms at 37%; on the other hand, losses caused by pests and diseases are below 20% (Orke, 2006). In a total negligence case, yield loss could be 100%. These weeds are known as segetal plants where they exist amongst crops or agrestal plants where they are found in cultivation systems (Munoz, et al., 2020). In short, it is known as arable weeds.

2.2 Weed identification and composition as the first step

Weed identification is a critical component of weed management (Dekker, 1997; Munoz, et al., 2020; Nkoa, Owen and Sawnton, 2015; Rijsdijk, 1986; Travlos, et al., 2018). Weed composition helps to predict weed thresholds on yield (Cowan, 1997). Weed diversity and abundance indicate the quantitative structure of a plant community. This knowledge will build a better understanding of the relationship between weeds and yield. The weed community is a dynamic phenomenon. Its composition is determined by both biotic and abiotic factors, such as crop species, cropping management practices, and herbicides used on agricultural landscapes. These factors may have single, simultaneous, or cumulative impacts on a farm site to an extent of interplaying on weed community (Nagy, et al., 2018; Zhu, et al., 2020).

Weed composition has high variation. The assemblages are most likely to shift in diversity and change in abundance over time responding to resource availability, selection pressure, and agronomy practices from the selection agent humans, as well as crops species (Antralina, et al., 2014; Neve, Vila-Aiub and Roux, 2009; Storkey and Westbury, 2007). For example, weed richness was higher in organic farms compared to other farms (Jastrzębska et al., 2013) Moreover, climate change effects such as rising temperature and carbon dioxide (CO_2) content could assist weed species in having a wider distribution (Zikas and Dukes, 2011).

About 200 species are considered arable weeds worldwide (Holm, et al., 1991). Farmers' inputs were used to categorize weed species into a severity ranking of serious, principal and common. The first three weed species pointed out by farmers were considered "serious" in affecting crop production. The next level "principal" would be next few species observed by farmers on farms and the number was rarely more than 10 species. The least concern group would be "common" whereby this group of weed species is widespread in their distribution but does not pose threats to crop production.

Eighteen weed species were identified to be in the primary ranking of troublesome (e.g., distribution, competition, and negative effects) worldwide from a minimum of 200 weed studies from 15 major crop species the world is dependent upon, and another 58 weed species were in a secondary order subjecting to region, climate and types of crop (Table 2.1). The grouping of major or troublesome weeds used in some studies without a relation to yield findings may be counterproductive in weed management (Varanasi, Vara Prasad and Jugulam, 2016). The additive effects of multiple weed species in causing more severe yield loss in a field situation remain under studied (Cowan, 1997).

Table 2.1. The 18 worst weeds for agriculture in the world.

No.	Family	Species
1	Amaranthaceae	*Amaranthus hybridus* (14)
		Amaranthus spinosus (15)
2	Chenopodium	*Chenopodium album* (10)
3	Convolvulaceae	*Convolvulus arvensis* (12)
4	Cyperaceae	*Cyperus esculentus* (16)
		Cyperus rotundus (1)
6	Poaceae	*Avena fatua* (13)
		Cynodon dactylon (2)
		Digitaria sanguinalis (11)
		Echincohola crusgalli (3)

		Echinochloa colonum (4)
		Elusine indica (5)
		Imperata cylindrica (7)
		Paspalum conjugatum (17)
		Rottboellia exaltata (18)
		Sorghum halepense (6)
7	Pontederiaceae	*Eichhornia crassipes* (8)
8	Portulaceae	*Portulaca oleraceae* (9)

Note: Number in the brackets next to species indicates ranking order starting from number 1 the most worst weed in the world.
(Source: Holm, et al., 1991)

Weed surveys could be conducted at the local, national, or regional level (Dekker, 1997). Each level is equally important to explain the presence and abundance of weed composition. Weed studies at the local level could be better to measure potential impacts on crop yield (Fried, et al., 2020). A three-year survey period was a common interval adopted in weed surveys, and the interval could be ranging from 17 to 47 years in Europe (Hanzlik and Gerowitt, 2016). Theoretically, weeds with high density and frequency are more likely to cause greater yield loss (de Mol, von Redwitz and Gerowitt, 2015). As part of species identification, weeds are grouped into three principal categories: grasses, sedges, and broadleaves.

In Malaysia, weed composition studies have been conducted in major commercial crops such as rice (*Oryza sativa*), oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*). To date, rice has received extensive research focus among weed scientists and is relatively well studied as compared to other crops. A minimum of 40 and a maximum of below 60 weed species were found in paddy fields (Azmi and Baki, 2007; Hakim, et al., 2010; Hakim, et al., 2013a and 2013b). Crop type could be a factor that gives rise to the existing weed community structure (Bourgeois, et al., 2019). Therefore, weed composition studies are equally important for other crops than the three major crops.

In these weed composition studies in Malaysia, no severity grouping has been assigned to weeds such as those by Holm, et al. (1991) mentioned earlier, although some weeds are labelled as “common” without explanations. With an exception for a group of weeds in which their management plans are to be taken seriously, there is a separation classification of invasive species (National Committee on Invasive Alien Species Malaysia, 2018). This group of living organisms, including invasive plants, animals or pathogens, is considered a biosecurity threat to the country, and hence, poses a serious threat to the environment.

2.2.1 The impacts of weeds on maize yield

Corn (*Zea mays*), also known as maize, is a crop that takes 60 to 70 days from sowing to harvesting in lowland Malaysia. It ranked as the 6th most produced crop in the world from 1994 to 2018, with an average of one giga tonne produced yearly (FAO, 2020). Maize production in Southeast-Asia has steadily increased over the recent decades due to demands for both food and livestock feed. In Malaysia, the total planted areas for vegetables and cash crops were 77,846 hectares (ha) in 2018, with maize topping the highest hectarage areas at 9,548.21 ha, accounting for 12.3 %. Perak was the highest maize producer state at 8.89 Mt per ha, followed by two other states Johor at 7.91 Mt per hectare and Kelantan at 7.28 Mt per ha (Department of Agriculture, 2018).

Weed density is identified as a key element affecting maize yield (Myers, et al., 2005; Van Heemst, 1985). Low to medium weed density could produce yields equivalent to weed-free growing condition; while high weed density would reduce maize yield by 12 to 15% (Myers, et al., 2005). A high density of combining the ratio of 2:1:1 of *Amaranthus blitum*, *Eleusine indica, Borreria latifolia* resulting of 338,980 plants per hectare, was found to cause a reduction in crop height and cob yield (Hasan and Miro, 1984). It was also found that different weed species would be causing yield loss at different rates (Beckett, Stoller and Wax, 1988). These studies have unanimously found that a higher density of weeds causes greater yield loss on maize.

Van Heemst (1985) ranked maize seventh out of 25 crops for its competitive ability in weed-crop competition, where higher ranking crops indicate stronger competition against weeds. Maize yield would be moderately reduced by weeds. Various percentage levels of losses have been recorded on maize farms in the tropics, making weeds a major constraint in maize production (Hossain, et al., 2019; Iderawumi and Friday, 2018). More weed species and higher weed density were found in planting plots applied with fertilizer compared to control (Kamuti, et al., 2015; Mtambanengwa, et. al, 2015). Weed management in maize farms is a priority.

2.2.2 Phytosociological attributes for weed communities

Understanding plant community dynamics in the context of diversity and abundance has its root in the field of ecology. It begins with qualitative descriptions of vegetation in forests and progresses to eventual quantitative analysis on floristic composition of a plant community. Weed density is identified as the second most crucial factor in crop-weed competition (Sawnton, Nkoa and Blackshaw, 2015). Curtis and McIntosh (1951) developed a summation index, which is the Important Value Index (IVI) consisting of species density, frequency and dominance, which will have a constant value of 300 for an area. This is a statistical method to advance Józef Konrad Paczosky’s plant phytosociology theory developed in 1896. Paczosky indicated that there are social relations among plants as well as between plants and the environment, and these relationships thus form plant composition and groupings (i.e., structure) in an area (Maycock, 1967).

Starting in the 1950s, researchers have used phytosociological characters as quantitative estimates to describe plant aggregations in natural areas or agriculture farms. The use of these mathematical indices became popular since the 1960s. Phytosociology enables an analytical explanation in plant distribution patterns and classifications in a meaningful way that could be useful for predicting vegetation homogeneity or heterogeneity (Booth, Murphy and Swanton, 2003; Odum, 1971). These attributes are expressed in frequency, density, constancy, abundance, presence, and mean area size (Curtis and McIntosh, 1950).

Values derived from these indices are indicating certain properties of the plant community. For example, with an origin in forestry, IVI is to magnify vegetational importance of a species (Curtis and McIntosh, 1951). On the other hand, with its origin in agriculture, the relative abundance value shows which species has a higher number of individual plants compared to others (Thomas, 1985). Though different in origin, these two indices have been interchangeably used in weed studies in order to explain species composition.

A development combining information on species richness and evenness has emerged and remains important in describing plant community characteristics in the context of occurrence probability (Thukral, et al., 2019). First, it starts with the number of individuals per species measured as density and expressed as the number of individuals m^{-2}. Next are species diversity indices that provide quantitative information on common and dominant species for the plant community structure in a study area. Represented by individuals from random samples in the field, these statistical indices are then grouped into a numerical structure for interpretations of plant community diversity. All species are assumed to be represented in samples in a surveyed area based on the communication theory (Spellerberg and Fedor, 2003).

Among these mathematical measures, Shannon-Wiener diversity index (H') measures information entropy of a community with sensitivity to species richness. It calculates proportional relations between species richness and evenness, referring to the number of species and the number of individuals per species, respectively (Shannon and Weaver, 1963). It indicates community heterogeneity in a numerical structure ranging from low (0) to high diversity (5). More individuals belonging to a species would give a low diversity index in an area. In other words, higher diversity occurs when there are more species with a relatively low number of individuals for each species.

Next is the Pielou's evenness index (*E*), which is sensitive to the distribution of species present. It was introduced in 1969 (Pielou, 1969). The index value will be 1 when all species are equal in number of individuals, while index value 0 indicates the presence of dominant species. There could be a dominant species, or a few dominant species, or species that are equally distributed in a plant community. When one or more species have the maximum number of individuals, a community will have a dominant species. The species' abundance present in a habitat will be known; for example, common species that are characterised by high numbers, without considering species richness. However, the definition and criteria for species classified as "common" remain subjective and vague.

The third index is Simpson's dominance index (D), which measures the probability that any two random species chosen at a site would be the same species (Simpson, 1949). The degree of dominance ranges from high diversity at 0 to low diversity at 1. Index values close to 1 indicate a higher likelihood that two random individuals are from the same species and thus indicating species homogeneity.

Each index has its strength and weakness in explaining a property of a plant community and remains independent from one another. There is no single ideal index, and for the purpose of comprehensiveness, at least two mathematical interrelations of diversity are recommended as complementary measures (Heip, Herman and Soetaert, 1998; Morris, et al., 2014; Strong, 2016). These three population indices have been used for the α-(alpha) level of spatial diversity, for example, on a farm representing an individual community (Booth, Murphy and Swanton, 2003; Thukral, et al., 2019).

2.3 The status of weed biology research

"Nothing in biology makes sense except in the light of evolution."

(Dobzhansky, 1973)

The answer to 'what makes a plant a weed' lies in biological characteristics (Sutherland, 2004). To begin with, weed biology is the study of the life cycle of weed species that starts from germination to senescence, including morphological and physiological traits. Throughout the life cycle, a weed will establish, grow and reproduce for the next generations. This field of study is an important aspect of integrated weed management, providing the basic understanding of weeds for control (Fernandez-Quintanilla, et al. 2008; Young, 2012). However, biological knowledge of invasive weeds is more readily available than non-invasive weeds for management purposes because of higher research interest among researchers. This is the second most researched topic after herbicides-related studies (Davis, et al., 2009). For non-invasive weeds, wild populations and treatment applications such as herbicides have been studied with a higher number of studies on the latter in relation to herbicide dose.

Weed biology study started in the 1930s in which a study compared rooting characteristics of weeds and crops (Bhowmik, 1997). Fast forward to the 1970s, weed societies in Canada and Australia made extensive efforts to study weed biology. Started in 1972 by the Canada Weed Science Society and in 1976 by the Australian Weeds Committee to emulate the Canadian weed society, two series, "The biology of Canadian weeds" and "The biology of Australian weeds" were initiated (Cavers, Darbyshire and Mulligan, 2013; Groves and Panetta, 2014).

Both series are outcomes reflecting the importance of weed biology knowledge in weed science. Canadian weed studies were published in the *Canadian Journal of Plant Science* and Australian weed studies are available in *Plant Protection Quarterly* and the *Journal of the Australian Institute of Agricultural Science*. A total of 265 species of 60 families were studied as of 2016. There were 201 species represented from 43 families studied under the Canadian publications, and 69 species from 36 families under the Australian publication (Appendix C). Species information has occasionally been updated with new knowledge, while most species are reviews and compilation.

Since the Australian weed series modeled the Canadian weed series, topics and format are identical for both series. Topics included species name; description and account of variation; economic importance; geographical distribution; habitat; history; growth and development; reproduction; hybrids; population dynamics; and response to herbicide, human manipulation, herbivory, disease and higher plant parasites. Each topic is described in detail through comprehensive literature review. Most studies are descriptive and qualitative studies. Arguably, such information was commented to not have links to ecological or evolutionary theories but mere compilation (Ward, et al., 2014).

Around the time when the two series of publications were initiated, Baker (1965, 1974) started pioneering work in describing weediness traits and became the first researcher to do so. Baker (1965) compiled around 20 weediness traits found in weeds. Broad ecological niches and high fecundity of weeds were the first insights into the group of plants labelled as weeds. According to Baker (1965), a weed thrives with non-specific environmental requirements for germination, and with a rapid growth to reach reproduction and high seed numbers coupled with asexual reproduction strategy. A weed could have one or few or all of the weediness characteristics. Weeds are considered major and serious for control when possessing more weediness traits. Baker's research works remain influential as a framework for weed biology and plant fitness studies (Chaney and Baucom, 2012; Sultan and Matesanz, 2015). However, the description of weediness traits still lacks of breadth and depth (Fried, et al., 2020).

An increasing use of Baker's descriptions of weediness is observed by weed scientists. However, these traits are qualitative and may not be quantitatively. This is the first challenge in the study of weeds. Chaney and Baucom (2012) studied *Ipomoea purpurea* using three traits from Baker's list – reproductive fitness, competitive ability and growth rate. Genetic variations are ranging from zero to different levels of expressions within populations of a species (Alloub, et al., 2005; Chaney and Baucom, 2012). This poses second challenge in weed study in terms of selection pressure and its extensiveness in the magnitude of gene expressions.

Another notable effort in advancing weed biology knowledge was by LeRoy Holm and his co-researchers in 1991 and 1997. Two books were published in 1991 (Holm, et al.) and 1997 (Holm, et al.), which had identified 180 worst weed species in the world, though they reckoned there are around 250 plants that fall under this category. From the weed series publications to Baker to various researchers who have provided a better understanding on weediness characteristics, their work is more of a descriptive type like Baker's rather than quantitative and predictive. Weed biology is the study of a living organisms consisting of morphology, physiology, anatomy, behavior, habitat, distribution, and origin (Talaka and Rajab, 2013).

Selection pressures driven by humans could have various effects on plants' survival and reproduction strategies. These impacts range from genotypic diversity to phenotypic plasticity and to ecological functions in response to surrounding species and environment (Palkovacs, et al., 2011). This is more profound especially on weeds (Alberti, 2015; Baker, 1974; Dekker, 1997; Kato, 2016; Sutherland, 2004). The level and extent of interactions between genotype and phenotype are broad spectrum and vary among species. These driving forces have continuously shaped variation strategies for a weed species to sustain its populations across spatial coverage and temporal levels (Li, Lindquist and Yang, 2015; Listl and Reish, 2014). Plant morphological and physiological traits reflect biological and ecological adaptations to changing environment and resources (He, et al., 2020).

Some examples of the above mentioned include a triploid genotype weed enables both sexual and vegetative reproductions. *Crepis sancta* was found to have lower dispersal and seedling establishment in urban environments than those in natural environment (Cheptou, et al., 2000). The genetic variations of *Ipomea purpurea* may express in reproduction and competition but not on growth (Chaney and Baucom, 2012). Species may vary in genotypic and phenotypic expressions in different populations (Sultan and Matesanz, 2015). Habitat changes and human interventions are some selection forces on farms in which land disturbances and fertilization are involved (Bourgeois, et al., 2019).

Unlike previous efforts in outlining weediness traits in a general sense, Bourgeois, et al. (2019) have detailed weeds' evolutions by identifying four adaptational traits. First, weeds have high leaf area. The second trait involves an early flowering onset and longer flowering period for seed production. The third adaptation involves growth where weeds favor fertile soil and sunny environment. The fourth is that plants with a shorter life cycle (e.g., annual) are more likely to be weediness over selective advantage because of a shorter generation period for adaptations to express.

Weeds' life cycle could range from a few months, for example, the three-month life cycle of *Euphorbia prunifolia* studied by Wilfred (1980), to perennial life cycles that take years. Weeds with a short life cycle could mean multi-season reproduction in a year, producing seeds as well as succeeding in the selection for weediness traits through rapid generations. *Ischaemum rugosum* could produce a total of 18,000 seeds from three life cycles annually (Baki and Nabi, 2003). After germination, *Fimbristylis miliacea* reached its maximum height in 10 weeks' time (Begum, et al., 2008). Shorter life cycle weeds have a fast relative growth rate and *r* reproductive strategy to establish populations.

Most weeds have annual and biennial life cycles (Sutherland, 2004). Grass is mainly composed of annual or biennial plants. Sedge could be both annual and perennial; the latter life cycle is made possible through rhizomes. Broadleaf consists of perennial plants. More likely, weeds are wet habitats adapted, regardless of whether they are native or exotic species. Arable weeds are mostly therophyte species with an annual life cycle following the planting cycles of crops (Gaba, et al., 2017).

There is a sentiment that research on weed biology has not been happening fast enough in the context of "how" and "why" than its urgency of need for management purposes (Ward, et al., 2014). Most often, existing studies do not provide necessary plant evolution nor ecology theories (Neve, Vila-Aiub and Roux, 2009; Ward, et al., 2014). That leads to a scenario where the "know-how" in terms of predictive power is still lacking in weed management with many important pieces of information still missing, especially linking with resource availability (i.e., fertilizer) (Cousens, 1999; MacLaren, et al., 2020; Mortensen, et al., 2000). Though fundamental biological research on insects is essential in pest management, the emphasis for weeds has not been observed in weed management.

2.3.1 Fertilizer on weed growth and development

Fertilizer application has become an indispensable farming input for crops resulting from the development of the Green Revolution (John and Babu, 2021; Pingali, 2012). Maize with and without fertilizer, specifically of nitrogen (N), phosphorus (P) and potassium (K) which is known as NPK, substantially causing differences in yield (Chipomho, et al., 2020; Hasan and Miro, 1984). Optimal fertilizer amount is desired for maximum maize yield (Imran, Ali and Safdar, 2021). Fertilizer comes in different combinations of NPK ratios, for example NPK 12:12:15 and NPK 15:15:15. These three elements work best together instead of one or two elements (Peterson, 2007).

Each element has its functions in plant growth. Nitrogen and phosphorus are crucial in optimising photosynthesis and vegetative growth, and potassium is for improving yield quantity and quality. These three elements are macronutrients, and they are the most limiting nutrients in lands (Sawnton, Nkoa and Blakshaw, 2015). Nutrients are a major factor in influencing weed-crop competition when the resource becomes the same goal for uptake (Ziska and Dukes, 2011). It is identified in the weed-crop competition theory, in addition to the resource of water and sun. Plants have different requirements for nutrient needs and uptake (Blackshaw, et al., 2004; Moreau, Milard and Munier-Jolain, 2013). It is postulated under the Resource Pool Diversity Hypothesis (Smith, Mortensen and Ryan, 2010).

Nitrogen is known to be the most in demand nutrient element for maize (Hoeft, et al., 2000). Dominant weeds in maize farms were found to be in the group that was able to capture more potassium, calcium (Ca) and magnesium (Mg) (Głowacka, 2011). Not only do these macronutrients assist crop growth, but they could have impacts on weed traits and composition. For example, NPK fertilizer increased the abundance of *Poa compressa* in grass field, while the number of Hawkweed (*Hieracium floribundum*) remained the same, making the former a dominant species over the latter (Reader and Watt, 1981). Fertilizer application in terms of fertilizer type, application methods, timing, nutrient element and rate could influence the growth and development of weeds; however, there may be no effects on some weeds (Bajwa, et al., 2014; Blackshaw and Brandt, 2008; Blackshaw and Molnar, 2009; Sweeney, et al., 2008).

Weeds are more aggressive in capturing nutrients than crops, for weeds have greater needs for the elements (Kaur, Kaur and Chauhan, 2018; Moody, 1981). Some weeds are luxury consumers of nutrients whereby they do not have a saturation point in nutrient uptake whenever nutrients are available (Andreasen, Litx and Streibig, 2006; Teyker, Hoelzer and Liebl, 1991). It was found that broadleaves are aggressive competitors for nutrients compared to grass and sedges (Blackshaw, Molnar and Janzen, 2004). Non-native weed species had higher growth rate and biomass production than native weed species in nutrient-rich cropping systems (Maillet and Lopez-Garcia, 2000). Single element or combinations of two or three elements of NPK could stimulate plant responses in terms of growth, thus influencing its distribution pattern (Little, et al., 2021; MacLaren, et al., 2020; Qi, et al., 2020). Fertilizer effects (i.e., type and rate) on weed growth and development are lacking (Little, et al., 2021).

Phenotypic traits could be a contributing factor to the relative abundance of some species in a habitat and community assembly (Kunstler, et al, 2016; Reader, 1998). Populations from different localities of the same species may have distinguishable physiological attributes (Alloub, et al., 2005; Annaletchumy, et al., 2005). The same weed species could vary in growth and development behavior with different crops or between the wild population and those found on farms (Hegazy, et al., 2005). However, both agricultural and non-agricultural weeds may not differ in phenotypic traits such as height and biomass (Awater, et al., 2018). Growth and development characteristics such as plant height, number of leaves, and seeds number and biomass are among determining measurements in plant responses (Alloub, et al., 2005; Westoby, 1998). There is also suggestion on other functional traits such as leaf area and plant biomass (Pakeman, et al., 2015). Biological measurements of such are still lacking for most weed species for a meaningful understanding.

Phenotypic plasticity studies have increasingly become a focus after 1980 (Schlichting, 1986). Phenotypic plasticity is genotypic expression interacting with environment inputs (Sultan, 2000), in which physiological and morphological characteristics of plants may modify in response to environmental conditions. Plasticity assessments through plant functional traits indicate plant fitness in a particular environment (Bufford and Hulme, 2021). Adaptive responses in plants, including weeds, occur through the life history of growth and development (Hauvermale and Sanad, 2020). *Amaranthus retroflexus* and *Chenopodium glaucum* showed germination plasticity to different sowing dates (Zhou, Wang and Valentine, 2005).

From observational data on *Plantago lanceolata*, leaves had higher plasticity than inflorescences, suggesting vegetative traits may act as a buffer to environmental variations (Villellas, et al., 2021). Growth and development characteristics such as plant height, number of leaves, seeds number, and biomass are among the determining measurements in plant responses (Alloub, et al., 2005; Westoby, 1998). Plant functional traits could be correlated to plant fitness when plants are under selection pressure from biotic and abiotic variabilities. Research in the field of phenotypic plasticity is complex, as the patterns of phenotypic plasticity may not be consistent among and between species (Gratani, 2014; Sultan, 2001). Therefore, the understanding of phenotypic plasticity remains limited (Bufford and Hulme, 2021).

Amaranthus retroflexus and *Rottboellia cochinchinesis* produced higher biomass with an increased dose of N fertilizer (Awan, Cruz and Chauhan, 2015; Teyker, Hoelzer and Liebl, 1991). Shoot and root growth among 22 agricultural weeds were found to have varied magnitude of trait responses to an increased amount of P fertilizer (Blackshaw, et al., 2004). With an increasing P level, the majority weed species had higher shoot biomass than wheat and canola; while fewer weed species exhibited higher root biomass than canola and none for wheat (Blackshaw, et al., 2004). It was found that *Sinapsis arvensis* had the highest dry weight of shoots, indicating a strong competitor than *Papaver rhoeas* and *Viola arvensis* with lowest dry matter (Andreasen, Litz and Streibig, 2006), among the six weed species with increased N and P levels.

From the same study of Andreasen, Litx and Streibig (2006), findings on N and P percentage content in weed species and barley (*Hordeum vulgare*) suggested that weed species took up more N and P than the crop. Weed dry shoot biomass was higher in fertilized NPK cassava (*Manihot esculenta*) farm compared to non-fertilized plot (Soares, et al., 2015). Basic research on one or more weed species (e.g., to fertility) is a good starting point for weed management (Fryer, 1981; Little, et al., 2021). Responses to biotic and abiotic factors may be species-specific (Zikas and Dukes, 2011). An understanding of plant functional traits in response to fertilizer is essential in fertilizer-weed management (Kaur, Kaur, Chauhan, 2018).

Utilizing a model for prediction based on biological traits of germination, population, and seed production, it was found that 17 out of the 18 weed species had unfavorable growth on maize farms, but these species had indicated the opposite with other crops (Borgy, et al., 2015). The more invasive a weed is, the higher chance a model is applied for prediction use (Hogan and Myerscough, 2017). Weed biology information is useful as an input in descriptive model (i.e., crop-weed competition) for a predictive approach in the weed management system. Weed productivity is found to be responding to soil fertility for its inherent biological characteristics, such as the need and availability for nutrient elements (Bhowmik, 1997; Little, et al., 2021).

With the continuing adaptations by weeds, modelling could be challenging for accuracy in predictability for weed control objective (Neve, Vila-Qiub and Roux, 2009). Still, modelling is a tool in enhancing understanding on weeds when total elimination is not possible and unrealistic (Nicols, et al., 2015). Empirical studies on weed biology are still limited. A paucity of research continues to hinder learning about the growth response of weeds to fertilizer and other environmental factors.

Considering the variations of genotypes and phenotypes in weeds, in addition to possible effects of different populations of a species, weed biology knowledge would be considered site-specific knowledge because of differences in farm management practices by farmers (Smith, Mortensen and Ryan, 2010). Basic research on one or more weed species (e.g., to fertility) is a good starting point for weed management (Fryer, 1981; Little, et al., 2021). Responses to biotic and abiotic factors may be species specific (Zikas and Dukes, 2011).

2.4 Weed management and control methods

Defining weeds is not as important as managing them (Randall, 1997), with a focus on benefiting crops from the weed-crop interactions. Weed control is needed as soon as desirable plants or crops emerge, serving as both a reactive measure for existing weeds and a preventive strategy to reduce future weed growth on the farm. Even with intensive weed control, a minimum of 10% yield loss is expected (Bastiaans, et al., 2000). Negligence in weed control could lead to 100% loss. Weeds become a permanent feature on farms, and removing one species can create ecological niche for others. Weed management interventions are essential to maintain crop quality and quantity.

Weed control emerged as a by-product of tillage practices for site preparation before 1500 AD, when farmers were not fully aware of weeds as a factor contributing to yield reduction on farms (Timmons, 1970). This remained the status quo for many centuries until the 1900s when there was an increasing interest in weeds and weed control. The invention of the rod weeder, a tool specifically for weed management in 1914 marked a significant development (Timmons, 1970), along with the use of inorganic compounds such as sodium arsenate, carbon bisulfide, and petroleum oils for chemical control (Kelton and

Price, 2010). In particular, the discovery of the first herbicide 2,4-D in the 1940s further intensified research interests in weeds and led to the establishment of the discipline of weed science (Kelton and Price, 2010).

Weed management is critical in every crop cycle, as existing weed populations are influenced by preceding practices and will continue to impact future generations (Mortensen, Bastiaans and Sattin, 2000). The goal is to control weed populations using all available control means with scientific knowledge and systematic strategies to benefit the growth of desirable plants (Fryer, 1981). Diversifying weed control methods benefits consumers, farmers, and the environment.

Various weed management methods are employed, with the chemical method being the predominant choice for farmers due to its convenient use, affordability, and satisfactory efficiency. The first commercial herbicide 2,4-D, was introduced in 1945 mimicking the auxin hormone that controls plant growth (Peterson, 1967). Thereafter, chemical weed control has become the dominant method in weed management practices worldwide.

Farmers have heavily relied on herbicides, but the dependence on herbicides as the main weed control practice in the last 70 years has led to three spin-off problems: environmental hazards, food safety concerns, and toxicity exposure. Despite these issues, some weed scientists predict the continued heavy use of existing and new mode-of-action herbicides in 2050, expecting it to remain the dominant control method (Westwood, et al., 2017).

Due to increasing social pressure, the chemical method has faced critical criticisms for being unsustainable. Other control methods are frequently highlighted to mitigate the negative effects associated with herbicides (Bastiaans, et al., 2000). There is also increased awareness that weeds pose more than just a herbicide-solvable problem. However, research on weed science progresses slowly, likely due to the enduring presence of weeds on farms and lack of attention from policy makers (Fernandez-Quintanilla, et al., 2008).

Other management controls include mechanical/physical, biological and cultural methods. Each has developed independently, but they share a commonality in being overlooked due to the convenience and reliance on herbicides for decades. Some mechanical methods have existed as part of soil bed preparation since the beginning of agriculture around 10,000 years ago, making them older than chemical control. The earliest mechanical equipment, the horse-drawn hoe, was invented by Jethro Tull in 1722, originally intended for soil ploughing (Timmon, 2005). Various cultivation tools have since been developed using either animals or machines for tillage purposes.

In contrast, biological control had its first attempt in Hawaii in 1902 on the weed *Lantana camara.* Today, biological control has evolved, utilising bio-agents such as microbes (i.e., bacteria, fungi and virus), herbivorous animals, natural enemies, and bioherbicides derived from plants' allelochemical. Cultural control aims to reduce the number of weeds or weed establishment on the farm, while enhancing crop competitiveness over weeds. Cultural practices include crop rotation, manipulations in sowing time, cropping systems, tillage, and resources management. The importance of fertilizer management is highlighted for its effects on weed densities and weed biology (Bajwa, et al., 2014). Blackshaw and co-researchers (2004, 2008, 2009) have conducted research related to application timing and placement (i.e., above soil or in the soil). However, challenges remain in translating the knowledge into practice, and more research is needed for better understanding to facilitate the translation.

Control methods need to be adjusted in correspondence with the shift in the weed community, considering changes in species composition and abundance (Karim, Man and Sahid, 2004). Knowledge of weed biology is a practical component in planning to optimise and complement various control methods, including managing herbicide resistance weeds (Mahajan and Chauhan, 2020; Neve, Vila-Aiub and Roux, 2009; Norris, 1992; Norsworthy, et al., 2012). For example, *Avena fatua* populations declined after intensive biological studies on the species over ten years. *Kochia scoparia* is removed in early spring before the plant has robust growth (Schwinghamer and Van Acker, 2008). The success in weed management was due to modifications in delaying harvesting timing and deploying multiple herbicide control programs (Fryer, 1981).

Some newer research areas, like critical period of weed control emphasize the timing of herbicide application with the objective of reducing herbicide usage. This includes weed thresholds in terms of weed density and economic thresholds at an acceptable level of yield loss. Although this is an important focus, it is more imperative to respond to an ever-growing consensus that emphasises ecologically friendly weed management. However, only a smaller group of weed scientists are working on non-herbicide related research topics (Davis, et al., 2009). So far, the consensus of the importance of a paradigm shift to non-chemical control methods has not necessarily been translated into research focus.

To create integral, sustainable and environmentally friendly weed management, knowledge on weed biology and ecology is an underlying requirement for site-specific application (Chauhan, et. al, 2017; Neve, et al., 2018). Most importantly, weed biology should be recognized as fundamental knowledge and hence incorporated in devising practical and integrated weed management (Birthisel, Clements and Gallandt, 2020; Gressel, 2011; Hamill, Holt and Mallory-Smith, 2004; Mahajan and Chauhan, 2020; Van Acker, 2009).

Some have challenged the assumption, but it does not deflect the intrinsic research interest of weed biology (Ward, et al., 2014). However, the integration may be easier said than done in practice due to its inextricable and multifaceted nature (Neve, Vila-Aiub and Roux, 2009; Van Acker, 2009). With the main research focus being on herbicides, much thinking needs to be done in weed science, resulting in slow progress in ecological weed management (MacLaren, et al., 2020).

The acceptance and incorporation of ecologically weed management are limited due to the continued overwhelming success of weed control by herbicides (Liebman, et al., 2016; Shaner and Beckie, 2013). The two dominant controls in developed and developing countries are herbicides and tillage (Maclaren, et al., 2020). Malaysia is no exception, and the chemical control method continues to dominate (Dilipkumar, et al., 2017). Weed management could be more challenging for smallholder farmers (Rao, et al., 2018). Most often, weed biology research has been ignored despite acknowledgement (Fernandez-Quintanilla, et al., 2008; Gressel, 2011; Mahajan and Chauhan, 2020; Norris, 1992).

2.5 An overview of weed science research in Malaysia

In 2006, Bakar published a book titled "*The Malaysian initiatives in weed science research*", serving as the only publication aiming to comprehensively document research abstracts of weed science studies from various sources, including journal papers and proceedings from 1918 to 2003. Not confined to agricultural weeds, the compilation scope also includes studies on roadsides, ecological succession, recreational sites and natural habitats.

Although the compilation was meant to be exhaustive, some studies included may not focus on weeds under any circumstances. For example, Burkill. I. H.'s "*A dictionary of the economic products of the Malay Peninsula*" vol. 1 in 1935 mostly described vegetables and forest products, not weeds (Annon, 1936). Another example is Holtum's ornamental plant *Cycas* article in 1953 published in the *Malayan Nature Journal.*

Bakar's (2006) compilation originally contained a total of 2,006 studies. However, excluding studies that were not related to weed species, lacked an agricultural context, or had double entries for the same study, the number of studies may be lower. The tabulation of research areas aligned with those of this study, including farmer community, weed species composition, and weed biology, provides an indication of the number of studies conducted in agriculture over a span of 85 years, adapted from the Bakar's book (Table 2.2). Interestingly, there were no studies on farmer communities in Malaysia.

Table 2.2. Number of studies on farmer community, weed species composition and weed biology in Malaysia from 1918 to 2003.

Research area	Number of studies	Year of the first study and its title
Farmer community	n.a.	n.a.
Weed composition	43	Reid, J.A., 1952. Some common grass. *Malayan Nature Journal 17,* pp. 136-147.
Weed biology	73	Ng, T.T. and Wong, T.H., 1975. Germination and seedling emergence of the tropical grass, *Ishaemum magnum* Rendle.

(Source: Adapted from Baker, 2006)

Reid's study in 1952 is considered the closest research area for weed composition in Malaya, although it has a noticeable limitation. The study relied on observations than systematic methods to quantitatively define "common" presence and abundance of weed species. Many subsequent studies have also used the term "common" for observations of weed species present on sites, such as common weeds in rubber plantations. Research on weed composition in rubber plantations and paddy fields, as well as studies on notorious weed species such as *Imperata cylindrica* and *Mikania micrantha,* were some key research areas in the 1980s and 1990s. These species were found in rubber, oil palm and cocoa plantations. However, there is no explanation on invasiveness characteristics of these noxious species, nor has the criteria of invasiveness provided.

Bakar categorized studies on plant species' taxonomy, morphology, anatomy, and cytology as part of the field of weed biology. However, a shortcoming is that some of these plants are general plant biology studies and may not necessarily pertain exclusively to weeds. Examples include Samsudin's "Studies in the taxonomy of the genus *Arthrophyllum* (Araliaceae)" in 1968, and Goh's "The morphology, anatomy and cytology of *Trigonobalanus verticillata* Forman (Fagaceae)" in 1970. Some of these studies focus on medicinal, horticultural, and edible plants, as well as the growth of lawn grasses. These studies are excluded from the counting on the number of weed-related studies. Weed biology studies that explore germination under different environmental factors or herbicide treatment, and studies on sexual or asexual reproduction of weed species, fall within the scopes of weed biology research.

After 2003, weed composition studies have continued in paddy fields and oil palm plantations, but with the decline of rubber and cocoa plantations, as they are no longer major plantation crops in Malaysia. Extensive weed research on paddy fields by university researchers and oil palm by planters and the industry has been conducted. A major application of knowledge on weed species is in deciding on the herbicides to be applied. Only one study has been conducted in vegetable farms of bayam (*Amaranthus* spp.), *Brassica rapa,* sweet potato (*Ipomea batatas*)*,* kangkong (*Ipomea reptans*) and leaf lettuce (*Lactuca sativa*) (Raya, et al., 2013). However, these studies were conducted without studying the impacts on yield, thus undermining the objective of weed studies, which is a linked to crop production and yield. Although weed surveys are equally important for other crops, a weed survey in maize farms has yet to be conducted.

Research on allelopathy properties has emerged as a recent interest in weed science. These studies have included allelopathic potentials and properties of some weeds, examining allelopathic effects on either crops or other weed species. Allelopathic effects were found to inhibit the germination and growth of targeted species (Aslani, et al., 2014; Favarani, Baki and Khalijah, 2008; Ismail, Tan and Chuah, 2015; Nurul Ain, Nornasuha and Ismail, 2016). Like previous studies, researchers have categorized few weed species as “common” weeds without elaborating on the selection criteria. This may create ambiguity regarding what common weeds are. The circumstances under which weeds are considered common need to be studied quantitatively in a meaningful context.

Throughout the years, the chemical control method and its related contexts have remained the most studied in Malaysia. For example, the wax content on leaf surface of a few weeds from oil palm plantations is considered a possible indicator for effective application of surfactants (Ngah, et al., 2011). Research attention and development on weeds in Malaysia are disproportionate to the importance of weeds on agriculture production. For instance, weed composition studies focus on major crops such as rice, rubber and oil palm, but there are hardly any weed studies in vegetable farms, despite vegetables being everyday food. Not much is known about weed composition other than in plantation crops, let alone about weed biology.

2.5.1 Farmer communities in Malaysia

Agriculture remains a main economic sector in Malaysia and is a priority sector promoted for industrial development in the Malaysia Plans. The national plans are five-year development agenda designed to drive targeted sectors with performance goals. As a result, employment in the agriculture sector was 444,531 and 835,974 people in 2015 and 2017, respectively (Department of Statistics, 2019a). Agronomy stands as the major sub-sector compared to livestock and fisheries, providing at least 80% of job opportunities in the agricultural sector. It has seen an increment of 43.8%, from 368,002 farmers in 2015 to 761,393 farmers in 2017.

Farmers are the backbone in agriculture. Weeds are a critical component for smallholder farmers for achieving desired crop yield (Sangkkara and Stamp, 2006). There is involvement of a social dimension in agriculture involving farmers. Every farmer community is different and unique in its characteristics. The social context of farmer community has not been well researched and its information is still lacking (Jordan, et al., 2016). Attitude is often the most surveyed topic, as it plays an important role in decision-making (Alreck and Settle 2003; Sanbonmatsu, et al. 2014). Beliefs, knowledge, and perceptions are companion scopes in farmers' surveys (Assis and Mohd. Ismail, 2011). Farmer community is recommended as a pillar component for study in weed science (Hamill, Holt and Mallory-Smith, 2004; Chauhan, et al., 2017).

Individual attitude is an indication of mental predisposition that could be influenced either to change or not to change in behavior through a learning combination of experience, values, and intentions (Pickens, 2005). Farmers' knowledge has been considered as informal knowledge as contrast to formal knowledge which is science-driven (Šūmane, et. al, 2018). Farmers learn from experience and various information sources that anchor the nature of knowledge in practicality and reality. Variables in the local context are then constructed as a representation of these underlying drivers.

Questionnaire survey findings could serve as a baseline understanding for different objectives. One objective is farm management strategies, which involve resource optimization for production maximisation on farms. Based on years of farming experience, and through the adaptation and adoption of agricultural practices, farmers have acquired behaviors and skills. These social relations of farming learning have made a farmer community is unique with its characteristics. These characteristics, associated with technical topics, could be studied through social approaches.

Surveys are a method used to collect information to describe, compare, or explain individual or societal knowledge regarding demographics, attitudes, feelings, values, preferences, needs, decisions, lifestyles, and behavior (Alreck and Settle, 2003; Fink, 2013). It is the only way to obtain such information and knowledge, and it is a method that is adopted across different disciplines for the purposes mentioned above.

Due to the apparent influence of farmers' attitudes and knowledge in agronomic practices, a number of studies have surveyed paddy farmers, and a few studies on pepper, tomato and oil palm growers in Malaysia. Most studies focus on paddy farmers and the shift to new technology and practices such as precision agriculture (Abdullah, Ahmad and Ismail, 2012), green fertilizer (Adnan, et al. 2017), sustainable agriculture (Abu Samah, et al. 2012), and weedy rice (Dilipkumar, et al*.,* 2021). These studies are useful in providing insights in forming strategies for the adoption of new initiatives among paddy farmers.

Weed management is a variable influencing sustainability in agriculture (Taylor, et. al, 1993). There is increasing pressure to reduce the use of herbicides in controlling weeds due to the prevailing concern of herbicide-resistant weeds. In addition, the chemical control method also causes undesirable effects in terms of harmful effects to human health and environmental pollution. Hence, outside Malaysia, some studies have focused on farmers' perceptions, beliefs and attitudes toward weeds, weed control and knowledge (Agahiu, et al., 2012; Jussaume and Dentzman, 2016; Kings, 2014; Laizer, Chacha and Ndakidemi, 2019; Vissoh, et al., 2004; Williams, et al., 1987; Wilson, et al., 2008). The general finding of these studies is that farmers tend to react to weed control rather than focusing on prevention. Farmers' attitudes are a crucial component in weed management (Gaba, et al., 2016).

The discovery of herbicide has contributed to establishing weed science as a discipline. Herbicide related studies have become a mainstream research topic with the purpose for it to remain as the main control method (Davis, et. al, 2009; Kraehmer, et. al, 2014; Westwood, et. al, 2017). Malaysia is known to be highly dependent on herbicides (Dilipkumar, et al., 2017). Without much surprise, only one questionnaire survey relating to weed control in organic farms (Shah Yusop, et. al, 2013).

Similar to the observation of weed surveys mainly conducted for major crops, none of questionnaire studies target vegetable farmers in Malaysia. In 2018, agriculture contributed 15.1% to the Perak economy, providing employment opportunities for 69,600 people, representing 6.7% of the state's workforce (Department of Statistics, 2019b). Vegetable smallholder farmers are considered as the major group of farming. It is important to understand farmer communities, as agriculture is a major economic sector in Perak, among other sectors such as manufacturing, construction, and mining and quarry. Additionally, farmers' choices of weed controls are reactions to the pressure level experienced from weeds on farms (Gaba, et al., 2016; Jabbour, et al., 2014). Hence, local farmers' opinions are essential in planning and adopting weed management (Birthisel, Clements and Gallandt, 2020).

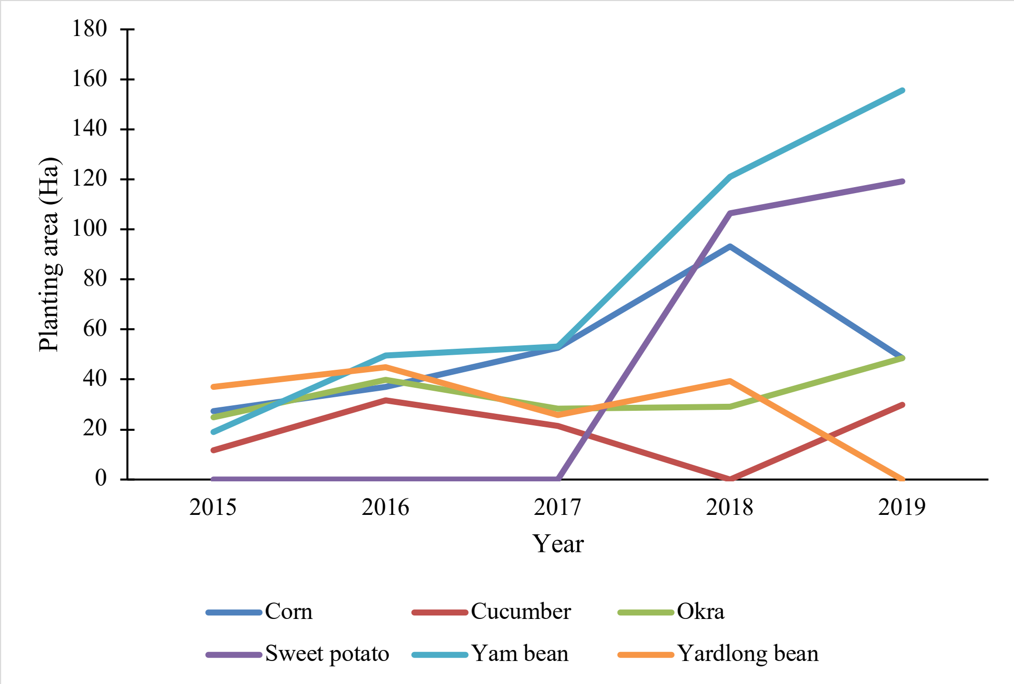
There are three types of survey questionnaire, namely open-ended, semi-structured and closed-ended. Each is known for its strengths and weaknesses. Open-ended questions provide opportunity for rich qualitative data. Some quantitative data and detailed information are collected in semi-structured surveys. The third type, closed-ended surveys, would be ideal for coding, quantitative research. Some limitations have been identified using the survey method. Amongst them are sensitive questions to be avoided for the target audience, and results to be taken as indications and not definitive (Alreck and Settle, 2003). People may change what they know and believe after gaining more experience. Non-response from respondents would also cause bias in survey results.

2.5.2 Agricultural development in Kampar, Perak

Agriculture in Malaysia is mainly consisting of plantation crops such as oil palm and rubber. The other group includes smallholders' crops of vegetables and fruits. Around 77,846 ha were planted with vegetables in Peninsular Malaysia in 2018. Perak is the third largest state with vegetable planting areas, after Pahang and Johor (Department of Agriculture, 2018). Agriculture has been an important economic activity for the Perak state. From the early days, the state government did not want to depend solely on tin mining as the sole income source (Lubis and Khoo, 2003). In the 18th and 19th centuries, tin miners spent more time on tin mining work after crop harvesting. These nests of tin mining towns are made up of the well-known Kinta Valley that is along Kinta River, which includes Gopeng, Malim Nawar, Tronoh Mines, and Kampar.

Kampar, with a land area of about 66,980 ha, is the smallest district in Perak, which is among the 11 districts in Perak. Of these, 20,266 ha were used for agriculture in 2016, representing 30.2% of the total land area in Kampar (Perak State Government, 2016). The population was estimated to be around 106,000 in 2016 (Perak State Government, 2016). After 1985, many tin mining areas that once boasted townships experienced a transition in economic activities compared to other industries. Over time, former tin mining areas were converted to agricultural uses for crops, aquaculture and livestock (e.g., duck).

In Kampar, vegetables are the main agricultural crops. Among those commonly planted vegetables are including bitter gourd *(Momordica charantia)*; brinjal *(Solanum melongena)*; chilli *(Capsicum* spp.*)* and lemongrass *(Cymbopogon schoenanthus)*. Few crops emerged as farmers' choices. From 2015 to 2019, the five most planted crops were found to be maize *(Zea mays)*, cucumber *(Cucumis sativus)*, okra *(Abelmoschus esculentus)*, sweet potato *(Ipomoea batatas)*, yam bean *(Pachyrhizus erosus)* and yardlong bean (also known as Chinese long bean) *(Vigna unguiculata* subsp. *sesquipedalis)* (Department of Agriculture, 2020) (Figure 2.1). These agricultural clusters would advance agricultural development for Kampar.



(Source: Department of Agriculture, 2020)

Figure 2.1.: Five crops with the highest planted areas from 2015-2019 in Kampar.

Agriculture made up 44.5% of income source for the people of Kampar District in 2014 (Majlis Daerah Kampar, Jabatan Perancangan Bandar dan Desa Perak Darul Rizduan, and Jabatan Perancangan Bandar dan Desa Semenanjung Malaysia, 2015). Hence, agriculture clusters have been identified according to types of crops and locations for further development to maintain the economic importance of agriculture in the Kampar district. For instance, Kota Bahru is demarcated as oil palm cluster. These agricultural clusters would advance agricultural development for Kampar.

2.6 Conclusion

A multi-pronged approach involving weed management education and research is needed to achieve sustainable agriculture (Chauhan, et al., 2017; Fryer, 1981; Gaba, et al., 2016). These components may include farmers' survey, weed composition inventory and weed biology studies. Firstly, the amount of literature on smallholders' survey is almost non-existing in Malaysia. Most questionnaire studies focus on paddy farmers regarding the shift to new technology and practices such as precision agriculture (Abdullah, Ahmad and Ismail, 2012), green fertilizer (Adnan, et al. 2017), sustainable agriculture (Abu Samah, et al. 2012), and weedy rice (Dilipkumar, et al., 2021), albeit a few studies on pepper, tomato and oil palm growers in Malaysia.

In some countries such as France and Czech Republic, databases have been established to understand weed community dynamics over a temporal-spatial scale (Lososová, Chytrý and Kühn, 2008; Munoz, et al., 2020). Though weed composition is recognised as the first step in weed management, weed composition studies have been conducted in major commercial crops such as rice (*Oryza sativa*), oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) in Malaysia. To date, rice has received extensive research focus among weed scientists and is relatively well studied as compared to other crops. The research realm is disproportionate for the areas of crop types, and types of growers (i.e., smallholders and commercial growers). This concludes the second component of multidisciplinary weed management approach.

Thirdly, existing weed biology knowledge is widely descriptive; however, such biological knowledge should be empirical questions. Biology involves a vast range of studies that covers any stages of life cycle. Though fundamental biological research on insects is essential in pest management, the emphasis for weeds has not been observed in weed management. The interactions of weeds and selection pressure (i.e., fertilizers) make biological studies complex. Studies including basic research and plant responses to external factors remained under-explored.

Weed science studies are more varied in terms of research interests, a positive indication in moving away from the 'herbicide-based' discipline, inadequacies are still identified in the above three principal areas of studies. With answers are needed for under-explored research topics, this provides a direction for this study.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study site

Malim Nawar in Kampar District, Malaysia, is envisioned as a potential major production site for vegetable crop cultivation for modern high-technology farms by 2030 (Figure 3.1). The agricultural planning is expected to lead to the development of intensive agricultural activities and weed management practices.

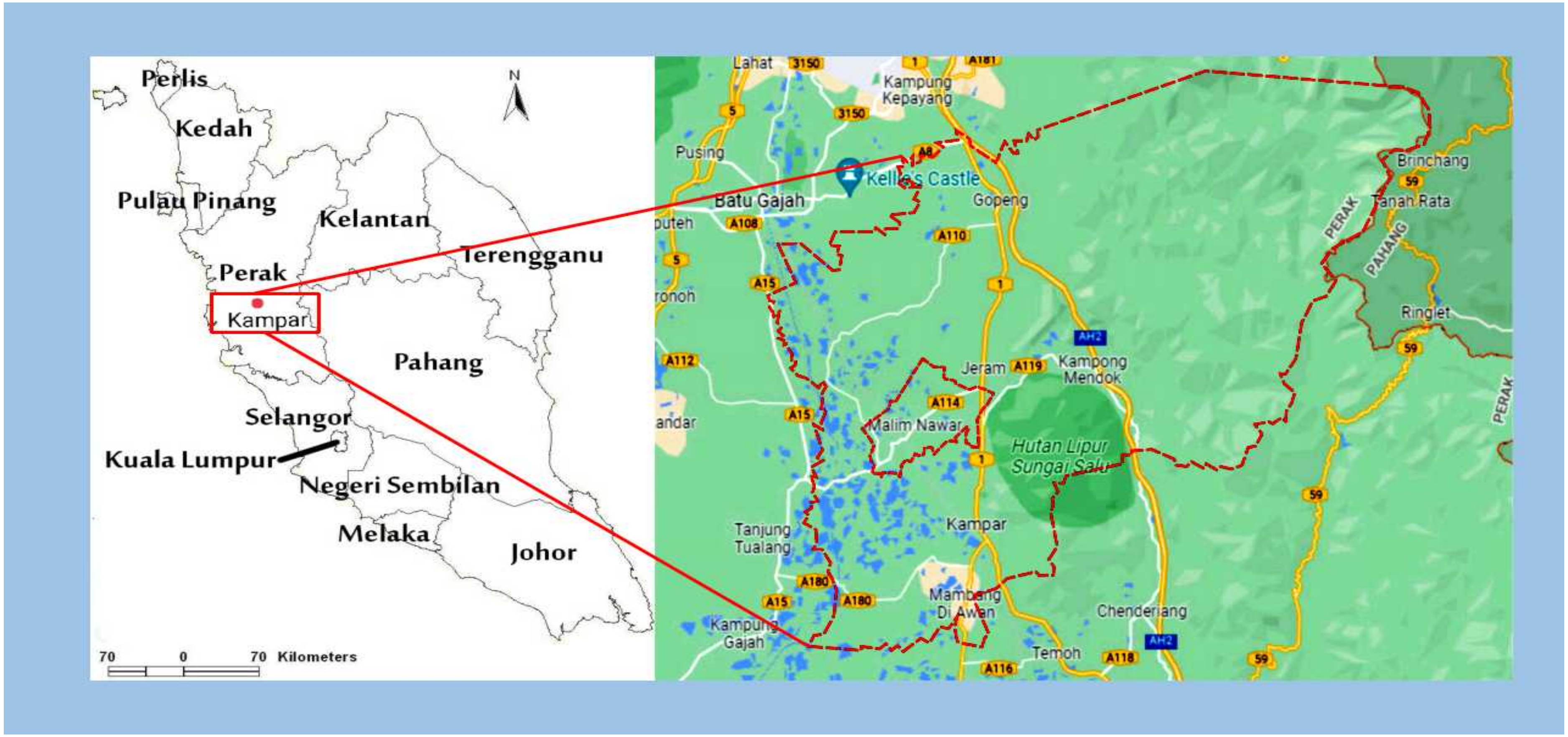


Figure 3.1.: Location of study site: Malim Nawar in Kampar, Perak.

3.2 Farmer survey questionnaire

Members of a local farmers' organisation, called the Malim Nawar Vegetable Farmers Association (official name in Malay: *Persatuan Pekebun Sayur Malim Nawar*), were recruited for this study. Convenient sampling was conducted, with a total of 97 participants randomly selected from the list. The margin of error is 7.16% at a confidence level of 95%.

Farmers working on the same farm were excluded. The survey period was scheduled from June to October 2018 because of the non-responsiveness of some respondents and continued persuasion of some participants. Semi-structured interviews, through face-to-face, were conducted. As the first step, exploratory interviews were conducted with few key informants to design questions based on local knowledge. The second step was a pilot study for ten farmers from the Association, and followed by a full-fledge survey questionnaire.

A three-section questionnaire was designed: Section A assessed participants' demographic information, Section B assessed their perceptions of weeds and constraints affecting crop production, and Section C assessed how they learned weed management practices. The questionnaire was in Appendix D. The surveys were conducted through face-to-face interviews so that the questionnaire could be explained to the farmers, and they could reliably answer the questions. The interviews took place in a familiar environment (e.g., coffee shops, farms), as suggested by the farmers. The participants' responses were written on the sheets by the researcher, as the respondents were not very confident in filling out the questionnaire themselves.

3.3 Weed survey in maize farms

The weed inventory was conducted over three years, in 2017, 2018, and 2020, during the month of June in Malim Nawar, where farmers' survey was conducted. Weed inventory study was not conducted in 2019 because farmer was not planting in June 2019. The planting site remained the same throughout the study period; although the cropping area size varied slightly each year, with 0.99 ha in 2017, 0.86 ha in 2018, and 0.63 ha in 2020. The annual weed survey was conducted 30 days after planting, utilising the transect sampling method with the soil beds delineating the transects. The sampled soil beds were randomly selected and the sample quadrats measured 0.5 m × 0.5 m. The first and last quadrats of each sample were positioned 5 m from each end of the soil bed to avoid edge effects, as the weed composition in the fringe may not be representative of the weed composition in the farm (Hakim, et al., 2010; Munoz, et al., 2020). The quadrats were placed at 5 m intervals, resulting in forty quadrats surveyed in 2017, 2018, and 2020, totaling 120 quadrats for the three-year survey. All weeds growing in each quadrat were identified by species and the number of individuals was recorded.

Maize seeds were sown at a density of 8 plants m^{-2}, with two seeds per planting hole spaced at a distance of 0.4 m × 0.4 m. The soil bed width was 0.6 m, and the distance between rows of soil beds was 0.9 m. Before planting, the planting site was treated with glyphosate-based herbicide. Pesticides containing the active ingredient emamectin benzoate were applied 30 days after sowing, and subsequently, on days 46, 55, and 59. Fertilizer was applied five times throughout the planting season, starting on day 12 after sowing and continuing on days 20, 34, 46, and 58. An N:P:K fertilizer in the ratio of 15:15:15 was applied to maize during the first three rounds of fertilization, while an N:P:K fertilizer in the ratio 12:12:17 was applied during the final two rounds. Total maize yield data (including kernel, ears, and silk), measured in metric tonnes on a fresh weight basis, were provided by the small farmers. Climate variables such as average mean temperature (°C) and mean rainfall (mm) data were obtained from the Malaysian Meteorological Department.

3.4 *Amaranthus viridis* in 50% shade house and in the wild

3.4.1 Study species

Amaranthus viridis had the second highest mean field density and relative abundance out of 15 weed species found in smallholder maize farms, according to field surveys conducted in 2017, 2018, and 2020 in Malim Nawar, Malaysia. High mean density and relative abundance reflect the degree of difficulty in controlling a particular weed (de Mol, von Redwitz and Gerowitt, 2015; Hakim, 2010). The *Amaranthus* genus consists of 75 species found in the tropics and temperate regions (Mabberley, 2017). They are distinguished in the form of crops, ornamental, wild, and weeds (Brenner, et al., 2000). *Amaranthus viridis* is widely distributed, being native to 33 countries and introduced to 98 countries (Holm, et al., 1997; POWO, 2021). It is an annual broadleaf weed with a C_4 photosynthetic pathway and can be found on farms and in open habitats, such as roadsides, and utilizing seed propagation mechanisms (Xu and Deng, 2017).

3.4.2 Fertilizers NPK 12:12:17 and NPK 15:15:15

Seeds of *Amaranthus viridis* were sown for a life cycle study; however, none of the 100 seeds germinated, with and without scarification, and with or without vegetable seeds, either in the shade and under the sun, respectively. A total of 600 seeds were used in the germinatial trials. Transplanting was then resorted to. Thirty plants from natural habitat in Universiti Tunku Abdul Rahman with a height between 5 cm to 20 cm were transplanted into polybags measuring 20 cm (length) x 15 cm (width) x 30 cm (height). Plants from the same location were obtained from the same batch of seeds with similar heights observed (Hanzawa and Kalisz, 1993; Kirkpatrick, 1984). Polybags were filled with soil from a site where *A. viridis* was found. The soils were mixed with tailing parent material with a pale brown to brown upper layer of 30–70 cm. The soil consisted of sandy clay to clay, weak fine subangular blocky, friable, overlaying brown silty clay to clay, olive-brown to brown coarse sandy clay loam with some clay balls

(Selliah, 2015). Plants were arranged in a Randomized Complete Block Design (RCBD) in six blocks for five treatments, in a shade house with relative light intensity of 50% in the north-south direction.

The five treatments included a control and four different dosages of Behn Meyer Nitrophoska® Green NPK 15-15-15+2S, produced by Eurochem Agro without specific location mentioned, at 1 g, 2 g, 4 g, and 8 g. Fertilizer was applied one month after transplanting and subsequently on a weekly basis throughout the study period from March to September 2020 for a total of 7 months. The weekly fertilizer application was adopted from farmer's practice. Simultaneously, six plants in the wild population were studied without any treatment and were not transplanted. The number of leaves, inflorescences, and height (cm) of each plant were recorded weekly. Flowers were arranged in terminal panicle spikes. Each spike was counted as an inflorescence. Plant organ was considered a trait reflecting functional characteristics of growth, competitive ability, and reproduction (Garnier and Navas, 2012).

The experiment was repeated from May to September 2021 for five months with another 30 plants. The fertilizer was changed to AgroBridge NPKMg 12-12-17-2+TE, a muriate of potash (MOP) based fertilizer imported from Europe, without a specific manufacturer or location. The duration of both studies lasted as long as the maize planting cycle or longer to understand plant responses to fertilizer treatments. These two fertilizers were commonly used by smallholders in maize planting from where the weed surveys were conducted, so these fertilizers were used to study *A. viridis* growth and development.

3.5 Data analyses

In the analysis of the farmers' survey questionnaire, chi-square test (χ^2) was employed using SPSS 20.0. For weed communities on maize farms, various statistical tests were utilised: two-proportion z-test, Student's t-test, hierarchical clustering analysis, and general linear model. In the *A. viridis* fertilizer studies, the following statistical methods were used: normality Shapiro-Wilk test, Person correlation coefficient (*r*), and linear regression (R^2). These analyses were conducted using SPSS 20.0.

3.5.1 Survey questionnaire

Statistical analyses included descriptive statistics and a comparative non-parametric chi-square test (χ^2) to study the association between two variables. A p value < 0.05 was considered significant.

3.5.2 Phytosociological analysis

Weeds were collected and identified. The total number of plants categorized according to grass, sedge, and broadleaf populations in 2017, 2018 and 2020 were analyzed using a two-proportion z-test with a Bonferroni correction. This aimed to determine whether two multinomial probability distributions (i.e., pairwise for 2017 and 2018; 2017 and 2020; and 2018 and 2020) were distributed equally for each weed type. The Bonferroni correction involved adjusting the alpha (α) level to mitigate Type 1 error, which is rejecting the null hypothesis falsely.

The adjusted alpha level was calculated as 0.05/3 (three groups consisting of broadleaves and others, grasses and others, and sedges and others) = 0.016667.

When the p value was lower than the adjusted alpha level, populations compared were statistically significant between the pair, indicating variation in the number of individuals.

For every weed species, the number of individuals was analysed with five measurements on frequency, field uniformity (FU), mean field density (MFD), mean occurrence field density (MOFD) and relative abundance by Thomas (1985).

$$F_k = \frac{\sum^{n} Y_i}{n} \times 100$$

Where F_k = Frequency for weed species k, Y_i = Presence (1) or absence (0) of weed species k in field *i*, n = number of fields surveyed.

$$U_k = \frac{\sum^{n} \sum^{40} X_{ij}}{40n} \times 100$$

Where U_k = Field uniformity for weed species k, X_{ij} = Presence (1) or absence (0) of weed species k in quadrat *j* in field *i*, n = number of fields surveyed and number of quadrats per field is 40.

The difference between mean field density (MFD) and mean occurrence field density (MOFD) was that the former computes the mean number of plants per m^{-2} in all fields, whereas the latter calculates the mean within fields where the species was found.

$$MFD_k = \frac{\sum^{n} D_i}{n}$$

Where MFD_k = Mean field density of weed species k (expressed as number of weeds/m^2) for all surveyed field and n = number of fields surveyed.

$$MOFD_k = \frac{\sum^{n} D_i}{n-a}$$

Where $MOFD_k$ = Mean occurrence field density of weed species k (expressed as number of weeds/m^2), which is obtained by diving the sum of density of weed species k with the number of field in which the species k is present, n = number of fields surveyed and *a* = number of field in which species k is absent.

The total relative abundance value was 300 for all species in the study area. The relative abundance of a species is the sum of the relative frequency, relative field uniformity, and relative mean field density, according to the following formulae:

i. $$RF_k = \frac{\text{Frequency for weed species k}}{\text{Sum of frequency for all weed species}} \times 100$$

Where RF_k = relative frequency for weed species k

ii. $$RU_k = \frac{\text{Field uniformity for weed species k}}{\text{Sum of field uniformity for all weed species}} \times 100$$

Where RU_k = relative field uniformity for weed species k

iii. $$RD_k = \frac{\text{Mean field density for weed species k}}{\text{Sum of mean field density for all weed species}} \times 100$$

Where RD_k = relative mean field density for weed species k

Indices of community ecology at alpha diversity (α-diversity) spatial scale were used for analyses. Shannon-Wiener diversity index (*H*') was to express the diversity of species, in terms of richness and evenness, in a community (Shannon- and Weaver, 1963). Higher value indicated a more diverse species in the community.

$$H' = -\sum [p_i (\ln p_i)] \qquad \text{where } p_i = \frac{n_i}{N}$$

p_i refers to proportional abundance of a given species (call this species 'i'), n_i refers to density or number of the *i*th species (i.e. any particular species you choose) and *N* refers total number of individuals of all species in the community.

The value of H' from the different communities was tested with Student's t test (Booth, Murphy and Swanton, 2003). The t_{crit} and t_{obs} were compared. If $t_{obs} > t_{crit}$, there was significantly different in terms of the Shannon–Wiener diversity index ($p < 0.05$) of the two communities.

$$\mathrm{Var}(H') \text{ or } H'_{var} = \frac{\sum p_i\,(ln\,p_i)^2 - [\sum p_i\,(ln\,p_i)]^2}{N} + \frac{S-1}{2N^2}$$

$$t_{obs} = \frac{|H'_1 - H'_2|}{\sqrt{Var(H'_1) + Var(H'_2)}}$$

$$\text{Degree of freedom } (\nu) = \frac{[Var(H'_1) + Var(H'_2)]^2}{[Var(H'_1)]^2/N_1 + [Var(H'_2)]^2/N_2}$$

t_{crit} = Based on p-value (e.g $\alpha = 0.05$) and degree of freedom (ν)

Pielou's evenness index (E) ranged from 0 to 1, encompassing the spectrum from extremely uneven in species distribution to maximum species distribution (Pielou, 1963). In another word, index value 0 represented domination by a single species to index value one indicated non-exist domination by a single species.

$E = \dfrac{H'}{\ln S}$, where ln S also known as H'_{max}

S refers to number of species present in the community.

Simpson's dominance index (D) indicates species evenness or dominance in a community (Simpson, 1949). The dominance value ranged from high diversity at 0 to low diversity at 1. It was expressed in inversion format, which is Simpson's reciprocal index (1/D) (Smith and Wilson, 1996). After the inversion, lower D^{-1} value indicated low diversity. Greater diversity was reflected with higher value.

$$D = \sum \frac{n_i(n_i - 1)}{N(N-1)} \qquad D^{-1} = \frac{1}{D}$$

The exploratory method of agglomerative hierarchical clustering analysis was used to analyse species relations through identifying homogenous groups and subgroups that differ from each other, revealing underlying structure. Maximum or complete linkage clustering analysed the furthest neighbour between two data points, representing maximum dissimilarity (Sokal and Michener, 1958). Nearest distance measurements and linkage type were systematically merged to form clusters and branches (Bratchell, 1989). The presence (1) and absence (0) values of weed species in 40 quadrats for the three years (2017, 2018 and 2020) were standardised prior to the analysis. Squared Euclidean distance was used to determine distances or similarities between cases or clusters of cases, and z scores were used to standardize the value for each case.

A bivariate form of the general linear model determined the maize yield predicted by the sum of weed species, average mean temperature, and mean rainfall (Tabachnick and Fidell, 2007). Results with $p < 0.05$ were considered statistically significant.

3.5.3 Bivariate Pearson's correlation coefficient (*r*), coefficient of determination (R^2) and one-way ANOVA analyses for plant traits

Using different statistical analyses on the same set of data would be beneficial in understanding relations in weed studies (Crossman and Bass, 2008). The normality test Shapiro-Wilk determined if the population represented a normal distribution for appropriateness of parametric tests (Shapiro and Wilk, 1965). The Shapiro-Wilk test was employed to assess whether the measurements of height, number of leaves, and number of inflorescences in wild populations, NPK 12:12:17 and NPK 15:15:15 had a normal distribution. The null hypothesis (H_0) for each distribution in the population, with p-value being equal to or greater than 0.05. Conversely, the alternative hypothesis (H_1) suggested that the variable did not follow a normal distribution. Descriptive statistics involving mean, standard deviation, box plot, bivariate statistics, and scatter plot were used in data analysis to generate summaries (Kaliyadan and Kulkarni, 2019).

Bivariate Pearson's correlation coefficient (*r)* and coefficient of determination (R^2) of linear regression were used to test the association between height, the number of leaves and the number of inflorescences, and predicting one variable over others, respectively. The absolute value of *r* will be interpreted categorially for its correlation coefficient: i.) 0.00–0.19 "very weak"; ii.) 0.20–0.39 "weak"; iii.) 0.40-0.59 "moderate"; iv.) 0.60-0.79 "strong", and v.) 0.80-1.00 "very strong" (Evans, 1996). Statistically significant correlations between two variables were determined at the Sig (2-Tailed) value is equal to or less than 0.05.

Three models were analyzed for the correlation between variables: Model 1, where the dependent variable was the number of leaves and the independent variable was height; Model 2, where inflorescence was the dependent variable and the number of leaves served as the independent variable; and Model 3, where inflorescence was the dependent variable and the number of leaves and height were the independent variables. The gradient (β) was tested for significance. A relationship existed when the gradient was not zero ($p < 0.001$).

The Levene's test was used to test the homogeneity of variance for every dependent variable, namely, leave, inflorescence, and height studied under NPK 12:12:17 and NPK 15:15:15, respectively. The null hypothesis of the assumption of equal variances across groups was accepted when $p > 0.05$. The alternate hypothesis of equal variances was violated when $p < 0.05$. The analysis of variance (ANOVA) was performed if the null hypothesis was met. One-way ANOVA tested differences in the means of between groups containing control, 1g, 2g, 4g and 8g for the two fertilizer treatments conducted separately. The significance level was set at 95% confidence level ($p < 0.05$) for at least one of the groups to be different in means. To determine which group mean(s) were different from one another, a multiple comparison (or post-hoc) Tukey HSD test was performed.

CHAPTER 4

RESULTS

4.1 Rural farmers' learning on weed management

4.1.1 Participants' demographic information

By the end of the survey period, data were collected from 62 participants out of the 97 initially selected using convenience sampling. Among the remaining 35 participants, 30 refused to participate (most did not share their reasons for refusal, while a few expressed that the survey questionnaire would not benefit them). The remaining five participants, whose data were not collected, were family members of the participants who were interviewed (i.e., father-son) or relatives who were also members of the association; they were randomly selected and subsequently excluded as they worked on the same farm as their family members who were already chosen to participate.

Of the 62 participants who were surveyed, 60 (96.8%) were male, and 2 (3.2%) were female (Table 4.1). There was a significant association between farmers and their backgrounds (grandparents and parents being farmers), ($\chi^2(1) = 13.18$, $p = 0.000$). The ages of the participants ranged from 20 to 70 years, and 27 (more than 40%) were above 70 years of age. Hakka was the most spoken dialect, followed by Cantonese. Only 3 (4.8%) participants had no formal education, while 37 (59.7%) had secondary school education, and only 2 (3.2%) had tertiary education. One-third of the surveyed farmers had more than 25 years of farming experience. Early dropping out of school was associated with many years of farming experience ($\chi^2(4) = 18.51$, $p = 0.001$).

Table 4.1. Characteristics of the participants recruited in the survey.

Characters	N (%)
Gender	
Female	2 (3.2)
Male	60 (96.8)
Age (years)	
20–30	1 (1.6)
31–40	4 (6.5)
41–50	7 (11.3)
51–60	7 (11.3)
61–70	16 (25.8)
>70 years	27 (43.5)
Speaking dialect	
Hakka	47 (75.7)
Cantonese	7 (11.3)
Others (Teochew, Hokkien)	8 (13)
Level of education	
No formal education	3 (4.8)

Primary education	20 (32.3)
Secondary school (SRP/PMR)*	13 (21.0)
Secondary school (SPM/SPMV)**	24 (38.7)
College degree	2 (3.2)
Years of farming experience	
1–5	8 (12.9)
6–10	11 (17.7)
11–15	9 (14.5)
16–20	12 (19.4)
21–25	1 (1.6)
>25 years	21 (33.9)

*SRP/PMR – Sijil Rendah Pelajaran (SRP) and Penilaian Menengah Rendah (PMR) are public examinations for Form Three students in Malaysia. PMR was formerly known as SRP. SRP/PMR is Lower Secondary Education, after spending three years in secondary school.
**SPM/SPMV – Sijil Pelajaran Malaysia (SPM) and Sijil Pelajaran Malaysia Vokasional (SPMV) for Form Five students in Malaysia. SPM/SPMV is equivalent of the General Certificate of Secondary Education (GCSE) in England.

Farmers planted a variety of crops as their main crops, and it was found that these were not limiting to vegetable choices. A variety of crops planted included both cash crops and fruit crops (Table 4.2), totaling 21 crops planted by farmers. Maize (*Zea mays*) was the most planted crop, followed by sweet potato (*Ipomoea batatas*).

Table 4.2. Crop types and number of farmers planting in Malim Nawar.

No.	Crops	Number of farmers planting				
		1st choice	2nd choice	3rd choice	4th choice	5th choice
1	Maize (*Zea mays*)	20	17			
2	Sweet potato (*Ipomea batatas*)	16	1			
3	Oil palm (*Elaeis guineensis*)	6	1	1	1	
4	Yam bean (*Pachyrhizus erosus*)	4	9	6		
5	Long bean (*Vigna unguiculata*)	4	3	1	1	
6	Okra (*Abelmoschus esculentus*)	4	1	11		
7	Lime (*Citrus* x *aurantifolia*)	4	1	1	1	1
8	Banana (*Musa* sp.)	2	1			
9	Malabar spinach (*Basella alba*)	1		1		
10	Basil (*Ocimum basilicum*)	1				
11	Red chilli (*Capsicum annuum*)		6	1	3	
12	Papaya (*Carica papaya*)		4	1	2	

13	Durian (*Durio zibethinus*)	2			
14	Jackfruit (*Artocarpus heterophyllus*)	1			
15	Watermelon (*Citrullus lanatus*)	1			
16	Melon (*Cucumis melo*)	1		1	
17	Coconut (*Cocos nucifera*)		1		
18	Cucumber (*Cucumis sativus*)		1		
19	Guava (*Psidium guajava*)			1	
20	Radish (*Raphanus sativus*)				1
21	Four angle bean (*Psophocarpus tetragonolobus*)				1

4.1.2 Perceptions of weeds and constraints affecting crop production

More than 60% of the farmers considered pests and diseases as major constraints in crop production, followed by weeds (Figure 4.1). Herbicides were the main control method used by the farmers. Prolonged seasonal droughts or excessive rain were the main environmental constraints in crop production. Labour shortage due to declining involvement of locals and foreigners was found to be a cause of concern, whereas farm inputs such as agrochemicals were not a limiting factor if their prices were affordable.

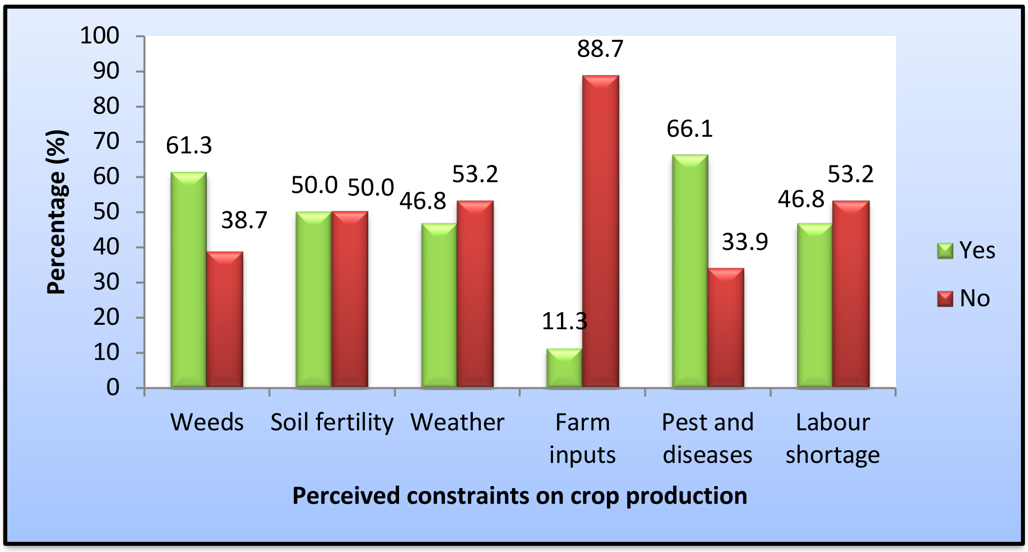


Figure 4.1.: Perceptions of constraints affecting crop production.

There were 20 farmers (32.3%) practicing crop rotation while another 39 farmers (62.9%) did not have the practice (Table 4.3). Some farmers who practiced crop rotation mentioned soil fertility was a factor for the practice. Others practiced crop practice following what some farmer friends had done. Small farm size was the reason for those who did not practice crop rotation.

Table 4.3. Crop rotation practice by farmers.

	N (%)
Yes	20 (32.3)
No	39 (62.9)
n.a.	3 (4.8)
Total	62 (100)

4.1.3 Participants' perceptions of weeds

Two weed species - *Eleusine indica* and *Cyperus* spp. - were frequently mentioned as the most harmful weeds. The survey showed an association between farmer's knowledge of weed species and perceived economic losses caused by weeds ($\chi^2(4) = 16.40$, $p = 0.037$) (Table 4.4). The farmers opined that knowledge of weed species on farms was important, as it helped them select suitable herbicides (e.g., selective or broad-spectrum) for weed control. Moreover, identifying the weeds at an early stage helps remove seedlings before they mature into adult plants. On the contrary, some farmers argued that it was not necessary to learn about weed species to apply herbicides.

Table 4.4. Association between perceived economic loss by weeds and the importance of knowledge of weed species.

Perceived economic loss	Knowledge of weed species is important				Chi-square (χ^2) value, p-value
	Yes	No	NA	Total	
Very high	11	2	2	15	
High	17	5	5	27	$\chi^2(4)$=16.40, p=0.037
Medium	7	2	2	11	
Low	1	5	1	7	
Very low	-	2	-	2	

Furthermore, an association was found between knowledge of weed species and exploration of the potential uses of weeds ($\chi^2(4) = 20.15$, $p = 0.010$) (Table 4.5). Less than 10% of the queried farmers agreed that weeds could be beneficial for crop production. Some farmers suggested certain benefits, such as nutrient release, soil improvement, and their function as cover crops. However, none of the farmers had strongly agreed to the potential benefits of weeds. Weed-crop competition, pest harbouring, and an increase in labour requirement for weeding owing to their root systems were the major disadvantages of weeds reported by the farmers. The farmers wanted to learn about certain weed species (i.e., *E. indica* and *Cyperus* spp.) to estimate yield losses and explore their potential benefits.

Table 4.5. Association between the importance of knowledge of weed species and potential benefits of weeds.

Weed could be beneficial	Knowledge of weed species is important				Chi-square (χ^2) value, p-value
	Yes	No	NA	Total	
Agree	5	1	-	6	
Neutral	4	7	-	11	$\chi^2(4)=20.15$, $p=0.010$
Disagree	16	5	9	30	
Strongly disagree	10	3	-	13	
NA	1	-	1	2	

4.1.4 Perceptions of weed management learning

The relationship between knowledge of other farmers' weed management practices and knowledge of the said practices, particularly in Malim Nawar, was significant ($\chi^2(3) = 9.01$, $p = 0.029$) (Table 4.6). None of the participating farmers had strongly disagreed on the learning of other farmers' weed management practices. Farmers generally agreed that sharing information on weed management and learning new strategies from the experiences of other farmers were useful strategies for their own farming practices. However, the participating farmers claimed that the practices of farmers in their vicinity would not be different from their own practices. This was the reason most of them did not know about the practices of other farmers in Malim Nawar although they admitted the importance of such knowledge. They had knowledge of the practices of some farmers outside of Malim Nawar.

Table 4.6. Benefits of sharing information on weed management practices.

Knowledge of how other farmers controlling weeds is important	Knowledge of other farmers' weed management practices in Malim Nawar			Chi-square (χ^2) value, p-value
	Yes	No	Total	
Strongly agree	4	4	8	$\chi^2(3)=9.01$, p=0.029
Agree	14	12	26	
Neutral	4	22	26	
Disagree	-	2	2	

Furthermore, the survey demonstrated correlations between farmers' resistance to learning about non-chemical control methods and the reasons behind this attitude (Table 4.7). A total of 47.8% of the participants stated that "chemical herbicides are harmful to the environment" and that they did not want to learn about non-chemical weed control measures; 39.1% stated that "chemical herbicides are harmful to consumers", that "some weeds became herbicide resistant", and that they did not want to learn about non-chemical weed control measures; and 34.8% of the participants who stated that chemical herbicides are harmful to farmers and workers also stated that they did not want to learn about non-chemical weed control measures. These results showed that despite being aware of the harmful effects of herbicides, the farmers were sceptical of using non-chemical control methods. The reasons behind this resistance and scepticism included possible high costs, time needed to learn and practice using non-chemical control methods, and perceived high efficiency of herbicides.

Table 4.7. Attitudes toward chemical herbicides and learning non-chemical control methods.

Reason		Do you want to learn non-chemical weed control?				Chi-square (χ^2) value, p-value
		Yes	No	NA	Total	
Chemical herbicides are harmful to the environment	Yes	11	-	-	11	$\chi^2(2)=22.66$, $p=0.000$
	No	12	25	14	51	
Chemical herbicides are harmful to consumers	Yes	9	-	-	9	$\chi^2(2)=17.85$, $p=0.000$
	No	14	25	14	53	
Chemical herbicides are harmful to farmers and workers	Yes		18		8	$\chi^2(2)=15.58$, $p=0.000$
	No	15	25	14	54	
Some weeds can become herbicide resistant	Yes	9			9	$\chi^2(2)=17.85$, $p=0.000$
	No	14	25	14	53	
Chemical herbicides are convenient	Yes		18		19	$\chi^2(2)=33.92$, $p=0.000$
	No	23	7	13	43	
Chemical herbicides are cost-effective	Yes		17	1	18	$\chi^2(2)=31.09$, $p=0.000$
	No	23	8	13	44	
Other methods are less effective than chemical herbicides	Yes		6		6	$\chi^2(2)=9.83$, $p=0.007$
	No	23	19	14	56	

Information on weed management practices was obtained from formal and informal sources. The formal sources included the Association, government agencies, workshops, civil society, and agrochemical companies, whereas the informal sources were friends of the participating farmers. Both agrochemical companies (64.5%) and informal sources (64.5%) were equally important sources of information on weed control practices (Table 4.8). Workshops and seminars were not popular options for obtaining information on weed management practices. Moreover, all farmers had access to at least one of these sources of information.

Table 4.8. Sources of information and knowledge on weed management practices.

Sources of information	N (%)
Malim Nawar Vegetable Farmer Association	24 (38.7)
Workshops and seminars	0 (0)
Government agencies	15 (24.2)
Civil society	3 (0.05)
Friends	40 (64.5)
Agro-chemical companies	40 (64.5)
No access	0 (0)

4.2 Weed community dynamics

4.2.1 Weed species and type

A total of 9 families and 15 weed species were identified in 2017, 2018 and 2020 (Table 4.9) (Appendix E). The number of species ranged from 8 to 11, which was 10 species, 8 species and 11 species in 2017, 2018 and 2020 respectively. Five weed species were consistently found in the three years surveyed: *Amaranthus viridis, Cleome rutidosperma, Cyperus* sp., *Eleusine indica* and *Phyllanthus virgatus.* There were nine species with a C_3 photosynthetic pathway and four C_4 weeds. Two weeds could not be identified at the species level, and the genus contained both C_3 and C_4 plants.

Broadleaves (Acanthaceae, Amaranthceae, Cleomaceae, Commelinaceae, Euphorbiceae, Phyllanthaceae and Rubiaceae), sedges (Cyperaceae family) and grasses (Poaceae, also known as Graminae, family) were among the weed groups found. Among these was the Rubiaceae family had the highest number of species (4), followed by Poaceae (3) and Phyllantaceae (2). Other families were represented by one species.

Table 4.9. Weed species on maize farm for 2017, 2018 and 2020 in Malim Nawar.

Year	No.	Species	Family	Type of weed	Photosynthetic pathway	Life cycle
2017	1	*Amaranthus viridis*	Amaranthaceae	Broadleaf	C_4	Annual
	2	*Asystasia gangetica*	Acanthaceae	Broadleaf	C_3	Perennial
	3	*Cleome rutidosperma*	Cleomaceae	Broadleaf	C_3	Perennial
	4	*Cyperus* sp.	Cyperaceae	Sedge	C_3 and C_4	Annual, perennial
	5	*Digitaria longiflora*	Poaceae	Grass	C_4	Annual
	6	*Eleusine indica*	Poaceae	Grass	C_4	Annual
	7	*Euphorbia hirta*	Euphorbiaceae	Broadleaf	C_4	Annual
	8	*Hedyotis corymbosa*	Rubiaceae	Broadleaf	C_3	Annual
	9	*Mitracarpus hirtus*	Rubiaceae	Broadleaf	C_3	Annual
	10	*Phyllanthus virgatus*	Phyllanthaceae	Broadleaf	C_3	Annual

2018	1	*Amaranthus viridis*	Amaranthaceae	Broadleaf	C_4	Annual
	2	*Cleome rutidosperma*	Cleomaceae	Broadleaf	C_3	Perennial
	3	*Cyperus* sp.	Cyperaceae	Sedge	C_3 and C_4	Perennial
	4	*Eleusine indica*	Poaceae	Grass	C_4	Annual
	5	*Euphorbia hirta*	Euphorbiaceae	Broadleaf	C_4	Annual
	6	*Hedyotis corymbosa*	Rubiaceae	Broadleaf	C_3	Annual
	7	*Phyllanthus amarus*	Phyllanthaceae	Broadleaf	C_3	Perennial
	8	*Phyllanthus virgatus*	Phyllanthaceae	Broadleaf	C_3	Annual
2020	1	*Amaranthus viridis*	Amaranthaceae	Broadleaf	C_4	Annual
	2	*Borreria latifolia*	Rubiaceae	Broadleaf	C_3	Annual
	3	*Commelina* spp.	Commenlinaceae	Broadleaf	C_3 and C_4	Annual and perennial
	4	*Cyperus* spp.	Cyperaceae	Sedge	C_3 and C_4	Annual and perennial

5	*Digitaria longiflora*	Poaceae	Grass	C_4	Annual
6	*Eleusine indica*	Poaceae	Grass	C_4	Annual
7	*Mitracarpus hirtus*	Rubiaceae	Broadleaf	C_3	Annual
8	*Oldenlandia corymbosa*	Rubiaceae	Broadleaf	C_3	Annual
9	*Panicum dichotomiflorum*	Poaceae	Grass	C_3	Annual
10	*Phyllanthus amarus*	Phyllanthaceae	Broadleaf	C_3	Perennial
11	*Phyllanthus virgatus*	Phyllanthaceae	Broadleaf	C_3	Annual

A total of 2,252 plants were recorded in 2017, 2,950 plants in 2018 and 1,453 plants in 2020. Broadleaves had the highest number of plants in 2017 and 2018, compared to sedges and grasses, at 1,203 individual plants (53.4%) in 2017 and 2,793 plants (94.7%) for in2018, but decreased to 154 individuals (10.6%) in 2020 (Table 4.10). The number of sedges was 900 individuals in 2017 (40.0%), decreased to 125 individuals (4.2%) in 2018, and increased to 1,299 individuals (89.4%) in 2020. Grass had 149 individuals (6.6%) in 2017, 32 individuals (1.1%) in 2018, and 501 individuals (34.5%) in 2020.

All weed groups – broadleaf, grass and sedge were statistically significant in the number of individuals between years: 2017 and 2018; 2018 and 2020; 2017 and 2020. Broadleaves increased from 2017 and 2018; while both grasses and sedges decreased during the same timeframe. From 2018 to 2020, the number of broadleaves and grasses showed a decreasing trend, and the number of sedges increased.

Table 4.10. Weed types on maize farms for 2017, 2018 and 2020 in Malim Nawar.

Year	Type of weed	2017	2018	2020	Adjusted α level	p-value
2017 and 2018	Broadleaf	1,203	2,793		0.017	< 0.001
	Grass	149	32		0.017	< 0.001
	Sedge	900	125		0.017	< 0.001
2018 and 2020	Broadleaf		2,793	154	0.017	0
	Grass		32	0	0.017	< 0.001
	Sedge		125	1,299	0.017	0
2017 and 2020	Broadleaf	1,203		154	0.017	< 0.001
	Grass	149		0	0.017	< 0.001
	Sedge	900		1,299	0.017	< 0.001

Note: p-value is obtained from pairwise comparisons using multiple z-tests of two proportions with a Bonferroni correction.

4.2.2 Community indicators: frequency (F), field uniformity (U), mean field density (MFD), mean occurrence field density (MOFD) and relative abundance (RA)

Among the weeds recorded in 2017, 2018 and 2020, grass *E. indica,* sedge *Cyperus* sp*.,* and broadleaves *A. viridis* and *P. virgatus* were the four weed species that had a 100.00% frequency, as they were found in all three years (Table 4.11). The second highest frequency group, at 66.67%, included broadleaves *C. rutidosperma*, *E. hirta*, *H. corymbosa, M. hirtus* and *P. amarus,* as well as grass *D. longiflora.* The lowest frequency group, at 33.33%, included *A. gangetica, B. latifolia, Commelina* sp., *O. corymbosa* and *P. dichtomiflorum.*

Field uniformity measured the presence of a weed species in surveyed quadrats for the three years. The most occurring weed species was sedge from the family Cyperaceae (71.67%), followed by grass *E. indica* (58.33%) and broadleaf *P. virgatus* (47.50%). The three lowest occurring weed species were grass *P. dichtomiflorum* (1.67%)*,* broadleaves *B. latifolia* (0.83%) and *Commelina* sp. (0.83%).

Cyperus sp. had the highest mean density of 14.86 plants m^{-2}, followed by broadleaves *H. corymbosa* (11.84 plants m^{-2}) and *A. viridis* (10.89 plants m^{-2}). Three weeds with a density of between five to 10 plants m^{-2} were *E. indica, H. corymbosa* and *P. amarus*. The remaining nine weed species had plant density below five plants m^{-2}. The weed species with the lowest plant density was *Commelina* sp. (0.07 plants m^{-2}).

The composite index relative abundance (RA) quantitatively proportioned the number of plants for every species in fields, providing an understanding of which species existed more and which one was less prevalent. The species with the highest RA value was *Cyperus* sp. (55.83). In descending order, there were *A. viridis* (39.55), *E. indica* (35.45), *H. corymbosa* (33.08) and *P. amarus* (31.82). These five species accounted for 65% of total RA (300). *Phyllantus virgatus* (28.63) was the only species had below RA value 30.00. Three species below an RA value 20.00 were *E. hirta* (18.33), *C. rutidosperma* (15.48), and *M. hirtus* (10.79). Sixe species with less than an RA value of 10.00 were *D. longiflora* (9.65), *A. gangetica* (4.54), *O. corymbosa* (4.85), *P. dichtomiflorum* (4.48), *Commelina* sp. (3.79) and *B. latifolia* (3.73).

Table 4.11. Frequency (F), field uniformity (U), mean field density (MFD), mean occurrence field density (MOFD) and relative abundance (RA) of weeds in maize fields in Malim Nawar, Perak.

Weed species	F_k (%)	U_k (%)	MFD_k (m^{-2})	$MOFD_k$ (m^{-2})	RA_k
Amaranthus viridis	100.00	36.67	10.89	10.89	39.55
Asystasia gangetica	33.33	3.33	0.13	0.38	4.54
Borreria latifolia	33.33	0.83	0.03	0.10	3.73
Cleome rutidosperma	66.67	24.17	1.27	1.90	15.48
Commelina sp.	33.33	0.83	0.07	0.20	3.79
Cyperus sp.	100.00	71.67	14.86	14.86	55.83
Digitaria longiflora	66.67	9.17	0.20	0.30	9.65
Eleusine indica	100.00	58.33	5.48	5.48	35.45
Euphorbia hirta	66.67	30.00	2.00	3.00	18.33
Hedyotis corymbosa	66.67	45.83	7.89	11.84	33.08
Mitracarpus hitrus	66.67	10.83	0.59	0.89	10.79
Oldenlandia corymbosa	33.33	4.17	0.18	0.53	4.85

Panicum dichotomiflorum	33.33	1.67	0.33	1.00	4.48
Phyllanthus amarus	66.67	38.33	8.28	12.41	31.82
Phyllanthus virgatus	100.00	47.50	3.27	3.27	28.63
Total					300

4.2.3 Species richness and abundance

With values starting from 0 indicating low diversity to 5 being high diversity, the Shannon-Wiener diversity index (H') was highest (1.5015) in 2018, followed by H' in 2017 (1.4257) and the lowest index was 2020 (1.2662) (Table 4.12). Weed diversity was greater in 2018 compared to 2017 and 2020. Variances in Shannon-Wienner, Var(H') varied from 0.0003 in 2018 to 0.0004 in 2017 and 0.0009 in 2020.

Table 4.12. H' – Shannon - Wiener diversity index, Var(H') - variance in Shannon-Wiener diversity, E – evenness, D^{-1} - reciprocal value of Simpson's dominance index of weeds in maize fields.

Year	H'	Var(H')	E	D^{-1}
2017	1.4257	0.0004	0.6192	3.2821
2018	1.5015	0.0003	0.7221	3.3699
2020	1.2662	0.0009	0.5280	2.5847

Pielou's evenness index value close to 0 indicates dominance by only a single species, while an index value of equal to 1 suggests that all species present have a similar number of individuals. The evenness values for 2017, 2018 and 2020 were greater than 0.5000. The highest evenness value was 0.7221 in 2018, followed by 0.6192 in 2017 and 0.5280 in 2020. There was no dominant weed species for the three years surveyed.

Simpson reciprocal values ranged from the possibility of two random species at the lowest value of 1 to the total number of species (*k*) at a site. The reciprocal value was highest at 3.3699 in 2018. Simpson reciprocal values followed the same trend as the Shannon-Wiener diversity index and Pielou's evenness index. The year 2017 was found to have the next higher value at 3.2821 and the lowest value 2.5847 in 2020. These values indicate a low possibility of two randomly chosen species being the same, suggesting non-dominance among species on farms.

Table 4.13. Student's t-test result for Shannon-Wiener diversity index in maize fields in 2017, 2018 and 2020.

Years	**Degree of freedom (ν)**	**t_{crit} ($\alpha/2 = 0.025$)**	**t_{obs}**
2017 & 2018	4875	1.96	2.916347
2018 & 2020	2479	1.96	6.912033
2020 & 2017	2677	1.96	4.526747

This significant test is a two-tailed test, thus $\alpha = 0.05$ need to be divided by 2. The t_{crit} is obtained from t-table where corresponding to degrees of freedom and $\alpha/2$.

Since the t_{obs} value in Table 4.13 was greater than t_{crit}, it was concluded that the Shannon-Wiener diversity index values in 2017, 2018 and 2020 were significantly different between the years (at $p = 0.05$). Species richness and evenness were representing different communities uniquely in each of the three years where weed inventory was conducted.

4.2.4 Species relations based on frequency

Weed species were grouped using Hierarchical Clustering analysis to explore dissimilarity structure based on the species presence-absence data through visualization. The further the height of branches on the horizontal axis (x-axis), the less similar pairwise observation were, representing distance. Small dissimilarity values were closer to each other. Each node of the tree had a dichotomous split. In the initial solution at 0 on the x axis representing the distance scale, there was no observation paired with another (Figure 4.2). There were nine clusters at the dissimilarity distance of five, while there were six clusters at the distance dissimilarity of 10.

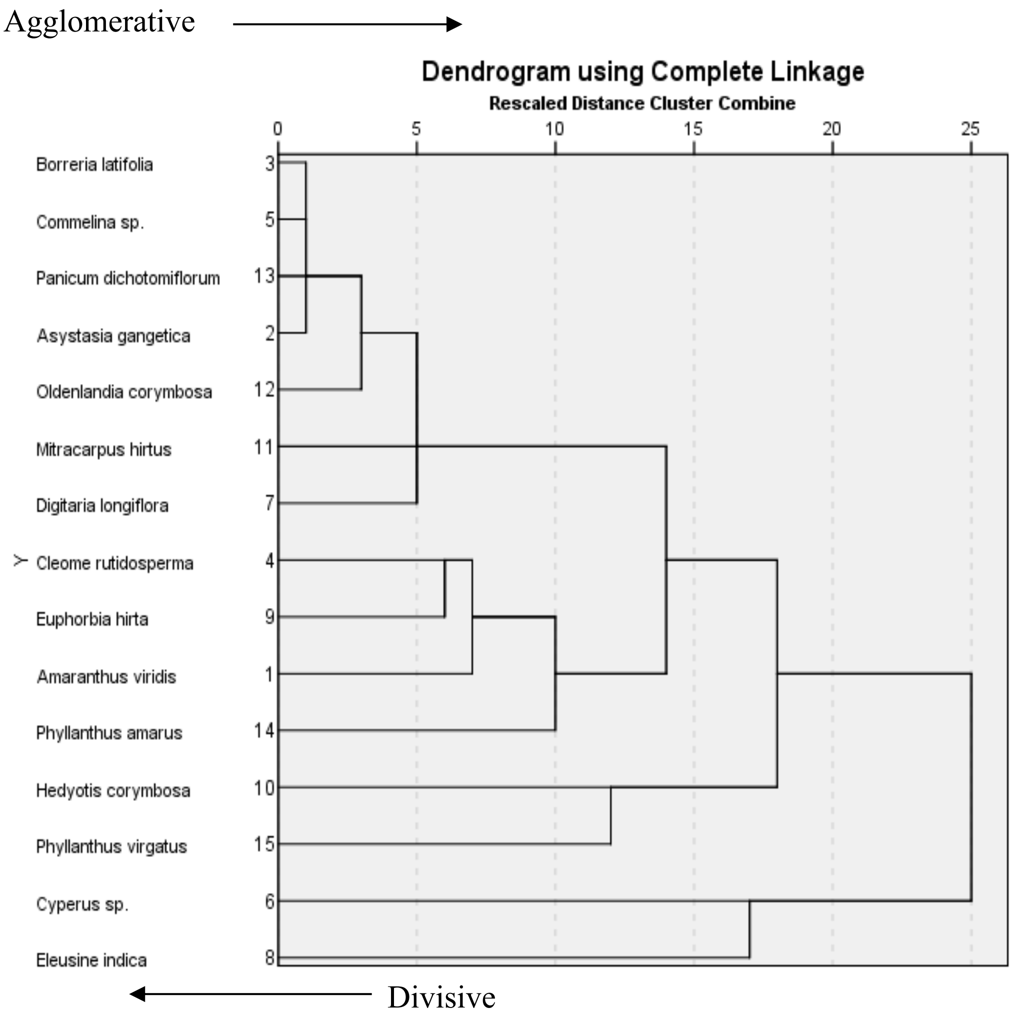


Figure 4.2.: Dendrogram of weed species from 2017, 2018 and 2020 based on Hierarchical Clustering analysis.

The dendrogram had a partition of four clusters occurring at a dissimilarity of approximately 15. The first cluster (top) composed of 11 observations which were *B. latifolia, Commelina* sp*., P. dichotomuflorum, A. gangetica, O. corymbosa, M. hirtus, D. longiflora, C. rutidosperma, E. hirta, A. virisdis, and P. Amarus.* The second cluster (second top) had two species which were *H. corymbosa* and *P. virgatus.* The third and fourth clusters (the bottom two) had one species each – *Cyperus* sp. and *E. indica* respectively.

At a dissimilarity distance of 20, there were two clusters (Figure 4.2). One major group comprised *Cyperus* sp. and *E. indica,* which were sedge and grass. Sedge and grass were independent of the existing clusters. The other major group comprised of the remaining 13 species with sub-level groupings and singletons, and they were broadleaves. Other species followed the nodes and linkage down the two clusters.

4.2.5 Weed composition and maize yield

The fresh-weight basis maize yield was 20.1 t, 19.8 t, and 15.7 t in 2017, 2018, and 2020, respectively. The statistical analysis indicated that temperature, rainfall, and weed density did not have a significant effect on maize yield (Table 4.14).

Table 4.14. Effect of average mean temperature, mean rainfall, and weed species on maize yield using a general linear model.

Parameter	Estimate	Standard error	*t* value	p-value
Mean rainfall	-0.000407283	0.00059901	-0.68	0.6199
Average mean temperature	0.003201266	0.00128208	2.5	0.2425
Amaranthus viridis	7.67E-08	0.00000082	0.04	0.9769
Cleome rutidosperma	2.57E-07	0.00000708	0.04	0.9769
Cyperus spp.	-3.447E-07	0.00000138	-0.25	0.8437
Eleusine indica	1.6722E-06	0.00000181	0.92	0.5258
Euphorbia hirta	-8.997E-07	0.00000728	-0.12	0.9217
Hedyotis corymbosa	-1.3281E-06	0.00000038	-3.54	0.1754
Mitracarpus hirtus	-0.000013825	0.00000790	-1.75	0.3304
Phyllanthus spp.	-1.487E-07	0.00000115	-0.13	0.9178
Others	8.3603E-06	0.00000977	0.86	0.5495

"Others" include *Asystasia gangetica*, *Borreria latifolia*, *Commelina* spp., *Digitaria longiflora*, *Oldenlandia corymbosa*, and *Panicum dichotomiflorum.*

4.3 Responses of plant functional traits in *A. viridis*

Height, number of leaves, and number of inflorescences in wild populations, NPK 12:12:17 and NPK 15:15:15 had a normal distribution, where $p > 0.05$ from the Shapiro-Wilk test.

4.3.1 NPK 12:12:17

For the height variable in *A. viridis*, the p-value was 0.437. For the number of leaves, the p-value was 0.125, and for the number of inflorescence, it was 0.148. Since all these p-values are greater than 0.05, the null hypothesis that the data were normally distributed was accepted for *A. viridis* in this study (Table 4.15).

Table 4.15. Test of normality Shapiro-Wilk on height, leaves and inflorescences under NPK 12:12:17.

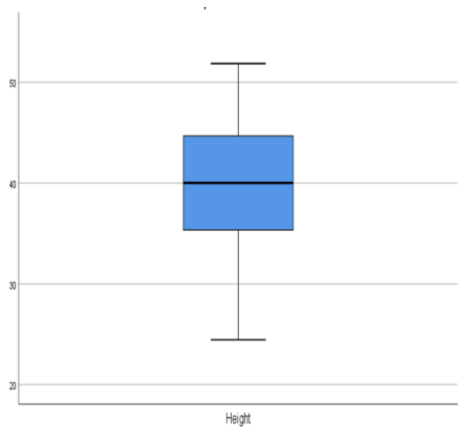
Variables	**Statistics**	**df**	**Sig.**
Height	0.966	30	0.437
Leaves	0.945	30	0.125
Inflorescences	0.966	30	0.148

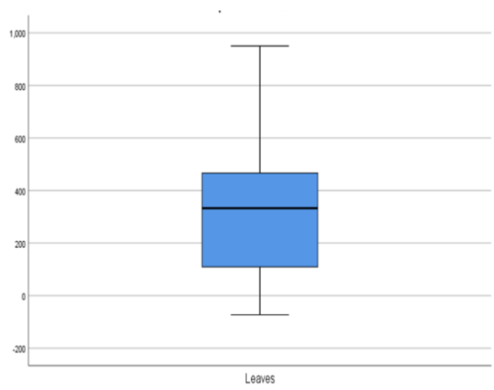
The average height for *A. viridis* studied under NPK 12:12:17 was 40.02 ± 6.24 cm per plant. The average number of leaves was 294.97 with a standard deviation (SD*)* of 240.93. Additionally, there were 96.40 inflorescences on average per plant, with a standard deviation of 66.92 (Table 4.16).

Table 4.16. Median, mean and standard deviation for height, leaves and inflorescences under NPK 12:12:17.

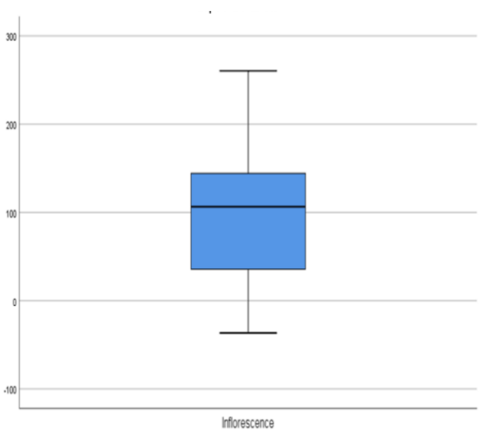
Variables	Median	Mean	Standard deviation
Height (cm)	40.02	39.91	6.24
Number of leaves	332.83	294.97	240.93
Number of inflorescences	106.50	96.40	66.92

The height of the plants ranged between 24.44 to 51.86 cm (Figure 4.3). The height distribution showed that 75% of the plants had a height of 44.70 cm. While 25% of the plants had a height of 34.75 cm. Regarding the number of leaf, the lower and upper quartiles were 102.48 and 468.38, respectively. This indicates that 75% of the plants had 144.97 inflorescences and 25% had 35.00 inflorescences.





i. Height (cm) ii. Number of leaves



iii. Number of inflorescences

Figure 4.3.: Boxplots for (i.) height (cm), (ii.) number of leaves, and (iii.) number of inflorescences under treatment NPK 12:12:17.

4.3.2 NPK 15:15:15

The Shapiro-Wilk test results for the approximately normally distributed data indicated p-values of 0.105 for height, 0.242 for leaves, and 0.443 for inflorescences (Table 4.17). Since all these p-values were greater than the 0.05 level of significance, the null hypothesis that the data followed a normal distribution was retained. Therefore, it was concluded that the data for height, leaves, and inflorescences followed a normal distribution.

Table 4.17. Test of normality Shapiro-Wilk on height, leaves and inflorescences under NPK 15:15:15.

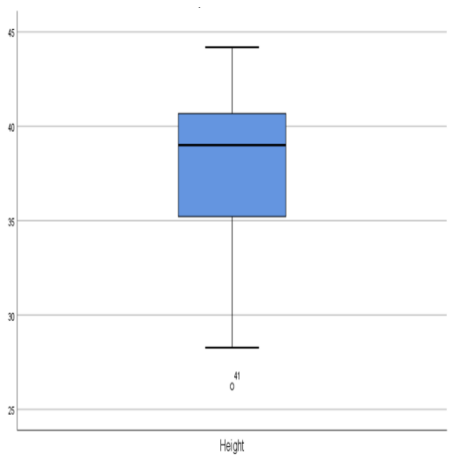
Variables	Statistics	df	Sig.
Height	0.942	30	0.105
Leaves	0.956	30	0.242
Inflorescences	0.966	30	0.443

The average plant height was 37.59 cm with a standard variation of 4.73. Each plant had an average of 434.48 leaves with a standard deviation of 498.79, and the average inflorescence number was 61.03 with a standard deviation of 37.46 (Table 4.18).

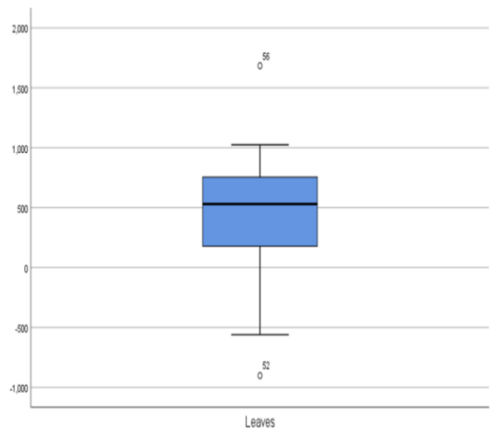
Table 4.18. Median, mean and standard deviation for height, leaves and inflorescences under NPK 15:15:15.

Variables	Median	Mean	Standard deviation
Height (cm)	39.00	37.59	4.73
Number of leaves	529.51	434.48	498.79
Number of inflorescences	68.10	61.03	37.46

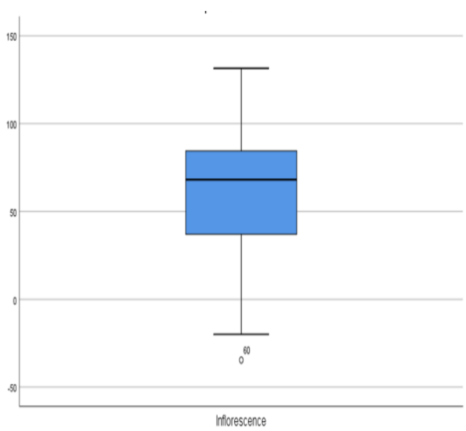
For *A. viridis* under NPK 15:15:15 treatment, the height ranged from 26.22 cm to 44.18 cm. The upper (75%) and lower quartile (25%) for height were 40.71 cm and 34.82 cm, respectively (Figure 4.4). The leaf numbers had a lower quartile (25%) of 170.43 and an upper quartile (75%) of 760.01. Additionally, the lower quartile for the number of inflorescences was 36.95, and the upper quartile was 84.74.



i. Height (cm)



ii. Number of leaves



iii. Number of inflorescences

Figure 4.4.: Boxplots for (i.) height (cm), (ii.) number of leaves, and (iii.) number of inflorescences under treatment NPK 15:15:15.

4.3.3 Wild populations

The data on height, leaves and inflorescences had a normal distribution, with p-values greater than 0.05. The values of W for height (W = 0.945), leaves (W = 0.916) and inflorescences (W = 0.875) were close to one, and indicating normality of the data (Table 4.19). The null hypothesis was accepted for the samples, suggesting that they came from a normal distribution.

Table 4.19. Test of normality Shapiro-Wilk on height, leaves and inflorescences for wild population.

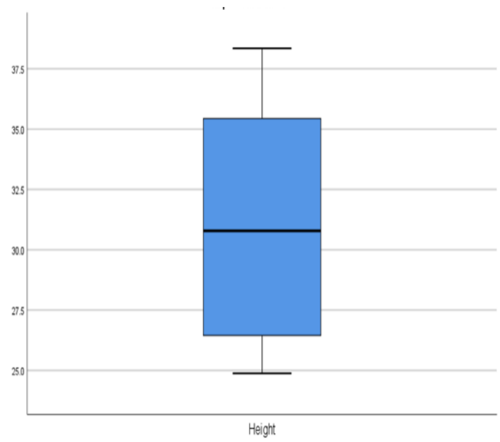
Variables	Statistics	df	Sig.
Height	0.945	6	0.698
Leaves	0.916	6	0.476
Inflorescences	0.875	6	0.247

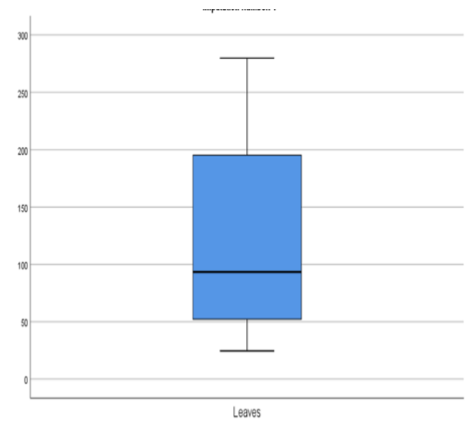
The wild population had an average height of 31.12 cm (SD = 5.33) (Table 4.20). The mean number of leaves was 123.13 (SD = 97.64), and the inflorescence number was 17.13 (SD = 14.50).

Table 4.20. Median, mean and standard deviation for height, leaves and inflorescences for wild populations.

Variables	Median	Mean	Standard deviation
Height (cm)	30.79	31.12	5.33
Number of leaves	93.42	123.13	97.64
Number of inflorescences	13.75	17.13	14.50

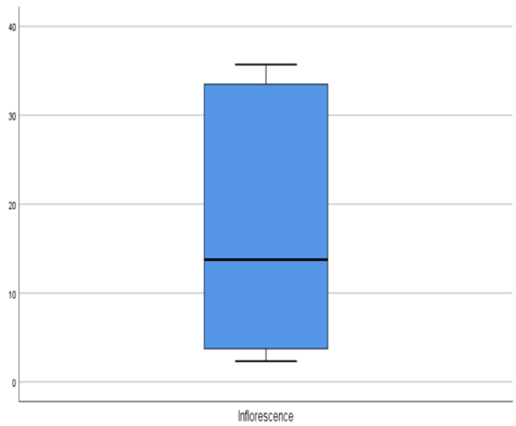
Seventy-five percent (75%) of the plants had a height 36.17 cm (Figure 4.5), while twenty-five percent (25%) of the plants had a height 26.08 cm. The height range was between 24.88 cm and 38.35 cm. For the number of leaves, the lower and upper quartiles were 45.28 and 216.45, respectively. Seventy-five percent (75%) of the plants had 34.03 inflorescences, while 25% had 3.39 inflorescences.





i. Height (cm)

ii. Number of leaves



iii. Number of inflorescences

Figure 4.5.: Boxplots for (i.) height (cm), (ii.) number of leaves, and (iii.) number of inflorescences for the wild population.

4.3.4 Trait-based approach

The scatterplot and correlation analysis indicated positive correlations among the variables. Specifically, there was a positive correlation between height and leaf number (r = 0.679, N = 18, p = 0.002), leaf number and inflorescence number (r = 0.888, N = 18, p = 0.000), and height and inflorescence number (r = 0.755, N = 18, p = 0.000) (Figure 4.6). These correlations were strong, while a very strong correlation found between leaf number and inflorescence number. All correlations were statistically significant.

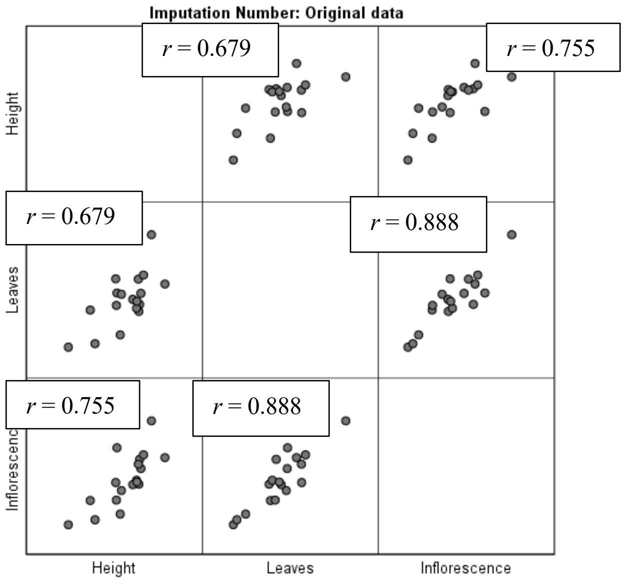


Figure 4.6.: Scatterplot for height, leaf number and inflorescence number under NPK 12:12:17.

The three pairs of variables – height and leaf number, leaf number and inflorescence number, and inflorescence number and height, showed linear correlations. Two pairs of variables – height and inflorescence number (r = 0.646, N=19, p = 0.002), and height and leaf number (r = 0.662, N = 19, p = 0.003) were moderately correlated (Figure 4.7). A very strong correlation was found for leaf number and inflorescence number (r = 0.949, N = 19, p = 0.000).

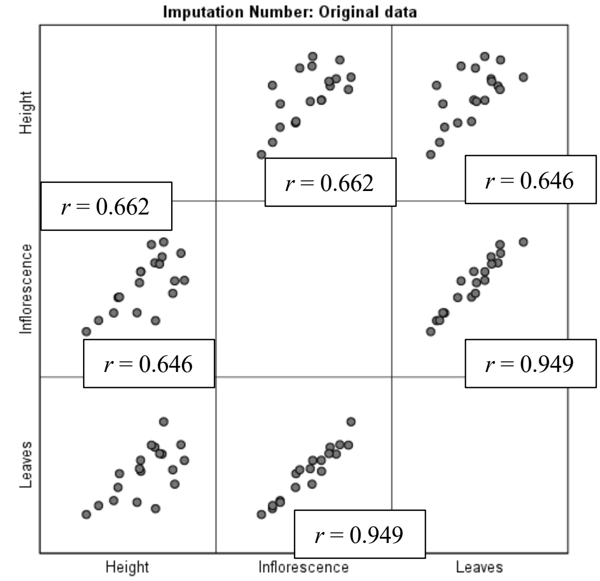


Figure 4.7.: Scatterplot for height, leaf number and inflorescence number under NPK 15:15:15.

The pairing variables showed a strong correlation when one variable increased, the companion variable also increased by approximately the same rate. All the pairing variables had strong correlations for height and inflorescence number (r = 0.966, N = 5, p = 0.007), inflorescence number and leaf number (r = 0.969, N = 5, p = 0.006), and height and leaf number (r = 0.971, N = 5, p = 0.006) (Figure 4.8).

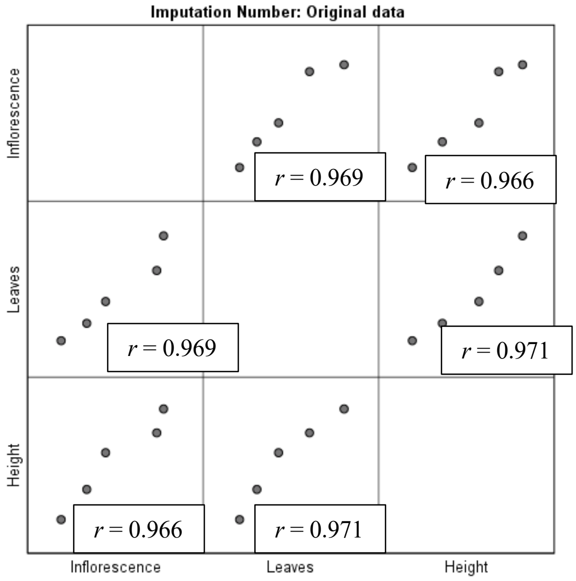


Figure 4.8.: Scatterplot for height, leaf number and inflorescence number for wild plants.

Model 1 Dependent variable: leaves, independent variable: height

The leaves and height of *A. viridis* studied under NPK 12:12:17 showed a positive correlation ($r = 0.679$, Figure 4.9.i.). The relationship was significant ($b = 21.821$, $SE_b = 5.900$, $\beta = 0.679$, $t = 3.698$, p = 0.001). The slope coefficient for leaves was 21.82, indicating that for every 1 cm increase in height, there was an associated increase of 21.82 leaves. The R^2 value was 0.461 suggesting that 46.1% of the variability in leaves could be explained by the model containing only height.

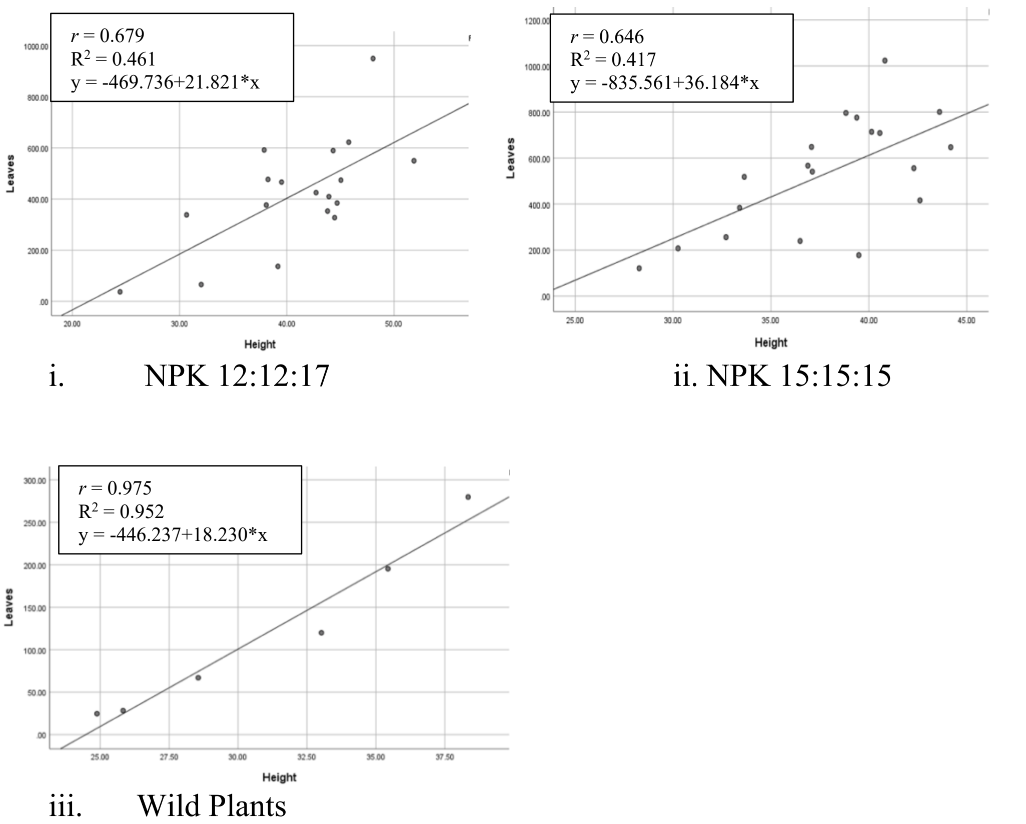


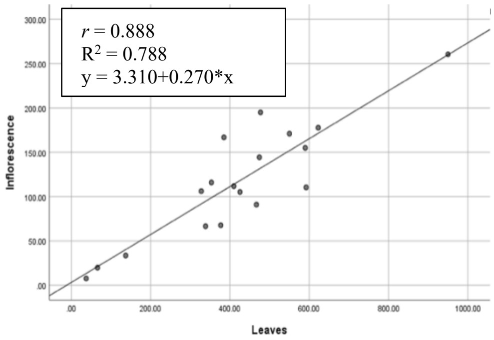
Figure 4.9.: *A. viridis* studied under i. NPK 12:12:17, ii. NPK 15:15:15 and iii. wild plants with leaves as dependent variable and height as independent variable.

The Pearson correlation coefficient of 0.646 showed a positive relationship between leaves and height for *A. viridis* studied under NPK 15:15:15 (scatter diagram ii. in Figure 4.9). The relationship was statistically significant (b = 36.184, SE_b = 10.383, β = 0.646, t = 3.485, $p < 0.001$). An increment of 1 cm in height led to an increment of 36.18 leaves. Approximately 41.7 % of the variation in leaves could be explained by height.

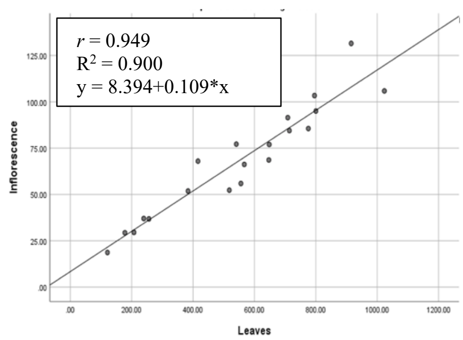
The positive relationship between plant height and the number of leaves had an *r* value of 0.975 for plants studied in wild population (scatterplot iii. in Figure 4.9). Plant height significantly predicted the number of leaves (b = 18.422, SE_b = 2.015, β = 0.975, t = 8.864, p = 0.001). The model explained 95.2% of the variance in the number of leaves, indicating that every cm increase in height resulted in an increase of 18.23 leaves.

Model 2 Dependent variable: inflorescences, independent variable: leaves

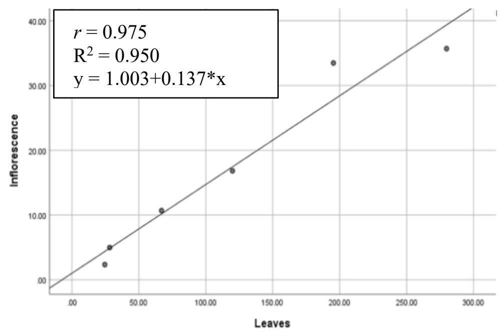
The Pearson correlation coefficient of 0.888 showed a positive correlation between inflorescences and leaves for *A. viridis* studied under fertilizer NPK 12:12:17 (scatterplot i. in Figure 4.10). Linear regression analysis showed a significant relationship (b = 0.270, SE_b = 0.035, β = 0.888, t = 7.706, $p < 0.001$). The slope coefficient for leaves was 0.270, meaning that the number of inflorescences increased by 0.270 by every additional leave. This relationship was strong, with 78.8% (R^2 value) of the variance in inflorescences accounted for by leaves.



i. NPK 12:12:17



ii. NPK 15:15:15



iii. Wild Plants

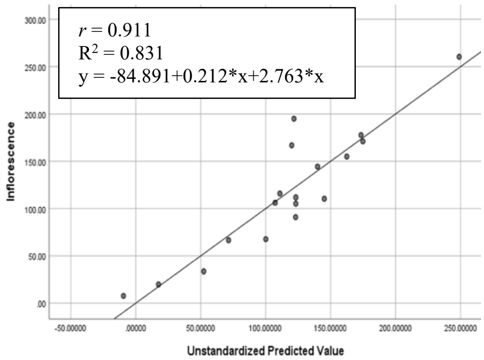
Figure 4.10.: *A. viridis* studied under i. NPK 12:12:17, ii. NPK 15:15:15 and iii. wild plants with inflorescence as dependent variable and leaves as independent variable.

For *A. viridis* under NPK 15:15:15, the positive correlation between leaves and inflorescences ($r = 0.949$) was depicted in scatterplot ii of Figure 4.10 and was statistically significant ($b = 0.109$, $SE_b = 0.009$, $\beta = 0.949$, $t = 12.708$, $p < 0.001$. The slope coefficient for inflorescences was 0.109, indicating that inflorescences increased by 0.109 for every additional leave. The R^2 value showed that 90% of the variation in inflorescence could be explained by the number of leaves.

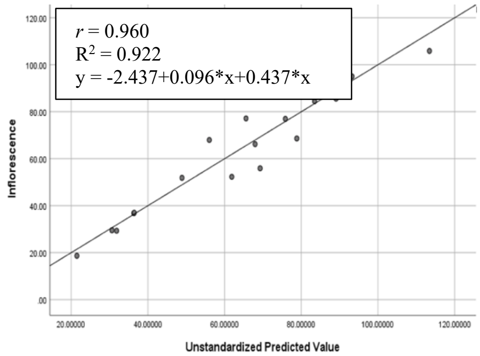
Additionally, in wild plants, the positive correlation between leaves and inflorescences (r = 0.975) was statistically significant (b = 1.003, SE_b = 0.016, β = 0.975, t = 8.745 p = 0.001) as shown in scatterplot iii. in Figure 4.10. Every leave was associated with an increase 0.137 inflorescences. The proportion of variance in the number of inflorescences -explained by the number of leaves was 95%.

Model 3 Dependent variable: inflorescence, independent variable: leaves and height

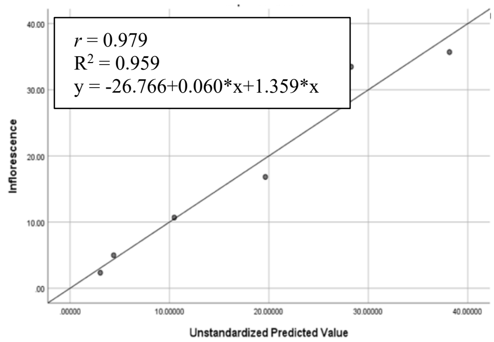
The scatterplot illustrated a strong linear relationship between inflorescences, and both leaves and height, with a Pearson correlation coefficient of (r) of 0.911, as shown in scatterplot i. in Figure 4.11. This relationship was statistically significant (b = 0.212 for leaves, 2.763 for height, SE_b = 0.044 for leaves, 1.415 for height, β = 0.696 for leaves, 0.282 for height, t = 4.810 for leaves, 1.952 for height, $p < 0.001$). According to the model, every inflorescence was associated with an increase of 0.212 leaves and 2.763 in height. The R^2 value indicated that 83.1% of the variance in inflorescences could be explained by both leaves and height.



i. NPK 12:12:17



ii. NPK 15:15:15



iii. Wild plants

Figure 4.11.: *A. viridis* studied under i. NPK 12:12:17, ii. NPK 15:15:15 and iii. wild plants with inflorescence as dependent variable and leaves and height as independent variable.

The Pearson correlation coefficient of 0.960 indicated a strong linear relationship between inflorescences and both height and leaves, as seen in scatter plot ii. of Figure 4.11. This relationship was statistically significant (b = 0.096 for leaves, 0.437 for height, SE_b = 0.010 for leaves, 0.540 for height, β = 0.910 for leaves, 0.074 for height, t = 9.935 for leaves, 0.809 for height, $p < 0.001$). The model suggested that every increase of 0.096 leaves and 0.437 in height corresponded to an increase in the number of inflorescences. Both leaves and height together accounted for 92.2% of the variation in the number of inflorescences.

The strong correlation found for inflorescence to leaves and height was 0.979, (as depicted in scatter plot iii. of Figure 4.11. A significant predictive relationship was identified, where the number of leaves and plant height were predictors for the number of inflorescences (b = 0.078 for leaves, 1.359 for height, SE_b = 0.085 for leaves, 1.650 for leaves, β = 0.449 for leaves, 0.557 for height, t = 0.820 for leaves, 1.609 for height, p = 0.008). This model accounted for 95.9% of the variance in the number of inflorescences.

4.4 Fertilizer treatments of control, 1 g, 2 g, 4 g and 8 g on *A. viridis*

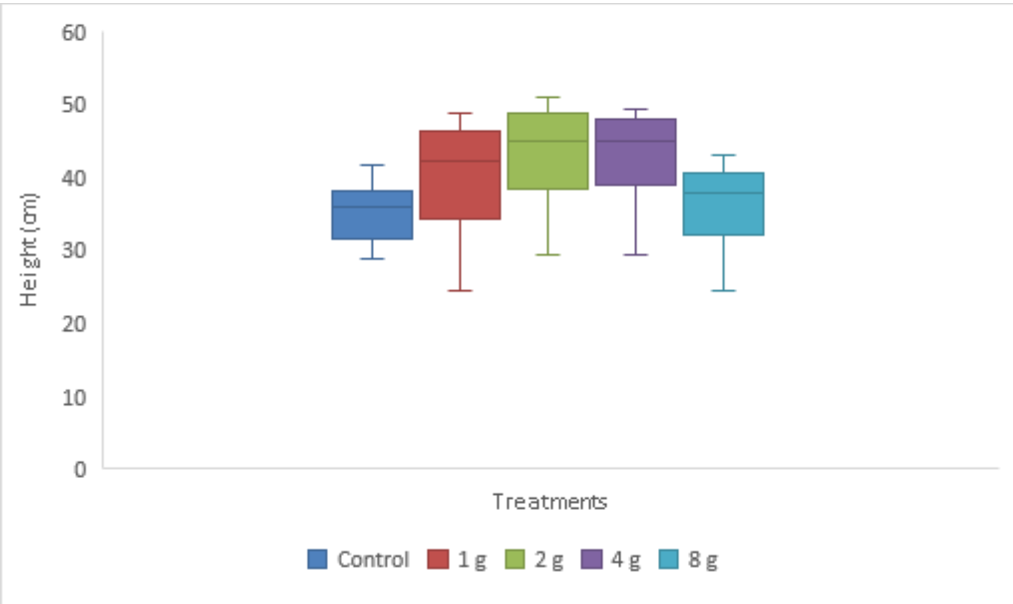
The Levene's tests for equality of variances for the height, leaves and inflorescences parameters were conducted. Under NPK 12:12:17, Levene's test showed that the variances were not significantly different for height ($F(4,25)$ = 1.209, p = 0.332), leaves ($F(4,25)$ = 2.672, p = 0.055), and inflorescences ($F(4,25)$ = 1.391, p = 0.266). Similarly, for the set of plants under NPK 15:15:15, the homogeneity assumption of the variance was met for height ($F(4,25)$ = 0.445, p = 0.775); leaves ($F(4,25)$ = 1.451, p = 0.265) and inflorescences ($F(4,25)$ = 0.635, p = 0.603). In both fertilizer treatments, the variances for the three parameters were statistically non-significance ($p > 0.05$), supporting the null hypothesis of equal population variances. Subsequently, a one-way ANOVA was performed.

4.4.1 NPK 12:12:17

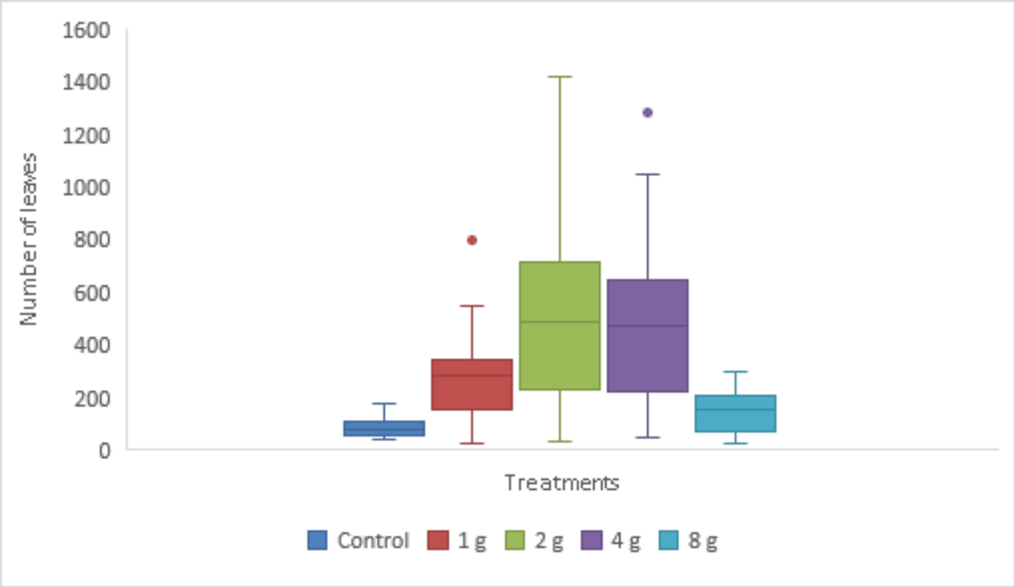
Medians for the height of the five treatments (i.e., control, 1 g, 2 g, 4 g and 8 g) were close to the upper adjacent values (boxplot i. in Figure 4.12). Height medians of 2 g and 4 g were higher at 44.90 cm and 44.97 cm than in other treatments. The relatively short boxplot of the control group exhibited a high level of similarity among its members. The dispersion of the interquartile range was longest for the 1 g treatment, suggesting a wider variation in height among the plants treated under 1 g. Lower whiskers were longer than upper whiskers for 1g, 2 g, 4 g and 8 g treated plants, indicating that shorter plants were more spread out than taller plants.

Medians for leaf numbers under 1 g, 2 g, 4 g and 8 g treatments were closer to the upper adjacent values (boxplot ii. in Figure 4.12). Plants treated with 2 g and 4 g fertilizers had higher median values in leaf numbers, with 490.83 and 473.58 leaves, respectively. Plants under control and 8 g treatment exhibited high similarity in leaf numbers among individual plants, compared to other treatments. The dispersion of leaf numbers was observed in plants treated under 2 g fertilier. Plants in 1 g, 2 g, 4 g and 8 g had relatively longer upper whiskers than lower whiskers, suggesting more variations in leaf numbers when higher. Among these four groups, plants in 2 g with the longest upper whisker showed variations in plants with a higher number of leaves.

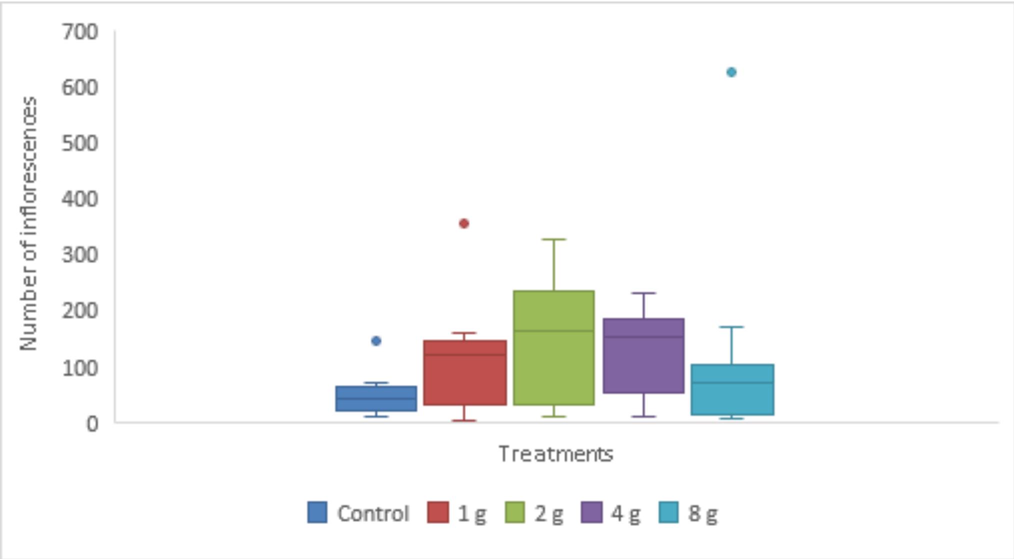
Inflorescence medians for 1 g, 2 g, 4 g and 8 g were left-skewed towards upper adjacent values (boxplot iii. in Figure 4.12). Plants treated with 2 g and 4 g fertilizers had higher median values for inflorescences at 163.75 and 153.5, respectively. Plants under 2 g treatment were the most dispersed, with the longest interquartile box indicating that the treatment group had more scattered data compared to other groups. Plants under the control group were similar with regard to inflorescence numbers, with the shortest boxplot. Plants with fewer inflorescences had fewer variables for 2 g and 8 g, while more inflorescences showed more variables.



i. Height



ii. Number of leaves



iii. Number of inflorescences

Figure 4.12.: Boxplots for *A. viridis* of control, 1 g, 2 g, 4 g and 8 g under NPK 12:12:17.

There was a statistically significant difference between groups, as demonstrated by one-way ANOVA at the $p < 0.05$ for inflorescence ($F(4,25) = 4.403$, $p = 0.012$) and leaves ($F(4,25) = 11.633$, $p = 0.000$) at control, 1 g, 2 g, 4 g and 8 g (Table 4.21). There was no statistically significant difference for height between fertilizer amounts ($p = 0.102$).

Table 4.21. One-way ANOVA on plant height (cm), number of leaves and number of inflorescences under NPK 12:12:17

Dependent variables		df	Sum of squares	Mean square	F	Sig.
Height (cm)	Between groups	4	299.405	74.851	2.165	0.102
	Within groups	25	864.406	34.576		
	Total	29	1163.811			
Number of leaves	Between groups	4	931860.579	232965.145	11.633	0.000
	Within groups	25	500676.467	20027.059		
	Total	29	1432537.046			
Number of inflorescences	Between groups	4	44428.980	11107.245	4.043	0.012
	Within groups	25	68687.800	2747.512		
	Total	29	113116.780			

A Tukey post hoc test showed that the plants applied with 2 g of NPK 12:12:17 were able to grow more leaves and inflorescences and were statistically significant than other groups at $p < 0.05$ (Table 4.22). There was no statistically significant difference between 1 g and 8 g for leaves, and 1 g, 4 g and 8 g for inflorescences.

Table 4.22. Mean and standard deviation for height (cm), leaves and inflorescences per treatment under NPK 12:12:17.

Treatments	**Parameters**		
	Height (cm)	**Number of leaves**	**Number of inflorescences**
Control	35.42±8.92	85.23 ± 77.63^{a}	47.77 ± 61.45^{a}
1 g	40.00±10.45	275.41 ± 259.51^{ab}	117.24 ± 146.98^{ab}
2 g	42.80±8.96	524.81 ± 396.51^{c}	144.44 ± 123.34^{b}
4 g	43.00±7.78	487.73 ± 487.28^{bc}	126.34 ± 125.23^{ab}
8 g	36.30±8.49	147.51 ± 147.66^{ab}	97.51 ± 197.78^{ab}

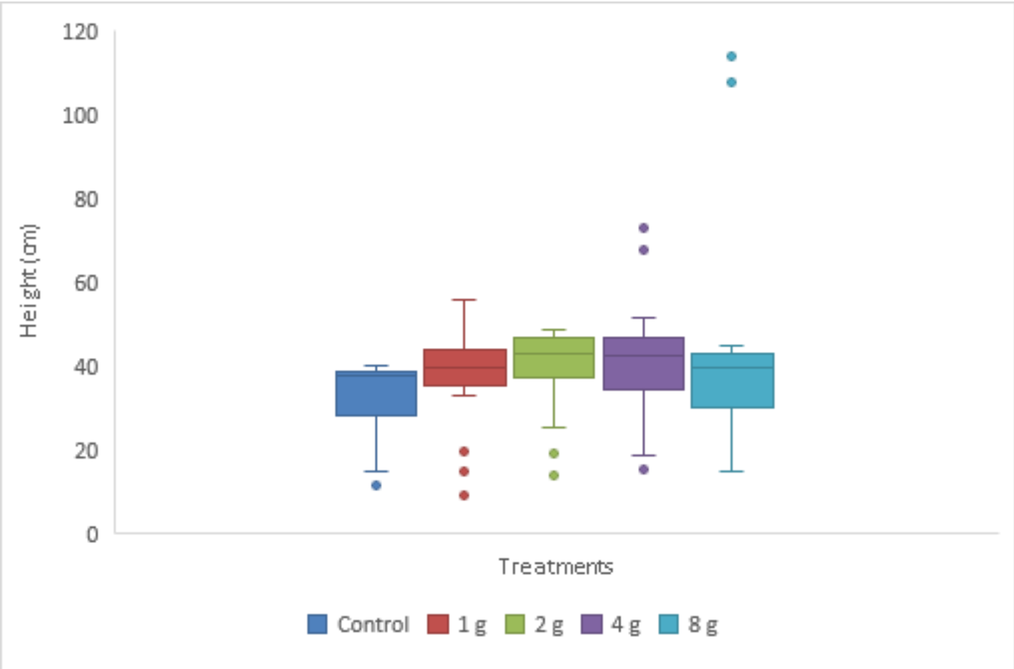
Note: Means not sharing subscripts differ significantly at $p < 0.05$ as indicated by Tukey's HSD.

4.4.2 NPK 15:15:15

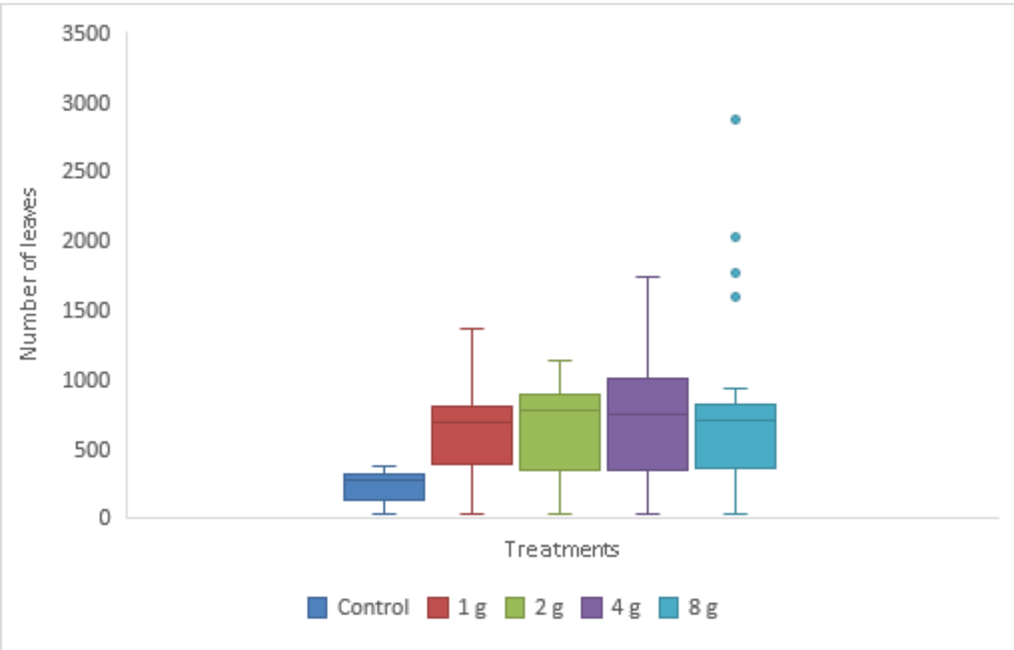
Height medians of control, 2 g, 4 g and 8 g were close to the upper adjacent values (boxplot i. in Figure 4.13). Plants under the treatments had a similar median in height, ranging from 37.89 cm for control with the lowest height among the treatments to 42.97 cm for plants under the 2 g treatment. The relatively short boxplot of the 1 g treatment suggested a high level of similarity within the plants. The relatively longer dispersion of the interquartile range of 4 g and 8 g treatments suggested a wider variation of height among the plants. Lower whiskers were longer than upper whiskers for control, 2 g, 4 g and 8 g illustrating left-skewed distribution.

The plants under 2 g had the highest median value at 774.58 leaves (boxplot ii. in Figure 4.13). The dispersion for 4 g was the greatest, with the longest interquartile range. Median values for 1 g, 2 g, 4 g and 8 g were closer to upper adjacent values. Leaf numbers for 1 g and 4 g were right-skewed. There was a wider range in the data values in upper whiskers. Contrasting with 1 g and 4 g plants, other groups of control, 2 g and 8 g were more spread out in lower whiskers.

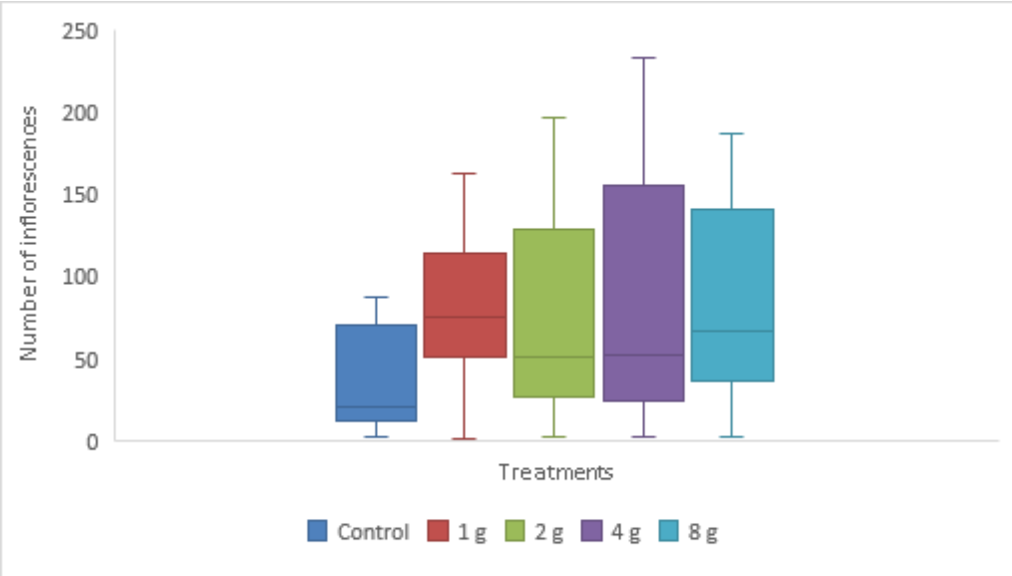
The 1 g plants had the largest median value at 75.97 inflorescences (boxplot iii in Figure 4.13). Plants under 4 g showed a larger range than other groups, with the longest boxplot length. The median values for the five groups were closer to lower adjacent values. The 2 g and 4 g plants were skewed right. This indicated a higher number of inflorescences were more variable than plants with a lower number of inflorescences.



i. Height



ii. Number of leaves



iii. Number of inflorescences

Figure 4.13.: Boxplots for *A. viridis* of control, 1 g, 2 g, 4 g and 8 g under NPK 15:15:15.

Analysis of variance showed effects of fertilizer amounts of control, 1 g, 2 g, 4 g and 8 g at $p < 0.05$ on height ($F(4,25) = 4.763$, $p = 0.005$) (Table 4.23). Dependent variables of leaf and inflorescence numbers did not differ significantly among the five treatments applying with NPK 15:15:15.

Table 4.23. One-way ANOVA on plant height (cm), number of leaves and number of inflorescences under NPK 15:15:15

Dependent variables		df	Sum of squares	Mean square	F	Sig.
Height (cm)	Between groups	4	291.751	72.938	4.763	0.005
	Within groups	25	382.274	15.315		
	Total	29	674.625			
Number of leaves	Between groups	4	2305955.624	576488.906	.985	0.433
	Within groups	25	500676.467	20027.059		
	Total	29	16932274.169			
Number of inflorescences	Between groups	4	8446.035	2111.509	1.137	0.512
	Within groups	25	68687.800	2747.512		
	Total	29	40693.267			

Post hoc analysis using Tukey HSD indicated that plants under control, 1 g and 2 g were statistically significant in height from plants under 4 g and 8 g at $p < 0.05$ (Table 4.24). Plants within the treatment groups of control, 1 g and 2 g were not statistically significant; the same for plants under 4 g and 8 g treatments were not significantly different.

Table 4.24. Mean and standard deviation for height (cm), leaves and inflorescences per treatment under NPK 15:15:15.

Treatments	Parameters		
	Height (cm)	**Number of leaves**	**Number of inflorescences**
Control	33.43 ± 10.22^a	230.78±159.72	33.87±33.03
1 g	38.46 ± 15.71^a	639.27±496.61	80.88±58.25
2 g	40.00 ± 10.50^a	651.20±396.81	72.96±69.01
4 g	41.50 ± 19.35^b	749.11±2418.17	84.39±94.29
8 g	42.19 ± 27.88^b	781.74±2694.47	84.02±98.31

Note: Means not sharing subscripts differ significantly at $p < 0.05$ as indicated by Tukey's HSD.

CHAPTER 5

DISCUSSION

5.1 Challenges for rural farming in adopting non-chemical control method – age and attitude

The challenges faced by the agricultural community in Malim Nawar, particularly the ageing farmer population, align with broader trends observed in Malaysian agriculture. The data indicates that 50 (80.6%) farmers in our cohort were over 50 years old, against an average life span of 74.5 years for Malaysian (Department of Statistics, 2019c). Similar trends have been reported in the paddy sector, where the average age of farmers age was above 50 years old (Alam, et al., 2010; Abdullah, Ahmad and Ismail, 2012; Omar, Shaharuddin and Tumin, 2019). The low involvement of the younger generations continues to be a persistent issue in Malaysia's agriculture. Despite harboring positive perceptions of agriculture, young people show limited interest in pursuing careers in the sector (Abdullah, Abu Samah and Othman, 2012).

Male farmers constitute the predominant workforce in Malim Nawar. Their wives typically serve as housewives but occasionally assist on farms during harvesting seasons. This dynamic contrasts with paddy planting, where both women and men actively participate in farming activities from planting to harvesting. In the context of paddy farming in Malaysia, farmers' level of experience tends to correlate with their age. Specifically, older farmers tend to have more extensive farming experience, measured in terms of the number of years engaged in agricultural practices (Dilipkumar, et al., 2021).

The current study's findings echo those of Serebrennikov et al. (2020) and Dilipkumar et al. (2021), revealing that the adoption of new agricultural practices is influenced by farmers' age and education levels. The research observed that elderly farmers with lower levels of education exhibited greater resistance compared to their younger and more educated counterparts. Similar challenges are noted among aged smallholder farmers in Malaysia involved in paddy, rubber, and oil palm plantations, where technical knowledge and support for improving weed management practices are lacking (Dilipkumar, et al., 2017; Dilipkumar, et al., 2021). Resistance to adopting new practices is attributed to potential risks, such as uncertainty in yield and increased cost, particularly among elder farmers. Interestingly, despite scepticism towards new practices, there is prevailing trust in the efficiency of herbicides, highlighting farmers' concerns for crop production outputs. The study suggests that value-based conflicts are common among farmers, where recognize the unsustainability of the existing practice but are unwilling to make changes (Jordan, et al., 2016).

Crop rotation is recognized as an effective weed management strategy for suppressing weed density (Weisberger, Nichols and Liebman, 2019), but did not resonate with the farmers recruited in this study. Their primary motivation for practising crop rotation was associated with soil fertility rather than weed management practices among the farmers, leading to a preference for herbicide usage.

Pests and diseases were perceived as more severe constraints compared to weeds in crop production, aligning with findings from a farmer survey in Africa (Laizer, Chacha and Ndakidemi, 2019). According to the farmers interviewed in the present study, insect populations experienced dramatic increases depending on the weather. On dry and hot days, *Thrips palmi, Tetranychus urticae, Polyphagotarsonemus latus,* and *Empoasca fabae* were prevalent, while *Helicoverpa armigera, Maruca vitrata, Maruca testulalis,* and *Plutella xylostella* were prevalent during the rainy season. Farmers exhibited low tolerance level for weeds, especially during crop planting, making it challenging to maintain a low competitive level and ecologically beneficial weeds, as suggested by and Westbury (2007).

Herbicides were considered more effective in weed control compared to pesticides for managing insects and diseases, which were considered more harmful. Farmers used both pre-emergence (before planting) and post-emergence (after planting) herbicides. However, they lacked detailed knowledge of weed control methods, including active ingredients and their modes of action. They expressed a strong preference for ‘effective’ herbicides without necessarily understanding the components. Negative psychological perceptions posed significant barriers to learning and accepting environment-friendly methods in contrast to the prevalent chemical control methods. Some farmers reckoned that knowing weed species was unnecessary when using chemical methods. However, understanding weed species composition is crucial for the initial steps of effective weed management (Zimdahl, 2018).

Information sources play an important role in disseminating knowledge, as information accessibility and quality determine the adoption of sustainable agricultural practices (Rodriguez, et al., 2009; Serebrennikov, et al*.,* 2020). Limited information sources can constrain exposure to new methods and hinder learning. Television programs were identified as the only information source for farmers in Kedah and Selangor (Ramli, et al*.,* 2013). However, in Malim Nawar, the present study found that television programmes were not a significant source of information. Instead, informal sources such as phone calls, farm visits, and social relations served as major information sources. The study also revealed that about 15% of farmers received information from government agencies, a notable increase compared to the 1% reported in a survey in 2002 in Cameron Highlands (Mazlan and Munford, 2005).

In addition to informal sources, farmers in the study also relied on information from agrochemical companies, which is considered a formal source. The main strategies employed by agrochemical companies for disseminating information included farm visits by company representatives and organized talks for farmers. Farmers attended presentations organized by these agrochemical companies to learn about new products and application methods. Other motivations for attending included the meals provided by the companies and the opportunity to socialise. While agrochemical companies are formally recognized as a knowledge source (Šūmane, et al., 2018), their role in information dissemination should be scrutinized, as they are profit-driven entities with the primary goal of meeting sales requirements and promoting their products. Studies have shown that smallholders seeking advice from agrochemical retailers have tended to use more pesticides in Cambodia, Laos, and Vietnam (Schreinemachers, et al., 2017).

Farmers' perspectives and local socioeconomic factors are influential in information sharing and knowledge acquisition among rural farmers (Jordan, et al., 2016; Pratiwi and Suzuki, 2017; Zossou et al., 2019). The adoption of certain practices by an increased number of farmers can inspire others in the area to follow suit. Conversely, low participation might discourage other farmers from implementing novel practices (Figure 5.1). Survey results can be used in decision making processes or for practical purposes such as predicting situations and guiding implementation efforts (Alreck and Settle, 2003).

Improving farmers' knowledge of agricultural practices is critical for achieving sustainable agriculture (Šūmane, et al., 2018). Information accessibility is important for rural farmers' continuous learning, enabling them to improve their technical skills and practices (Franz, et al., 2010; Abdullah, et al., 2012; Adnan, et al., 2017; Aku, et al., 2018; Azman, et al., 2013; Serebrennikov, et al., 2020). The source and quality of information are critical factors in encouraging farmers to adopt new weed control methods that could potentially replace the dominant use of herbicides.

Agricultural education plays a pivotal role in addressing the sustainability goals of rural farmers (Anderson, 1984; Chittoor and Mishra, 2012; Chauhan, et al., 2017; Terlau, Hirsch and Blanke, 2019). While various knowledge sources could complement each other, government agricultural programmes emerge as the most influential agent of change in agricultural education (Arman, Mamat and Hasbullah, 2016; Danso-Abbeam, Ehiakpor and Aidoo, 2018; Rodriguez, et al., 2009). In Malaysia, agriculture-related research institutions and departments contribute to identifying knowledge types and dissemination mechanisms, ensuring the sector's development and progress (Arman, Mamat and Hasbullah, 2016).

New weed management programmes could capitalize on current activities, such as farm visits and social relations, to disseminate information on eco-friendly weed management practices; local farmer organisations could serve as a good starting point for systematic change. Farmer organisations are intermediaries between farmers and government agencies, facilitating the transfer of quality information. The Malim Nawar Vegetable Farmer Association, for example, plays a crucial role in promoting agricultural development and ensuring the well-being of its members. Collaborative efforts between farmer organizations and relevant government agencies can contribute significantly to advancing weed management practices, aligning with their overarching objectives of fostering sustainable agricultural growth and development.

Current scattered and ad hoc programmes must be reviewed to improve farmers' learning experiences. In collaboration with the Association, relevant government agencies should take a proactive approach to farmer education, employing small discussion groups, demonstration plots, and experiential activities such as hands-on workshops and on-farm demonstrations. Furthermore, fact-based learning methods, such as courses and seminars, could be used to enrich farmers' knowledge (Ismail 1995; Samah, et al*.,* 2012). It can be inferred that sequential capacity-building and educational programmes serve as catalysts of rural agricultural development. Innovative and localized methods, considering environmental sustainability and socioeconomic factors, are needed to ensure continuous learning for farmers with varying literacy levels and resistance levels. The absence of agricultural learning among farmers could pose challenges to existing weed control efforts (MacLaren, et al., 2020).

5.2 Weed community dynamics

5.2.1 Changes in weed richness and abundance

A low species diversity composition of 15 species was recorded in this study. In contrast, Raya, et al. (2013) identified 40 weed species in five farms planted with different vegetables in the Selangor state. The group with the highest number of species was broadleaves, suggesting its dominance. Broadleaves could be abundant on maize farms practising tillage (Streit, et al., 2003). This study found five weed species in common with Raya, et al. (2013), namely *C. rutidosperma, E. hirta, E. indica, H. corymbosa, P. amarus.* The number of *w*eed species in paddy fields in Malaysia is at least three times the number in maize farms, ranging from 29 species with grasses as the dominating weed group (Azmi and Baki, 2007) to 40 species dominated by broadleaves (Hakim, et al., 2013b); 42 species dominated by broadleaves (Hakim, et al., 2010); to 53 species dominated by broadleaves (Hakim, et al., 2013a). There is no overlap in weed species between this study and the weed studies in paddy fields.

Weeds may adapt to various man-made environments, including agriculture habitats (Lososová, et al., 2006; Munoz, et al., 2020; Wang and Wan, 2020). Some crops exhibit low weed species numbers. For instance, during wheat planting, only six weed species were identified, and an additional 12 species was planted with soybeans, resulting in a total of 18 species (Pan, et al., 2020). Weed species diversity composition may be lower in maize farms compared to other crops (Bourgeois, et al., 2019; Kamuti, et al., 2015). In Pakistan, Ahmad, et al. (2016) found 29 species from 65 maize farms. In Germany, de Mol, von Redwitz and Gerowitt (2015) recorded 111 species in 1,460 farms. Fried, et al., (2020) documented a total of 81 species from 659 farms in France over two survey periods in the 1970s and the 2000s. A survey over a 6-year period on maize farms in Zimbabwe revealed twenty-three species (Chipomho, et al., 2020). The consistent finding of a low number of weed species number on maize farms holds true across different continents.

The difference in the number of species observed between 2017, 2018 and 2020 ranged from three to eight species. Five weed species were consistently found in all three years of the survey: *A. viridis, C. rutidosperma, Cyperus* sp., *E. indica* and *P. virgatus.* It is noteworthy that none of these weed species is listed as invasive according to the national invasive species list (Department of Agriculture, 2021). Munoz et al., (2020) categorized the persistence levels of weeds, distinguishing between resident weeds adapted to cultivated lands and transient weeds still lacking robust adaptations to biotic and abiotic factors on farms. Fast growth, characterized by a short time frame from vegetative growth to reproductive stage, is an important trait contributing to a species' persistence. Weeds not persisting on a yearly basis may still have seed banks in the soil that do not germinate in a particular season (Borgy, et al, 2015). Other reproduction factors such as seed production and propagules may contribute to variations in species presence across space and time (Davis, 2017).

The species composition did not undergo substantial variation during the study period, consistent with the findings of a 9-year weed survey in maize farms in Germany, where weed composition remained almost constant (de Mol, Mazsu and Gerowitt, 2015). Similar weed species composition across farms in an area suggests almost identical land use patterns and practices among farmers (Mohan, Ramachandran Nair and Long, 2007). However, not all maize farms exhibit similar findings. In some cases, the majority of weed species are replaced with other weed species after several decades of maize cultivation. For instance, in France, eight weed species remained on maize farms out of a total of 81 weed species after 30 years of maize cultivation (Fried, et al., 2020).

Weeds exhibiting C_4 photosynthesis were found to dominate on maize farms, particularly in association with mono-cropping system (Fried, et al., 2020). The C_4 weed species tend to thrive in environments with increased light, nutrients and temperature, especially favoring the nutrient-rich conditions. In contrast, this study identified 9 out of 15 weeds as C_3 plants. It is worth noting that both C_3 and C_4 plants can be equally dominant on maize farms (Zikas, and Duke, 2011). The prevalence of C_4 photosynthesis weeds on maize farms in temperate country is often attributed to their competitive advantage over companion C_3 weeds, given that maize is typically planted during the summer season in such regions (Fried, et al. 2020).

The frequency and field uniformity contribute to Mean Field Density (MFD) and Mean Overall Field Density (MOFD). If a species has a higher density number in MOFD than MFD, it suggests specific factors such as site characteristics and management practices have played a role. The relative abundance, indicating species with higher values, could be considered dominating species and might pose challenges in weed management. It is important to note that dominant weed species may wary different between maize monoculture and intercropping systems, such as maize and cassava (Olorunmaiye, et al., 2013). Weeds, through the process of evolution, acquire different competitive abilities and degrees of weediness. These traits, derived from sympatric evolution, can influence the presence and abundance of weeds on a farm (de Wet and Harlan, 1975).

Locally abundant species often indicate wider distribution areas compared to weed species with lower density in terms of the number of individuals and frequency (Fried, et al., 2020; Lososová, Chytrý and Kühn, 2008). This study is consistent with findings in France (Munoz, et al., 2020) where most weeds on cultivated lands exhibit a therophyte life cycle characterized by a short life cycle of less than a year. This is due to the frequent ploughing of lands for crop cultivation, which tends to eliminate weeds with longer life cycles (i.e., biennial and perennial life cycle) during ploughing.

The composition of broadleaf, grass, and sedge weeds has shown changes in abundance across the years 2017, 2018, and 2020. Weed communities are likely to vary in diversity and abundance over time in response to selection pressures and agronomic practices (Nkoa, Owen and Swanton, 2015). For any weed species, a farm can be favourable for growth in one year, but the situation may continue or become adverse in the next year (Gaba, et al., 2017). These factors may have single, simultaneous, or cumulative effects on a location influencing weed communities to varying extents (Nagy, et al., 2018; Qi, et al., 2020; Zhu, et al., 2020). Agronomic practices, farm management and crop types, and biotic and abiotic factors collectively influence weed community structure on a farm (Sosnoskie, 2005).

The dynamic of weed communities exhibit various trends, including the persistence of certain species at a site in the relative abundance of species, and fluctuations in the overall composition and number of individuals over both spatial and temporal scales. The dynamic nature of weed richness and abundance at the local level provide insights into predicting weed occurrences in other maize farms within the same area (Fried, et al., 2020). The composition of weed communities is influenced by a multitude of factors, such as resources, adjacent lands, crop species and the agronomic practices employed by farmers (Gaba, et al., 2017; Jastrzębska, et al., 2013; Qi, et al., 2020). Weeds have evolved ecological strategies in response to the development of agriculture, integrating themselves into farming habitats and adapting to the conditions imposed by agricultural practices (Harlan and de Wet, 1965).

Findings of this study align with those reported by Ahmad et al. (2016) in their research on maize farms in Pakistan, where *Cyperus* emerged as the most abundant species. In turn, sedge weeds are widely distributed in tropical and subtropical regions (Xu and Zhou, 2017). The genera identified in the present study site correspond with those found in maize farms in Pakistan, such as *Phyllanthus* and *Oldenlandia* (Hossain, et al., 2019). Three weed species (*A. viridis*, *E. indica* and *E. hirta*) were consistently associated with maize, suggesting their ubiquity (Hossain, et al., 2019). In Sri Lankan, *E. indica* was found to be a dominating weed species on maize farms (Sangkkara and Stamp, 2006). Notably, the sandy soil texture at the depth of 25-50 cm in the study site, a former tin-mining land, aligns with previous research highlighting the significance of sand content in soil as a key variable contributing to the abundance of *A. viridis* (Ahmad, et al., 2016; Shamshuddin, Mokhtar and Paramananthan, 1986).

5.2.2 Weed groupings based on Cluster Analysis

Hierarchical cluster analysis was used as an exploratory method to unveil potential underlying structures within the weed species data set. It is essential to note that cluster analysis does not serve as a statistical inference representing a population but rather quantifies structural characteristics within a set of observations. This method acts as a complementary to non-hierarchical confirmatory methods (Hair, et al., 2010; Timm, 2002). The degree of distance, or “dissimilarity,” and the degree of association, or “similarity,” concerning species presence are measured for proximity matrix. It is crucial to explain the distance measure in conjunction with other descriptive variables (Hair, et al., 2010). The exploratory technique aids in providing an alternative explaination of the data and may suggest avenues for further studies, incorporating criteria or replications for validation (Dugard, Todman and Staines, 2010; Timm, 2002).

At a dissimilarity distance at 11, the cluster solution reveals six groups based on the presence of weeds on the farms (Figure 4.2). Examining the multi-dimensional aspects of weeds can enhance our understanding of the presence of weeds (Bajwa, et al., 2016). Weeds are found in disturbed sites, including open spaces, roadsides, and grasslands. Arable farms and gardens represent cultivated areas. The presence or absence of weeds distinguishes disturbed sites from cultivated lands and vice versa. Weeds thrive in human-modified landscapes, encompassing both categories. However, farmers and growers place emphasis on weeds due to their impact on yield production. Hence, the literature often makes a distinction between disturbed sites and arable farms. The following discussion does not differentiate between arable weeds and non-arable weeds unless literature explicitly highlights their presence or absence in a particular habitat.

In the context of this study, the origin of a weed may play a crucial role. Tropical weeds have expanded their distributions, and consequently, they are becoming ubiquitous in the tropics and sub-tropics (Table 5.1). Both native and naturalised weed species have been a focus for researchers and and a concern for agricultural management. The broadleaf *A. viridis* originated in Africa and is known for its widespread dispersal into tropical and sub-tropical areas, as well as temperate regions (Grubben and Denton, 2004). Broadleaf *A. viridis* shows a wide habitat adaptation, allowing it to survive in environments ranging from wet to extremely dry, leading to an extensive geographical distribution of this species (Xu and Deng, 2017).

The origins of some weed species may have been lost after decades of spreading distribution, such as *E. indica* (Xu and Zhou, 2017). However, *E. indica* is identified as a major weed species in cassava (*Manihot esculenta*), maize (*Zea mays*), cotton (*Gossypium* spp.), peanut (*Arachis hypogaea*), pineapple (*Ananas comosus*), rice (*Oryza sativa*), sorghums (*Sorghum bicolor*) and millets (*Setaria italica*), soybean (*Glycine max*), sugarcane (*Saccharum officinarum*) farms across the world (Holm, et al., 1991). Crop and soil type are factors in influencing weed community structure on farms, suggesting different weed management strategies are needed between locations (Mahgoub, 2021; Wang and Wan, 2020). Weeds with a wide and expanding distribution suggest a higher level of weediness traits (Bajwa, et al., 2016; Baker, 1974).

Table 5.1. Six weed groups at cluster solution at dissimilarity distance of 11.

Cluster	Species	Native distribution	Expanded distribution	Habitat	Remark
1	*A. gangetica*	10 countries	32 countries	Terrestrial habitats	Optimal growth in well-drained, moist, fertilized soil. Common in Malaysia plantations.
	B. latifolia	23 countries	27 countries	Terrestrial habitats - sandy and lightly shaded environment	Reproduce within two months after vegetative stage
	Commelina sp.	-	-	-	Common in Malaysia plantations.
	D. longiflora	57 countries, including Malaysia	19 countries	Terrestrial habitats	Common in Malaysia plantations
	M. hirtus	30 countries	44 countries	Terrestrial habitats	-
	O. corymbosa	61 countries, including Malaysia	35 countries	Terrestrial habitats	Preferred full sun environment

	P. dichotomiflorum	22 countries	38 countries		
2	*A. viridis*	33 countries	98 countries	From drought to wetland habitats	Clumps or predominant populations. Common in Malaysia plantations.
	C. rutidosperma	25 countries	33 countries	Mainly terrestrial habitats – damp environment	Form dense mats on the ground. Common in Malaysia plantations.
	E. hirta	36 countries	71 countries	Terrestrial habitats	Grows in any types of soils except polluted soils. Common in Malaysia plantations.
	P. amarus	35 countries	61 countries	Terrestrial habitats	-
3	*H. corymbosa*	60 countries, including Malaysia	34 countries	Terrestrial habitats	-

4	*P. virgatus*	28 countries, including Malaysia	0	Terrestrial habitats – moist, fertile or barren environment	
5	*Cyperus* sp.	-	-	-	Often with rhizomes and common in Malaysia plantations.
6	*E. indica*	74 countries, including Malaysia	72 countries	Terrestrial habitats	Strong root system, tough fibrous texture making it difficult for physical removal. Common in Malaysia plantations.

Note:

i. Compilation and modification from Chen, Foong and Ng (2015); Chung, et al., (2013); Holm, et al. (1991); POWO (2021); Xu and Deng (2017); Xu and Zhou (2017)
ii. List of countries for native and introduced distributions are in Appendix F.

Seven weed species - *A. gangetica, D. longiflora, A. viridis, C. rutidosperma, E. hirta, P. amarus,* and *E. indica* are aslso found in oil palm and rubber plantations in both Malaysia and Indonesia (Chung, et al., 2013), with *D. longiflora* and *E. indica* being native to Malaysia. The other three native weeds are *H. corymbosa, O. corymbosa* and *P. virgatus*. The next question is whether such groupings could be used to predict weeds present on maize farms established on sandy soil types. Morphological features, physiological characteristics, and ecological functional properties could overlap to overcome multiple selection pressures (He, et al., 2020). More closely related species are similar in niches than distantly related species (Garnier and Navas, 2012).

In addition to species origin, ecological niche is used to infer the presence of weeds with environmental conditions, resource utilisation, and interspecific competition embedded in the concept (Smith, Mortensen and Ryan, 2010; Wiens, et al., 2009). Weed species that demand a high level of nutrients and sunlight would have an extensive latitudinal distribution or be present in a wide range of habitats (Lososová, et al., 2006). They would thus become generalists in ecological niche requirements (Lososová, Chytrý and Kühn, 2008). Arable weeds are more generalists compared to weeds in non-agricultural, disturbed habitats, and therefore the former are more likely to persist in their existence (Munoz, et al., 2020). Generalist weeds exhibit greater genotypic and phenotypic plasticity than specialist weeds with a narrow ecological niche (Munoz, et al., 2020). Generalist weeds that can survive and thrive in different environments, both managed and unmanaged human-modified landscape, pose greater threats in agriculture compared to non-generalist weeds.

Weeds are becoming naturalised in the tropics and subtropics. Yet, generalisations about weeds, such as their distribution in the tropics and subtropics, as well as their presence in roadsides, open spaces, or arable farm habitats, without details of biological and ecological variables, are insufficient to interpret the weed grouping structure found in the maize farms studied. For example, Bajwa et al. (2016) found that the invasiveness of *Parthenium hysterophorus* is due to a combination of attributes in morphological characteristics, genetic plasticity, and physiological mechanisms, enabling adaptation to different habitats. Weed species may have specific and/or overlapping attributes that allow them to thrive in a particular habitat.

In light of the elusiveness of basic information, exploring weed biology and ecology variables at various breadth and depth levels is recommended to clarify weed community structure. A trait-based approach, including life cycle, growth habits, and physiological responses to agronomic practices. Exploratory statistical techniques involving biological and ecological traits in exploring the dimensionality of variables could help interpret homogeneity and heterogeneity. Understanding the relative contribution of each trait in dimensionality remains a research gap but is crucial for advancing ecological weed management (Garnier and Navas, 2012; Kunstler, et al., 2016; Lososová, Chytrý and Kühn, 2008; Mahgoub, 2021).

5.2.3 Indicators for weed diversity and abundance

Data inputs as the number of species, the number of individuals per species, and proportions of number of individuals of each species were used for indices analysis. The Shannon-Wiener diversity (*H'*) index values ranged from 0 indicating very low diversity, to 5 indicating high diversity. Higher number of plants belonging to a certain species resulted in lower diversity index. The values for this study in 2017, 2018 and 2020 ranged between 1.3 and 1.5 indicating low species diversity on farm. This is consistent with similar low diversity with values between 1.1 to 1.4 in maize farms in Indonesia (Kurdiadie, Uniyati and Widayat, 2016) (Table 5.2). This study's findings are consistent with other studies indicating low species diversity on farms, especially in degraded and disturbed habitats, suggesting that a less diverse weed community might be more competitive against crops (MacLaren, et al., 2020).

Table 5.2. Shannon-Wienner diversity and Pielous's evenness indices in different crops and cropping systems

References	Crop	Shannon-Wiener diversity (*H'*)	Pielou's evenness (*E*)
Chipomho, et al. (2020)	Maize	1.36-1.62	0.47-0.53
Jastrzębska, et al. (2013)	Root crops	2.64	0.617
	Spring barley under sown with red clover and grasses	3.03	0.722
	Red clover/grass mixture	3.44	0.953
	Winter triticale	3.47	0.813
Kurdiadie, Uniyati and Widayat (2016)	Maize	1.12-1.39	-
Légère, Stevenson and Benoit (2005)	Spring barley-red clover	<2.0	0.4-0.8
Pan, et al. (2020)	Wheat-soybean	1.78-2.00	0.70-0.78

Monoculture cropping system, intensive agriculture, and increased years of cultivation on the same area would cause an observable decline in species richness on a temporal scale (Mohan, Ramachandran Nair and Long, 2007; Sánchez, et al., 2021; Storkey and Westbury, 2007), acting as biotic and abiotic filters on weeds. Herbicide-treated plots and chemical fertilizers could result in lower weed species diversity (Qi, et al., 2020; Yuan, et al., 2016). Only a few weed species would consistently survive selection pressure factors such as fertilization, tillage, and crop type, thus allowing these weed species to persist and dominate on farms (Bourgeois, et al., 2019; MacLaren, et al., 2020). Weed community structure may be influenced by the niche breadth of weeds (Smith, Mortensen and Ryan, 2010; Travlos, et al., 2018).

Agricultural lands in Malim Nawar have been cultivated for around 40 years with the practices of chemical herbicides and tillage, according to surveyed farmers. Some farmers practice crop rotation systems. For example, surveyed farmers in Malim Nawar have claimed that controlling *E. indica* is increasingly difficult using herbicides. Weeds that exist in intensive agricultural systems have developed specialised adaptations to farm practices (Garnier and Navas, 2012).

Chemical control would reduce number of weed diversity compared to other management methods (Glowacka, 2011). The ecological functionality of weed species would become homogenized alongside declining weed species (Smart, et al., 2005). The chemical and mechanical technology would reduce weed diversity to weeds that are difficult to control (MacLaren, et al., 2020). Agronomic practices have caused a decline in species diversity and altered species abundance. Crop rotation systems would disrupt certain weeds' life history strategies with a particular crop, thus reducing weed diversity (Smith, Mortensen and Ryan, 2010).

Farm management practices such as tillage, herbicides, and fertilizer play a role in influencing weed composition. Tillage practices on farms are a factor in reducing weed diversity and species abundance compared to conservation tillage systems, which include no-tillage (Travlos, et al., 2018). Sites applied with herbicides are found to have lower weed diversity than areas without applying herbicides (Qi, et al., 2020; Rassam, Latifi and Kamkar, 2011). Lower weed diversity is found in farms applied with different fertilizer combinations of NPK (Pan, et al., 2020).

Pielou's evenness (*E*) index value is 1 when all species are equal in number of individuals, while an index value 0 suggests the evidence of a dominating species. The *E* value for three of the years in this study ranged from 0.5 to 0.7. These intermediate values suggest that the evenness of the weed species is most likely achieved, and the possibility of dominance by one weed species is low. This situation was supported by the high value of D^{-1}. Weed species are represented by almost an equal number of individuals on farms. All weed species were present in almost equal numbers of individuals, and there was no dominance among species in Pan et al.'s study (2020).

5.2.4 Weed and environmental factors on maize yield

Weed composition is a crucial aspect of crop and weed management (Bastiaans, et al., 2000; Chauhan, et al., 2017). Local or site-specific weed studies conducted over several years would be more useful in predicting impacts on crop yield (Chipomho, et al., 2020; Fried, et al., 2020; Little, et al., 2021). Sangakkara and Stamp (2006) found that grasses had the highest adverse impact on maize, reducing yield by 32% due to sharing a similar root depth zone with maize, leading to competition. In contrast, sedges had the lowest impact because of its prostrate life form. Weed numbers could be the key driver for focal crops (Kunstler, et al., 2016). Different weed groups may have varying impacts on yield, but this study found that none of the weed groups affected maize yield. Temperature and rainfall are identified as influencing abiotic factors in maize growth and development (Iderawumi and Friday, 2018), but these factors did not impact maize yield in this study.

The lower the abundance of weeds, the less impact on the crop growth and yield. Weed densities of 32 plants m^{-2} and below enable achieving crop yields equivalent to those achieved in weed-free areas (Concenço, et al., 2017). Weed density at 250 plants/m^2 in paddy fields did not affect paddy yield, similar to weed-free growing conditions (Begum, 2006). This study recorded 55.57 weeds m^{-2}, considered high weed density according to Myers, et al. (2005). High weed density may be a response to the abundance of NPK (Chipomho, et al., 2020). The study site is a former tin mining area with predominantly sandy soil that requires regular fertilization to compensate for nutrient leaching. Weed abundance may not always affect crop yields, including maize (Smith, Mortensen and Ryan, 2010). Weeds emerging after maize planting may not be advantageous in competition (Chaney and Baucom, 2012; Cowan, 1997). The additivity theory of multiple weed species causing more yield loss may be absent due to intra- and interspecific competition between weed species on farms (Cowan, 1997; Dekker, 1997).

Maize canopy and high crop density could overshadow weed species and thus reduce weed growth and even their seed production (Bhowmik, 1997; Jastrzębska et al., 2013). Under this scenario, maize may have been in symmetric competition with weeds before canopy closure, but growth and yield are more advantageous for maize than weeds after canopy closure (Little, et al., 2021). Maize grows taller than weeds in life form, thereby blocking the sunlight reaching weeds for growth (Rao, 2000). The first weeding has to be conducted no later than two weeks after planting maize to ensure optimum yield (Iderawumi and Friday, 2018). Maize would grow at its peak two to three weeks after planting. Understanding symmetric and asymmetric weed-crop competition for timely weed management control is imperative for maximum maize yield.

Planting density could determine maize yield. The higher the density the more yield expected (Gözübenli, 2010). The maize density was 8 plants m^{-2} in the farms surveyed in this study. In modern plant varieties, high maize yield correlates with high population density, that is, between 6 and 9 plants m^{-2} (Abuzar, et al., 2011; Amiri, Tavakkoli and Rastgoo, 2014; Greveniotis, et al., 2019). Optimal maize plant density may presumably be advantageous in competing against weeds (Amiri, Tavakkoli and Rastgoo, 2014; Wilson, et al., 1995). A higher density of weeds may not cause the loss of crop yield (MacLaren, et al., 2020).

In addition, existing maize varieties have been improved to tolerate biotic and abiotic stress conditions. Traits such as crop crowding tolerance, weed interference, and resistance to heat and drought are present in modern crop-plant varieties, allowing them to exhibit increased tolerance. These varieties also demonstrate enhanced physiological efficiency in the uptake and utilize of resources such as water and nutrients (Amiri, Tavakkoli and Rastgoo, 2014; Duvick, 2005; Tollenaar and Wu, 1999; Wilson, et al., 1995). These traits suggest that maize has more competitive life history strategies than weeds. Farmers can use information on weed abundance and crop yield to review post-emergence herbicide application, ensuring that weed controls are not counterproductive in terms of time and costs.

5.3 Growth and development of *A. viridis*

Amaranthus viridis under the treatments of NPK 12:12:17 and NPK 15:15:15 exhibited higher means in plant height, leaf and inflorescence numbers than wild populations. Weeds are highly responsive to macronutrients particularly NP, and sometimes K (Little, 2021).

5.3.1 Plant organ level traits and performance

Angiosperms are more weedy than gymnosperms, some families such as Gramineae and Amaranthaceae contain more weeds (Baker, 1974). Genera that are domesticated as crops are more likely to have weed species (Dekker, 2016), for example, a leafy vegetable known as Bayam (*Amaranthus* spp.) in Malaysia. *Amaranthus viridis* is an annual plant with C_4 photosynthesis. C_4 weeds are more competitive than C_3 weed; they are predicted to have robust growth in response to higher temperatures (Ramesh, et al., 2017). The competitiveness makes weeds with a C_4 photosynthetic pathway ubiquitous in tropical countries (Ziska and Dukes, 2011). Functional traits such as leaves, inflorescences, and plant height were studied as a response to fertilizer types and amounts as an informative approach in characterising weediness. A trait-based approach is used to study general responses of weeds and is promising in advancing sustainable weed management (Gaba, et al., 2017).

Growth and development parameters are related and integrated throughout the plant life cycle (Dambreville, et al., 2015; He, et al., 2020). Trait descriptions and measurements represent certain ecological functions. Reproductive phenology is for reproduction, while height and leaves are for growth development (Garnier and Navas, 2012). These traits change in response to resource availability and the environment. Weeds exhibit continuous growth and development until senescence (Hegazy, et al., 2005).

Growth development of a species is an indication of competitive ability. Correlated traits are considered as a single spectrum for growth development (He, et al., 2020). The response-effect framework using functional traits is promising in predicting individual plant and species' behavior for weed management (Garnier and Navas, 2012; Lavorel and Garnier, 2002). A weed traits-based approach relating to survival, growth, and reproduction functions is recommended in weed management (Garnier and Navas, 2012).

The scatterplots from Models 1, 2 and 3 showed strong positive relationships between dependent and independent variables. Independent variables under the three models statistically significantly predicted the dependent variables, respectively. The dependent variable increased as the independent variable(s) increased. Wild populations mirror the growth and development patterns of weeds studied under NPK 15:15:15 and NPK 12:12:17. Fertilizer is a main selection pressure factor on arable weeds. This is in contrast to Lavorel and Garnier's (2002) hypothesis that wild populations would be different than weeds responding to fertilizer. Both wild and arable weeds largely overlap in ecological strategies, including reproduction (Bourgeois, et al., 2019). The three models are analyzed to explore functional relationships between traits for a choice of either model selected for a better understanding and prediction of other weed species, considering data availability. The trait-based approach would overcome heterogeneity within and between weed species (Gaba, et al., 2017; Lavorel and Garnier, 2002).

Resource availability is an environmental filter (Garnier and Navas, 2012). In agriculture, fertilization has a decisive role in influencing weed diversity and weed growth, positively or negatively (Kaur, Kaur and Chauhan, 2018). Broadleaf *Amaranthus* species respond well to fertile soils by producing more seeds (Bhowmik, 1997). Plant height as an indication of organ growth for growth rate and leaf numbers (Dambreville, et al., 2015; Kunstler, et al., 2016) and indicates reproduction maturity height in herbaceous plants (Garnier and Navas, 2012). *Amaranthus* species could grow until a maximum height of 2.2 m (Martínez-Núñez, et al., 2019). *Amaranthus retroflexus* has a linear increase in height throughout the life cycle (Li, Lindquist and Yang, 2015; Little, et al., 2021), the same as *A. viridis* in this study.

Leaves function in resource acquisition, and inflorescence is for reproduction. Higher leaf number indicates a better growth rate and has high connectivity with other plant traits (He, et al., 2020). The number of inflorescences is a good indicator for plants with a seed production strategy, which can predict seed numbers (Chaney and Baucom, 2012). Each inflorescence of *A. viridis* contained an average of 347 seeds with a seed length of 1.25±0.15 mm. Negative correlation between growth rate and flower number was found in *Ipomoea purpurea* suggesting a trade-off between growth and reproduction (Chaney and Baucom, 2012).

These positive correlations indicate co-optimization for *A. viridis.* Under favourable conditions such as nutrient availability, weeds would maximise both vegetative and reproductive strategies in increasing plant fitness (Li, Lindquist and Yang, 2015; Little, et al., 2021). Inflorescences biomass is linearly correlated with vegetative biomass in *A. retroflexus* and *Chenopodium glaucum.* Weeds allocate relatively more resources to reproduction (Hegazy, et al., 2005). Model 3 was a hub trait, and Models 1 and 2 were mediator traits (He, et al., 2020). Strong correlations are considered as a single spectrum for the traits (He, et al., 2020). A hub trait (i.e., inflorescence) has a high degree of correlation with other traits and plays a central regulatory role, while a mediator trait has betweenness of two variables (Kleyer, et al., 2018).

The increment of vegetative parts such as height and leaves would promote the competitive ability of weed species (Hegazy, et al., 2005). Weed species are found to have trade-off in resource allocations to growth, reproduction and roots; this study has found that continuous resource availability (i.e., fertilizer) promotes co-optimization between traits. Weeds continue to grow and produce inflorescence until they senescence (Hegazy, et al., 2005). The response-effect framework could generate patterns reflecting functional responses, enabling species grouping at the community level, for example, scaling up from individual plants' responses to fertilizers (Lavorel and Garnier, 2002).

Weeds evolve and adapt to the farm environment on temporal and spatial scales, Research efforts could be extended to other weed species on the same farm to understand if their basic biology shares the same pattern as *A. viridis*, or the same species from different locations. With detailed information on the growth and development parameters of weed species on a farm, the revision of weed management practices could be realised. For example, the dose, timing and frequency of applying post-emergence herbicides at certain height to reduce seed numbers could be reviewed accordingly, as part of vegetation management on farms. For example, there was no correlation of herbicide rate on weed composition nor wheat yield (Gaba, et al., 2016). Biological intensification management is less straightforward, though theories are true (Gaba, et al., 2017; Little, et al., 2021).

Research efforts using this framework are suggested to involve smallholders in validation and in a joint effort with smallholders to review their herbicide and fertilzser applications. Experimental studies are suggested to have a timeframe between 4 to 6 years in the fields and need to consider farmers' pressure resulting from weeds that will be reflected in their decisions and practices (Gaba, et al., 2016). In this study, an assessment of these traits on farm would provide insight into the above-ground growth and development patterns. Growth development patterns in individual plant's behavior at trait level, as a next step for species comparative and a broader generalisation, may be a first step in systemic approach to weed controls in practice (Little, et al., 2021). A follow-up programme combining trait and response-and-effect approach is desired to demonstrate conclusively growth and development patterns (Gaba, et al., 2017; Garnier and Navas, 2012; Fryer, 1981).

Smallholders could benefit from learning simple concepts and suitable technology through continuous learning (Fryer, 1981; Terlau, Hirsch and Blanke, 2019; MacLaren, et al., 2020). Farmers' participation in research is crucial for the development of sustainable weed management (Hall, et al., 2000). Although chemical herbicides remain central as a control method, refining chemical applications to reduce herbicide use could be achieved through adjustments in dosage and application timing (Bastiaans, et al., 2000).

5.3.2 Effects of fertilizers NPK 12:12:17 and NPK 15:15:15

This study has demonstrated inherent responsiveness of *A. viridis* to NPK 12:12:17 and NPK 15:15:15. Mean values were higher for height, leaf numbers, and inflorescence numbers for 2 g under NPK 12:12:17, compared to other treatments of 1 g, 4 g and 8 g. Mean values were higher in height and leaf numbers for plants under 8 g of NPK15:15:15, but 4 g plants had a higher mean value for inflorescence numbers. Plants of 1 g, 2 g, 4 g and 8 g under NPK

15:15:15 had more leaves than their matching groups for NPK 12:12:17. The treatment group of 1 g, 2 g, 4 g and 8 g under NPK 12:12:17 had more inflorescences than its matching group under NPK 15:15:15. Plants under control groups for both NPK 12:12:17 and NPK 15:15:15 were less variable in data values compared to 1 g, 2 g, 4 g and 8 g. Control group plants also had the shortest height, lowest leaf and inflorescence numbers compared to the fertilizer treatments of 1g, 2g, 4 and 8g under NPK 12:12:17 and NPK 15:15:15, respectively.

Agricultural weeds could be more responsive towards fertility and sunny environment, thus being abundant in plant community (Bourgeois, et al., 2019; Little, et al., 2020; Lososová, Chytrý and Kühn, 2008). The theory of luxury consumption posits that plants could uptake excess nutrient amounts than the level that is required for growth (Droop, 1973). Terrestrial wild plant species tend to be luxury consumers for nutrients (de Mazancourt and Schwartz, 2012; Van Wijk, et al., 2003). This study suggests that *A. viridis* fits into the theory of luxury consumption as fertilized *A. viridis* had a better growth and development than the control plants.

Plant height under NPK 12:12:17 and NPK 15:15:15 were ranged between 33.43 cm to 43 cm. Sedge *Fimbristylis miliacea,* when applied with a basal fertilizer of urea, whole triple super phosphate (TSP), and muriate of potash (MOP), grew to a maximum height at 64.05 cm in the 10th week after seeds emerged, with an average of 134 inflorescences per plant (Begum, et al., 2008). Broadleaf *A.*

viridis continued to show height increment throughout the study period, suggesting the plant had not reached its maximum height after five months under NPK 12:12:17 and seven months for NPK 15:15:15. All plants were flowering throughout the study period which was five months for NPK 12:12:17 and seven months for NPK 15:15:15. A long flowering period until senescence is a trait for arable weeds with advantages in continuously producing seeds and expanding species distribution (Bourgeois, et al., 2019; Lososová, Chytrý and Kühn, 2008).

The standard deviation for leaves and inflorescences were large and suggesting values in the data sets are farther away from mean values. *Amaranthus* species are known to have a high degree of phenotypic plasticity (Martínez-Núñez, et al., 2019). Growth and development variations in weed populations could be large. Ratio of leaf number to seed number was found to range from 1:4.6 to 1:15.8 in itchgrass (*Rottboellia cochinchinensis*) collected from Kedah, Perlis, and Selangor in Peninsular Malaysia (Alloub, et al., 2005). Wrinklegrass (*Ischaemum rugosum*) was found with reduced fitness in seed germination in the second generation of synthetic populations than the first generation (Baki and Nabi, 2003). Morning glory (*Ipomoea purpurea*) has genetic plasticity for reproduction and not on growth rate (Chaney and Baucom, 2012). Weeds exhibit biological plasticity in any stage of the life cycle in response to selection pressure, habitat, and environmental conditions (Bajwa, et al., 2016).

There was statistical significance for the parameters of leaves and inflorescences amongst plants treated with NPK 12:12:17. Leave and inflorescence numbers had the highest average under the 2 g treatment with an average number of 524.81 leaves and 144 inflorescences. For the treatment of NPK 15:15:15, the height parameter was statistically significant, but not the number of leaves and inflorescences. Control, 1 g and 2 g were in a group of similarity, while plants under 4 g and 8 g of NPK 15:15:15 were in another group. Plants of 8 g were the tallest, with an average height of 42.19 cm.

Optimum fertilizer ratio and dosage are studied among crops and between crop varieties. It has been found that optimum yields responding to optimum fertilizer ratios and dosages, and do not necessarily respond to the highest fertilizer dosages (Géant, et al., 2020; Hariyadi, et al., 2021; Kulekci, Polat and Ozturk, 2009). This study suggests an optimum dose for *A. viridis* under NPK 12:12:17 and NPK 15:15:15 for certain growth and development parameters. Leaves and inflorescences were highest in number for 2 g under NPK 12:12:17 and 8 g under NPK 15:15:15. *Amaranthus tricolor*, for example, showed showed an optimum amount of NPK for growth, with maximum plant height at 100 kg N per ha, 25 kg P per ha and 50 kg K per ha, and the highest leaf numbers at 150 kg N per ha, 25 kg and 50 kg K per ha (Ahammed, Rahman and Karim, 2015). *Amaranthus viridis* grew tallest in height under NPK 15:15:15 compared to the other 20 treatments involving plant residues and animal manures in south-western Nigeria, while root length (cm) and leaf area (cm^2) were higher under the mixtures (Moyin-Jesu, 2009). Higher biomass was also found in *A. viridis* applied with rice bran and animal manure compared to NPK 15:15:15 and the control group (Ojo, et al., 2021).

Amaranthus species have demonstrated higher biomass responses to combined NPK fertilizers and increased nitrogen (N) rates in various studies (Alonge, et al., 2007; Ohshiro, et al., 2016; Skwaryło-Bednarz and Krzepiłko, 2013). In studies involving nitrogen and/or phosphorus, researchers such as Chakatrakan (2003) and Meyo (2004) reported that parameters like plant height, leaf numbers, grain yield and fresh weight increased with higher N and P levels. However, this response may not always be consistent. *Amaranthus viridis* was found to have higher dry matter weight when treated with poultry manure and under the control group, compared to plants treated with NPK 15:15:15 in south-western Nigeria (Adeoluwa, 2014).

Studies investigating the effects of organic and NPK 15:15:15 fertilizers on various *Amaranthus* species are prevalent in Africa, especially Nigeria where the genus is an important source of leafy vegetables and grains (Abayomi and Adebayo, 2014; Alonge, et al., 2007; Sanni, 2016). Findings from these studies often indicate better growth and yield of *Amaranthus* species with organic fertilizer compared to NPK 15:15:15. It is worth noting that this study is distinct from others on *Amaranthus* species, as it focuses on plants germinated from seeds for agricultural production rather than wild plants studied as weeds.

Various factors, including weed ecotype, fertilizer type and amount, as well as environmental conditions, play a crucial role in affecting the growth and development of weeds (Bhowik, 1997; Bourgeois, et al., 2019). The species characteristics of *A. viridis* have shown a relative responsiveness to the ratio of N, P and K. In China, broadleaf *Stellaria media* exhibited taller height in the control group than in the NPK treatment, while grass *Beckmannia syzgachne* was taller in height under NPK treatment than control plants (Yuan, et al., 2016). Knowledge derived from weed biology is valuable for reviewing weed management strategies towards sustainable agriculture by regulating rather than eradicating (MacLaren, et al., 2020). This study has demonstrated that the application of NPK 15:15:15 has a greater impact on height, while NPK 12:12:17 affects leaves and inflorescences. Higher nitrogen and phosphorus levels promote the growth of plant height, root diameter and its length (Razaq, et al., 2017; Wang, et al., 2020) which resulted *A. viridis* had better growth under NPK 15:15:15 compared to NPK 12:12:17. The choice of fertilizer sources can significantly influence weed growth and development (Liebman and Mohler, 2001).

Fertilizer management, encompassing factors such as type, placement, and dosage, can be considered a method in ecological weed management (MacLaren, et al., 2020; Mahajan and Timsina, 2011). Intense and short-term crop cycles, combined with tillage practices and fertilizer applications, may expedite weediness traits such as faster growth and reproductive strategies (Garnier and Navas, 2012; MacLaren, et al., 2020). Fertilizer management practices should be designed to favour crop growth and outcompete weeds (MacLaren, et al., 2020). For instance, redroot pigweed *Amaranthus retroflexus* competes more effectively against maize with a high level of NO_3-N, but its growth is restricted when N is in the form of NH_4^+ (Teyker, Hoelzer and Liebl, 1991). Nutrient addition may drastically boost weed growth without increasing grain yield when the optimum level has been reached (Mahajan and Timsina, 2011). Determining the responses of both weeds and crops to fertilizers for effective real-world weed management.

Fertilizer acts as a selection pressure in functional responses for both weeds and crops, where both plant groups exhibit similar responses to fertilizer applications (Lavorel and Garnier, 2002). The resource pool diversity hypothesis suggests that nutrient acquisition competitions may intensify between crops and weeds due to the sudden surge of NPK availability after fertilization (Smith, Mortensen and Ryan, 2010). Higher fertilizer dosages may not increase yield when the field also has high weed density (Begum, 2006). Weeds have evolved and adapted to high fertility conditions (Little et al., 2021). Weediness traits include leaves indicating resource acquisition rate; while flowers/inflorescences and height indicate site colonization ability (Fried, et al., 2020). Plant responses reflect the strength of selection pressure; but information in this area remains limited (Lavorel and Garnier, 2002; Mahajan and Chauhan, 2020). Species-level responses to fertilizer through direct testing should be an active research concern for validating hypotheses (Little, et al., 2020; Smith, Mortensen and Ryan, 2010; Ward, et al., 2014).

More studies on weed growth and development, involving functional traits, are necessary to validate the accuracy of crop protection models (Bastiaans, et al., 2000; Dambreville, et al., 2015; Westoby, 1998). Weed species exhibit differential growth behaviors when growing alone, with other species, either crops or weeds, or both (Pakeman, et al., 2015). Weeds respond to various crops cultivars, farm practices, weed species and their densities. Any of these factors can act as selection pressures for an individual weed and weed populations. Genetic and phenotypic diversity are found in weed species, allowing them to adapt and survive in response to cropping systems and practices, making weeds heterogenous in behavior (Dekker, 1997; Gaba, et al., 2017). Studies focusing on a single weed species may have advantages without confounding effects of intraspecific and interspecific competition (Little et al., 2021).

5.4 Limitations of this study

5.4.1 Rural farmers' weed management learning

Farming is the main economic activity in Malim Nawar. Farmers in this area are registered with the Malim Nawar Vegetable Farmers Association (official name in Malay: *Persatuan Pekebun Sayur Malim Nawar*), which was established on November 23, 1992.

The mandates of the Association are as follows:

- To strengthen networking among farmers,
- To share information and exchange experiences on agricultural practices,
- To contribute to Malaysia's agricultural development, and
- To safeguard the Association's members' benefits.

The number of registered members in Malim Nawar has increased over the years However, the membership list has not been updated with deceased members and members who have left farming still included. This presents the first challenge - updating the member list. Moreover, there are no specific guidelines for obtaining membership in this association. For example, entrepreneurs in aquaculture and oil palm growers were both accepted, leading to a continuous influx of new members. Currently, there are 218 members. Furthermore, out of these 218 members, 123 (56.4%) have registered with the Malim Nawar Vegetable Farmers Association without contact details. The actual number of active members remains unknown, potentially causing bias in sample selection. In the present study, some limitations were related to respondents' literacy levels. Some farmers did not comprehend the questions even after receiving an explanation or were unfamiliar with certain answers, such as the scientific names of weed species. Respondents faced challenges in providing accurate answers in the survey questionnaire (Fowler, 2014).

5.4.2 Weed composition and maize yield

One limitation of this study is that only one planting density and one maize variety were investigated. These factors, density and variety, could affect maize competition with weeds. Optimum plant density and maximum crop yield are correlated (Abookheili and Mobasser, 2021; Deng, et al., 2012). Other factors such as weed composition and crop variety may also play a role in affecting crop yield. As an example of weed composition and crop yield, Esposito et al. (2023) suggested two theories. First theory is increasing weed biodiversity will discourage the establishment of dominant weeds that may become problematic weeds to control. Second theory is managing problematic weeds at the density threshold level where maximum density of problematic weeds is set. From an empirical study, three cultivars of maize were tested (Zhang, et al., 2021). It was found that the planting density and cultivar of maize influenced crop yield through the characteristics of crop canopy structure and resource use efficiency (i.e., photosynthetic rate).

5.4.3 Weed biology at organ- and individual-level under NPK 12:12:17, NPK 15:15:15 and wild population

The effects of NPK 12:12:17 and NPK 15:15:15 nutrient additions at 1 g, 2 g, 4 g and 8 g on *A. viridis* may limit understanding on the intraspecific interactions. The response mechanism in the context of interspecific variations for weed species and between weeds and crops was also not incorporated in the study. Results from controlled environments (i.e., shade house) need to be followed up with field experiments for practical weed management strategies (Van Acker, 2009). The interactions of functional traits in plant growth and development may need to be studied under the ecology and evolutionary frameworks for an improved understanding of weed responses (Lavorel and Garnier, 2002).

5.5 Recommendations for future research

5.5.1 Decision-making on weed management

The challenge of weed management is indeed complex, involving intricate decision-making processes for farmers. Current practices often rely on trial and error, shaped by individual experiences. There is a recognized lack of a systematic decision-making framework that can effectively integrate the complexity of weed management to advance existing farming practices. The complexity arises from the multifaced knowledge required across a wide spatial-temporal scale. Crops and weeds can exhibit diverse ecological relationships, including negative, neutral and positive interactions, and their responses to various biotic and abiotic factors further contribute to the intricacy of the problem. Understanding the dynamics of these interactions on farms poses a significant challenge to weed science studies, necessitating an interdisciplinary approach. To address these challenges, there is a need for a holistic decision-making mechanism that is based on scientific knowledge but also support the development of more effective and sustainable weed management strategies.

5.5.2 Weed composition over temporal-spatial scales

Agricultural intensification and expansion are expected to continue as crucial strategies to meet the growing needs of the world's population for both food and non-food products. To gain a comprehensive understanding of the evolving weed communities in terms of species composition and population sizes, long term monitoring is deemed essential. The environment on farms undergoes continuous changes at both temporal and spatial scales, driven by evolving agronomic practices. Regular weed inventory, through data collection, can help identify problematic weeds in a timely manner, contributing to the enhancement of existing weed management strategies. It is recommended to conduct weed surveys that include hypotheses testing to explore associations between weeds and factors such as fertilizer, weather patterns, soil types, crop species, and crop varieties. Additionally, with global warming expected to influence the distribution of agricultural weeds, monitoring becomes even more crucial in adapting to changing environmental conditions (Patterson, 1995).

5.5.3 Weed ecology and biology

There are significant knowledge gaps in weed biology that remain to be addressed, despite the recognition by weed scientists in shifting the paradigm from the chemical control to more environmentally friendly methods. The emergence of herbicide-resistant weeds in the 1970s prompted a reevaluation of weed management strategies. However, progress in weed biology research has been slow over the past five decades, hindering the transformation of weed management practices from herbicide reliance to more sustainable methods. The growth behaviors of weeds in natural environments, on farms, and under experimental settings are still not fully understood.

The discipline of weed science initially focused on developing control methods, particularly herbicides, rather than studying weed biology and ecology (Iderawumi and Friday, 2018). There is a pressing need for more comprehensive studies on weed species belonging to different groups such as grasses, sedges and broadleaf plants under controlled environments. Weediness traits exhibit a wide spectrum of variation that requires a better understanding. Further research is essential to comprehend the effects of nutrients on weed growth and development in field situations with mixed weed species and weed-crop interactions. This knowledge, when tested on farms, can be translated into practical applications (i.e., know-how) through the refinement of predictive modelling, contributing to the realization of sustainable agriculture goals.

Several regional and national databases focusing on spatial-temporal scales for weed community assemblage and plant traits have been established in Western countries. These datasets contribute valuable information for understanding weed ecology and dynamics. Here are seven notable datasets: i.) Czech Republic's 381 weed species data (Lososová, Chytrý and Kühn, 2008); ii.) France's Biovigilance Flore Network contains 332 weed species sampled from 1,440 field plots in Western France over nine years (Munoz, et al., 2020); iii.) France's Plant Functional Diversity of Grasslands (DIVGRASS) contains information on 5,245 weed species (Munoz, et al., 2020); iv.) France's 25-year Long Term Social-Ecological Research Site Zone Atelier Plaine & Val de Sèvre (LTSER ZA-PVS), a collaboration between scientists and farmers started in 2006, contains 399 weed species (Munoz, et al., 2020); v.) Weed community structure in France maize fields in the 1970s and 2000s (Fried, et al., 2019); vi.) Northwest Europe's dataset includes information on 126 plant species from 381 fields (Kleyer, et al., 2018); and vii.) United States of America's Synthesis of the North American Flora consisting of data on 19,960 plant species (Sutherland, 2004).

These datasets provide valuable insights into the intrapopulation and interpopulation variability of weeds in Europe, showcasing efforts to advance weed biology knowledge. However, it is noted that such initiatives are currently lacking in developing countries, including Malaysia. There are practical limitations in quantifying weeds' adaptations in these regions, and weed studies in these areas tend to focus more on taxonomy without providing sufficient biological information (Wee, Rao and Khoo, 2013). To enhance the utility of weed databases, there is a potential for improvement by incorporating additional information related to agronomic practices, such as herbicide application and fertilizer use. This expansion could offer a more comprehensive understanding of the interactions between weed populations and agricultural management strategies. Furthermore, there is a call for greater knowledge underpinning in functional ecology, evolutionary ecology, population ecology, and community ecology. Applying these ecological principles contribute to the development of more sustainable weed management practices, addressing the specific challenges faced by agriculture in different regions.

5.5.4 Climate change and weeds

Climate change has become a widely discussed global issue, marked by rising carbon dioxide levels, increasing temperatures, and variations in other climate variables such as rainfall. The implications on agriculture, particularly with regard to food security, are a major concern. Weed management is a critical aspect of this concern, as weeds may exhibit more adaptive responses to climate change compared to crops (Varanasi, Vara Prasad and Jugulam, 2016; Ziska and Dukes, 2011). However, the specific impacts of these changes remain unknown and unclear (Ramesh, et al., 2017). Weeds possess genetic and phenotypic plasticity, enabling them to adapt and exhibit differential responses based on factors such as the C_3 and C_4 photosynthetic pathways, as well as the weed categories including grasses, sedges and broadleaf plants.

To refine weed control strategies, it is imperative to study broad scenarios of interactions between weeds and crops, gaining a better understanding of the knowledge generated. Predicting weed occurrence and distribution in response to different levels of climate variables is crucial (Adhikari, et al., 2020). Without such information, economic losses could be substantial. For example, changing climate conditions might stress crops, rendering them more vulnerable in competition against weeds (Ramesh, et al., 2017).

CHAPTER 6

CONCLUSIONS

Weed science is an applied science. The discipline should be able to provide practical solutions to smallholders' needs, as well as achieve sustainable agriculture. A multi-disciplinary approach involving the farmer community, weed composition, and weed biology would be a more promising strategy towards sustainable weed management. The survey showed an association between farmer's knowledge of weed species and perceived economic losses caused by weeds ($\chi^2(4) = 16.40$, $p = 0.037$). The farmers opined that knowledge of weed species on farms was important, as it helped them select suitable herbicides (e.g., selective or broad-spectrum) for weed control. The survey demonstrated correlations between farmers' resistance to learning about non-chemical control methods ($\chi^2(3) = 9.01$, $p = 0.029$). Information on weed management practices was obtained from formal and informal sources. The formal sources included the Association, government agencies, workshops, civil society, and agrochemical companies, whereas the informal sources were friends of the participating farmers. Both agrochemical companies (64.5%) and informal sources (64.5%) were equally important sources of information on weed control practices. Workshops and seminars were not popular options for obtaining information on weed management practices. Two general trends have been observed regarding the development of rural agriculture; these are lack of technical knowledge among farmers and the lack of educational programmes by relevant government agencies. Weed management is a continuous process in agricultural production, and accessibility to knowledge sources can strengthen farmers' expertise and experience.

Weed survey is a critical component in weed management. Weeds are considered to cause yield loss. However, this needs to be tested by going one step further of weed composition. The link between weed composition and yield data is necessary in understanding the possible impacts of weeds on yield and thereafter to review the predominantly chemical weed control method. Fifteen weed species belonging to 14 genera and 9 families were identified in 2017, 2018, and 2020. This study recorded 55.57 weeds m^{-2}, which is considered a high weed density. In contrast, the effects of the association of mean temperature, average mean temperature, and weed species on maize yield were not statistically significant. Maize have closed canopy by growing taller than weeds, and have thus shaded weeds, giving growth advantageous to maize in weed-crop competition. The optimal planting density and modern varieties of maize are significant factors contributing to high maize yield; furthermore, they confer a significant advantage to crop plants in the weed–crop plant competition.

Relationships between functional traits (i.e., height, leaves and inflorescences) were studied for a better understanding of trait correlations and prediction on other weed species, to overcome genotypic heterogeneity within and between weed species. All three models for *A. viridis* under NPK 12:12:17, NPK 15:15:15 and the wild population, in which i.) model 1 where dependent variable was leaves and independent variable was height; ii.) model 2 had inflorescence as dependent variable and leaves as independent variable; iii.) model 3 was inflorescence as dependent variable and leaves and height were independent variables, had high correlation using Pearson correlation coefficient. The correlation relationships were statistically significant at $p < 0.001$.

Control group plants had the shortest height, lowest leaves, and inflorescence numbers compared to the fertilizer treatments of 1g, 2g, 4 and 8g under NPK 12:12:17 and NPK 15:15:15, respectively, suggesting luxury consumption by weeds. There was statistical significance for the parameters of leaves and inflorescences amongst plants treated with NPK 12:12:17. For the treatment of NPK 15:15:15, the height parameter was statistically significant but not the number of leaves and inflorescences. This study also suggested the optimum dose for *A. viridis* under NPK 12:12:17 and NPK 15:15:15 for certain growth and development parameters. Weed biology research is an indispensable component in sustainable weed management.

Results from this study have revealed that components of sustainable weed management should include rural farmers' learning on weed management, weed composition and yield, and plant functional traits with roles in:

- Providing insights into weed management practices among smallholders, and challenges that demand attention and efforts towards improvement for existing weed control, which is predominantly chemical herbicides;

- Monitoring weed composition and crop yield for informed decisions on weed management among rural farmers; and
- Improving the prediction of weediness characteristics through knowledge of weed growth and development, plant functional traits, and weed responses to fertilizers.

Each or combined component could be used to reassess, deliberate and design weed management by complementing and leveraging chemical control for smallholders through examining the use of herbicides and fertilizers to deliver sustainable agriculture and food security goals (Figure 6.1). A multidisciplinary approach is recommendable for practical weed management.

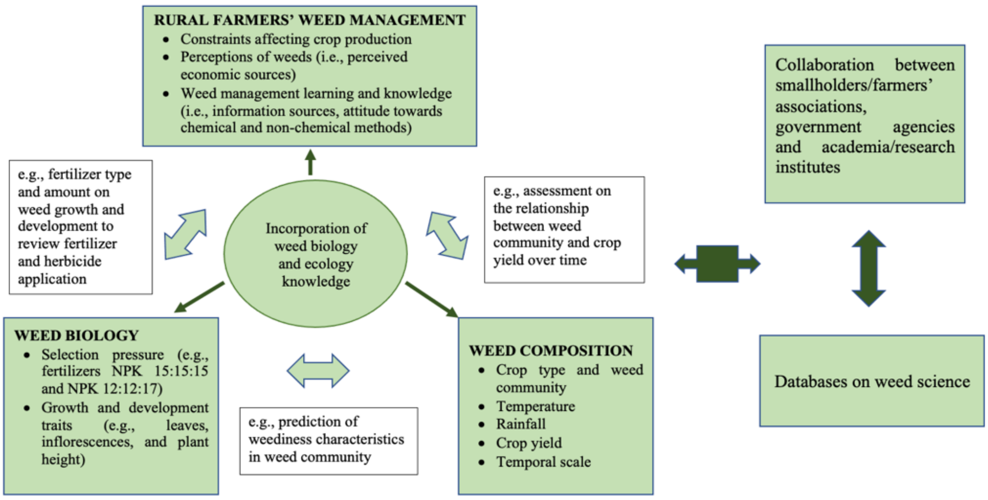


Figure 6.1.: Conceptual framework on sustainable weed management for smallholders. (Source: this study)

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Appendix A. Tong, P.S. and Lim, T.M., 2022. Weed composition and maize yield in a former tin-mining area: a case study in Malim Nawar, Malaysia. *Open Agriculture, 7,* pp.478-485. https://doi.org/10.1515/opag-2022-0117

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Research Article

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Weed composition and maize yield in a former tin-mining area: A case study in Malim Nawar, Malaysia

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Abstract: Weed species composition has been assessed for major crops such as rice, rubber, and oil palm but not for cash crops in Malaysia. In this study, we determine the associations between maize yields and weed species, weed density, mean temperature, and mean rainfall. Annual field surveys of weeds were conducted in maize (*Zea mays* L.) in a former tin-mining land in Malim Nawar, Perak, Malaysia, during June of 2017, 2018, and 2020 to determine the effects of weeds on maize yields. The field surveys in 2017, 2018, and 2020 involved 120 quadrats (0.5 m × 0.5 m) with 40 replicates. Fifteen species were observed, representing 14 genera and 9 families and consisted of 9 broadleaves, 3 grasses, and 1 sedge. Phytosociological characteristics, namely, frequency, relative frequency, density, relative density, abundance, and relative abundance, were used to analyze weed species composition at the study site. The species with the highest mean density and relative abundance were *Cyperus* sp., followed by *Amaranthus viridis*, *Eleusine indica*, *Hedyotis corymbosa*, and *Phyllanthus amarus*. These five species accounted for 65% of the total relative abundance. Individual broadleaf, sedge, and grass weed types were compared between paired years using a two-proportion *z*-test. The variation in number of individuals in each group was significant between 2017 and 2018, 2018 and 2020, and 2017 and 2020. The relationship between maize yield and mean rainfall, mean temperature, and weed species was analyzed using a general linear model, none of which affected maize yields. The results of this study provide a foundation for practical weed management in maize fields in Malaysia, thereby contributing to sustainable agriculture and food security.

Keywords: maize, weeds, competition, growth, yield, phytosociology

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1 Introduction

Maize (*Zea mays* L.) is a cash crop that takes 60–70 days from sowing to harvest in lowland Malaysia. Maize, wheat, and rice are the three most important cereal staple foods globally [1]. From 1994 to 2018, corn was the sixth most globally produced crop with an average production of one giga ton per year [2]. Maize production in Southeast Asia has increased steadily, owing to the increasing demand for both food and livestock feed. In Malaysia, the total planted vegetables and cash crop areas in 2018 was 77,828 ha, with maize occupying the largest area (10,361.6 ha). Perak is the highest maize production state [3], and the Malim Nawar subdistrict is one of the main planting areas in Perak, consisting of small holders. Small rural farms have been an essential part of food security systems in terms of production [4]. Weeds are the main constraint hindering plant yields and result in varying yield losses depending on the crop type [5].

Weed surveys have become a prerequisite for pest management programs because of the emerging issues related to herbicide resistance. Weed inventories are conducted at all levels (from local to regional, to national) to determine the presence and abundance of weed species for weed management. The standard duration period in weed surveys is 3 years, whereas the interval between assessments varies from 17 to 47 years in Europe [6]. Weed density has been identified as a key element that affects maize yields [7,8]. Low to medium weed densities can result in crop yields that are equivalent to those achieved under weed-free conditions, whereas high-density weed infestations reduce maize yields by 12–15%.

Appendix B. Tong, P.S., Lim, T.M. and Wu, M.C., 2022. Rural farmers' learning of weed management methods in Malaysia. *Future of Food: Journal of Food, Agriculture and Society, 10(4)*. DOI : 10.17170/kobra-202204136013

Research Paper

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Rural farmers' learning of weed management methods in Malaysia

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Sustainable agriculture; Weed Management; agricultural education; government agencies; smallholders

Malim Nawar in Kampar District, Malaysia, is a potential major production site for modern high-technology farms by 2030. To achieve this, a significant increase in intensive agricultural activities and weed management practices is required. To develop strategies and achieve the goals of sustainable agriculture, the present study used a semi-structured questionnaire survey to assess farmers' knowledge and perception of weeds, their sources of information, and their reasons for willingness or unwillingness to adopt non-chemical weed control methods. The survey was conducted from June to October 2018 and included 62 members of the Malim Nawar Vegetable Farmers Association. Descriptive and chi-square statistics were used for the statistical analyses. Of the 62 participants, 50 (80.6%) were over 50 years of age, and 47 (75.7%) spoke the Hakka dialect. Pest infestation and crop diseases were the most important constraints in crop production, followed by weed infestation. Knowledge of weed species led to the anticipation of yield loss and exploration of potential control methods. Social networking and agriculture chemical companies were the main sources of information on weed control methods. Despite knowing the harmful effects of chemical herbicides, farmers' willingness/resistance to adopt non-chemical weed control methods depended on many different factors. The survey results showed that the proactiveness of farmers' associations and relevant government agencies is a prerequisite for achieving agricultural development through education. Moreover, structure and systematic learning using innovative methods adjusted to local socioeconomic conditions could facilitate a paradigm shift from chemical control to environment-friendly weed control methods.

1. Introduction

Agriculture is the backbone of the industrial sector in many countries. In 2019, the contribution of agriculture to the GDP of Malaysia was 7.1%. Despite its small contribution to the economy, it is recognised as one of the most important sectors that provide food and employment to the rural inhabitants of Malaysia. In general, rural farming is a prominent feature of developing countries. For farmers, weeds can hinder crop yield as they compete with the crop for light, water, and nutrients, resulting in varying extents of yield loss depending on crop type (Gharde, Singh, Dubey, & Gupta, 2018). Therefore, weed management is critical for ensuring food security and environmental sustainability (Yaduraju & Rao, 2013).

Farmers have been learning weed control methods on a trial-and-error basis in Malaysia; however, their limited knowledge of weed control hinders the improve-

Appendix C. Weed species published under the series of "The biology of Canadian weeds" and "The biology of Australian weeds" as of 2016

No.	Family	Species	Number of species
1	Alismataceae	1. *Sagittaria platyphylla**; 2. *Limnocharis flava**	2
2	Asclepiadaceae	1. *Asclepias syriaca^*	1
3	Amaranthaceae	*1.Alternanthera philoxeroides**; 2. *Amaranthus albus*^; 3. *A., blitoides*^; 4. *A. blitum*^; 5. *A. hybridus*^; 6. *A. powellii*^; 7. *A. retroflexus*^; 8. *Atriplex patula*^; 9. *A. porstrata*^; 10. *A. rosea*^; 11. *Chenopodium album*^; 12. *Kochia scoparia*^; 13. *Salsola australis**; 14. *S. pestifer*^; 15. *S. tragus*^; 16. *Sclerolaena birchii**	16
4	Anacardiaceae	1. *Rhus radicans*^;	1
5	Apiaceae	1. *Anthriscus sylvestris*^; 2. *Cicuta douglasii*^; 3. *C. maculate*^; 4. *C. virosa*^; 5. *Daucus carota*^; 6. *Pastinaca sativa*^;	6
6	Apocynaceae	1. *Apocynum cannabinum*^; 2. *Cryptostegia grandiflora**	2
7	Asparagaceae	1. *Asparagus asparagoides**	1
8	Asteraceae	1. *Achillea millefolium*^; 2. *Acroptilon repens*^; 3. *Ambrosia artemisiifolia*^; 4. *A. psilostachya*^; 5. *A. trifida*^; 6. *Articum lappa*^; 7. *A. minus*^; 8. *Artemisia absinthium*^; 9. *A. biennis*^; 10. *A. vulgaris*^; 11. *Baccharis halimifolia**; 12. *Carduus acanthoides*^; 13. *C. nutans*^; 14. *Carduus nutans* spp. *nutans*; 15. Cartamus lanatus**; 16. *Cassinia arcuata*;* 17. *Centaurea diffusa*^; 18. *C. maculosa*^; 19. *Chondrilla juncea**; 20. *Chrysanthemoides monilifera**; 21. *Cirsium arvense*^; 22. *Conyza bonariensis**; 23. *C. canadensis*^; 24. *Crepis tectorum*^; 25. *Erechtites hieraciifolius*^; 26. *Galinsoga parviflora*^; 27. *G. quadriradiata*^; 28. *Helianthis tuberosus*^; 29. *Hypochaeris radicata*^*; 30. *Iva axillaris*^; 31. *Lactuca serriola*^; 32. *Lapsana communis*^; 33. *Leucanthemum vulgare*^; 34. *Onopordum acanthium*^; 35. *Parthenium hysterophorus*;* 36. *Senecio jacobaea*^; 37. *S. madagrarscariensis*;* 38. *S. vulgaris*^; 39. *Solidago canadensis*^; 40. *S. nemoralis*^; 41. *Sonchus arvensis*^; 42. *S. asper*^; 43. *S. oleraceus*^; 44. *Symphyotrichum ericoide*^; 45. *S. lanceolatum*^; 46. *S. lateriflorum*^; 47. *S. novae-*	55

		angliae^; 48. *S. pilosum*^; 49. *Taraxacum officale*^; 50. *Tragopogan dubius*^; 51. *T. porrifolius*^; 52. *T. pratensis*^; 53. *Xanthium occidentale**; 54. *X. spinosum**; 55. *X. strumarium*^;	
9	Bignoniaceae	1. *Macfadyena unguis-cati**	1
10	Boraginaceae	1. *Cynoglossum officinale*^; 2. *Echium plantagineum**; 3. *E. vulgare*^; 4. *Heliotropium europaeum**; 5. *Lappula squarrosa*^	5
11	Brassicaceae	1. *Alliaria petiolata*^; 2. *Barbarea vulgaris*^; 3. *Brassica napus*^; 4. *B. rapa*^; 5. *Camelina alyssum*^; 6. *C. microcarpa*^; 7. *C. sativa*^; 8. *Cardaria draba*^; 9. *C. pubescens*^; 10. *Descurainia sophia*^; 11. *Erucastrum gallicum*^; 12. *Hesperis matronalis*^; 13. *Lepidium chalepense*^; 14. *Neslia paniculata*^; 15. *Raphanus cathartica*^; 16. *R. raphanistrum*^*; 17. *Sinapsis arvensis*^; 18. *Thlaspi arvense*^	18
12	Cabombaceae	1. *Cabomba caroliniana**	1
13	Cactaceae	1. *Cylindropuntia rosea**; 2. *C. tunicate**	2
14	Caprifoliaceae	1. *Diasacus sylvestris*^; 2. *Lonicera japonica*^*	2
15	Caryophyllaceae	1. *Gypsophila paniculata*^; 2. *Silene alba*^; 3. *S. latifolia*^; 4. *Stellaria media*^;	4
16	Commelinaceae	1. *Tradescantia fluminensis**	1
17	Compositae	1. *Matricaria perforate*^	1
18	Convolvulaceae	1. *Convolvulus arvensis*^; 2. *Cuscuta campestris*^; 3. *C. epilinum*^; 4. *C. epithymum*^; 5. *C. gronovii*^; 6. *C. umbrosa*^; 7. *Polymeria longifolia**	7
19	Cornaceae	1. *Cornus canadensis*^	1
20	Crassulaceae	1. *Bryphyllum* spp.*	1
21	Cyperaceae	1. *Cyperus esculentus*^	1
22	Dennstaedtiaceae	1. *Dennstaedtia punctilobula*^; 2. *Pteridium aquilinum*^	2
23	Equisetaceae	1. *Equisetum arvense*^	1
24	Ericaceae	1. *Gaultheria shallon*^; 2. *Kalmia angustifolia*^; 3. *Rhododendron groenlandicum*^	3
25	Euphorbiaceae	1. *Euphorbia cyparissias*^; 2. *E. esula*^; 3. *Jatropha gossypiifolia**	3

26	Fabaceae	1. *Acacia nilotica* spp. *indica**; 2. *Cytisus scoparius*^; 3. *Cytisus scoparius* ssp. *scoparius**; 4. *Leucaena leucocephala*;* 5. *Lotus corniculatus*^; 6. *Medicago lupulina*^; 7. *Melilotus alba*^; 8. *M. officinalis*^; 9. *Mimosa pigra**; 10. *Parkinsonia aculeata**; 11. *Prosopis* spp.*; 12. *Trifolium repens*^; 13. *Ulex europaeus*^*; 14. *Vicia angustifolia*^; 15. *V. cracca*^; 16. *V. sativa*^; 17. *V. tetrasperma*^; 18. *V. villosa*^	18
27	Geraniaceae	1. *Erodium cicutarium*^	1
28	Haloragaceae	1. *Myriophyllum spicatum*^	1
29	Hydrocharitaceae	1. *Elodea canadensis*^; 2. *Hydrilla verticillata**; 3. *Hydrocharis morsus-ranae*^; 4. *Vallisneria americana*^	4
30	Hyperiaceae	1. *Hypericum perforatum*^*	1
31	Lamiaceae	1. *Galeopsis tetrahit*^; 2. *Stachys palustris*^	2
32	Lythraceae	1. *Lythrum salicaria*^	1
33	Malvaceae	1. *Abutilon theophrasti*^; 2. *Malva parviflora**; 3. *M. pusilla*^	3
34	Melanthiaceae	1. *Veratrum viride*^	1
35	Melastomataceae	1. *Clidemia hirta**	1
36	Myricaceae	1. *Comptonia peregrina*^; 2. *Myrica pensylvanica*^	2
37	Oleaceae	1. *Ligustrum lucidum**; 2. *L. sinense**	2
38	Onagraceae	1. *Epilobium angustifolium*^; 2. *Oenothera biennis*^	2
39	Oxalidaceae	1. *Oxalis corniculata*^; 2. *O. dilenii* spp. *dilenii*^; 3. *O. dilenii* spp. *filipes*^; 4. *O. pes-caprae**; 5. *O. stricta*^	5
40	Pittosporaceae	1. *Pittosporum undulatum**	1
41	Plantaginaceae	1. *Plantago lancelolata*^; 2. *P. major*^; 3. *P. rugelii*^	3
42	Poaceae	1. *Agropyron repens*^; 2. *Apera spica-venti*^; 3. *Avena fatua*^; 4. *Bromus diandrus**; 5. *B. inermis*^; 6. *B. rigidus*;* 7. *B. tectorum*^; 8. *Danthonia spicata*^; 9. *Echinochloa crus-galli*^; 10. *Holcus lanatus*^; 11. *Hordeum jubatum*^; 12. *Hymenachne amplexicaulis**; 13. *Hyparrhenia hirta*;* 14. *Muhlenbergia frondosa*^; 15. *Nasella trichotoma*;* 16.	27

		Panicum capillare^; 17. *P. milliaceum*^; 18. *Phragmites australis*^*; 19. *Poa annua*^; 20. *Setaria faberi*^; 21. *S. pumila*^; 22. *S. verticillata*^; 23. *S. viridis*^; 24. *Sorghum halepense*^; 25. *Thinopyrum junceiforme**; 26. *Vulpia bromoides**; 27. *V. myuros**	
43	Polygalaceae	1. *Polygala myrtifolia**	1
44	Polygonaceae	1. *Emex australis**; 2. *Fagopyrum tataricum*^; 3. *Polygonum aviculare*^; 4. *P. convolvulus*^; 5. *Rumex acetosella*^	5
45	Ponteriaceae	1. *Eichhornia crassipes**	1
46	Portulacaceae	1. *Portulaca oleracea*^	1
47	Potamogetonaceae	1. *Potamogeton crispus*^	1
48	Ranunculaceae	1. *Ranunculus repens*^	1
49	Resedaceae	1. *Reseda lutea**	1
50	Rhamnaceae	1. *Ziziphus mauritiana**	1
51	Rosaceae	1. *Cataegus crus-galli*^; 2. *Potentilla anserine*^; 3. *P. argentea*^; 4. *P. norvegica*^; 5. *P. recta*^; 6. *Prunus serotine*^; 7. *P. virginiana*^; 8. *Pyrus melanocarpa*^; 9. *Rubus fruticosus*^*; 10. *R. hispidus*^; 11. *R. parviflorus*^; 12. *R. spectabilis*^; 13. *R. strigosus*^; 14. *Spiraea latifolia*^	14
52	Rubiaceae	1. *Galium aparine*^; 2. *G. mollugo*^; 3. *G. spurium*^;	3
53	Salviniaceae	1. *Salvinia molesta**	1
54	Solanaceae	1. *Datura stramonium*^; 2. *Eremophila mitchellii**; 3. *Solanum carolinense*^; 4. *S. elaeagnifolium**; 5. *S. nigrum*^; 6. *S. ptycanthum*^; 7. *S. rostratum*^; 8. *S. sarrochoides*^	8
55	Scrophulariaceae	1. *Linaria dalmatica*^; 2. *L. vulgaris*^; 3. *Verbascum blattaria*^; 4. *V. thapsus*^;	4
56	Typhaceae	1. *Typha* x *glauca*^; 2. *Typha angustifolia*^; 3. *T. domingensis**; 4. *T. orientalis**; 5. *T. latifolia*^	5
57	Urticaceae	1. *Urtica dioica*^	1
58	Verbenaceae	1. *Lantana camara**; 2. *L. montevidensis**	2
59	Violaceae	1. *Viola arvensis*^	1

60	Zygophyllaceae	1. *Tribulus terrestris**	1
		Total	265

Note:
^ Species studies under the series of "The biology of Canadian weeds"
* Species studied under the series of "The biology of Australian weeds"

Appendix D. Survey questionnaire designed for this study

Survey on farmer attitude toward weeds, weed management practices
and knowledge on weed control in Malim Nawar

The questionnaire will be conducted with farmers who are registered with Persatuan Pekebun Sayur Malim Nawar. The main focus is weeds and its associated variables such as attitude, practices and knowledge.

All information will be kept strictly confidential and for academic purpose only. Your active participation is highly appreciated and valuable in contributing to the understanding of farmer community and weeds.

Section A: Respondents' information

1. Age
   □ 20-30 □ 31-40 □ 41-50 □ 51-60. □ 61-70. □ >70

2. Gender
   □ Female □ Male

3. Dialect
   □ Hakka □ Cantonese □ Hokkien

   □ Others: ________________________

4. Level of education
   □ No formal education □ Primary school

   □ Secondary school (SRP/PMR) □ Secondary school

   (SPM/SPMV)

   □ Diploma □ Degree □ Others:

   ____

5. Farming experience (in years)

☐ 1-5 ☐ 6-10 ☐ 11-15 ☐ 16-20 ☐ 21-25

☐ >25

6. Were your parent(s) farmer?

☐ Yes ☐ No

If yes, were your grandparent(s) farmer?

☐ Yes ☐ No

7. Is your relative(s) involved in farming?

☐ Yes ☐ No

8. Is your spouse involved on the farm?

☐ Yes ☐ No

If yes, please indicate the capacity involved:

☐ Supervisor ☐ Field workers ☐ Marketing

☐ Others:

____

9. Are your children involved on the farm?

☐ Yes ☐ No

If yes, please indicate the capacity involved:

☐ Supervisor ☐ Field workers ☐ Marketing

☐ Others:

____

10. Main crops planted on the ranking order of:
i. ______________________________
ii. ______________________________
iii. ______________________________
iv. ______________________________
v. ______________________________

11. Do you practice crop rotational system on the farm?
□ Yes, proceed to question 12

□ No, proceed to question 13

12. The reason(s) is:
□ Soil fertility □ Pest control □ Weed control
□ Others:
____

13. The reason(s) is:
□ Small farm size
□ Others:
____

Section B: Attitude toward weeds

14. Perceived economic losses in yield caused by weeds.
□ Very high □ High □ Neutral □ Low
□ Very low

15. Perceived constraints on crop production (can choose more than one).
□ Weeds □ Soil fertility □ Weather □ Farm inputs
□ Pest and diseases □ Labour shortage

16. Do you think knowing weed species is important?
□ Yes, proceed to question 16

□ No, proceed to question 17

17. The reason(s) is:
☐ Knowing weed species could lead to other methods than the chemical control
☐ Others:
____

18. The reason(s) is:
☐ Chemical herbicides could be applied without knowing weed species
☐ Others:
____

19. Are you satisfied with the level of weed control achieved on the farm?
☐ Very high ☐ High ☐ Neutral ☐ Low
☐ Very low

20. Do you think weeds could be beneficial to you?
☐ Strongly agree ☐ Agree ☐ Neutral
☐ Disagree ☐ Strongly disagree

21. Reason(s) for Q19:
____

Section C: Weed management practices

22. Weed control methods used on the farm (can choose more than one).
☐ Cultural control (e.g. soil solarization, crop rotation, manuring)
☐ Mechanical control (e.g. tillage)
☐ Biological control (e.g. biological agents)
☐ Chemical control (e.g. herbicides)

23. How many types of herbicides used on the farm?
☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ >6

24. Frequently used herbicides on the ranking order of:
i. ___________________________
ii. ___________________________

iii. ______________________________

iv. ______________________________

v. ______________________________

Section D: Knowledge on weed control

25. Knowing how other farmers control weeds is important.
☐ Strongly agree ☐ Agree ☐ Neutral

☐ Disagree ☐ Strongly disagree

26. Sources of information on learning weed control methods.
☐ Malim Nawar Vegetable Farmer Association ☐ Friends

☐ Workshop and seminar ☐ Civil society (e.g. NGO)

☐ Agro-chemical company ☐ Government agency

☐ No access

27. Do you know how other farmers in Malim Nawar control weeds?
☐ Yes, proceed to question 28

☐ No

28. Channels of knowing other farmers' weed control methods in Malim Nawar.
☐ Phone calls

☐ Social sessions (e.g tea break)

☐ Farm visits

☐ Others:
____

29. Do you like to learn non-chemical weed control?

□ Yes, proceed to question 30

□ No, proceed to question 31

30. The reason(s) is:

□ Chemical herbicides are harmful to the environment

□ Chemical herbicides are harmful to consumers

□ Chemical herbicides are harmful to farmers and workers

□ Some weeds became herbicide resistance

□ Others:

____

31. The reason(s) is:

□ Chemical herbicides are convenience

□ Chemical herbicides are cost-effective

□ Other methods are less effective

□ Others:

____

Appendix E. Weed species identified in this study

Species	Descriptions	Photo/picture
Amaranthus viridis	Stem: erect, green or somewhat tinged purple, conspicuously angulate, slightly branched, glabrous Leaves: Leaf blade ovate, ovate-oblong, or ovate-elliptic, 3-9 cm long, 2.5-6 cm wide, base broadly cuneate or subtruncate, margin entire or slightly undulate, apex notched or rounded, with a pointed mucro; both surfaces green or somewhat tinged purplish red, adaxial usually V-shaped grayish white striped; petiole 3-6 cm Flower: Complex thyrsoid structures terminal, 6-1am cm long, 1.5-3 cm wide, branched, composed of spikes; spikes erect, slender, terminal ones longer than lateral ones; rachis 2-2.5 cm; bracts and bracteoles lanceolate, shorter than 1 mm, apex pointed; tepals oblong or broadly oblanceolate, 1.2-1.5 mm, apex acute; stamens shorter than perianth; stigmas 2-3 (Source: Xu and Deng, 2017).	

Asystasia gangetica	Stem: Old stems greyish; young stems greenish with a sparse to dense indumentum of up to c. 1 mm long spreading to appressed hairs. Leaves: Leaf blades narrowly lanceolate to ovate, up to 23-50 x 7-3o mm, sparsely to densely pubescent with c. 0.5-1 mm long spreading hairs, especially towards the base, apex obtuse to somewhat apiculate, base attenuate to truncate; petiole up to c. 5-30 mm long. Flower: Inflorescences lax, few-flowered terminal or subterminal spikes with 1 flower pernoder; bracts and bractelotes inconspicuous, trianglue, c. 1 mm long. Coralla white, lower lobe with violet markings, 11-42 mm long; lobes free from each other for up to c. 4-5mm. Anthers 1.5-4 mm long. (Source: Plants of the World Online https://powo.science.kew.org)	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Borreria latifolia	Stem: n.a. Leaves: Leaf-blades often red margined, elliptic, 1.2-5 cm. Long, 0.8-2.9 cm. Wide, acute at the apex, cuneate at the base, pubescent or ± scabrid above with tubercule-based hairs, pubescent beneath or almost glabrescent all over save for the scabrid margins; petiole 0.5-3 mm. Long; stipule-sheath 1.5 mm. long, with 5-9 setae 1.5-3.5 mm. long. Flower: Flowers in axillary clusters ± 8 mm. wide. Calyx-tube pubescent, obconic, 2.5 mm. long; lobes 4, oblong to lanceolate, 1.2-2 mm. long. Corolla whitish, blue or pink; tube funnel-shaped, 5 mm. long; lobes ovate-triangular, 1.5 mm. long and wide. (Source: Plants of the World Online https://powo.science.kew.org)	

Cleome rutidosperma	Stem: Stem with few or more rarely many eglandular hairs or stalked glands on the upper part. Leaves: Leaves petiolate, 3-foliolate; leaflets elliptic, obovate-elliptic or practically rhombic, 1-6 cm. long, 0.4-1.8 cm. wide, glabrous or sparsely-pubescent; petiole up to 7cm long. Flower: Inflorescence lax and not clearly demarcated, very short or up to 20 cm long; bracts usually similar in size to the leaves. Sepals linear to linear-lanceolate, (2-)3-4.5 mm long, glandular-puberulent. (Source: Plants of the World Online https://powo.science.kew.org)	
Digitaria longiflora	Stem: Culms 20-50(80) cm, erect, ascending or creeping, glabrous, nodes dark and glabrous. Leaves: Leaf sheaths glabrous to loosely hairy. Ligule 0.5-1.5 mm. long, truncate, entire. Leaf laminae (1)5-10(15) x 0.2x0.6 cm., linear, flat, smooth or minutely scaberulous, subglabrous or with scattered bulbous based bristles on both surfaces, scabrous along the margin. Flower: Inflorescence composed of (1)2(4) racemes, (1.5)2.5-10(17) cm. long, one subsessile, the other pedicellate on a very short common axis, erect to patent. Pedicels 3-nate, 0.5-2.5 mm. long, subterete, smooth, broadened at the apex. (Source: Plants of the World Online https://powo.science.kew.org)	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Eleusine indica	Stem: Tufted, erect, or geniculate at base; plants up to 10-90 cm tall. Leaves: Leaf blades flat or folded, 10-15 cm long, 0.3-0.5 cm wide, glabrous or adaxial surface tuberculate-pilose; sheaths compressed, keeled, glabrous, or tuberculately pilose, orifices sometimes pubescent; ligule 1 mm, membranous, sparsely ciliolate. Flower: Inflorescence digitate; racemes 207, linear, ascending, 3-10 cm long, 0.3-0.5 cm wide, 1 or 2 racemes often set below the rest, spikelets elliptic, 4-7 mm long, 2-3 mm wide, florets 3-9; glumes lanceolate, scabrid along keel; lower glume 1-veined, 1.5-2mm; upper glume with small additional veins in the thickened keel, 2-3 mm; lemmas ovate, 2-4 mm, keel with small additional veins, acute; palea shorter than lemmas, keels winged, pilose. (Source: Xu and Zhou, 2017).	

Euphorbia hirta	Stem: Spreading or creeping, basal geniculately ascending, usually tinged purplished red, branched near base, hispidulous, densely upper. Plants up to 30-60 cm tall. Leaves: Leaves opposite. Leaf blades lancelolate-oblong or oblong-ovate or ovate-lancelolate, 1-5 cm long, 0.5-1.5 cm wide, apex acuminate or obtuse, basal oblique, asymmetrical, margins serrulate, adaxially green to red, sometimes tinged purplish blotches along midribs, abaxially grayish green, both surfaces pilose, abaxially, and veins densely hairy. Petioles 1-2 mm. Stipules membranous, lanceolate or linear-lanceolate, 0.8-1.5 mm long, margins setae-like lacerated. Flower: Cyathia densely arranged to tightly capitate, axillary, pedunculate cymes at upper nodes, peduncle to 25 mm, all parts densely hairy. Involucres campanulate, 1-1.2 mm long, 0.8-1 mm wide, densely pubescent outside, apex 405-lobed, glands 4, funnelform, shortly petiole, with petallike appendages. Male flowers 4 or 5, 1 stamen each flower, anthers red. Female flower 1, solitary on central involucres, pedicels short, exserted involucres, ovary 3-angular, sparsely pilose, styles free, stigmas slightly bifid. (Source: Xu and Deng, 2017).	

Hedyotis corymbosa	Stem: Stems prostrate to ± erect, 1.5-30 cm. long, ridged glabrous or scabridulous or pubescent on the ribs. Leaves: Leaf-blades linear to narrowly elliptic, 0.6-3.5(-5.3) cm. long, 0.5-7 mm. wide, acute and apiculate at the apex, narrowed to the base, glabrous to sparsely scabridulous above and on margins and also beneath, particularly on the main nerve; petioles not developed; stipule-sheath 0.5-2(-3) mm. long, produced at the middle with (2-)3-5 unequal fimbriae, 0.5-1(-2.5) mm. long. Flower: Flowers not heterostylous, variously arranged, either 1-several single flowers in the axils or in 2-5(-6)-flowered pedunculate umbel-like inflorescences, both kinds present on one branch or even on one node, the peduncles and pedicels mostly long and slender but rarely the flowers are fasciculate; peduncles (0-)0.5-1.8(-2.3) cm. long; pedicles (1.8-)3-6(-13) mm.long (Source: Plants of the World Online https://powo.science.kew.org)	
Mitracarpus hirtus	Stem: Erect or spreading annual herb (5)9-40 cm. tall, with unbranched or sparsely to much-branched stems; branchlets pubescent with short curled ± appressed hairs and often with spreading ones as well, the older with epidermis eventually peeling' sometimes quite woody at the base. Leaves: Leaf blades 1-6 x 0.3-2.3 cm., elliptic, subacute at the apex cuneate at the base, glabrescent to scabrid-pubescent above, glabrescent or glabrous beneath save for hairs on the main nerves; margins often scabrid; petiole c.1 mm. long, often densely pubescent and with ciliate margins; stipule sheath 1-3 mm. long, divided into 6-9(15) often colleter-tipped fimbriae, 1-5 mm. long, ciliate.	

	Flower: Inflorescencs numerous, present in most axils, subglose, (0.5)0.8-1.8 cm. in diam.; flowers sessile or almost so; bracteoles filamentous, white, 1-2mm. long. C (Source: Plants of the World Online https://powo.science.kew.org)	(Photo credit: Plants of the World Online https://powo.science.kew.org)
Oldenlandia corymbosa	Stem: Stems prostrate to ± erect, 1.5-30 cm. long, ridged glabrous or scabridulous or pubescent on the ribs. Leaves: Leaf-blades linear to narrowly elliptic, 0.6-3.5(-5.3) cm. long, 0.5-7 mm. wide, acute and apiculate at the apex, narrowed to the base, glabrous to sparsely scabridulous above and on margins and also beneath, particularly on the main nerve; petioles not developed; stipule-sheath 0.5-2(-3) mm. long, produced at the middle with (2-)3-5 unequal fimbriae, 0.5-1(-2.5) mm. long. Flower: Flowers not heterostylous, variously arranged, either 1-several single flowers in the axils or in 2-5(-6)-flowered pedunculate umbel-like inflorescences, both kinds present on one branch or even on one node, the peduncles and pedicels mostly long and slender but rarely the flowers are fasciculate; peduncles (0-)0.5-1.8(-2.3) cm. long; pedicles (1.8-)3-6(-13) mm.long (Source: Plants of the World Online https://powo.science.kew.org)	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Panicum dichotomiflorum	Stem: Annual. Culms geniculately ascending, or decumbent; 100-200 cm long. Culm-nodes glabrous. Leaves: Leaf-sheaths glabrous on surface. Ligule a ciliate membrane; 2 mm long. Leaf-blades 12-50 cm long; 3-12(-20) mm wide. Leaf-blade midrib conspicuous. Leaf-blade surface glabrous, or puberulous; hairy adaxially. Leaf-blade margins scabrous. Flower: Inflorescence a panicle; terminal and axillary' embraced at base by subtending leaf. Panicle open, ovate; 12-40 cm long. Primary panicle ascending. Panicle axis smooth, or scabrous. Panicle branches stiff. Spieklets appressed; solitary. Fertile spikelets pedicelled. Spikelets comprising 1 basal sterile florets; 1 fertile florets; without rhacilla extension. Spikelets ovate; dorsally compressed; 2.4-3 mm long; falling entire. (Source: Plants of the World Online https://powo.science.kew.org)	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Phyllanthus amarus	Stem: A glabrous erect or ascending annual herb up to 75 cm tall, sometimes woody at the base. Lateral shoots up to c.15 cm long, the older ones usually co-axillary with secondary lead shoots. Leaves: Scale leaves 1-1.3 mm long, linear-subulate, blackening at the apex; stipules 1.5 x 1 mm, broadly triangular-lanceolate, asymmetrical at the base, dark brown. Leaf blades 5-10 x 2-5 mm, mostly oblong, rounded-subtruncate at apex and base, membranaceous, dull green above, paler beneath; lateral nerves in 4-6 pairs, looped at the apex, inconspicuous above, not prominent beneath. Flower: Male and female flowers often occurring together in the distal axis, female flowers usually solitary in the proximal axis. (Source: Plants of the World Online https://powo.science.kew.org)	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Phyllanthus virgatus	Stem: Erect, sometimes prostrate or geniculately ascending, usually slightly woody at base, branchlets often from base, flat and angled upper, glabrous. Plants up to 60-100 cm tall. Leaves: Leaves nearly leathery. Leaf blades linear-lanceolate, oblong, or narrowly elliptic, 0.5-2.5 cm long, 2-7 mm wide, apex obtuse or acute, mucronulate, basal rounded, slightly oblique, midrib raised abaxially, flattened adaxially, lateral veins obscure. Subsessile. Stipule membranous, ovate-triangular, 0.5-1 mm long, brownish red. Flower: Monoecious. Flowers axillary, usually fascicled with 2-4 male and 1 female flower. Male flowers 0.5-1 mm in diameter, pedicels 1.5-2 mm, sepals 6, broadly ovate or rotund, 0.3-0.5 mm, disk glands 6, oblong, stamens 3, filaments free, anthers subglobose. Female flower pedicels 4-5 mm, calyx 6-parted, sepals ovate-oblong, 0.5-1 mm, refleced, purple with whitish membranous margins, persistent in fruit, disk orbicular, undivided, ovary globose, 3-loculed, with raised scales, rarely smooth, styles free, bifid nearly to base, usually recurved. (Source: Xu and Deng, 2017).	 (Photo credit: Plants of the World Online https://powo.science.kew.org)

Appendix F. List of countries for native and introduced distribution of weed species

Species	Native countries	Introduced countries
Amaranthus viridis	33 countries - Antigua and Barbuda, Africa, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Grenada, France, Guatemala, Haiti, Jamaica, Mexico, Netherlands, Nicaragua, Panamá, Paraguay, Peru, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Trinidad-Tobago, Uruguay, United Kingdom, United States, Venezuela.	98 countries -Afghanistan, Algeria, Africa, Angola, Armenia, Austria, Australia, Azerbaijan, Bahrain, Bangladesh, Benin, Brunei, Burkina, Canada, Cambodia, Cameroon, Kiribati, China, Comoros, Congo, Cyprus, Czech, Denmark, Djibouti, Egypt, Eritrea, Ethiopia, Fiji, Finland, France, Gabon, Gambia, Ghana, Greece, Georgia, Guyana, Iraq, Italy, Ivory Coast, India, Indonesia, Italy, Kenya, Korea, Kuwait, Laos, Lebanon, Libya, Malaysia, Maldives, Mali, Tuamotu, Mauritania, Mauritius, Mexico, Morocco, Mozambique, Myanmar, Nauru, Nepal, New Guinea, Niger, Nigeria, New Zealand, Oman, Pakistan, Palestine, Philippines, Portugal, Qatar, Russia, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Seychelles, Solomon Is., Spain, Sri Lanka, Sudan, Suriname, Sweden, Syria, Tadzhikistan, Tanzania, Thailand, Togo, Tonga, Tunisia, Turkmenistan, Uganda, United States, Uzbekistan, United Arab Emirates, Yemen, Zambia, Zimbabwe
Asystasia gangetica	10 countries - Australia, Bangladesh, Cambodia, India, Indonesia, Myanmar, New Guinea, Sri Lanka, Thailand, Vietnam.	32 countries - Antigua and Barbuda, Australia, Bahamas, Barbados, Belize, Brazil, China, Costa Rica, Cuba, Dominican Republic, El Salvador, France, Fiji, Grenada, Haiti, Jamaica, Kiribati, Malaysia, Mauritius,

		Nauru, Nicaragua, New Zealand, Panamá, Portugal, Saint Kitts and Nevis, Tonga, Trinidad-Tobago, United Kingdom, United states, St. Lucia, St. Vincent and Grenadines, Venezuela
Borreria latifolia	23 countries - Antigua and Barbuda, Africa, Argentina, Belize, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, France, Guatemala, Guyana, Mexico, Nicaragua, Panamá, Paraguay, Peru, Suriname, Trinidad-Tobago, United States, United Kingdom Venezuela	27 countries - Australia, Bangladesh, Brunei, Cambodia, Cameroon, China, Congo, Fiji, Gabon, Ghana, Guinea, India, Ivory Coast, Indonesia, Kiribati, Laos, Liberia, Malaysia, Myanmar, Nepal, Samoa, Sierra Leone, Sri Lanka, Taiwan, Thailand, Uganda, United States.
Cleome rutidosperma	25 countries - Africa, Angola, Benin, Burundi, Cameroon, Chad, Congo, Côte d'Ivoire, Gabon, Ghana, Guinea, India, Liberia, Mozambique, Myanmar, Nigeria, Sao Tome and Principe, Senegal, Sierra Leone, Sri Lanka, Sudan, Tanzania, Togo, Uganda, Zambia	33 countries - Antigua and Barbuda, Bangladesh, Barbados, Brunei, Brazil, Cambodia, China, Australia, Comoros, Cuba, Dominican Republic, France, Grenada, Haiti, India, Indonesia, Jamaica, Laos, Malaysia, Mexico, Nauru, Nepal, Nicaragua, Panamá, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Taiwan, Thailand, Trinidad-Tobago, United Kingdom, United states, Venezuela
Digitaria longiflora	57 countries - Africa, Angola, Armenia, Australia Azerbaijan, Bangladesh, Benin, Bhutan, Brunei, Botswana, Burkina, Burundi, Cambodia, Cameroon, Chad, China, Ethiopia, France, Gabon, Gambia, Georgia, Ghana, India, Indonesia, Ivory Coast, Kenya, Laos, Liberia, Madagascar, Malawi, Malaysia, Mali, Mauritania, Mauritius, Mozambique,	19 countries - Antigua and Barbuda, Barbados, Brazil, Colombia, Costa Rica, Cuba, France, Grenada, Guyana, Kiribati, Nicaragua, Samoa, Suriname, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Trinidad-Tobago, United Kingdom, United States

	Myanmar, Namibia, Nepal, New Guinea, Nigeria, Pakistan, Philippines, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, Sri Lanka, Sudan, Taiwan, Tanzania, Thailand, Togo, Uganda, Vietnam, Zambia, Zimbabwe	
Eleusine indica	74 countries - Africa, Armenia, Angola, Azerbaijan, Bangladesh, Benin Bhutan, Brunei, Botswana, Burkina, Burundi, Cambodia, Cameroon, Chad, China, Comoros, Congo, Ethiopia, Egypt, France, Gabon, Gambia, Georgia, Ghana, Greece, India, Indonesia, Iran, Ivory Coast, Japan, Kenya, Korea, Laos, Lebanon, Liberia, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritius, Mozambique, Myanmar, Namibia, Nepal, New Guinea, Niger, Nigeria, Oman, Pakistan, Palestine, Philippines, Russia, Rwanda, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Sao Tome and Principe, Solomon Is., Sri Lanka, Sudan, Syria, Taiwan, Tanzania, Thailand, Togo, Turkey, Uganda, Uzbekistan, Vietnam, Zambia, Zimbabwe	72 countries - Antigua and Barbuda, Algeria, India, Argentina, Australia, Africa, Austria, Bahamas, Barbados, Belize, Bolivia, Brazil, Bulgaria, Bosnia and Herzegovina, Canada, Croatia, Colombia, Costa Rica, Cuba, Czech, Dominican Republic, Chile, Ecuador, Egypt, El Salvador, Fiji, France, Georgia, Germany, Grenada, Greece, Guatemala, Guyana, Haiti, Hungary, Italy, Jamaica, Japan, Kiribati, Kosovo, Libya, Portugal, Mauritania, Mexico, Morocco, Montenegro, Nauru, Netherlands, New Zealand, Nicaragua, North Macedonia, Panamá, Paraguay, Peru, Portugal, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Samoa, Suriname, Spain, Switzerland, Serbia, Slovenia, Tonga, Trinidad-Tobago, Tuvalu, Uruguay, United Kingdom, United State, Vanuatu, Venezuela
Euphorbia hirta	36 countries - Africa, Antigua and Barbuda, Argentina, Barbados, Bahamas, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, France, Georgia, Grenada, Guatemala, Haiti, Jamaica,	71 countries - Angola, Australia, Africa, Bangladesh, Benin, Bahrain, Botswana, Burkina, Burundi, Cambodia, Cameroon, Chad, China, Comoros, Cameroon, Congo, Cyprus, Chile, Djibouti, Ecuador, Eritrea, Ethiopia, Fiji, France, Gabon, Gambia, Ghana, Gilbert Is. India, Indonesia, Ivory Coast, Japan, Kenya, Kiribati, Kiribati, Liberia, Madagascar, Malawi,

	Mexico, Netherlands, Nicaragua, Panamá, Paraguay, Peru, Trinidad-Tobago, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, United Kingdom, United States, St. Lucia, St. Vincent and Grenadines Venezuela	Maldives, Mali, New Guinea, Mauritania, Mexico, Mozambique, Nauru, Nepal, New Zealand, Nigeria, Oman, Pakistan, Palestine, Qatar, Rwanda, Samoa, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Sudan, Sao Tome and Principe, Taiwan, Tanzania, Thailand, Togo , Tonga, United Kingdom, United States, United Arab Emirates, Vietnam, Zambia, Zimbabwe
Hedyotis corymbosa	60 countries - Africa, Angola, Bangladesh, Benin, Bhutan, Brunei, Botswana, Burkina, Burundi, Cambodia, Cameroon, Chad, China, Congo, Egypt, Eritrea, Ethiopia, France, Gabon, Gambia, Ghana, India, Indonesia, Ivory Coast, Kenya, Korea, Lebanon, Liberia, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritius, Mozambique, Myanmar, Nepal, New Guinea, Nigeria, Sri Lanka, Japan, Oman, Pakistan, Rwanda, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Syria, Somalia, Sudan, Taiwan, Tanzania, Thailand, Togo, Uganda, Vietnam, Yemen, Zambia, Zimbabwe	34 countries - Australia, Barbados, Belize, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, France, Georgia, Grenada, Guatemala, Guyana, Haiti, Jamaica, Kiribati, Mexico, Nauru, Netherland, New Zealand, Nicaragua, Panamá, Peru, Seychelles, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Trinidad-Tobago, United Kingdom, United States, Venezuela,
Mitracarpus hirtus	30 countries - Argentina, Barbados, Belize, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Ecuador, El Salvador, France, Guatemala, Grenada, Guyana, Haiti, Jamaica, Mexico, Netherlands Nicaragua, Panamá, Paraguay, Peru, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Trinidad-Tobago, United Kingdom,	44 countries - Africa, Angola, Australia, Bangladesh, Benin, Burkina, Burundi, Cameroon, Chad, China, Congo, Eritrea, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, India, Ivory Coast, Kenya, Liberia, Madagascar, Malawi, Malaysia, Mali, Mauritania, Mexico, Myanmar, New Guinea, Niger, Nigeria, Philippines, Senegal,

	United State, Uruguay, Venezuela	Seychelles, Sierra Leone, Sri Lanka, Sudan, Tanzania, Thailand, Togo, United states, Uganda, Zambia,
Oldenlandia corymbosa	61 countries - Africa, Angola, Australia, Bangladesh, Benin, Bhutan, Brunei, Botswana, Burkina, Burundi, Cambodia, Cameroon, Chad, China, Congo, Egypt, Eritrea, Ethiopia, France, Gabon, Gambia, Ghana, India, Indonesia, Ivory Coast, Japan, Kenya, Korea, Lebanon, Liberia, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritius, Mozambique, Myanmar, Nepal, New Guinea, Nigeria, Oman, Pakistan, Rwanda, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Syria, Somalia, Sri Lanka, Sudan, Taiwan, Tanzania, Thailand, Togo, Uganda, Vietnam, Yemen, Zambia, Zimbabwe	35 countries - Australia, Barbados, Belize, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Florida, France, Georgia, Guatemala, Guyana, Grenada, Haiti, Jamaica, Kiribati, Mexico, Nauru, Netherlands, New Zealand, Nicaragua, Panamá, Peru, Seychelles, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, United Kingdom, Trinidad-Tobago, United States, Venezuela
Panicum dichotomiflorum	22 countries - Africa, Argentina, Bahamas, Bolivia, Brazil, Canada, Chile, Colombia, Cuba, Dominican Republic, Ecuador, Georgia, Guyana, Haiti, Mexico, Panamá, Paraguay, Peru, Suriname, Trinidad-Tobago, United States, Venezuela	38 countries - Albania, Austria, Armenia, Azerbaijan, Bangladesh, Belgium, Bosnia and Herzegovina, China, Croatia, Czech, France, Finland, Germany, Georgia, Greece, Hungary, Italy, Ireland, Iceland, Japan, Korea, Kosovo, Luxembourg, Malaysia, Montenegro, Myanmar, Netherlands, New Zealand, Norway, North Macedonia, Russia, Serbia, Slovenia, Sweden, Switzerland, Taiwan, United Kingdom, United States
Phyllanthus amarus	35 countries - Africa, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, France, Grenada, Guatemala, Guyana, Haiti, Jamaica,	61 countries - Africa, Angola, Australia, Bangladesh, Benin, Brunei, Burkina, Belize, Cambodia, Cameroon, Chad, Comoros, Congo, Ethiopia, El Salvador, Frances, Fiji, Gabon, Gambia, Ghana, India, Indonesia, Japan,

	Mexico, Netherlands, Nicaragua, Panamá, Paraguay, Peru, Suriname, Trinidad-Tobago, Uruguay, Saint Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, United Kingdom, Venezuela	Kenya, Kiribati, Laos, Liberia, Madagascar, Malaysia, Maldives, Marquesas, Mauritania, Mozambique, Myanmar, Nauru, New Zealand, New Guinea, Nigeria, Nicaragua, Oman, Panamá, Philippines, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Sri Lanka, Sudan, Sulawesi, Taiwan, Tanzania, Thailand, Togo, Tonga, Tuvalu, United Kingdom, United States, Uganda, Yemen.
Phyllanthus virgatus	28 countries - Australia, Bangladesh, Bhutan, Brunei, Cambodia, China, Fiji, France, India, Indonesia, Kiribati, Laos, Malaysia, Myanmar, Japan, Nepal, New Guinea, New Zealand, Pakistan, Philippines, Samoa, Sri Lanka, Taiwan, Thailand, Tonga, United State, Vanuatu, Vietnam	-