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Experimental approach to determine the efficacy of a tine mechanism for auto weeding machine

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Experimental approach to determine the efficacy of a tine mechanism for auto weeding machine

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DEDICATION

To my wife Suhaima Abdullah, my two daughters, Sumayyah and Nusaybah, parents, Dr. Johari Jiken Abdullah and Seriyati Badaruddin, family, professors, lecturers, teachers and friends. With love.

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ABSTRACT

Weeds in row crops compete for resources available to crop plants and thus will affect crop yield and quality. However, consumers show a growing interest in organic food or foods produced with fewer agricultural chemicals. Therefore, a need exists to develop alternative weed control methods. A tine mechanism for an autonomous weeding machine was developed, and the interaction of a single tine and a rotating tine mechanism with the soil was investigated. The goal of this research was to develop a laboratory methodology for evaluating the effectiveness of a tine and rotating tine mechanism in disturbing weed plants simulated by individual wood pieces. Two experiments were performed using the tine and tine mechanism under a controlled environment. Soil in a large rotating bin was processed and sieved to a maximum size of 5 mm. The soil was then conditioned with water to produce the desired moisture content. A single tine was used in the first experiment. The experimental factors for this test were the tine diameter, tine depth and the speed that the tine moved through the soil. For the second experiment, four tines were attached to a disk that rotated about a vertical axis. The rotational tine mechanism was tested at different working depths and disk rotational speeds. All of these tests were conducted in a rotating soil bin with a controlled speed. The orientation of each simulated weed was observed in each trial. The observations were captured in a Mean Likelihood of Control (MLC) parameter which was intended to indicate the mean likelihood of simulated weed being controlled. In the first experiment, significant differences were observed in MLC across tine

diameter, tine working depth and travel speed. There was evidence of a significant interaction between tine diameter and tine working depth. As for the second experiment, significant differences were observed in MLC across tine working depth and rotational speed of tine mechanism. Evidence of a significant interaction between working depth and tine mechanism rotational speed was observed. All of the factors tested were important and could be used to determine machine settings in the field.

CHAPTER 1 GENERAL INTRODUCTION

Background

In 2015, fresh market vegetable and melon production in United States was estimated to be 20.3 million metric tons with a total harvested area of 6,273 km^2 (USDA, 2015). Vegetable production resulted in a revenue of almost 12 billion, USD so raising vegetables is an important economic sector in the U.S. The three largest produced crops are onions, melons and lettuce, which accounted for almost 40 percent of the total production. California is the top fresh vegetable producer with 51 percent of production and 58 percent of the economic value. The large values associated with this sector indicate that consumers demand high quality products for a healthy and well-balanced diet. However, there is serious competition between weed and vegetable crops which results in reduced quality and yield (Das & Yaduraju, 1999).

Weeds in crop field compete for soil nutrients, soil moisture, sunlight (Tollenaar & J. Wu, 1999), space, water and other ecological factors throughout the whole growing season (Maxwell, O’Donovan, Upadhyaya, & Blackshaw, 2007). Some weed species are dangerous to livestock and release toxins through the soil which endanger other plants (Marer, 2000). Without a proper weed management program, weeds will affect crop yield and quality, resulting in reduced revenue for the grower.

The most effective method of weed management is by controlling the weeds through eliminating or suppressing the weed growth. There are several types of weed control options practiced by farmers around the world. These options include manual, biological, chemical and mechanical methods of weed control.

The earliest form of weed control is manual control which is time consuming and laborious (Gianessi & Reigner, 2007). The technique damages the weed with hand or handheld tools and has a high labor requirement. It reduces soil disturbance (Buchanan, 1992; Tu, Hurd, & Randall, 2001), minimizes damage to crop and nature, and reduces soil erosion (Hajek et al., 2016).

Biological control utilizes natural enemies of weed plants such as herbivores, predators, insects, parasites, or diseases to control the germination of weed seed and reduce the vigor and size of infestations (Clausen, 1978; McEvoy, Cox, & Coombs, 1991; Stiling, 1992). It is the most selective, cost efficient method to control aggressive weeds and cover large areas for long term periods (Hajek et al., 2016).

The most common weed control method in modern agricultural practices is the chemical method (Cloutier, Van der Weide, Peruzzi, & Leblanc, 2007). It uses herbicides to control the weed growth or weed seed germination by speeding up, stopping or changing the normal growth of weeds plant. It is low cost, easy to use, and generally has high efficacy compared to other methods. However, many people are now concerned with the effects of agricultural chemicals on human health, the environment and agricultural workers (Bak & Jakobsen, 2004). Moreover, there is high demand for organic product and foods produced and processed without synthetic substances (McEachern, Seaman, Padel, & Foster, 2005). With all the reasons mentioned, agricultural producers need a better alternative weeding method that eliminates weed plants without possible negative effects on human health, workers safety and natural systems. Mechanical weed control is an alternative to chemical weed control with high potential for sucess. This method eliminates or suppresses weeds through physical disruption using mechanical tools.

T. Ahmad, Tang, and Steward (2014) reported there are two types of mechanical weeding machines: inter-row weeders, which control weeds growing between the crop plant rows and intra-row weeders, which control weeds very near or within the crop plant rows. The most common machines for mechanical weed control available commercially are inter-row cultivators, basket weeders and rotary cultivators (Cloutier et al., 2007). Inter-row cultivators and rotary cultivators are implements with cutting edges that either bury the weed plants with soil, cut the weed stems or uproot the weed plants. The basket weeder has steel-shaped rolling cages, which loosen and pulverize the soil and uproot the weed plants.

Weed control for intra-row operations is more challenging as many weeds grow very close by or within the crop plant rows. Several tools have been developed for this purpose, such as harrows, torsion weeders, finger weeders and brush weeders. The brush weeder, which is made with fiberglass or nylon brush material, uproots or buries intra-row weed plants with soil. It is very effective in eliminating young weeds (Fogelberg & Gustavsson, 1999). The torsion weeder uses spring steel tines, which are mounted on a rigid frame to control neighboring weed plants. The finger weeder uses two circular shaped rotating disk with flexible rubber spikes to dislodge weed plants by penetrating the soil from the surface. All of the intra-row machines work effectively if the vehicle steering method is precise and accurate as physical contact with the crop plants could cause damage.

A main issue with the above mechanical weed control approaches is they do not have the capability to differentiate between weed and crop plants, thus limiting the effectiveness of controlling the weeds that are close to crop plants. Several weeders, however, are equipped with machine guidance systems. For example, there is an intra-row weeder which utilizes the Global Positioning System (GPS; Griepentrog, Nørremark, & Nielsen, 2006) and other weeders which use laser transmitters and receivers as guidance sensors (Van Zuydam, Sonneveld, & Naber, 1995). Until now, there are only a few complete autonomous weed control systems, which have been tested in the field. Mazin, Won Suk, Thomas, Gregory, and Gezan (2013) developed an automated weeder with a roller mechanism that uproot weeds. Pérez-Ruíz, Slaughter, Fathallah, Gliever, and Miller (2014) developed a low cost intra-row weeding co-robot that reduced manual labor for intra-row weed control. Automated weeding has the potential to overcome labor shortages, human mistakes, and the high costs associated with manual labor.

There are few reports on the efficacy of mechanical and automated weeders (Cirujeda, Melander, Rasmussen, & Rasmussen, 2003; Mazin et al., 2015). The lack of efficacy study are due to challenges faced by researchers to conduct such studies. Ahmad (2012) reported that differences in weed density and soil conditions affected his results, while Mazin et al. (2015) found that weeding efficacy was effected by the weed species. Thus, reports of in-situ efficacy studies of mechanical weeding machines are limited.

Determining the efficacy of a mechanical weeder is difficult to accomplish in the field for several reasons. These reasons include time constraints, no standard efficacy test methods, and uncontrolled parameters during field operations. Often, most of the research time is allocated for the development and testing of mechanical and automated weeders and less time to determine weed control efficacy. Highly variable weather conditions and the short growing seasons of temperate climates make it more difficult for in-situ efficacy studies to be executed. There is also no standard method to guide engineers and researchers for an efficacy study for mechanical or automated weeders. In a field operation, many uncontrolled parameters need to be considered such as the surrounding temperature, the soil type, and soil moisture content (Ahmad, 2012). The physical variety of weeds can also result in a less systematic study of weeding efficacy (Van der Weide et al., 2008). Systematic efficacy studies investigating different parameters can provide the settings required by the machine and the weeding mechanism to researchers.

This lack of efficacy knowledge and uncontrolled parameters during field experiments leads to the need for a systematic approach to investigate weeding efficacy. One potential approach is to conduct an in-situ efficacy study, but there are still limitations with uncontrolled variables. Another approach is to conduct an experimental approach under controlled conditions to determine the efficacy of mechanical weeding mechanism in disturbing simulated weeds. A laboratory experiment with controlled ambient temperatures and soil conditions could facilitate studies of the effects of different parameters on weed control.

Objectives

The overall goal of this research was to investigate the performance of a tine and a tine mechanism in disturbing soil and simulated weed plants under controlled laboratory conditions. This tine mechanism was designed for an automated intra-row weeding machine in vegetable crop production. The specific objectives of this research were to:

1. Investigate the effect of tine diameter, tine working depth and travel speed on the ability of a single tine to disturb simulated weed plants.
2. Investigate the effect of tine working depth and the rotational speed on the performance of a tine rotating tine mechanism in disturbing simulated weed plants.

Thesis Overview

This thesis consists of four chapters. Chapter 1 introduces the research. Chapter 2 provides background literature review for the research. Chapter 3 is a journal article describing research investigating the efficacy performance by tine mechanism. Chapter 4 summarizes conclusions from the research and recommendations for future work. References for each chapter are given at the end of the individual chapters.

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CHAPTER 2 LITERATURE REVIEW

In 2015, fresh market vegetable and melon production in United States was estimated to be 20.3 Million metric tons with a harvested area of 6,273 km^2 (USDA, 2015). Additionally, vegetable production resulted in a revenue of almost 12 billion dollars, an increase of 11 percent from the previous year. Vegetable production is an important economic sector in the U.S. The three vegetable crops with the largest produced mass are onions, watermelons, and head lettuce, which accounted for almost 40 percent of the total produced mass. The three highest vegetable crop values are romaine lettuce (USD 1 Billion), head lettuce (USD 1.25 Billion) and tomatoes (USD 1.243 Billion) with a combined value that was 29 percent of the value of all vegetable crops. California is the top fresh vegetable producing state with 51 percent of production and 58 percent of the value, followed by Florida (7.8 percent of production and 9.3 percent of value) and Arizona (7.2 percent of production and 8.5 percent of value). The large numbers associated with this sector indicates that consumers have a high demand for vegetables as a part of a healthy diet. A major challenge in vegetable production, however, is the competition between weed plants and crop plants which results in reduced crop quality and yield (Das & Yaduraju, 1999).

Weed control is a significant issue in agricultural production and has been under the attention of agricultural experts for many decades. Weeds are valueless wild plants that interfere with crop plant growth. Farmers strive to improve crop production through greater crop yield and quality, but weeds are a barrier to these improvements. Weeds in row crops compete for soil nutrients, moisture, and sunlight available to crop plants (Tollenaar & J. Wu, 1999). Moreover, crops and weeds compete for space and other ecological factors throughout the whole growing season. Some weed species are dangerous to livestock and release toxins through the soil which endanger other plants (Marer, 2000). Without a proper weed control program, weeds will affect crop yield and quality, thus resulting in economic loss for the grower. Granitto, Navone, Verdes, and Ceccatto (2002) reported that weed infestations lead to crop losses in part due to the competition between crops and weeds for available nutrients and moisture.

There are several studies on crop yield losses due to the existence of weeds. Johnson (1971) reported higher oil contents and seed yields for sunflowers grown in plots with lower weed competition. Felton (1976) conducted an experiment to determine the reduction in soybean yield due to weed pressure. The presence of weeds caused a reduction of 37% of yield. Tollenaar, Nissanka, Aguilera, Weise, and Swanton (1994) reported the mean grain yield of four maize (*Zea mays L.*) hybrids across three years of experiment was 65% higher in weed-free treatments. Another study reported that the existence of weeds in rice crop fields could result in a yield reduction of 57% (Smith, 1968). An effective method for managing weeds is needed to minimize the adverse effects of weeds on crop production (Walker, 1994).

There are several types of weeding control options used by farmers around the whole world. These options include manual, biological, chemical and mechanical methods of weed control. Each of these methods has its own advantages and disadvantages in term of efficacy in controlling weeds, health risks to the farmer and cost. Each of these methods will be discussed in this chapter. This chapter will also discuss the need for autonomous weeding robots, and the need for weed control efficacy studies for mechanical and automated weed control.

Manual Weed Control

Manual weed control is the earliest form of weed control. It is a time consuming and laborious method in which farmers use their hands or hand tools to eliminate weeds (Gianessi & Reigner, 2007). Techniques such as pulling, cutting and damaging the weed plants are normally practiced under conditions where low cost labor is available. The benefits of this method are that it minimizes soil disturbance (Buchanan, 1992; Tu et al., 2001), minimizes damage to crop, and reduces soil erosion (Hajek et al., 2016).

Pulling or uprooting weeds is considered the best approach to control small-scale weed infestations, especially for the earliest growth stage weeds when the weed plants are still young or when chemicals cannot be applied in a particular area. This action is accomplished by pulling the weed plant by hand or with weed-pulling handheld tools, which assist the user in gripping the weed by its stem and uprooting it. The tool’s size, weight and shape are designed for different sizes and types of weeds. Generally, there are two types of hand tools: short-handled and long-handled. Examples of short-handled weeding tools are the *Fishtail Weeder*, the *Hoe Dag* and the *Dee Weeder* (Figure 2.1; Hemingway, 2015); while examples of long-handled tools are the *Dutch Hoe*, the *CobraHead Weeder* and the *Radius Weeder* (Figure 2.2; Cook, 2014 & Hemingway, 2015). The idea of applying tools for weed control opens the door for mechanical weed control, discussed later in this chapter.

(a) (b) (c)

Figure 2.1. Short handled weeding tools, from left (a) Fishtail weeder, (b) Hoe dag, and (c) Dee weeder (Hemingway, 2015).

(a) (b) (c)

Figure 2.2. Long handled weeding tools, from left (a) Dutch hoe, (b) Cobra Head Weeder and (c) Radius weeder (Cook, 2014; Hemingway, 2015).

Biological Control

Recently, some farmers have practiced biological weed control in agricultural crops (Tilman, Tilman, Crawley, & Johnston, 1999). Biological control is the technique of applying natural enemies of weed plants such as herbivores, predators, insects, parasites, or diseases to control the germination of weed seed and reduce the vigor and size of infestations (Clausen, 1978; McEvoy et al., 1991; Stiling, 1992). Some farmers use sheep to control tansy ragwort or leafy spurge and goats for brush weed and Russian knapweed (Pickett, 1998; Tu et al., 2001; Walker, 1994). Biocontrol insects can control weeds (Table 2.1). These insects are released on target sites that require weed control management.

Table 2.1. Biocontrol insects for different weed species ("Biocontrol Conservation," 2016; Croft, 1990; Pickett, 1998).

Biocontrol Insects	Weed Species
Flea beetles	Leafy spurge
Cinnabar moth, Tansy flea	Tansy ragwort
Chrysolira beetle	St. John’s Wort
Bindweed mites, Bindweed moth	Field bindweed
Mecinus janthinus	Dalmatian toadflax
Larinus minutus	Diffuse knapweed
Gall midge, Gall wasp	Russian knapweed
Rosette weevil	Musk Thistle
Root weevil	Spotted knapweed
Gall fly	Canada thistle

There are advantages and disadvantages in exercising biological weed control. On the positive side, it is the most selective and cost efficient method to control aggressive weeds. Moreover, it attacks specific weeds and is able to cover large areas for long time period (Hajek et al., 2016). On the contrary, regional managers are concerned with the damage on non-target plants caused by the biological control agents as they have the capability to spread to other regions far from the original control sites and cause different impacts across the landscape (Kaser & Ode, 2016; Klapwijk, Bylund, Schroeder, & Björkman, 2016).

Chemical Control

The most commonly-used weed control method in the United States and other developed countries today is chemical weed control (Cloutier et al., 2007). It is the technique of applying herbicides to weeds or the soil to control the weed growth or weed seed germination by speeding up, stopping or changing the normal growth of the weed plant or drying out the weed leaves or defoliating the weed. Generally, there are two ways of applying herbicide, which are selective application by using individual spray nozzles to apply chemical to individual weeds and broadcast spraying with multiple spray nozzles. The latter has the advantage of quickly covering large field areas. Chemical weed control has several advantages over other weed control methods. Herbicides are low cost, easy to use, rapidly applied, and generally have high efficacy.

Despite all of the available methodology, weeds are adaptable plants that continually evolve as a natural response to herbicides (Maxwell et al., 2007). Farmers must rotate and apply complicated chemical mixtures for pre and post-emergence weed control, while minimizing costs to avoid herbicide resistance among weeds (Friesen, Ferguson, & Hall, 2000; Norsworthy et al., 2012). On the other hand, the general public is concerned about the effects of agricultural chemicals on human health, the environment, and agricultural workers (Bak & Jakobsen, 2004). Workers can be exposed to herbicides in a treatment area and during the mixing and application processes. Herbicides can cause headaches and nausea for low levels of exposure and blurred eyesight, strong headache and blistered skin for high levels of exposure and eventually death for extreme cases

(Marer, 2000). Herbicides may also have long term effects such as elevated risk of cancer and disturbed immune systems (Horrigan, Lawrence, & Walker, 2002). The application of weed control chemicals could also lead to different environmental issues such as soil and water contamination (Horrigan et al., 2002; Margni, Rossier, Crettaz, & Jolliet, 2002; Spliid, Carter, & Helweg, 2004).

With all the potential negative impacts of chemical weed control methods on human health and safety and environment, there is a need to develop alternative methods for controlling weeds including new mechanical methods and robotic platforms to assist farmers in controlling weeds mechanically.

Mechanical Control

Recently, mechanical weed control methods have been investigated as an alternative to chemical weed control. There is a growing interest among consumers in organic agriculture, and demand is increasing for foods produced and processed without synthetic substances (McEachern et al., 2005). Several studies indicated that the reasons consumers are now opting for organic food are health consciousness (Tregear, Dent, & McGregor, 1994; Zanoli & Naspetti, 2002), taste (Hill & Lynchehaun, 2002; Magnusson, Arvola, Koivisto Hursti, Åberg, & Sjödén, 2001), environmental concern (Soler, Gil, & Sanchez, 2002; Squires, Juric, & Bettina Cornwell, 2001; Wandel & Bugge, 1997) and concern over food safety (Kouba, 2003; Squires et al., 2001).

The advent of mechanization paved the way for the development of mechanical means of weed control. This method eliminates or suppresses weeds through physical disruption using mechanical tools. Some of the methods are pulling, plowing, disking and mowing. In the earlier times of mechanization, harrows and hoes were pulled by draft animals. This approach is still being practiced in developing countries. Developed countries shifted to mechanical weed control implements being powered by tractors. Farmers started to apply harrowing as this approach reduced labor requirements in crop management. In row crops, harrowing is currently also used in addition to hoeing to target weeds in the intra-row area (Van der Weide et al., 2008). Although this old method has been modernized, the application of harrowing at early crop growth stages is limited. Cirujeda et al. (2003) reported the harrowing method is efficient in controlling weeds only at their early growth stage. This process needs to be repeated throughout the growing season in order to gain sufficient control (Kurstjens & Kropff, 2001).

T. Ahmad et al. (2014) categorized mechanical weeding machines into two classes: inter-row weeders and intra-row weeders. Inter-row weeders are designed to control weeds growing between the crop plant rows. Intra-row weeding technologies seek to control weeds growing very close by or within the crop plant rows.

Inter-row Weeders

Generally, weeding mechanisms for the mechanical inter-row weeding operations include harrow, sweep, ducksfoot, hoe, and brush mechanisms. The oldest mechanical and nonchemical weeding methods are harrowing and hoeing. These mechanical operations treated the whole soil surface to eliminate weeds or reduce weed density. To reduce yield losses, machine settings and timing are essential for each weeding operation (Pullen & Cowell, 1997; Rasmussen, 1990). The most common machines for mechanical weed control available commercially are inter-row cultivators, basket weeders and rotary cultivators (Cloutier et al., 2007). Inter-row cultivators and rotary cultivators are implements with cutting edges that perform weed control action. Rotary cultivators have rotating tine mechanisms that bury the weed plants with soil, cut the weed stem or uproot the weed plant; while basket weeders have rolling cages made of spring steel shapes. Several baskets are attached to a tool bar, which is mounted to a tractor. Basket weeders remove weed plants by loosening and pulverizing the soil and uprooting the weed plants.

Intra-Row Weeders

While most of the available inter-row weeding machines perform well for the operations, weed control for intra-row operation are more challenging as weeds can grow very close to the crop or within the crop plant rows. Several tools have been developed for this purpose, such as torsion weeders and finger weeders. Below are a few examples of available machines used for intra-row weeding operations.

Brush Weeder

The brush weeder employs brush elements made of fiberglass or nylon which are rotated about a vertical axis (Figure 2.3). Its main weeding technique is to uproot the weed plants or bury the weed plants with soil. It is very effective in eliminating young weeds (Fogelberg & Gustavsson, 1999). The condition of the soil is important for this method. The weeder will only remove the top parts of the weed plants above the soil surface if the soil is too hard. Precise guidance by an operator is important to use this machine as it could damage the crop (Melander, 1997).

Torsion Weeder

The torsion weeder uses spring steel tines, which are mounted on a steel, firm frame. The tine is bent so it passes near the crop plants to control neighboring weed plants (Figure 2.4). The crop slips through the tine pairs during the weeding operation. The gap between the tines can be adjusted for different crops and different crop growth stages. The advantage of the torsion weeder that it is gentle on crop plants and can be combined with inter-row hoeing. On the other hand, this method needs precise guidance relative to the crop row during the weeding operation to work close to the crop without damaging it. This liability leads to slow weeding operations.

Finger Weeder

The finger weeder is specifically designed to control small and emerging weed plants. It uses two circular shaped rotating disk with flexible rubber spikes (Figure 2.5). This pair of mechanisms is positioned at a desired angle towards the crop, and the spikes dislodge the weeds by penetrating the soil surface. This method is ideal to control weeds for crops such as broccoli, cauliflower and cabbage. Similar to torsion weeders, crop damage could occur if the weeding mechanism was inaccurately guided relative to the crop row.

Other Methods

Blow Weeder

This method controls weed plants by utilizing compressed air to blow them from the top soil (Figure 2.6). It is able to control weeds larger than a finger weeder could handle. The downside of this method is that it could cause crop damage and requires substantial power (Norremark, Sorensen, & Jorgensen, 2006). For example, the weed blower needs a 60 kW tractor to operate which is double the power required for normal hoeing.

Flame Weeding

Flame weeding, also known as flame cultivation, was used in 1940 to mid-1960s for cotton and sorghum crops, but then usage stopped as herbicide weeding control was adopted. This method come back in the 1990's as a non-chemical weed control alternative, especially for organic farming. It uses liquefied petroleum gas (LPG) and propane gas burners to produce flames that are directed toward the weed plants (Figure 2.7). This method is costly to operate (Nemming, 1993).

Figure 2.3. Brush weeder needs precise maneuvering by an operator to eliminate weed and avoid contact with crop plants (Melander, 1997).

Figure 2.4. Torsion weeder uses bending steel spring tines to reach neighboring weed plants (Van der Weide et al., 2008).

Figure 2.5. Finger weeder uses two circular shaped rotating disk with flexible rubber spikes to control weed plants (Source: http://www.suttonag.com).

Figure 2.6. Blow weeder uses compressed air to blow weed from the top of the soil (Van der Weide et al., 2008).

Figure 2.7. Intra-row flame directs flame to weed plant (Source: http://www.bhu.org.nz/).

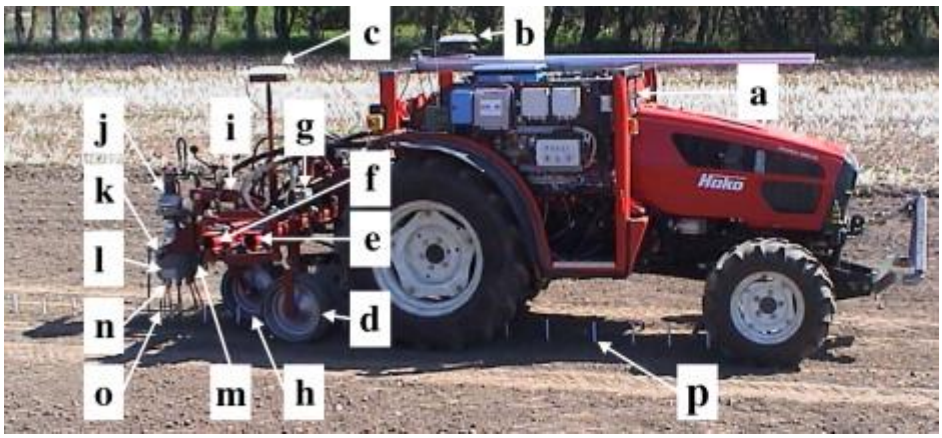

Figure 2.8. An autonomous and GPS-based system for intra-row mechanical weed control in operation at the field experiments. (a) Autonomous tractor, (b) tractor GPS antenna, (c) side-shift and cycloid hoe GPS antenna, (d) wheel for height adjustment, (e) front pass (Nørremark, Griepentrog, Nielsen, & Søgaard, 2008).

Figure 2.9. *Sarl Radis* uses light sensor to detect crop and guides a hoe in and out of the crop row.

Autonomous and Robotic Technology In Mechanical Weeding

The main issue with the above mechanical weed control methods is they do not have the capability to differentiate between weed and crop plants. This limits the effectiveness of controlling the weeds that are close to the crop plants, especially within crop rows. A potential solution is to integrate autonomous and robotics technology with mechanical weeding machines (Grundy et al., 2005). The application of robotic approaches to weed control is a relatively new idea for sustainable agricultural practices. Autonomous approaches to weed control shows potential to control weeds with higher accuracy and with less energy (Toledo, Steward, Tang, & Gai, 2014). With automation technology, the weeding process will be more efficient and ecofriendly.

Harrell, Slaughter, and Adsit (1988) stated that an autonomous agricultural and robotic weeder incorporates three basic components: a sensing system, the ability to perceive the environment and make decisions from the collected data, and actuators or end-effectors to execute those decisions.

In a review of autonomous robotic weed control systems, Slaughter, Giles, Fennimore, and Smith (2008) stated that a general-purpose autonomous robotic weed control system requires vehicle guidance using either global or local localization sensors, weed detection and identification by sensors, and precision weed control. Precision weed control can be accomplished through several means including cutting, micro-spraying, electro-mechanically guided cultivating tools, or thermal heating of the weed plants.

Automatic guidance technology utilizes machine vision systems to detect row crop or the global positioning system (GPS) to localize the vehicle and steer the vehicle to follow a desired path. There are several studies about the performance of automatic guidance of weeders. Griepentrog et al. (2006) developed an autonomous RTK (Real-time Kinematics) GPS-based intra-row weeder powered by an electrohydraulic motor. Nørremark et al. (2008) showed that by utilizing the global positioning system, the autonomous weeder could execute hoeing within crop rows without any contact with the crop plants (Figure 2.8). Laser transmitters and receivers have also been applied as localization sensors for automatic guidance. Van Zuydam et al. (1995) applied this technology in their robot thus enabling weeding and other field operations to be executed at day or night.

One of the important processes in intra-row weed control is weed plant detection and classification. The machine should have the ability to distinguish between the crop and weed plants. It is critical for an intra-row weeding machine to operate close to individual crop plants to remove or suppress the near-by weed plants. Heisel, Andreasen, and Christensen (2002) reported a decrease in yield for sugar beets with weeds that were growing close to the crop. Machine vision systems and image processing technology offer a high possibility to detect and identify the weeds during the weeding operations. Reid, Zhang, Noguchi, and Dickson (2000) reported that sensors, which are installed in automated weeding machines, have the capability to determine and differentiate crop from weeds, and precisely remove them. For example, the “Sarl Radis” (Figure 2.9), an automated weeder developed in France, used light sensors for crop detection and a control system to control the motion of the hoe relative to the crop row and around the crop plants (Cloutier et al., 2007). The travel speed of this automated weeder was 3 km/h, limited by the hoe mechanism. Chaisattapagon (1995) developed a machine vision system to distinguish weeds using three different features: color, shape and texture. Saber et al. (2015) used ultrasonic sensors to detect vegetable crops for automated mechanical intra-row pinch roller weeding mechanism. Gai, Tang, and Steward (2015) in their study stated that two-dimensional (2D) and three-dimensional (3D) vision sensors are reliable to perform plant discrimination and localization for autonomous agriculture robots. Their system detected individual crop plants in crop rows.

Until now, there are only a few complete robotic weed control systems which have been tested in the field. Mazin et al. (2013) developed an automated mechanical weeder to control intra-row weeds. This weeder could uproot weeds with heights from 10 cm to 18 cm. A robotic weeder for transplanted lettuce was developed by Blasco, Aleixos, Roger, Rabatel, and Molto (2002). Attached to the robotic end-effector was a pair of electrodes that delivered 15 kV of electrical potential to the weed plants, which eliminated them. The system operated using two machine vision systems, which identified and localized weed plants. A field test showed that the machine could identify 84% of the weeds and 99% of the lettuce plants. Pérez-Ruíz et al. (2014) developed a low-cost intra-row weeding co-robot. This machine was operated in a transplanted tomato field without harming the plants while eliminating the intra-row weeds. It reduced manual labor for intra-row weed control. Lamm, Slaughter, and Giles (2002) developed an auto-weeding machine, and the research team tested it in several commercial cotton fields. The system differentiated weed plants from cotton plants. Then, the precise micro-spray system applied chemicals to identified weed plants at a forward travel speed of 0.45 m/s. In fourteen commercial cotton field tests, the system sprayed 88.8% of the weeds and identified 78.7% of the cotton plants. Iida, Kudou, Ono, and Umeda (2000) also reported on an experiment in which an autonomous weeder resulted an 83% improvement in weed elimination compared to a mechanical approach.

Automation and robotics are technologies that can be effective in weed management. Automated weeding has the potential to overcome production concerns such as labor shortages, human mistakes resulting from fatigue, and the high costs associated with manual labor. Moreover, this technology could reduce environmental impact and promote good weed management practices. Growers can utilize the information provided in this chapter to identify and analyze the need for auto-weeding machines in their farm. Moreover, agricultural machinery manufacturers can also benefit from this research to produce improved automated weeders.

Mechanical and Automated Weed Control Efficacy

While the main purpose of a weeder is to eliminate or suppress weeds in an agriculture field, there are only a few reports documenting the efficacy of mechanical and automated weeders (Cirujeda et al., 2003; Mazin et al., 2015). A number of weeding mechanisms and automated weeding machines have been developed, but efficacy studies are largely absent. There are several reasons why efficacy results are difficult to find. Ahmad (2012) reported that differences in weed density and soil conditions affected his results. Mazin et al. (2015) found, during a performance test of a pinch-roller weeding machine, the weeding efficacy was affected by the weed species. Thus carrying out in-situ efficacy studies of weeding machines has challenges. There are some reasons why efficacy studies are difficult to execute in field operations. These reasons include time constraints, lack of standard efficacy tests and uncontrolled variables during field operations.

Time constraints are primarily due to development and testing of automated weeders taking substantial amounts of time. These requirements result in less time to focus on weeding efficacy studies. An efficacy study requires time for preparation of crop, weeds, and soil as the field conditions are highly variable. In addition, unpredictable weather events and the short growing seasons in temperate climates make it difficult to execute in-situ efficacy studies. Secondly, no standard test procedures are available to conduct an efficacy study for mechanical or automated weeders. Typically, engineers and researchers without a background in weed science develop weeders. Thus, they may not have the expertise to execute weeder efficacy studies.

Nevertheless, a systematic efficacy study has the potential to test mechanical weeders and compare their performance. As in-situ tests of mechanical weeders and automated weeders were conducted, many uncontrolled parameters need to be considered such as the surrounding temperature, soil type and moisture content (Ahmad, 2012). The variety of weeds with type, size, root depth and growth stage resulted a less systematic study of weeding efficacy (Van der Weide et al., 2008).

Even though some of the studies claimed to do efficacy tests, it is hard to compare the results with other machines as there are variety of uncontrolled variables.

Moreover, it is important how the end effector, for this case the weeding mechanism of an automated weeder, interacts with the crop biological system. The weeding mechanism has the potential to destroy or damage the crop as well as not eliminating the weeds due to uncontrolled parameters. Thus, systematic efficacy studies on different parameters can provide the settings required by the machine and the weeding mechanism to users.

This lack of efficacy knowledge and uncontrolled parameters during field experiment leads to a need for a systematic approach to gain the weeding efficacy studies. One of the possible approach is to conduct an in-situ efficacy study, but there are still limitations with uncontrolled variables such as ambient temperature, soil moisture content, soil type and variety of weeds. Another potential method is to conduct experiments under controlled conditions to determine the efficacy of mechanical weeding mechanisms in disturbing simulated weeds. A laboratory experiment with controlled ambient temperatures and soil conditions could be an effective approach to understand the effect of different parameters on weed control efficacy.

Laboratory Experimental Approach

According to an assessment of performance of sweep cultivators, row cultivators, rotary hoes and tine mechanisms conducted by Alexandrou and Coffing (2001), the latter mechanism was the most effective method for intra-row weeding.

Thus, the tine mechanism was chosen as the weeding end-effector for this research as it has several advantages:

1. It serves the purpose of controlling the weeds within intra-row crops by burying them with soil, uprooting the weeds, or cutting the weed plants.
2. It is low cost with easy maintenance and replaceable.
3. The size is relatively small. Thus with good positioning control, it could reach near the crop plant without damaging it.

A laboratory experiment was designed to test a tine and tine mechanism on simulated weeds. Wood cylinders were used to simulate weed plants as the shape is uniformed, constant and resembles the weed stem. The experiment could be conducted by simulating weed plants with various root depths, spacing density and distance between each weed plant. The experimental factors for a single tine were tine diameter, tine working depth and tine travel speed. The experimental factors for the tine mechanism were tine working depth and rotational speed of the tine mechanism. The details of these factors and experimental design are discussed on next chapter.

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CHAPTER 3 EXPERIMENTAL APPROACH TO DETERMINE THE EFFICACY PERFORMANCE BY TINE MECHANISM FOR AUTO WEEDING MACHINE

A paper to be submitted to the *Transactions of ASABE*
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Abstract

Weed plants in row crops compete for resources available to crop plants, and thus will affect crop yield and quality. Consumers show a growing interest in organic food or foods produced with fewer agricultural chemicals. Thus, there is a need to develop alternative weed control methods. A tine mechanism for an autonomous weeding machine was developed, and the interaction of a single tine and a rotating tine mechanism with the soil was investigated. The goal of this research was to develop a laboratory methodology for evaluating the effectiveness of a tine and rotating tine mechanism in disturbing weed plants simulated by individual wood pieces. Two experiments were performed using the tine and tine mechanism under a controlled laboratory environment. Soil in a 2.44 m diameter rotating bin was processed and sieved to a maximum size of 5 mm. The soil was then conditioned with water to produce a moisture content of 17%. A single tine was used in the first experiment. The experimental factors for this test were the tine diameter, tine depth and the speed of the tine being moved through the soil. For the second experiment, four tines were attached to a disk that rotated about a vertical axis. The rotational tine mechanism was tested at different working depths and disk rotational speeds. All of these tests were conducted in a rotating soil bin at a controlled speed. The position and orientation of each simulated weed were observed in each trial. The effects of the tines were captured in a Mean Likelihood of Control (MLC) parameter,

an estimate of the mean likelihood of simulated weeds being control by the tine. Significant differences were observed in the MLC across tine diameter, tine working depth and across travel speed. Interaction of tine diameter and the tine working depth had a significant effect on MLC. For the second experiment, significant differences were observed in MLC across tine working depth and rotational speed of tine mechanism. Interaction of working depth and tine mechanism rotational speed had a significant effect on MLC. All of the factors tested were important and can be used for determining machine settings in the field.

Keywords: tine mechanism, weeds, mechanical weed control, automated intra-row weeding.

Introduction

Weed control is a significant issue in agricultural production and has been under the attention of agricultural experts for many years because weed competition reduces crop yield and quality. Weeds in row crops compete for nutrients, space, moisture, and sunlight available to crop plants (M. Tollenaar & J. Wu, 1999). Without effective weed control, reductions in crop yield and quality will reduce revenue for growers. Granitto et al. (2002) reported that weed infestations lead to crop losses because of nutrient and moisture competition between crop and weeds. Tollenaar et al. (1994) reported that the mean grain yield of four maize (*Zea mays* L.) hybrids across three years of experiments was 65% higher in weed-free treatments. With the negative effect of weeds on crop production, effective methods for controlling weeds are needed. Weed control efficacy is important to obtain high crop yield and quality.

Generally, there are four types of weed control methods: manual, biological, mechanical, and chemical control. Manual weed control is the earliest method in which farmers used their hands or hand tools to eliminate weeds. It is, however, time consuming and laborious (Gianessi & Reigner, 2007). With the advent of mechanization, mechanical weed control methods were developed, first with cultivators being pulled by draft animals and then with engine-powered tractors. More recently, some farmers have practiced biological weed control in agricultural production by using natural enemies of the weeds, such as herbivores, predators, insects, parasites or diseases (McEvoy et al., 1991; Stiling, 1992). The most commonly used weed control method today in the United States and other developed countries is chemical weed control (Cloutier et al., 2007). Chemical weed control has the advantages of low cost, easy and rapid application, and good efficacy compared with the other three methods.

Despite the effectiveness of chemical weed control, weeds are adaptable plants that continually evolve in response to herbicides (Upadhyaya & Blackshaw, 2007). Moreover, there is an increasing public concern about the use of agricultural chemicals for food production, and the demand for organic food is increasing (McEachern et al., 2005). Other alternatives to chemical weed control have thus been explored such as biological control and mechanical control. Mechanical weed control has several advantages over the other methods. It is faster, less laborious and more efficient compared to manual and biological control (B. Melander, Rasmussen, & Bàrberi, 2005; Pannacci & Tei, 2014). Mechanical weed control kills or damages weeds by cutting or bruising roots, leaves, or stems of the weed, burying weed plants with soil, or uprooting the weed plants. Consequently, it is good to investigate the effectiveness of mechanical weed control mechanisms.

Ahmad et al. (2014) reported there are two types of mechanical weeding machines: inter-row weeders and intra-row weeders. Inter-row weeders are designed to control weeds growing between the crop plant rows. Intra-row weeding technologies seek to control weeds growing very close by or within the crop plant rows. Mechanical inter-row weeders such as inter-row cultivators, basket weeders and rotary cultivators are already available commercially (Cloutier et al., 2007).

There are several mechanical weed control methods, namely: weed pulling, mowing and tillage (Tu et al., 2001). Weed pulling involves a tool grasping the weed stem and removing the weed together with its root. Mowing is a method of cutting, shredding or removing the above ground biomass. Tillage is the process of turning over the soil and disturbing the weed plant. Example of implements to mechanically control weeds are row cultivators, hoes and rotary tillers (Bowman, 1997). However, it is challenging to control weeds for intra-row weeding mechanically. Several types of mechanical weeders are available for intra-row weeding operations including harrows, brush weeders, torsion weeders and finger weeders.

The application of automation and robotic approaches to weed control is a relatively new idea for sustainable agricultural practices. Autonomous approaches to weed control show potential to control weeds with higher accuracy but with less energy (Toledo et al., 2014). With automation technology, the weeding process will be more efficient and ecofriendly. Reid et al. (2000) reported that sensors, which are applied in an automated weeding machine, have the capability to determine and differentiate crop plants from weed plants, and assisting the machine to remove them. For example, the “Sarl Radis”, an automated weeder developed in France, used light sensors for crop detection and a controller system to control the motion of a hoe relative to the crop row and around the crop plants (Cloutier et al., 2007). Iida et al. (2000) also reported on an experiment in which an autonomous weeder resulted an 83% improvement in weed elimination compared to a mechanical approach.

Until now, there are only a few complete autonomous weed control systems which have been tested in the field. Mazin et al. (2013) developed an automated mechanical weeder to control intra-row weeds which could uproot weeds with heights from 10 cm to 18 cm. Pérez-Ruíz et al. (2014) developed a low cost intra-row weeding co-robot which reduced manual labor for intra-row weed control by 58%. Although with all the development of autonomous and robotic weed control systems, there are few studies reporting on the efficacy performance of the weeding control.

It is challenging to conduct an efficacy study of a mechanical weeder. Ahmad (2012) in his performance study of an automated mechanical weeder reported that differences in weed density and soil conditions affected his results. During a performance test of pinch-roller weeding machine, Mazin et al. (2015) found that weed species was one of the major factors effecting weeding efficacy.

There are several reasons why few mechanical weeder efficacy studies have been reported. These reasons include time and seasonal constraints restricting the time available to conduct experiments, the weeder designers may not have background or expertise in weed science needed to perform the experiments and many uncontrolled parameters in the field that need to be considered such as the ambient temperature, soil type, soil moisture content and soil strength (Ahmad, 2012). The variety of weeds with varying sizes, root depths and growth stages can result a less systematic study determining weeding efficacy (Mazin et al., 2015).

This lack of efficacy knowledge and uncontrolled parameters during field experiment leads to a need for a systematic approach to gain understanding of the weeding efficacy of mechanical weeders. One of the potential approach is to conduct an in-situ efficacy study, but there are still limitations with uncontrolled variables. The other approach is to conduct experiments under more controlled conditions. A laboratory experiment with controlled ambient temperatures and soil conditions could uncover the effects of different parameters on weed control.

According to an assessment conducted by Alexandrou and Coffing (2001) of the performance of sweep cultivators, row cultivators, rotary hoes and tine mechanisms, the latter mechanism was the most effective method for intra-row weeding. Therefore, this research mainly focused on the performance of tine mechanism. This tine mechanism was designed for automated intra-row weeding machine in vegetable crop production.

The specific objectives of this research were to:

1. Investigate the effect of tine diameter, tine working depth and travel speed on the ability of a single tine to disturb simulated weed plants.

2. Investigate the effect of tine working depth and the rotational speed on the performance of a tine rotating tine mechanism in disturbing simulated weed plants.

Materials and Methods

Experiment Apparatus

Two experiments were conducted in Advanced Machinery Systems Lab (AMSL) at Iowa State University in Ames, Iowa. The first experiment investigated the effect of a single tine on simulated weed plants. The second experiment was designed to determine the performance of a rotating tine mechanism design for intra-row weeding. This mechanism consisted of a circular disk that rotated about a vertical axis, with four tines mounted on it. A 2.44 m diameter circular soil bin was used for this experiment (Figure 3.1). The bin was rotated by a hydraulic power unit. The soil bin had a rotary tiller powered by another hydraulic power unit. The tiller mixed the soil, and an adjustable horizontal blade levelled the soil at the beginning of every experimental trial.

Figure 3.1. The circular soil bin with controlled speed used for the tine-soil interaction experiment located at AMSL at Iowa State University with a diameter of 2.44 m.

Soil Characterization

The particle size distribution of the soil was measured using ASTM C136 and had a composition of 32% sand, 43% silt and 24% clay. According to the USDA Soil Classification System, the soil was classified as loam.

The soil Atterberg engineering properties including the soil liquid limit and soil plasticity limit were measured according to ASTM D4318. The plasticity index was calculated from the soil plasticity limit and soil liquid limit as shown in:

$$P_I = P_L - L_L \tag{1}$$

where P_I is the plasticity index,

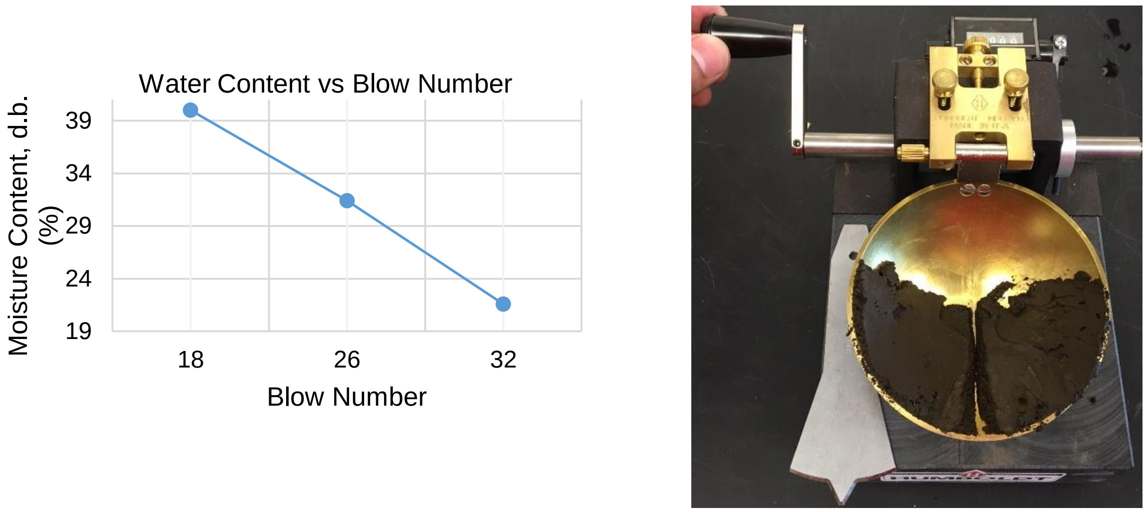
P_L is the plastic limit, and

L_L is the liquid limit,

all of which are in terms of moisture contents on a dry basis. These soil parameters are used to characterize engineering soil behavior such as shear and stress strength, compressibility and permeability.

The soil water content (%, dry basis) vs blow number was plotted for the loam soil to determine the liquid limit (Figure 3.2a). Blow number is the number of drops of a brass cup containing the soil under test required to close a groove in the soil sample after drawing the grooving tool through the soil (Figure 3.2b). According to the ASTM D4318 standard, the liquid limit is the soil moisture content at a blow number of 25. In this case, the liquid limit of was 32 % (d.b.).

The soil's plastic limit moisture content was determined using the method described in ASTM D4318. The soil moisture content at the plastic limit was 23 % (d.b.).



(a) (b)

Figure 3.2 Soil Water content vs blow number (a) measured using the Liquid Limit Apparatus (b) for loam soil. At Blow Number, N=25 the value of soil moisture content was 32% representing the liquid limit.

The soil Atterberg limits and associated visual observation of the engineering behavior of the soils under shearing loading were used for monitoring the wetting schedule of the soil in the bin.

To determine soil compressibility behavior under different soil moisture content, (Tekeste, Habtzghi, & Koolen, 2013) showed that soils with moisture content approximately 2/3 of that at the soil plastic limit were in friable soil aggregate states. For the soil bin study on tine-soil interaction, friable and low soil smearing behavior was preferred. Soil samples were prepared at two levels of soil moisture content namely 17% and 20% M.C., which were 2/3, and 5/6 the difference between plastic limit and air-dry limit respectively. The air-dry limit was 4% M.C. At 17% M.C., visual inspection of soil aggregates under thumb shearing showed friable and low smearing behavior. At 20% M.C., the soil exhibited a higher smearing behavior and thus was not suitable for the experiment. Therefore, for all the tine-soil interaction tests of loam soil in the circular soil bin, the soil moisture content was maintained at 17% M.C. (d.b.) by periodically rewetting with a water mist.

Soil Preparation for Tine Experiment

The soil bin was filled with approximately 2.2 m^3 of 5 mm sieved loam soil. The soil had an initial soil bulk density of 1.27 g /cm^3 and an initial air-dry soil moisture content of 3.58% (d.b.). The mass of soil was 1,145 kg, which was calculated using:

$$M = V\rho \tag{2}$$

where ρ is the density in kg/m^3,

M is the mass in kg, and

V is the volume in m^3.

The dry soil mass was calculated as 1,106 kg using the equation:

$$M_{D.S} = \frac{1}{1 + M.C.} M_s \tag{3}$$

where $M.C.$ is the moisture content of the water (dry basis),

$M_{D.S.}$ is the mass of dry soil in kg, and

M_s is the mass of soil in kg.

The sieved loam soil was prepared in a uniformly loose condition by tilling with a rotary tiller to a depth of about 160 mm. The soil surface was then levelled with a scraper blade. This tilling and leveling process was repeated for every trial.

The soil moisture content was controlled throughout the experiments. Samples were taken to a laboratory for measuring the moisture content by using an industrial oven according to the ASTM D4318 standard.

Test Procedure

The first experiment was conducted from 15th to 20th of May 2016, to investigate the soil disruption and the disruption to weed plants at different tine depths, travel speeds and tine diameters. Small, young weed plants were simulated by using 70 mm long and 2 mm diameter wood cylinders. Wood cylinders were used to simulate weed plants for this laboratory experiments because they are consistent, uniform, and resemble the weed stems. They easily penetrated the soil and their depth was easily adjusted. The wood cylinders were inserted into the soil to a depth of 50.8 mm in a row perpendicular to the direction of travel of the tine at a spacing of 6.35 mm between cylinders.

For each experimental trial, five sets of 15 wood cylinders were inserted into the soil (Figure 3.3). For each set, the eighth wood cylinder, counting from the inside end of the row, was placed at the center of the row approximately at the tine line of action (Figure 3.4). A three factor factorial design was used for this experiment with three different tine diameters (6.35 mm, 7.94 mm, and 9.525 mm), three working depths (25.4 mm, 50.8 mm, and 76.2 mm) and two travel speeds (0.23 m/s and 0.45 m/s; Table 3.1). Eighteen experimental trials were conducted per experimental replication.

The experiment consisted of three replications resulting in a total of 54 trials. There were 4,090 observations consisting of the status of individual wood cylinders after a tine passed through the wood cylinder row. The observations were made by categorizing the effects of the tine on the wood cylinders.

Figure 3.3. Five sets of each with 15 woods cylinders was set up in the soil bin for a trial.

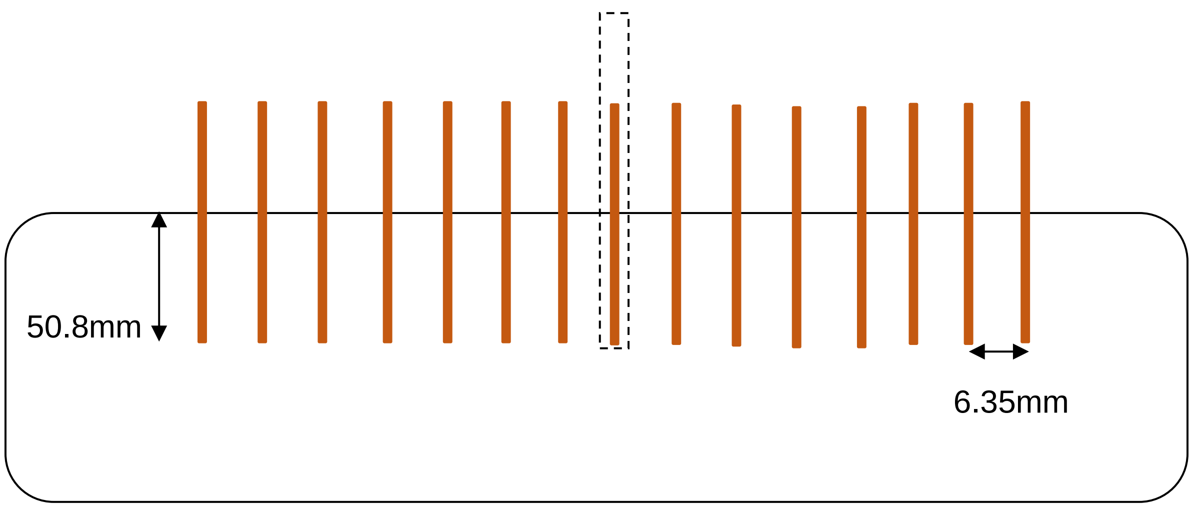


Figure 3.4. Schematic for the wood cylinders setting with depth penetration of 50.8 mm and distance of 6.35 mm from each other. The eighth wood cylinder was placed at the center of row.

Table 3.1. Levels of different tine diameters, working depths and travel speeds used for the first experiment.

Factor	First Level	Second Level	Third Level
Tine Diameter	6.35 mm	7.94 mm	9.53 mm
Working Depth	25.4 mm	50.8 mm	76.2 mm
Travel Speed	0.23 m/s	0.45 m/s	None

In both experiments, the effect of tines on the simulated weed plants were observed. The effect of the tine resulted in changes in the location and orientation of each simulated weed. Each individual simulated weed plant observation was captured in a Likelihood of Control (LC) parameter which was intended to indicate the mean likelihood of simulated weeds being controlled (i.e. uprooted, cut or buried) by the mechanism. There were five LC categories in which each wood cylinder was placed depending on the movement of the wood cylinder caused by the interaction (
Table **3.2** and

Figure **3.5**). These categories were:

1. The most extreme case where the simulated weed was completely extracted from the soil and laying on the soil surface. Simulated weeds affected in this way were assigned an LC value of 90 percent.
2. The simulated weed was moved from its original position and tilted. Simulated weeds affected in this way were assigned an LC value of 60 percent.
3. The simulated weed was moved from its original position but was still vertically oriented. A 30% LC value to each simulated weed in this state.
4. The simulated weed was still in its original position but tilted and assigned a 10% LC value.
5. For simulated weed with no change in location or orientation, a 0% LC value was assigned.

Table 3.2 Code and the description of the affected simulated weed disturbed by tine.

CODE	Likelihood of Control (LC) %	DESCRIPTION
	90	The stick was pulled completely out of the soil.
	60	The stick was moved from its original position and tilted.
	30	The stick was moved from its original position but was still horizontally straight.
	10	The stick was on its original position but tilted.
	0	No change was observed.

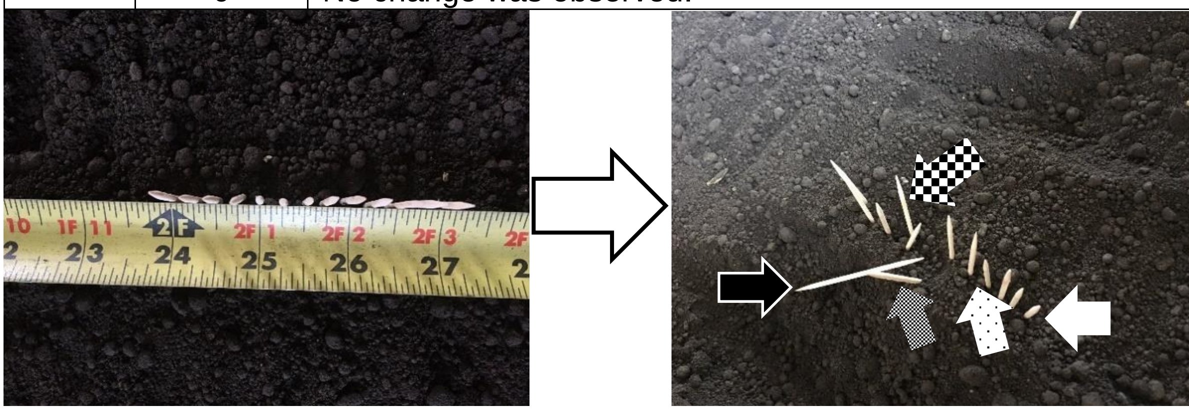


Figure 3.5 The arrangement of one set of wood cylinders as the simulated weed (left) and the effect of tine to a set of wood cylinders after a trial with pattern as indicated in Table 3.5 (right). The pattern arrow matches the pattern code in Table 3.5.

The second experiment was conducted on May 30th 2016. In this experiment, a rotating tine mechanism was used. The mechanism had four tines inserted into a steel disk located with equal spacing around a circle with a 7.94 mm diameter (Figure 3.6). Each tine was circular with a 152 mm diameter cross section. A two factor factorial design was used for this experiment with two working depth levels (25.4 mm and 76.2 mm) and three tine mechanism rotational speed levels (25 rpm, 50 rpm and 100 rpm; Table 3.3). The soil bin linear speed at the center of the tine mechanism was 0.45 m/s. The experiment consisted of six experimental trials per replication with three replications for a total of 18 experimental trials. The same method of using wood cylinders to simulate weed plants as the first experiment was used. However for this experiment, the rotating tine mechanism had a wider width of influence as compared with a single tine, thus 21 wood cylinders were used per row with a spacing distance of 12.7 mm between wood cylinders resulting in 254 mm long rows. A total of 1,890 observations of the status of individual wood cylinders were recorded after the rotating tine mechanism passed through them.

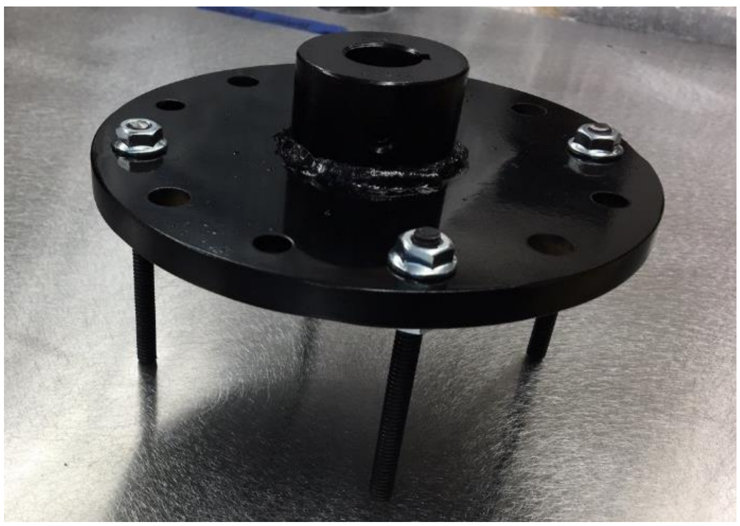


Figure 3.6. Rotating tine mechanism with four mounting tines.

Table 3.3. Levels of different working depth and rotational speed of tine mechanism used for the second experiment.

	First Level	Second Level	Third Level
Working Depth	25.4 mm	76.2 mm	None
Speed of Tine Mechanism	25 rev/min	50 rev/min	100 rev/min

Data Analysis

For the first experiment, the SAS (SAS 9.4) MIXED procedure was used to analyze the dependent variable, the Mean Likelihood of Control (MLC) percentage. MLC was calculated by taking the mean value of the Likelihood Control (LC) values for each individual simulated weed plant from each trial. In the first experiment, a 3 (tine diameter) x 3 (tine working depth) x 2 (travel speed of tine) analysis of variance (ANOVA) was performed on the MLC percentage. Diameter of tine, tine working depth, travel speed, interaction between diameter of tine and tine working depth, interaction of diameter of tine and travel speed, interaction of tine working depth and travel speed, and three way interaction between diameter, tine working depth and travel speed were treated as fixed effects. For statistically significant fixed effects, post hoc pairwise comparisons with a Tukey adjustment were performed. A priori significance level was set at 0.05.

The same SAS MIXED procedure was applied for the second experiment to analyze the MLC percentage as the dependent variable. For the second experiment, a 2 (tine working depth) x 3 (rotational speed of tine mechanism) analysis of variance (ANOVA) was performed. Tine working depth and rotational speed of rotating mechanism and the interaction between these two independent variables were treated as fixed effects. Pos hoc pairwise comparisons with a Tukey adjustment were performed for statistically significant fixed effects.

Results and Discussion

In the first experiment, there was a significant main effect for all three factors; tine diameter (F (2, 36) =47.29, *p*= <.0001), tine working depth (F (2, 36) =65.51, *p*= <.0001), and travel speed of tine (F (1, 36) =5.29, *p*= 0.0274). As for the interaction case, there was statistical evidence of an interaction of tine diameter and the working depth of tine (F (4, 36) =4.66, *p*= <.0039). However, there was no statistical evidence of an interaction of tine diameter and travel speed and the interaction of working depth and speed.

The interaction of tine diameter and working depth had a significant effect on the MLC. Because of this interaction, post hoc pairwise comparisons with a Tukey adjustment were performed (Table 3.4).

The residuals are consistent with random error (Figure 3.7). The random errors were assumed to be normally distributed. The residual plot shows the variance between the calculated and measured values of the dependent variable as a function of the measured values. The residuals were randomly distributed about the line of error with zero mean. The histogram of the residual shows they were normally distributed (Figure 3.8). The symmetric bell-shaped histogram which was evenly distributed around zero indicates that the normality assumption is likely to be true.

Table 3.4. Effect of diameter and depth interaction on the Mean Likelihood of Control (%). Values are mean ± standard deviation. Within a column, means followed by the same letter are not significantly different at $p < 0.05$.

Diameter (mm)	Depth (mm)	Mean Likelihood of Control (%)
6.35	25.4	9.51 ± 3.43 a
	50.8	14.78 ± 3.73 a b
	76.2	19.00 ± 3.26 b c
7.94	25.4	14.89 ± 4.44 a
	50.8	19.360 ± 3.6 b d
	76.2	23.93 ± 2.01 c e
9.53	25.4	14.91 ± 3.85 a d
	50.8	26.40 ± 5.15 e
	76.2	34.02 ± 7.08 f

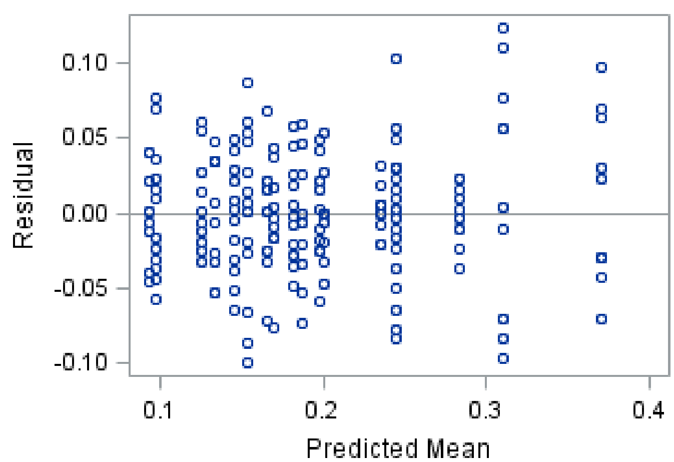


Figure 3.7. Residuals plotted against predicted mean shows the residuals were constant with random error.

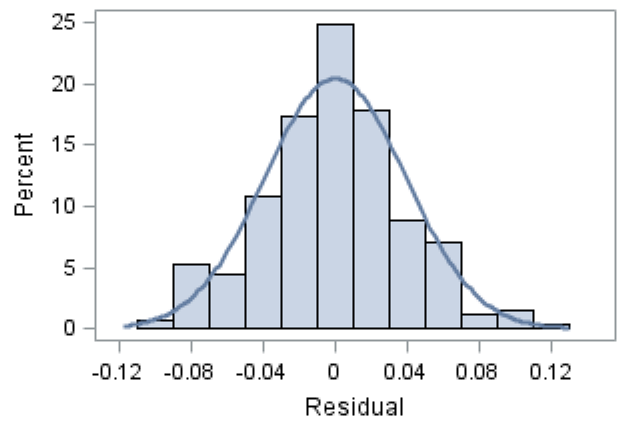


Figure 3.8. The symmetric bell-shaped histogram of the residuals was evenly distributed around zero.

Data were further analyzed by graphically representing the LC values assigned to individual simulated weeds (Figure 3.9). For example, in the first replicate with tine diameter of 7.92 mm, working depth of 50.8 mm and speed of 0.45 m/s, all the simulated weeds placed in the middle of each row were completely removed with LC value of 90. The LC value decreased to 60 and 30 when the simulated weeds were further from the tine. The four simulated weeds furthest from the tine were not affected by the tine. Using the LCs for each simulated weed observation, the mean of LC for each trial was calculated (Table 3.5). The frequency of individual observations of each simulated weed for this trial with all three replications were also presented in a histogram (Figure 3.10). This histogram represented a case with an MLC near the middle of the MLC range and was achieved with the tine size and working depth factors at the middle levels. It can be compared to those representing the results associated with cases with low MLC values (Figure 3.11) and high MLC values (Figure 3.12). One can observe a decrease in simulated weed disturbances in the low MLC case with no simulated weeds being completely “uprooted.” More high value LCs resulted for the trials with bigger sizes of tine diameter, larger working depth and higher lateral speed. All these factors have a substantial effect on weed plant disruption.

The histograms are presented with in order of treatments with increasing MLC values. The frequency of 0% LC observations decreased, and 90% LC observation increased across the treatments associated with figures 3.10, 3.11 and 3.12.

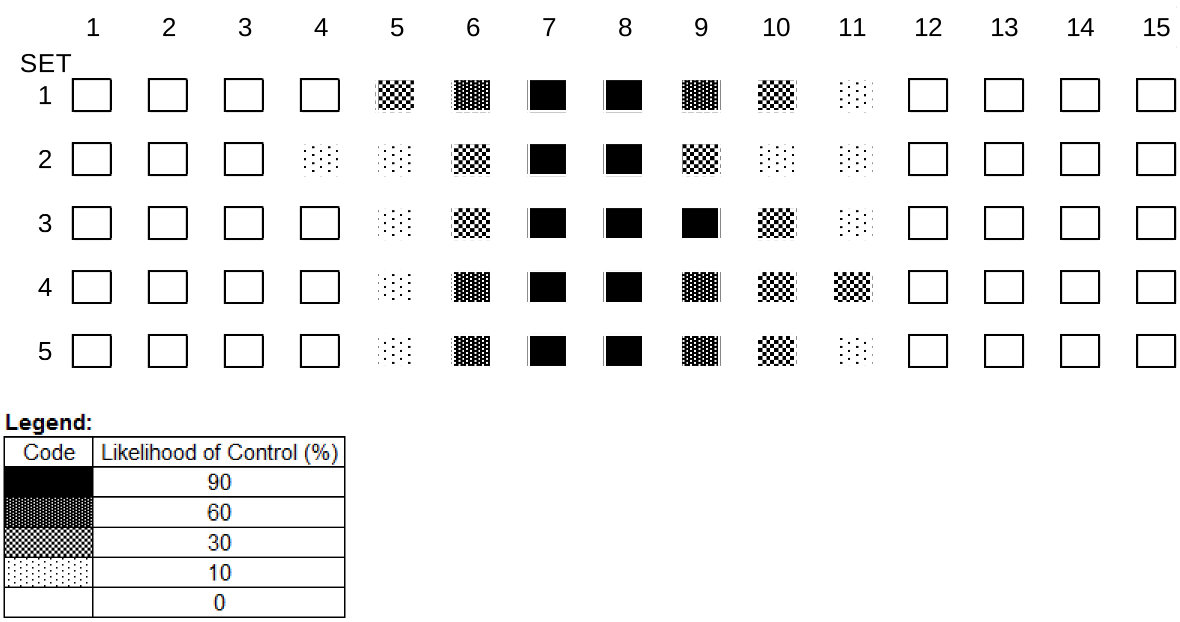


Figure 3.9. Results from the first replication of case of tine diameter of 7.92 mm, working depth of 50.8 mm and speed of 0.45 m/s. The squares represent the observations associated with each individual wood cylinder (fifteen wood cylinders per set with five sets per experimental trials). The black pattern represents and observation with an LC value of 90 with the gray scale becoming gradually light for small values of LC.

Table 3.5. Tabulated results from the first replication of case of tine diameter of 7.92 mm, working depth of 50.8 mm and speed of 0.45 m/s. Each simulated weed observation was assigned an LC code by stick number and the MLC mean of each set were calculated.

	Stick Number															Set Mean
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	0	0	0	0	30	60	90	90	60	30	10	0	0	0	0	24.7
2	0	0	0	10	10	30	90	90	30	10	10	0	0	0	0	18.7
3	0	0	0	0	10	30	90	90	90	30	10	0	0	0	0	23.3
4	0	0	0	0	10	60	90	90	60	30	30	0	0	0	0	24.7
5	0	0	0	0	10	60	90	90	60	30	10	0	0	0	0	23.3

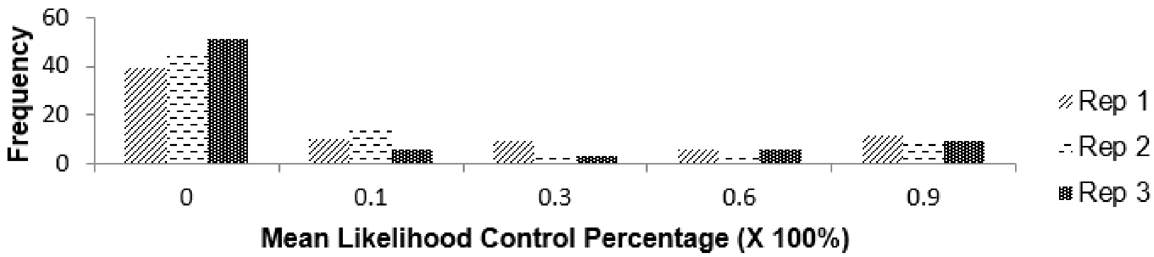


Figure 3.10 The frequency of individual observation of each simulated weed for case of tine diameter 7.94 mm, working depth 50.88 mm and speed 0.45 m/s with all three replications.

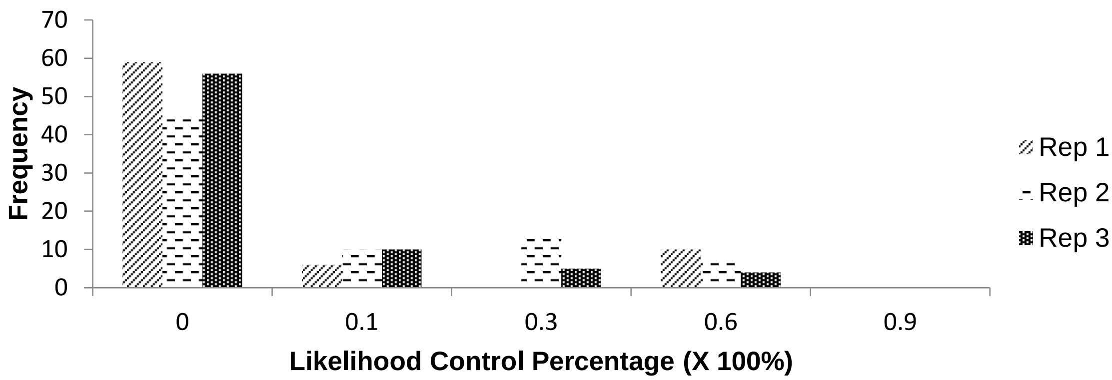


Figure 3.11 The frequency of individual observation of each simulated weed for case of tine diameter 6.35 mm, working depth 25.44 mm and speed 0.23 m/s with all three replications.

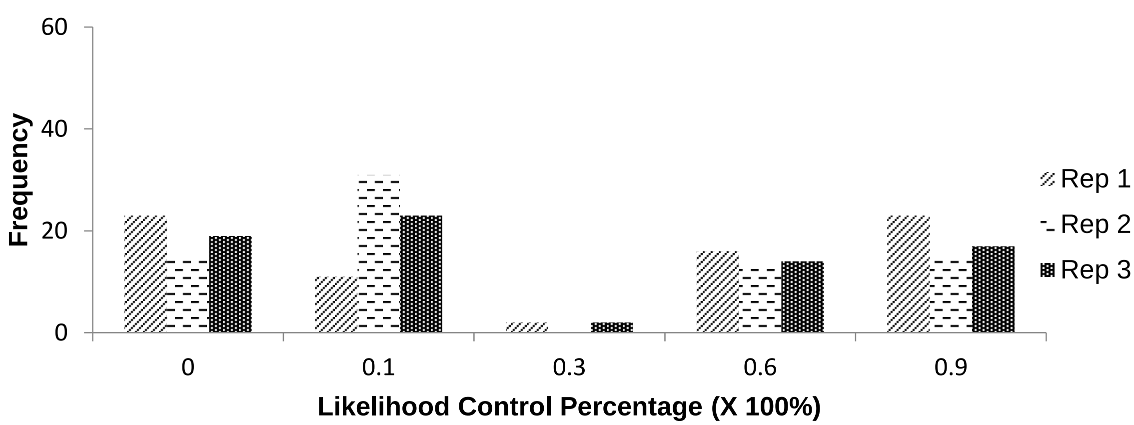


Figure 3.12 The frequency of individual observation of each simulated weed for case of tine diameter 9.53 mm, working depth 76.2 mm and speed 0.45 m/s with all three replications.

Table 3.6 Mean Likelihood of Control (MLC) Percentage for diameter 6.35 mm, 7.94 mm & 9.53 mm; depth 25.44 mm, 50.88 mm & 76.2mm; and speed 0.23 m/s & 0.45m/s.

Speed 0.23 m/s			**Speed 0.45m/s**		
Diameter (mm)	Depth (mm)	MLC %	Diameter (mm)	Depth (mm)	MLC %
	25.44	9.3 ± 2.9		25.44	9.7 ± 4.0
6.35	50.88	12.6 ± 3.0	6.35	50.88	16.7 ± 3.0
	76.2	18.2 ± 3.4		76.2	19.8 ± 3.0
	25.44	15.3 ± 5.4		25.44	14.5 ± 3.4
7.94	50.88	20.0 ± 3.1	7.94	50.8	18.7 ± 4.1
	76.2	23.5 ± 1.5		76.2	24.4 ± 2.4
	25.44	13.3 ± 3.8		25.44	16.5 ± 3.3
9.53	50.88	24.4 ± 6.7	9.53	50.88	28.4 ± 1.8
	76.2	31.0 ± 7.6		76.2	37.0 ± 5.2

When the MLC was tabulated by the combinations of experimental factors (Table 3.6), the mean MLC value increased with larger time diameters and higher tine working depths for both of the travel speeds. When the mean MLC values were plotted against tine diameter and by working depth (Figures 3.13 and 3.14) some patterns were observed. First, larger tine diameters yielded higher MLC values. This result was expected as larger tine diameters resulted in larger soil disruption areas, and then affected more simulated weed plants. This pattern was observed in all cases except for the case of a 9.53 mm diameter, a 25.44 mm depth, and a 0.23 m/s speed (Figure 3.13).

The MLC percentage of the simulated weeds increased with the higher values of working depths. This pattern was observed with every tine diameter and travel speed. This pattern was expected as deeper working depths affects wider widths of soil. The increasing pattern of the MLC percentage was also significant for higher speed trials. However, the increasing speed did not have as large an effect as that observed with the rotational speed and working depth factors.

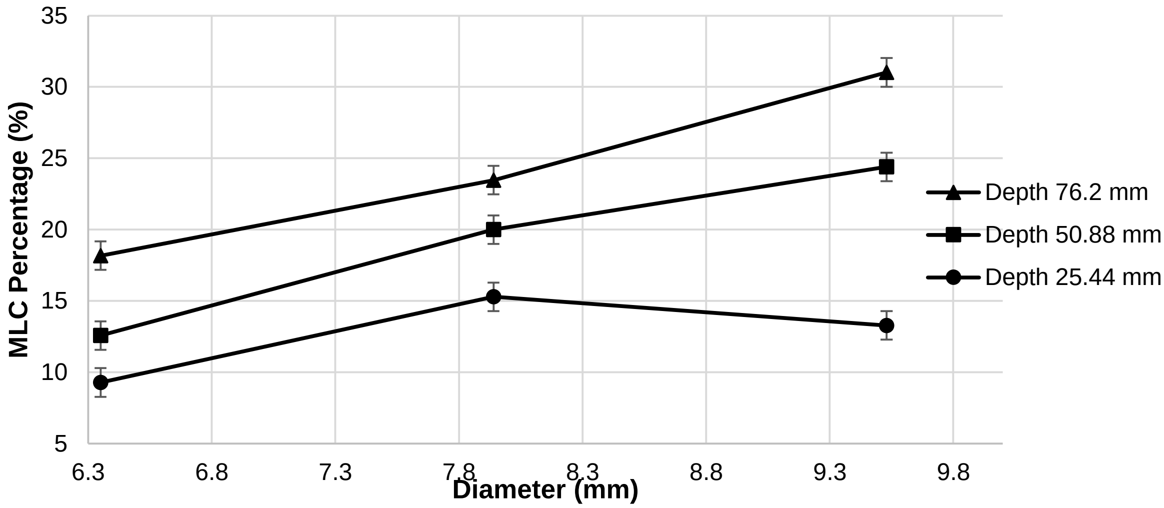


Figure 3.13. Mean Likelihood of Control (MLC) percentage vs diameter level for case speed = 1 (0.23 m/s) shows an increasing pattern in simulated weed MLC percentage except for depth = 25.44 mm & diameter = 9.5 mm.

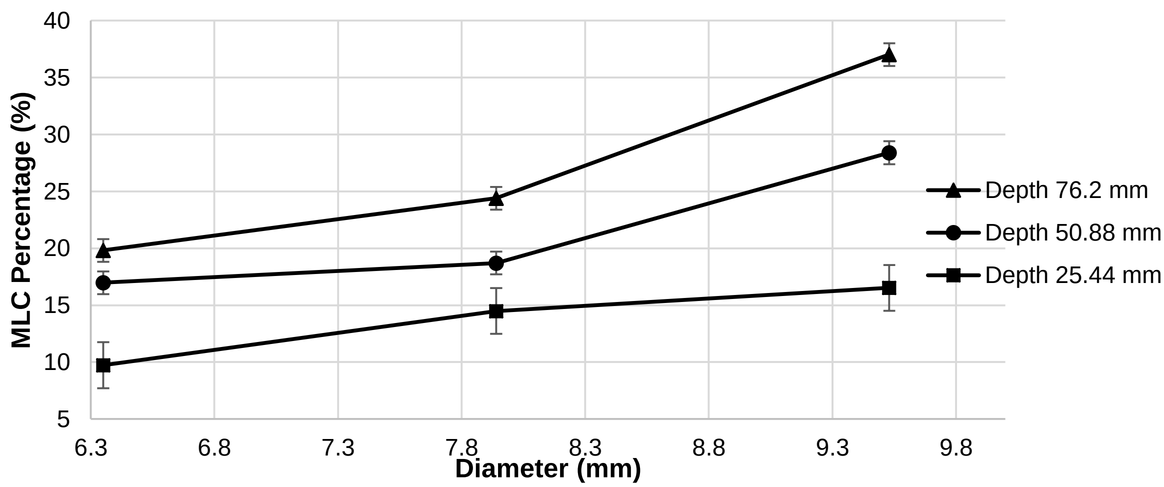


Figure 3.14. Mean Likelihood of Control (MLC) percentage vs diameter level for case speed = 2 (0.45 m/s) shows an increasing pattern in simulated weed MLC percentage.

For the second experiment, both factors had a significant main effect on MLC. For tine working depth, $F(1, 12)$ was 39.78 (p= <.0001) and for rotational speed of tine mechanism, $F(2, 12)$ was 52.5, (p<.0001). There was also statistical evidence of an interaction of tine working depth and the rotational speed of tine mechanism on the MLC percentage $F(2, 12) = 4.77$, ($p = <.0299$).

The residuals were consistent with the assumption of random error, and the model was correct on average for all fit values (Figure 3.15). The symmetric bell-shaped residual histogram was also evenly distributed around zero demonstrates that the normality assumption was likely to be true (Figure 3.16).

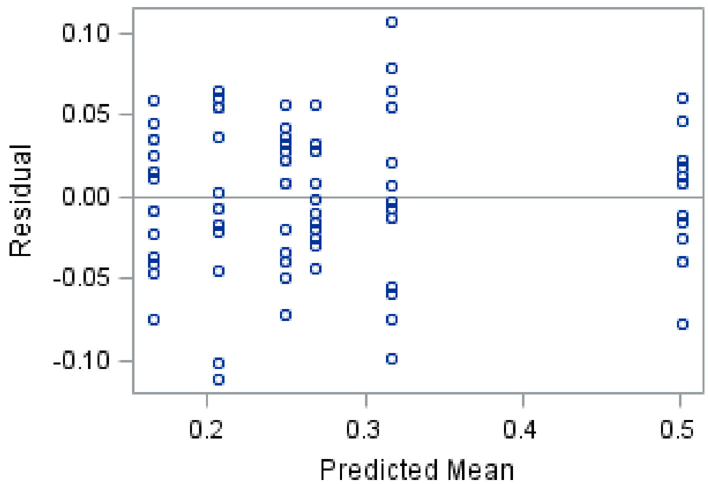


Figure 3.15. Plot of residuals vs predicted mean shows the residuals are constant with random error for the rotating tine mechanism experiment.

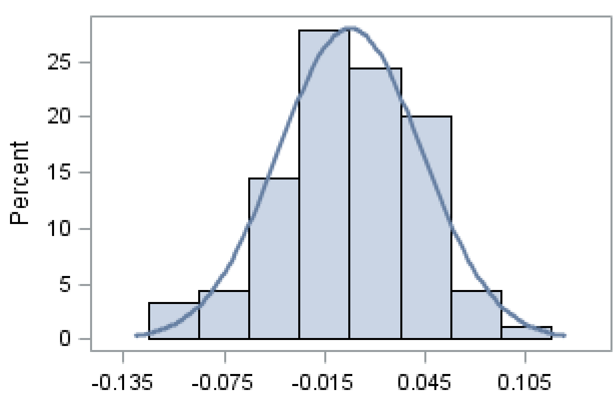


Figure 3.16. The symmetric bell-shaped histogram showed that the residuals were evenly distributed around zero for the rotating tine mechanism experiment.

Table 3.7. Mean Likelihood of Control (MLC) Percentage ± standard deviation value presented with different working depth and rotational speed of tine mechanism. Within a column, means followed by the same letter are not significantly different at p < 0.05.

Working Depth (mm)	Rotational Speed (rpm)	Mean Likelihood of Control Percentage (%)			
25.4	25	16.5 ± 4	a		
	50	20.7 ± 6	a		
	100	31.7 ± 6		b	
76.22	25	24.9 ± 4	a		
	50	26.8 ± 3		b	
	100	50.2 ± 4			c

The MLC percentage was highest at the working depth of 76.22 mm tine mechanism rotational speed of 100 rpm with the MLC value of 50.2% and a standard deviation of 4% (Table 3.7). The lowest MLC was observed at a working depth of 25.4 mm and a rotational speed of 25 rpm, with a MLC value of 16.5% and a standard deviation of 4%. A small difference was observed of 2% MLC between 25 rpm and 50 rpm at working depth of 76.22 mm. The MLC value almost doubled at 100 rpm. Because of the significant interaction between tine working depth and the rotational speed, post hoc pairwise comparisons with a Tukey adjustment were performed.

The MLC percentage increased with deeper working depth (Figure 3.17). The pattern applied to all three rotational speeds, (25 rpm, 50 rpm and 100 rpm). Deeper working depth caused a wider soil disturbance region. Thus, the probability of weed MLC was higher. This effect was observed through the increases in MLC percentage for each higher speed. MLC increased rapidly for the 100 rev/min treatments as with the depth of 6.2 mm indicates that more simulated weeds being disturbed during the experiment.

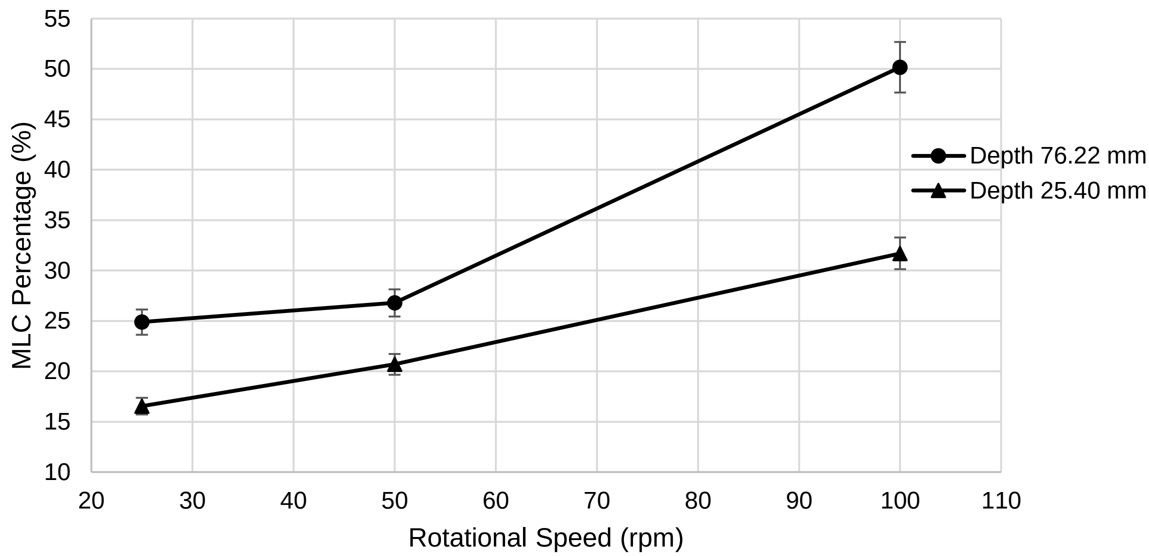


Figure 3.17. Mean Likelihood of Control (MLC) percentage vs rotational speed for rotating tine mechanism experiment displays an increasing pattern on the MLC percentage.

As for the other factors, the MLC value increased with higher rotational speeds. The pattern was observed in both 25.4 mm and 76.2 mm tine working depths. This result was expected as higher rotational speeds should disturb a larger area around the tine and then disturb a larger number of simulated weeds. This observation implies the most effective weed control occurs with higher rotational speeds and deeper working depths. Similarly, increases in MLC were observed with increases in tine mechanism rotational speed because higher rotational speeds led to a smaller distance between passes of the rotating tines and wider disturbance regions around each tine caused more disturbance on the simulated weeds.

Conclusions

A mechanical rotating tine weeding mechanism was developed for an automated intra-row weeder. Two experiments were conducted to investigate effects of the tine on simulated weeds through the soil disruption caused by the tine. The purpose of the first experiment was to investigate the effects of three factors: tine diameter, working depth and travelling speed. The second experiment investigated the effects of working depth and rotating speed of the weeding mechanism on simulated weeds. Wood cylinders were used to model the weed plants. From the experiments, it can be concluded:

1. There is statistical evidence that tine diameter, tine depth and travel speed had an effect on simulated weed MLC percentage. Larger diameter, deeper working depth and higher travel speed caused a higher MLC percentage.
2. Tine working depth and the rotating tine mechanism speed affect simulated weed MLC. The rotating tine mechanism should have better weed control with a deeper tine working depths and higher rotating tine mechanism speeds.

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CHAPTER 4 : GENERAL CONCLUSIONS

General Discussion

This research investigated the effects of a tine and a tine weeding mechanism on simulated weeds. Two experiments were conducted in a laboratory under controlled environment and soil conditions by using woods cylinders to simulate weed plants. The movement of each simulated weed due to nearby interaction with the tine mechanism was observed in each trial. The observations were captured in a Likelihood of Control parameter, which was intended to indicate the likelihood of simulated weed being controlled by the mechanism. The first experiment investigated the effect of different single tine experimental factors on simulated weed plants. The second experiment studied the effects of a rotating tine mechanism with different experimental factors on simulated weed plants.

The experimental factors of the first experiment were tine diameters, different tine working depths and travel speeds. Based on the results from the single tine experiment in Chapter 3, it was concluded that the tine diameter, tine working depth and the travelling speed of the tine all have significant effects on weed control efficacy. Moreover, there is statistical evidence of an interaction between tine diameter and the tine working depth. The potential for weed control efficacy over a wide region around the tine increased as tine diameter, working depth and travel speed increased. The largest diameter, the deepest working depth and the highest travel speed case resulted in the highest MLC value as the tine disrupted a wider soil region.

For the second experiment, statistical analysis showed that both rotational speed and depth of rotating tine mechanism affected weed control efficacy. In addition, there was an interaction between tine working depth and the rotational speed of the tine mechanism. The potential to control weeds effectively increased with deeper working depths and with faster rotational speeds. Deeper working depths led to a wider region of soil disturbance. Similarly, increases in MLC were observed with increases in tine mechanism rotational speed because higher rotational speeds lead to a smaller distance between passes of the rotating tines and wider disturbance regions around each tine caused more movement and disruption to the simulated weed plants.

From this research, the following conclusions were drawn:

1. Tine diameter, tine working depth and travel speed are significant factors in eliminating or causing damage to weeds.
2. As for tine mechanism, the tine working depth and rotational speed of the tine mechanism are significant. This implies the most effective weed control occur with higher rotational speeds and deeper working depth.

Recommendation for Future Research

This research supported the development of an auto-weeding machine which consisted of rotating tine mechanisms mounted on a pair of pivoting arms. Two prototypes are still under development and testing. One of them is powered by hydraulic actuators while the other one is powered by electrical motors. The research done and discussed in Chapter 3 was done with the latter machine but with a single arm and was performed in a controlled laboratory setting with controlled soil conditions. Since this prototype will be integrated with a machine vision system soon, it opens many of opportunities for future work with different factors, environments, soil conditions and different machines. The author would like to end this chapter with several suggestions.

1. The experiments with the single tine and the rotating tine mechanism, were carried out with loose loam soil. A similar test with different textural classes of soils and different compaction levels should be conducted to examine how these soil parameters affect weed control efficacy. This laboratory experiment could also be performed in soil conditions which are similar to vegetable crop farming in soil type, soil condition and moisture content. Statistical models from these tests could be used to calibrate the machine before the weeding process is done in different type of soils and compaction levels.
2. The effect of simulated weed depth representing different root depth for weed plants should be investigated. The results from this study might be used later to define the best machine variable settings as the tine working depth and the

rotational speed of tine mechanism to eliminate various type of weeds in a field.

3. This research was done with tine and the rotating tine mechanism moving into one longitudinal direction. Investigating the effect of lateral speed of the pivoting arm will be important for the final application.
4. In this research, different tine diameters attached to a rotating mechanism were used to test expected weed control performance. Using the methodology developed from this research, other tine designs should be tested to determine weed control efficacy performance advantages.