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Development of New Cotton Defoliation Sprayer Using Unmanned Ground Vehicle and Pulse Width Modulation Technology

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DEVELOPMENT OF NEW COTTON DEFOLIATION SPRAYER USING UNMANNED GROUND VEHICLE AND PULSE WIDTH MODULATION TECHNOLOGY

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ABSTRACT

Chemical spraying is one of the most important and frequently performed intercultural agriculture operations. It is imperative to utilize appropriate spraying technology as a selection of ineffective one leads to waste of agrochemicals to the non-target area. Several precision technologies have been developed in the past few decades, such as image processing based on real-time variable-rate chemical spraying systems, autonomous chemical sprayers using machine vision and nozzle control, and use of unmanned aerial and ground vehicles. Cotton (*Gossypium hirsutum* L.) is an important industrial crop. It is a perennial crop with indeterminate growth habit; however, in most parts of the United States, it is grown as an annual crop and managed using growth regulators. Cotton defoliation is a natural physiological phenomenon, but untimely and/or inadequate defoliation by natural processes necessitates the application of chemical defoliants for efficient harvest. Defoliation is a major production practice influencing harvester efficiency, fiber trash content, cotton yield, and fiber quality. Currently, defoliant spraying is done by conventional ground driven boom sprayer or aerial applicator and both systems spray chemical vertically downwards into the canopy, which results in less chemical reaching the bottom of the canopy. Thus, a new autonomous ground sprayer was developed using robotics and pulse width modulation, which travels between two rows covering the whole canopy of the plant. Field research was conducted to evaluate the (i) effect of duty cycles (20%,40%, and 60%) on droplet characteristic (droplet distribution, deposition, and drift potential), defoliation cotton fiber and (ii) effect of duty cycles on cotton yield and fiber quality. Droplet characteristics (droplet distribution, density, and potential droplet drift) were non-significant across the treatments and results from the water-sensitive paper field test showed adequate penetration with low flow rates. Therefore, a 20% duty cycle was sufficient to defoliate based on the result of the field experiment. Likewise, the defoliants could be applied safely at the duty cycles tested without influencing fiber quality except for nep/gm, length (Ln), L (5%), short fiber content (SFCn), trash content in field 1 and micronaire, nep size, length (Ln), span length (5%), SFC, and fiber fineness in field 2 which were significant. However, the 20% duty cycle significantly reduced the amount of defoliant and would be a good choice for the autonomous cotton defoliation. This is a significant development as there is a huge potential to save on the cost of applying defoliant chemicals and the environment.

Keywords: Agricultural sprayer; Cotton defoliation; fiber quality; intelligent spray; robotics

DEDICATION

I would like to dedicate this thesis to my grandparents, my parents (Bhagwati Neupane and Shubhakhar Neupane), my siblings (Nirmal, and Pratibha) and my dear husband (Sagar GC) for their support in making me pursue a master's degree abroad. I would like to dedicate this thesis to my major advisor, and my committee members for their proper guidance throughout my research and course work. At last, but not least, to all scientific community who is researching relentlessly for better future.

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ORGANIZATION OF THESIS

This thesis contains four chapters, including the Introduction (Chapter 1), The effect of controlled defoliant application on droplet characteristics and defoliation rate (Chapter 2), Effect of controlled defoliant application on Cotton fiber quality (Chapter 3), and Conclusion and Future Direction (Chapter 4).

CHAPTER ONE

LITERATURE REVIEW

1.1 INTRODUCTION

Chemical spraying is one of the most important and frequently performed intercultural operations in agriculture (Ahmad and Sultanm, 2021). Based on the target, pesticides are classified as herbicides, insecticides, and fungicides to kill weeds, insects, and pathogens, respectively (Yadav and Devi, 2017). Similarly, some chemicals are used to enhance the harvest process, such as harvest aids and defoliant (Jin et.al, 2020). Even though using agrochemicals can effectively enhance crop production, it does have impacts on production cost, human health, and the environment (Grisso et. al, 1989). Pesticide resistance is another major problem due to the overuse of chemicals (Hawkins, 2019). During the green revolution, more agrochemicals were used to increase crop production, which created environmental degradation, human health effects, and high yields (Wilson, 2000; Bjørling-Poulsen et. al, 2008)

Moreover, pesticides can remain active in soil and water for an extended period, which causes soil degradation, eutrophication, algal bloom, and decline in the fisheries (Wilson, 2000). Thus, it is vital to consider spraying methods, plant characteristics, the nature of chemicals, and weather conditions while applying agrochemicals to achieve an efficient and less harmful effect. According to a Food and Agriculture (FAO) report, 2.7 million tons of pesticides (active ingredients), equivalent to USD 41.1 billion, was used for agriculture purpose worldwide. The United States ranks first by consuming.

nearly 0.5 million tons of pesticides then followed by Brazil and China. Previously, China used to be top consumer; however, they significantly cutoff the use of pesticides (FAO, 2022).

1.2 SPRAY APPLICATION TECHNOLOGIES

Selection of the appropriate spray application technology can reduce waste of agrochemicals in the production and non-target areas. Advancements in new technologies in precision agriculture, such as the use of sensors, artificial intelligence, and unmanned vehicles has increased efficiency in agriculture.

Introduction of the different sprayer technology, including tunnel sprayer technology, has been proven most effective for the orchards and vineyards, which enclose the target spray mixture to reduce airborne drift and soil contamination. Moreover, it is based on the air circulation and liquid recycling principle as mentioned by Ade et al., (2007) where they found 20~50% of applied chemical liquid recycled with the application of tunnel sprayer on a vineyard. Jamar et al., (2010) also found an average 30% of the spray volume was recycled which contributed to more environmental sustainability compared with traditional machines. Tunnel sprayer was found to be more suitable for dwarf trees using traditional hydraulic nozzles.

A tower sprayer that sprays chemicals horizontally with airflow direction is suitable for taller plants. Tower air conveyor sprayers have greater advantages on the distribution of air and pesticides in the trees, which help to minimize the loss of pesticides during spraying (Cunningham and Harden, 1998), but the airspeed, airflow, and power should be considered as these factors significantly impact spray penetration into the orchard canopy

(Panneton et al., 2005). Cannon air blast sprayers with cylindrical outlets create high air velocity jets to break spray mixture into finer droplets which enhances good canopy penetration, especially in the orchards, such as blueberry, where spray is directed across the tops of the blueberry rows resulting in fewer passes in the field and reduces mechanical damage to developing fruits (Hanson 2000). Similarly, this air-assisted spraying technology is used in cereal production to control insect pests (Gimenes et.al, 2012).

Ultra-low volume (ULV) sprayers are very effective for controlling insects in cotton plants (Cauquil, 1987). Reduced application rate, drift potential, and waste are the primary benefits of ULV. Likewise, electrostatic techniques are emerging technology in agriculture. The concept behind ULV is the retention of the chemical on plant through imparted particle charge. Examples of this concept include air-assisted electrostatic spray, aero-dynamic electrostatic spray, postharvest electrostatic sprays, and electrostatic pollination (Edward Law, 2001).

Conventional tractor-mounted boom sprayers spray on the upper sides, which is not effective for controlling sucking insects because they are typically found on the bottom side of the leaves. Conventional application of pesticides at a uniform rate can result in off-target movement to sensitive areas. With advancements in sprayer technology, variable rate application of pesticides has the promise to apply the chemicals precisely to the pest target.

Many precision technologies have been developed in the past few decades, such as an image processing based on real-time variable-rate chemical spraying system (Tewari, 2020) autonomous chemical sprayer using machine vision and nozzle control (Terra, 2021), the use of un-manned aerial vehicle (Faiçal 2014; Faiçal, 2017), and electrical robots (Cantelli, 2019).

Esau et al., 2018 reported that a machine vision smart sprayer for spot-application of agrochemical in wild blueberry reduced fungicide use by 11.6% along with a significant increase in the health of plant and harvestable yield. Llorens et al., 2010 and Asaei et al., 2019 reported reduction of more than 50% of the pesticide with machine vision variable rate application compared to the fixed rate conventional sprayer in orchards. Using machine learning, spectral images have improved their ability to achieve precise and accurate application. Similarly, unmanned vehicles are be used for multiple purposes for example, unmanned aerial vehicles (UAV) are widely used for spraying, mapping, planting, crop health monitoring, and harvesting (Figure 1). However, there are some significant limitations to UAV, such as battery and flight time (Kim et.al, 2019). In cotton, researchers are using UAV to spray chemicals and predict application volume using images analyzed through the remote sensing (Chen et.al, 2022).

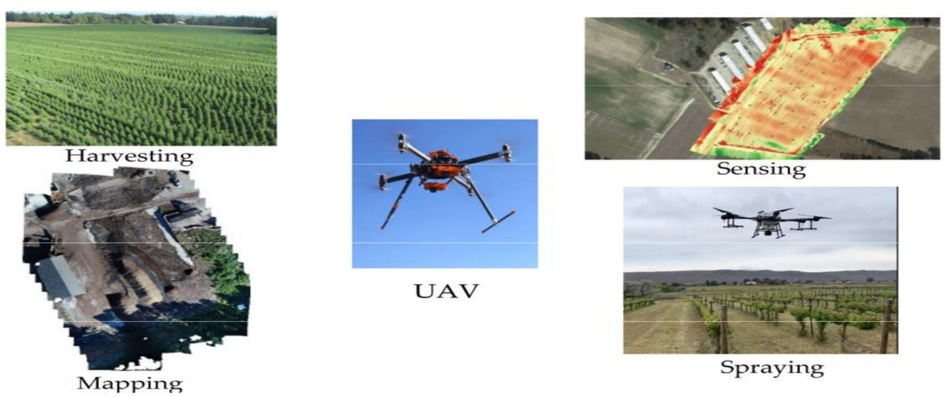

Figure 1: Multiple application of UAV in agriculture

Moreover, the use of unmanned ground vehicles is also increasing in agriculture. Mobile robots which are composed of two systems: hydraulic subsystem with liquid tank and electrical system with pump, pressure regulator, electric flux regulator, flow rate meter, and electric on/off valves (Cantelli et.al, 2019). These robots are sometimes referred to as 'electrical robots' when they are powered by electrical system. There is huge scope and opportunity of robotics in agriculture. Like UAV, the mobile robots have the potential for multiple tasks including scouting, spraying, weeding, and harvesting (Figure 2) (Barnes et.al, 2021).

Figure 2: Mobile robot's different applications in agriculture

1.3 COTTON

Cotton (*Gossypium hirsutum* L.) is a tropical shrub in the *Malvaceae* family (Maiti et.al, 2020). Cotton is a diversified and historical plant, which is justified by its fire-adaptive herbaceous perennial nature in northwest Australia to small trees in southwest Mexico which can cope with the dry season by dropping its leaves, and evidence suggests its emerged roughly 12.5 million years ago (Stewart et.al, 2009). There are 49 different species in the *Gossypium* genus. It exhibits tremendous morphological and ecological diversity, as well as a long history of chromosomal evolution. Human cultivation and modification of several species, including *G. arboretum*, *G. herbaceum*, *G. barbadense*, and *G. hirsutum* has led to significant agronomic advancement and germplasm improvement. *G. arboretum* is cultivated in some cotton in some countries, such as India and Pakistan (Rönnbäck and Theodoridis, 2022). Likewise, *G. herbaceum* is cultivated in Africa and Asia on a small scale, whereas recently, the cultivation of tetraploid cultivars, such as *G. barbadenseis* has been increasing in several regions in Asia and America due to its long, strong, and fine fibers (Shaheen, 2012). Despite the number of advantages, its production is limited to 10% of total world production due to its low yield. Most of the world's cotton production is dominated by the modern cultivar of *G. hirsutum* (i.e., upland cotton) (Stewart et.al, 2009). Cotton, which was considered 'White gold' before the industrial revolution, market was restricted to domestic within small regions. Later, after the establishment of many textile companies and intercontinental markets, cotton became one of the major export crops in the world. The U.S. has been one of the most important cotton exporters in the world since the beginning of the 1790s. The availability of enormous land and labor, and climatic suitability for cotton production in the United States, especially in the southeastern part of the county, such as the Carolinas and Georgia, contributed to becoming the top cotton exporter in the world. The United States is the world's third largest cotton producer after China and India (Stewart et.al, 2009).

Cotton is a multipurpose crop mainly grown for fiber and seeds. Although it is widely known for its natural fiber, its uses are not limited to the textile industry. Several activities are involved between cotton cultivation and cotton consumption, such as cultivation, harvesting, transportation, spinning, and production of other by-products. There may be some medicinal uses for cotton. In ancient times, people used young shoots, leaves, and flowers to treat ailments, such as asthma, convulsion, and skin diseases (Wegier et.al, 2016). Cotton seed products include hulls, kernels, and linters. Hulls provide the raw materials for rubbers and plastics, and the kernel provides raw materials for soap, glycerin, refined oil, animal feed, and fertilizers, and linters provide cotton fibers for the textile industry (Singh, 2010). Because of its diversified uses, the cotton plant significantly influences the world economy even though it is not a food crop.

1.4 PHYSIOLOGY AND GROWTH PATTERN OF COTTON

An understanding of the growth habit of cotton is very crucial for its management. It has an indeterminate growth habit. Cotton is a perennial plant and favorable conditions, such as high rainfall, nitrogen fertilization, and fertile soil encourages high vegetative growth at the expense of reproductive growth. From the economic perspective, reproductive growth and yield is very important; therefore, growth regulators are used to manage vegetative and reproductive growth (Jones et.al, 2019). The maximum growth rate of cotton occurs between 40 and 80 days after emergence (DAE). Canopy coverage also follows a similar pattern, such as height, in relation to days after emergence (Chu et.al, 2016). This result is also supported by Sun et al., 2018 study on cotton growth analysis using LiDAR.

At the vegetative stage, most of the carbohydrates produced are used for root and leaf development, but once the plant reaches the reproductive growth stage, the transport of carbohydrates shifts to the developing fruits (Ritchie et.al, 2004). The cotton plant has two different kinds of branches: fruiting (sympodia) and vegetative (monopodia). The 'stop-and-go' and the zigzag growth habit of fruiting branches differentiates them from vegetative branches which have a straight growth habit. Cotton leaf photosynthetic capacity varies and declines with age, reaching a maximum value about 20 days of leaf age. Low fertility and water stress causes premature aging of the cotton leaf canopy, which further reduces the photosynthetic capacity and the yield of the crop (Ritchie et.al, 2004).

Generally, two different colors of flower are seen in cotton, i.e., white, and pink. The white flower stage, or the first day the flower is open, is when pollination takes place. After pollination, the flower changes color to pink. As being indeterminate plant, the flowering occurs both horizontally (in same node) and vertically (in different node) simultaneously. The horizontal flowering interval is 5–6 days, whereas the vertical flowering interval is 2–3 days. Approximately three weeks after fertilization, fiber development starts and continues until it reaches the full staple length. When fiber reaches its maximum staple length, it begins maturing, or thickening, which happens because of the deposition of additional layers of cellulose (Wright et.al, 2005). The economic part of cotton is its fiber. Historically, growers used to harvest cotton boll manually which was very tedious and time consuming for commercial production. Later, mechanical harvesters and defoliation made harvesting more efficient and productive. Along with defoliant chemical, boll opener and growth inhibitors are also used to facilitate mechanical harvesting, maintain quality, encourage boll opening, and control the regrowth of the cotton plant.

1.5 COTTON DEFOLIATION

Defoliation is the shedding of leaves by natural physiological processes or artificial phenomena. Cotton defoliation is a natural process, but untimely and inadequate leaf defoliation by natural process hinders the mechanical cotton harvest (Xin et.al, 2018). Therefore, defoliants are used to facilitate timely mechanical harvesting (Meng et.al, 2021). Cotton defoliation is a major factor influencing mechanical harvesting, fiber quality, and the costs of cotton cultivation (Addicott and Lynch, 1957).

The importance of defoliation in cotton has been realized with increased mechanical/autonomous harvesting (Karademir and Karademir, 2021). Several factors, such as plant condition, temperature, and moisture during application of the defoliant influences the success of cotton defoliation (Snipes and Cathey, 1992). In addition, other chemical are added to accelerate the boll opening process and improve yield (Meena et. al, 2016). Historically, calcium cyanamide dust was the first defoliant used to promote aeration and reduce the boll rot in 1938 (Eaton, 1995). Chemical application is important from a production perspective and the most dangerous agricultural operation (Abbas et.al, 2020). Therefore, chemicals should be precisely applied to minimize costs and their adverse impacts on environments and living beings.

Generally, chemical defoliants are applied using ground-based or aerial-based vehicles, such as tractor-mounted boom sprayer, airplane mounted sprayer, unmanned aerial spraying (drone spraying), and unmanned ground sprayer (robots spraying). Each system has its own pluses and minuses and selection of these system depend on available technology, eco- nomic budget, cultivated area. Pivot attached sprayer system and conventional tractor-mounted sprayer resulted in better defoliation than chemigation (Sumner et.al, 2000). However, the UVA spraying system used significantly less pesticides compared to tractor-mounted boom sprayer (Dou et.al, 2022). Conventional spraying systems resulted in higher losses of chemical due to off target movement. Thus, to tackle this problem many advanced technologies including pulse width modulation technology (Salcedo et.al, 2020), LiDAR-guided system (Mahmud et.al, 2021), unmanned aerial vehicles (Xue et.al, 2016), unmanned ground vehicles, such as mobile robots (Mahmud et.al, 2020), and variable rate of application techniques has been developed to minimize the off-target loss and maximize the efficiency of chemical spraying. For cotton defoliation sprayers, U.S. farmers typically use a boom sprayer. The same boom sprayer is used for other pesticide and fertilizer applications. A study compared an air-sleeve sprayer with a hydraulic nozzle sprayer (single-fluid type of spray nozzle) for droplet coverage, insect control, and cotton defoliation. The air-sleeve sprayer was found to be more efficient than the hydraulic nozzle sprayer based on droplet coverage and defoliation (Manor et.al, 1989). Large machinery, such as tractors, causes soil compaction, mechanical crop damage, and yield losses (Cavalaris et.al, 2022). The use of UAV is increasing in cotton production, mainly for spraying of harvest aids. Good droplet coverage and leaf defoliant retention are crucial for proper defoliation. The application of vegetable oil adjuvant and harvest adds (defoliants and boll opener) was reported to increase defoliation and boll opening rates (Xiao et.al, 2019) significantly. A study was conducted to compare the efficacy of UAV spraying and traditional ground-based spraying in cotton. Based on the final cotton yield, the UAV sprayings were more efficient than traditional ground-based spraying (Cavalaris et.al, 2022; Chen et.al, 2022). There are few reasons why UAV are not used for defoliations in the US. The Federal Aviation Authority (FAA) policy on using a spray drone where one needs to file waivers and the steps of getting one takes some time and effort for the user to have the drone spraying on the field especially as these defoliants are chemicals. Other issues are off target of the products (Leon et.al, 2020). For ground-based, it is apparent that manual spraying is still being used especially in India. The most popular sprayer unit is an air-assisted sprayer mobile backpack (Singh et.al, 2017).

1.6 PULSE WIDTH MODULATION (PWM) TECHNOLOGY FOR SPRAYING

The basic concept behind the pulse width modulation is waveforms or the switching frequency, which exhibits the varying duty cycles of the power switches, and it is the concept of electronic power conversion (Holtz, 1994). The application of PWM has been increasing in agriculture mainly to improve the efficiency of pesticide application with higher precision (Zhu et.al, 2010). Moreover, the nozzle flow rate can be controlled by using PWM, which can significantly reduce pesticide use, off-target drift, environmental risk, and production cost (Salcedo, 2021). Although lower PWM results in a lower flow rate and minimizes chemical use, the proper droplet size, distribution, and coverage must be followed. Only minimizing chemical at the expense of these parameters should not be the primary goal. Therefore, selecting the right PWM, nozzle type, and pressure are critical for proper spraying. A study on the droplet size and nozzle tip pressure on a PWM sprayer found that the use of at least 40% duty cycle with a minimum pressure of 276 kPa and nonventuri type of nozzles to optimize and homogenize the spray droplet size across spray application (Butts et.al, 2019).

Similarly, a study was conducted to investigate the on/off latency in PWM nozzles and determine the effect of active nozzles on spray fan pattern latency and flow characteristics to simulate dynamic spray coverage. A 20 ms delay in nozzle pressure development during each cycle was reported, irrespective of the number of nozzles activated. Moreover, the spray coverage was found within ±10% of the target rate for each PWM duty cycle most of the time (Mangus et.al, 2017). The application of PWM can be found in various plant, such as apples (Salcedo et.al, 2020), vines (Grella et.al, 2022), and Palmer amaranth (Womac et.al, 2016). However, few studies about PWM have been found for cotton.

Boatwright et al., 2020 reported that intelligent spraying technology has a higher efficiency in controlling pests and brown rot disease with reduced spray volume and drift in peach orchards compared to conventional air blast systems. Likewise, Chen et al., (2022) used drones equipped with sensors and multispectral cameras to generate a defoliation prescription map using RGB and multispectral images. The spectral indices and cotton defoliation rate has strong correlation. Thus, their work highlighted the application of UAV remote sensing for cotton defoliation. Based on the review mentioned above, several studies have been conducted on conventional boom sprayer and UAV spraying; however, limited research has been conducted on of the use unmanned ground vehicle sprayer together with PWM technology for cotton defoliation.

1.7 DEFOLIATION TIMING

The timing of the defoliant application plays a significant role in cotton yield because premature defoliation reduces yield and late defoliation can result in fiber quality deterioration due to bad weather (Jones et.al, 2019). Gormus et al., (2017) concluded that early application of defoliants significantly reduces seed cotton yield, boll number per plant, micronaire, and fiber length. Various methods have been used to determine defoliant timing cotton. Traditionally, counting nodes above the cracked boll (NACB), and visually estimating the percentage of the open boll methods are used; however, these are more subjective and may differ according to growers' perception and observation. Generally, when 50– 60% boll is open and NACB is less than or equal to four, it is considered the optimum timing for cotton defoliation (Jones et.al, 2019).

Early application of defoliant (prior to 60% open boll) was found to decrease yield and fiber quality thus Snipes and Baskin 1994 suggested to apply defoliant when 60% of boll are open. However, the maturity of the variety can affect the timing (Faircloth et.al, 2004). However, there are no clear-cut guidelines for the perfect timing of defoliants. Some literature mentioned COTMAN concept to determine the timing of defoliation. COTMAN is a cotton management software program developed on concept of cotton plant growth and development. At first the concept of COTMAN was used to measure node above white flower (NAWF) for management of insect. Later, this concept adopted for defoliation. When NAWF is equal to 5, cotton is at physiological cut- out (Bourland et.al, 2008).

The amount of heat accumulated during a 24 h time when the average ambient temperature is greater than 15.5 degree (base threshold temperature) is define as heat unit (HU) in cotton. According to COTMAN program, NAWF = 5 and HU = 472 is considered the appropriate time for defoliation. However, Bynum and Cothren 2008 findings contradict COTMAN's recommendation based on their experiment. They consider NAWF (=3, 4, 5) and HU's (361, 417, 472, 528, and 583) as indicator for defoliation. A total of 29% more lint yield was observed when plant was defoliated at 60 percent of open boll timing (i.e., NAWF = 5 and 472 HU) than compared to COTMAN recommendation. Similarly, Clay et al., (2006) evaluated the effectiveness of defoliation at various heat unit accumulations: 630 HU, 730 HU, 830 HU, 930 HU, 1030 HU, 1130 HU, and 1330 HU and its impact on lint yield and fiber quality. The highest defoliation was found at 830 HU. Moreover, lint yield and gin turnout were the highest in early timings of defoliation but fiber qualities except the fiber strength were not significant across the defoliation timings. The HU accumulation can differ based on their weather conditions at each location and generalizing single research findings to the varied location might not be a good idea. Therefore, future multilocation research should be conducted to determine defoliation timing considering different methods.

1.8 DEFOLIANT AND FACTORS AFFECTING DEFOLIATION

The defoliants and harvest aids are categorized into two groups based on their nature of action: herbicide and hormone. Herbicide defoliants injure the plant, causing it to produce ethylene in response which promotes leaf abscission (Gwathmey and Craig, 2007). Some examples of herbicide defoliants are carfentrazone-ethyl, thidiazuron, diuron, and tribufos. In the case of the herbicide defoliant, for a successful leaf drop, optimum coverage is essential, as chemical penetration and evenness of the spray play a significant role in defoliation (Weicai et.al, 2016). In contrast, hormone defoliants enhance ethylene production and inhibit auxin transport in the plant, encouraging leaf abscission (Gwathmey and Craig, 2007). The hormone defoliants are generally more sensitive to temperature and crop conditions than herbicide defoliants (Logan and Gwathmey, 2002). It is very important to select appropriate chemical for efficient result. Application of harvest aids, such as thidiazuron and ethephon were found to have a significant effect on cotton defoliation and boll opening (Wang et.al, 2019). Several factors affect the efficiency of chemical defoliants, such as plant characteristics, applied nutrients, weather conditions, types of chemicals, and spraying methods. Wang et al., (2019) found a significant effect of nitrogen and harvest aid on defoliation efficiency and cotton yield. With increasing N levels, defoliation and boll opening percentages were significantly reduced and 150 kg N/ha together with 900 + 3000 g ai ha^{-1} of thidiazuron + ethephon was recommended for optimum cotton yield and efficient defoliation (Wang et.al, 2019). Weather factors that influence harvest-aid performance are temperature, relative humidity, seasonal rainfall, and the occurrence of precipitation following application. High seasonal night temperatures promote crop maturity and susceptibility to defoliation. Harvest aids work best when nighttime temperatures are 15.5 degrees Celsius or higher (Jones et.al, 2019). In general, herbicide defoliants, such as tribufos have lower minimum temperature activity requirments (12.7–15.6 °C) than hormone (15.6–18.3 °C), such as ethephon and thidiazuron (Wang et.al, 2019). Defoliation occurs twice as quickly at 35 ° C than it does at 25 ° C because the rate of activity doubles with a 10 ° C increase in temperature (Wang et.al, 2019). Defoliation was 17% with no adjuvant at five days after treatment (DAT) when day/night temperatures 29.5/21° C, 37% with crop oil concentrate added, 40% with ammonium sulfate, and 75% with both adjuvants combined whereas there was less than 10% leaf drop at 21/12.7° C day/night temperature under all treatments at 5 DAT (Hake et.al, 1996).

In general, excessive watering before and during defoliation can result in more vegetative growth of plants, whereas extremely dry condition before/during the defoliant application may reduce its activity. Terminating the irrigation at least 24 days before the defoliation resulted in good defoliation with single application of defoliant (Wills and Snipes, 1996).

Plant characteristic, such as leaf area index, has a significant effect on droplet deposition in the canopy and rate of defoliation (Nelson et.al, 1992), but the distribution of droplet size depends on several factors which can also affect defoliation. Plant characteristics (e.g., height, leaf area, and density) and spraying technology (spraying volume, nozzle type, pressure, and vehicle speed) influence the droplet coverage and vertical distribution in the plant canopy (Liao et.al, 2020).

Droplet deposition found significantly affected by droplet size, spray volume, and flight height of UAV. The droplet deposition in the lower part of the canopy increases with larger droplet size and volume of spray. Deposition is influenced by an interaction between flight height and droplet size. when the flight height is 1 m, no variation in the deposition among the droplet size (100, 150, and 200 m) was found. However, the average deposition of coarse droplets was greater when the flight height was 2 or 3 m (De Lima et.al, 2018). The upper leaves intercept droplets and reduce the number of droplets reaching the lower parts of the leaf canopy (Chen et.al, 2021). Zhu et al., (2004) reported that spray deposition decreased dramatically from the top to the bottom of the canopy throughout the growing season (Zhu et.al, 2004). This statement is also supported by Meng et al., (2019) who found the lowest droplet coverage on the bottom half of the cotton.

The main objective of this work is to evaluate the potential for this new spraying system for cotton defoliation by evaluating the impact of droplet characteristics and defoliation at the different application rates on cotton yield and quality.

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CHAPTER TWO

EFFECT OF CONTROL SPRAYING ON COTTON DEFOLIATION RATE

2.1 INTRODUCTION

Cotton is a diversified plant which can be found as perennial tree to a shrubby annual crop depending on the climatic regions. It is one of the leading agricultural crops in the world and its economic part is cotton fiber which is used by textile industry for making variety of fabrics and clothes (Britannica, 2023). Cotton fiber is a soft staple fiber that grows inside a protective structure (cotton boll) and the fiber is cellulose with minor percentages of waxes, fats, pectin, and water. The general cotton cultivation practices include soil testing and fertilization, variety selection, planting and stand establishment, insect and pest control, application of plant growth regulator, weed management, defoliation, and harvest (Jones et.al., 2021).

Cotton defoliation is very common practice, especially in United States, to produce high cotton yield and good fiber quality. Defoliation is the removal of the leaves from the plant. Defoliation is a mandatory task for the mechanical harvesting; therefore, it is done approximately two weeks before the expected harvest date. Besides improving harvest efficiency, cotton defoliation provides the better opportunity to minimize the trash content in the fiber, fastening the drying of dew, and increase the fiber quality (Xin et.al., 2018). Defoliation time (Jones et.al, 2019; Snipes and Baskin, 1994; Bourland et.al, 2008), selection of harvest-aid chemicals (Wang et.al, 2019), weather (Jones et.al, 2019), plant characteristics (Nelson et.al, 1992), and spraying method all have a significant role in cotton defoliation.

Conventional tractor mounted boom sprayer is the most common method for defoliant application (Weicai et.al., 2016); however, due to the weight of the machine, it can cause soil compaction and impact the soil health. Unmanned aerial spraying (Liao et.al., 2020; Chen et.al., 2022) has the potential to reduce or minimize soil compaction, but very fewer droplets can reach to the lower canopy of the plant due to wind turbulence and drift potential (Chen et.al., 2021). Insufficient droplet penetration in the canopy can result in poor defoliation and reduced yield and fiber quality. Similarly, spraying method has significant role on droplet distribution, penetration, and droplet uniformity which ultimately affect the defoliation. Therefore, novel research was conducted to develop new automatic ground sprayer using robotics and pulse width modulation technology which can operate between the cotton rows and have the ability to spray horizontally throughout the plant canopy (Neupane et.al., 2023). The objective of this study is to evaluate effect of different duty cycles (20%, 40%, and 60% pulse width) on droplets characteristic (droplet distribution, droplet density, and drift potential) and on defoliation rate.

2.2 MATERIALS AND METHODS

2.2.1 STUDY SITE

The research was conducted at the Edisto Research and Education Center in Blackville, SC, USA. Two locations at the research farm were selected (Field 1: 33.34736, −81.31925; Field 2: 33.35398, −81.31024). Both locations utilized a completely randomized experimental design, with 4 replications in Field 1 and 2 replications in field 2. In Field 1, cotton was planted in 6 rows. Each row was divided into 2 groups (P1 and P2), where each group was further divided into 3 smaller rows with a length of 9.8 m (32 ft.) (See Figure 3).

Figure 3: Cotton planted in field 1

In Field 2, cotton was planted in late May of 2022 and has a smaller size as compared to Field 1 (Figure 4). Six rows were selected with length ranging from 21 m to 27 m. Cotton on both fields were planted by skipping one row (skip row) to facilitate the movement of the mobile spray robot.

Figure 4: Cotton planted in field 2

2.2.2 AUTONOMOUS MOBILE PLATFORM AND SPRAYER UNIT

This work utilized the mobile platform (Husky A200, Clearpathrobotics, ON, CA) from other research work at the sensor and automation laboratory (Figure 5). The mobile platform is lightweight with the ability to pull or carry payloads up to 75 kg [85]. It is equipped with an inertial measuring unit (UM7, CH Robotics, Victoria, Australia), global positioning system (Swiftnav, Swift Navigation, CA, USA), motors, encoders, and laser scanner (UST-10LX, Hokuyo, Osaka, Japan) for its navigation.

The sprayer unit (Model #1598042, County Line, Austin, TX, USA) is a 94 L 2-nozzle trailer sprayer with a built-in 12V diaphragm 9.5 L/min pump. The rated pressure of the pump based on the specification was 482 KPa. The sprayer was retrofitted with 6 nozzles (Model #625147-001, Capstan Ag Systems Inc, Topeka, KS, USA), and all valves, O-rings, flynut, and other sprayer parts were provided by Wilger Inc. (Wilger Industries, SK, Canada). Three nozzles were situated on each side, with nozzles located at 38 cm, 84 cm, and 145 cm from the ground as shown on Figure 5. The nozzle from the bottom to the top were designated as low, mid, and top nozzles, respectively. An aluminum extrusion was used to hold the nozzles and the top nozzle were position on an angle of 40 degrees. The extrusion holding the top nozzle can be adjusted by three hex screws. This is intended for crop height changes during the field test. The distance of the bottom and middle nozzles was based on the spread of the tip used while the top was based on the height of the crop.

Each nozzle was retrofitted with a spray tip (ER110-06, Wilger Industries, SK, Canada). The ER series spray tip is a conventional flat fan nozzle with relative fine spray with consistent pattern. A link to the UGV and sprayer can be found in the Supplementary Materials that show the UGV and sprayer unit performance on the field.

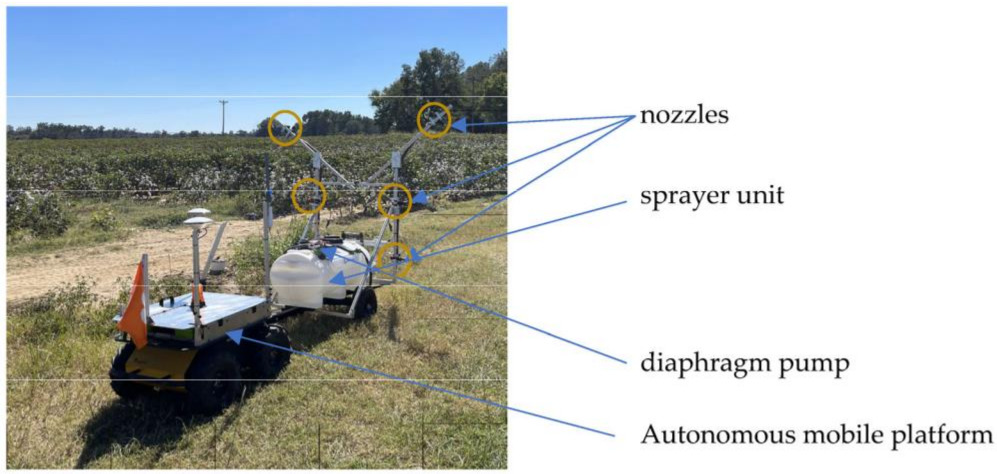

Figure 5: Autonomous mobile platform with the pull behind sprayer

2.2.3 SPRAYER CONTROLLER

The controller developed specifically for this project was an ARM Cortex-M4-based microcontroller (MK66FX1M0VMD18, NXP, Eindhoven, The Netherlands) with wireless transceiver (Telemetry Radio V3, Holybro, Hong Kong, China), microSD card socket, and global positioning system (GPS) module (MTK3339, GlobalTop Technology Inc., Taiwan). The ARM Cortex-M4 comes with a 256 Kb Static Random-Access Memory (SRAM), 1280 Kb of Flash RAM, 4 Kb of EEPROM, 6 UART, 3 SPI, 4 i2c, 2 USB controllers, and 1 Ethernet port. It also has 100 programmable GPIO pins with 25 16-bit Timer and 4 32-bit Timer. The sprayer controller has a separate external power for the pump (as shown in Figure 6—pump power) and can be controlled remotely. The pump power is a separate power specific only for the diaphragm pump to minimize issues with high amp power requirement. Although this functionality was not used for this current field test. The top board as shown in Figure 6 is the spray unit controller while the bottom board is the ARM cortex controller.

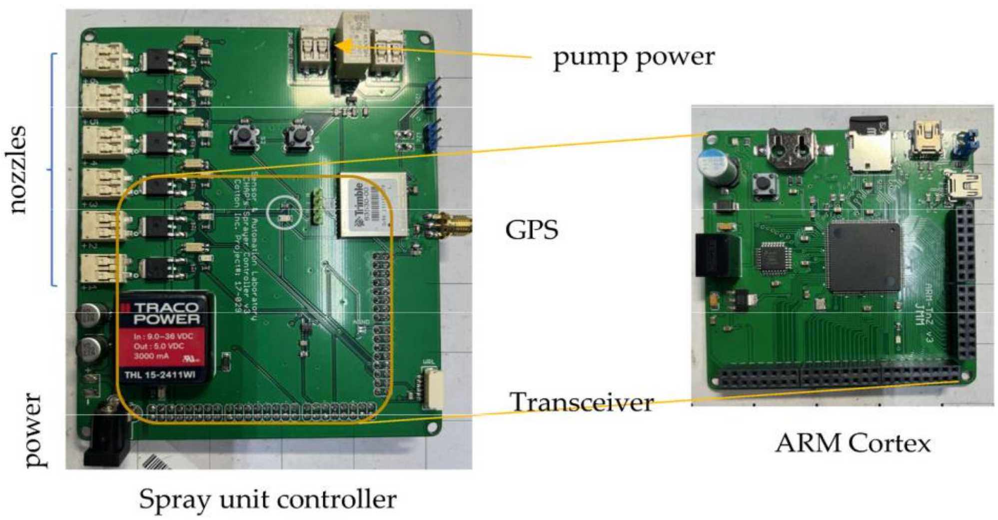

Figure 6: Sprayer controller developed for this project.

The sprayer controller was configured to use 10 Hz for the pulse width modulation frequency due to the specification requirement for the Capstan Ag coil assembly. Six GPIO pins were also configured to generate the pulse and each of the assigned pins can be configured from 0 to 100% duty cycle. Note that the duty cycle settings must be configured to the tip use and pressure of the spraying system. In this work, each nozzle was tested with the different duty cycles and determined the correct volume for the duty cycles—20%, 40%, 60%, 80%, and 100%, as shown in Table 1. Only three duty cycles (20%, 40%, and 60%) were used as a treatment for the field test.

Table 1: Laboratory test on duty cycle vs. volume rate

Duty Cycle (%)	Volume/Sec (mL/s)
20	13.0
40	22.8
60	31.9
80	42.7
100	49.5

The firmware code that runs on the board regularly monitor for incoming character for a new update on the duty cycle for each of the nozzle. At the same time, the controller also transmits the GPS, voltage of the board, and the different duty cycle assigned to each of the nozzle. The whole sprayer controller was housed in a waterproof enclosure with transparent lid at the back of the sprayer unit as shown in Figure 7.

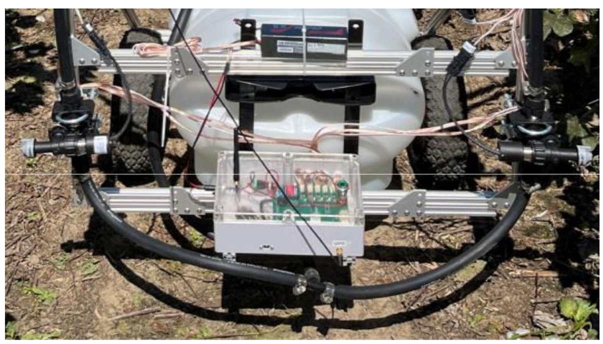

Figure 7: Placement of the sprayer unit enclosure

2.2.4 COTTON CULTIVARS AND DEFOLIANT CHEMICALS

Delta pine cultivars (DP 2038B3XF and D10 DP 2055) were planted in the first and second fields, respectively. The first field was planted on May 12, 2022, while the second field was planted on May 25, 2022. The management practices used for both fields were according to the South Carolina cotton growers' guide. A mixture of three different chemicals was used for the spraying; the information is shown in Table 2.

Table 2: Chemical formulations, active ingredients, and application rates

Product Formulation	Active Ingredient	Rate	Remarks
Folex 6 EC	tribufos	454 g/38 L	Cotton defoliant
Free fall SC	thidiazuron	91 g/38 L	Cotton defoliant
Super boll	ethephon	907 g/38 L	Plant regulator

2.3 DATA COLLECTION AND ANALYSIS

A total of 80 plants from Field 1 and 40 plants from Field 2 were randomly selected and tagged with red thread before the treatment application. Three different duty cycles were used for the field test as treatment: 20% (13.0 mL/s), 40% (22.8 mL/s), and 60% (31.9% mL/s). In this field test, control represented the plants where defoliation was conducted using a conventional tractor-mounted sprayer. The data on plant height, node count, and total boll was collected. The number of leaves on the same tagged plants was counted at the 0, 4, 8, 12, 16, and 20 days after treatment application (DAT). The defoliation rate was calculated using Equation (1):

$$Defoliation\ Rate = ((lfc_{n} - lfc_{n+1}) / lfc_{n}) * 100$$

where *lfc* is leaf count, and *n* is the days when the count was made. Note *n* is 0, 4, 8, 12, 16, and 20.

Similarly, a water-sensitive paper (WSP) was used to study the droplet characteristics. Ten plants were randomly selected per treatment, and WSP were placed at three different canopy heights, i.e., lower, middle, and upper canopy as shown in Figure 8. The paper was collected after drying and kept in a yellow envelope to prevent moisture contamination.

The WSP papers were then scanned using a WSP scanner (DropScope, SprayX, São Carlos, Brazil), providing different droplet characteristics. Likewise, cotton bolls were harvested manually on a standard sample length of 3 m row to study the yield after ginning, and the sample cotton fiber was sent to the Cotton Incorporated Laboratory for quality analysis. One-way ANOVA and Tukey test were conducted to study treatment effects and mean separation.

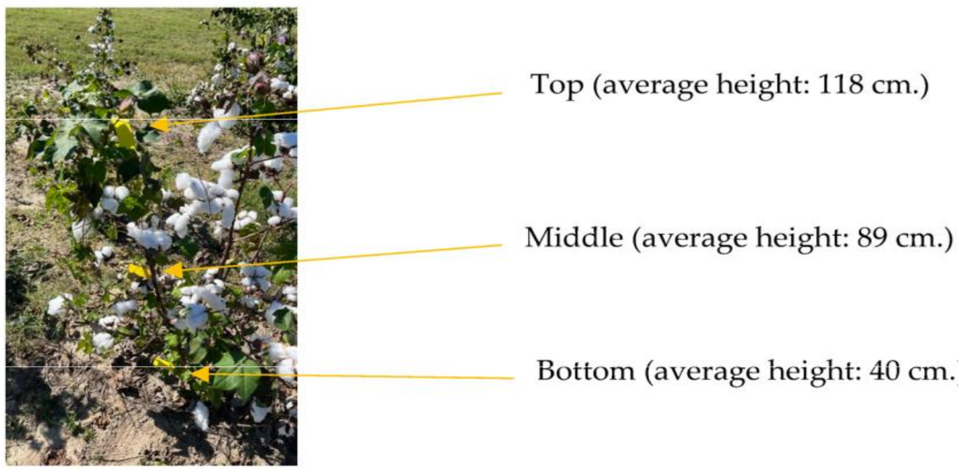

Figure 8: WSP placement during the field sprayer test

2.4 RESULTS

2.4.1DEFOLIATION RATE

Overall, the control has higher mean defoliation (Figure 9). The control represented the current practice where the defoliant was sprayed using the conventional tractor-mounted sprayer. There was no significant difference in defoliation across the three treatment levels, meaning the 20% duty cycle results were the same as the 60% duty cycle. Even though, the volume output is significantly higher at 60% compared to the 20% duty cycle. Note that there were three nozzles that sprayed one side of the cotton plants, which means that we did not have any issues with penetration as compared to the tractor-mounted spray where the nozzles were pointing to the top of the cotton canopy. Our spray systems successfully delivered the defoliants to the three levels of the cotton plants. The results suggest that even with less volume of defoliants (20%), there was enough defoliant reaching the plants equivanlent to top to bottom spray from the tractor-mounted system. This is a very promising result as there are no studies on cotton defoliation that sprayed the side of the cotton. This means that farmers can reduce the use of defoliants while achieving similar leaf drop levels as the conventional method. Moreover, there was an unexpected light rainfall just after the defoliant application. In contrast, the rain stopped when the control plot was sprayed with the tractor-mounted spray. This could be the reason behind the high defoliation rate on control treatment. In addition, two consecutive freezing nights one week after the spraying could have affected the defoliation on the three treatments. Freezing night temperatures can kill the leaves before the development of the abscission layer between the petiole and stem.

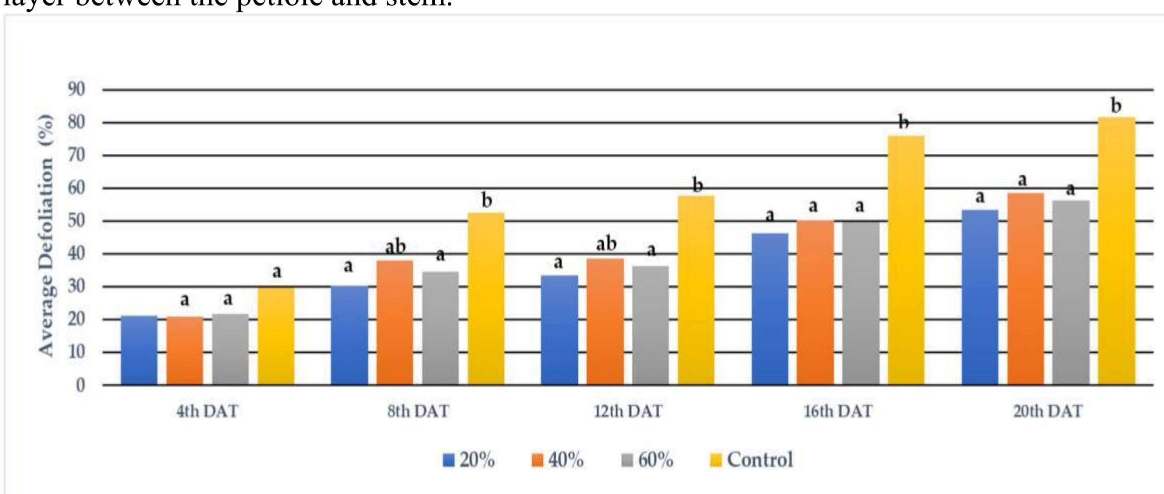

Figure 9: Average defoliation percentage on different days in field 1

The control has higher mean defoliation in Field 2, as shown in Figure 10. The results were similar to Field 1 except on the 16th day, where all treatments, including the control, had statistically similar defoliation. The defoliation is significantly higher at 20% on the 4th, 8th, and 12th day compared to the 60% duty cycle. In contrast, there is no significant difference in defoliation rate across the treatments on the 16th and 20th day.

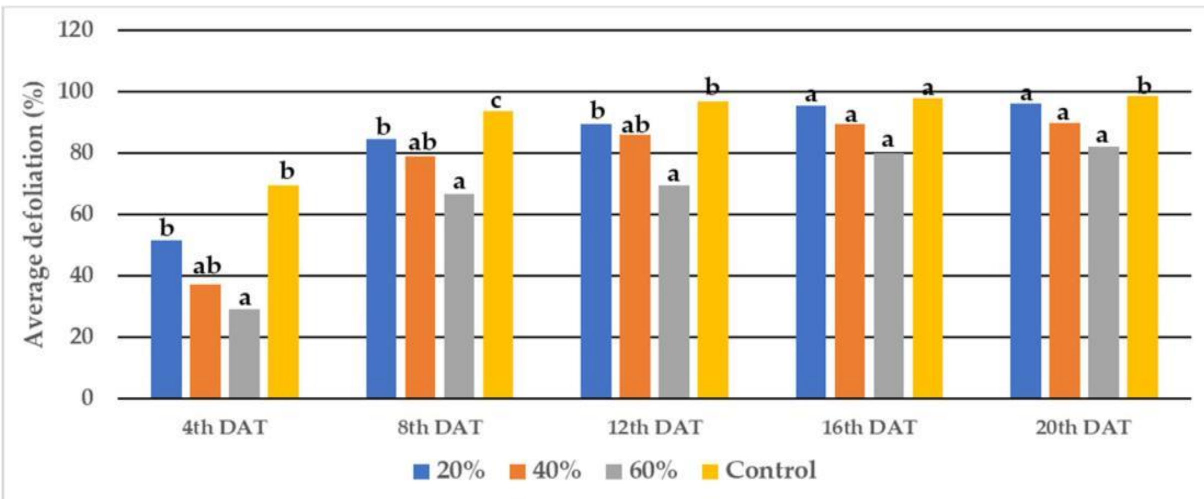

Figure 10: Average defoliation percentage on different days in field 2

2.4.2. DROPLET CHARACTERISTICS

The ANOVA analysis for droplet deposition, density, and droplet drift potential (see Tables 3–5) showed no significant treatment effect. Meaning using 20%~60%duty cycles have the same effect on droplet characteristics.

Table 3: ANOVA analysis for droplet deposition (*p ≤ 0.05, **p ≤ 0.01)

Source	Degree of Freedom	Sum of Squares	Mean of Squares	F-Value	*p*-Value
Treatment (duty cycle)	2	121.3	60.66	2.58	0.08269

Block (Canopy height)	2	328.8	164.39	6.99	0.00167 **
Interaction	4	277.4	69.36	2.95	0.02567 *
Residuals	72	1692.1	23.5		

Table 4: ANOVA analysis for droplet density

(*p ≤ 0.05, **p ≤ 0.01)

Source	Degree of Freedom	Sum of Squares	Mean of Squares	F-Value	*p*-Value
Treatment (duty cycle)	2	60365	30183	2.557	0.08457
Block (Canopy height)	2	146508	73254	6.206	0.0032
Interaction	4	46643	11661	0.988	0.41978
Residuals	72	849933	11805		

Table 5: ANOVA analysis for drift potential

(*p ≤ 0.05, **p ≤ 0.01)

Source	Degree of Freedom	Sum of Squares	Mean of Squares	F-Value	*p*-Value
Treatment (duty cycle)	2	0.00464	0.02318	1.634	0.2022
Block (Canopy height)	2	0.1918	0.09589	6.762	0.00204 **
Interaction	4	0.1102	0.02754	1.942	0.11262
Residuals	72	1.0209	0.01418		

2.4.3. COTTON YIELD

Figure 11 presents the average cotton boll number and weight in 10-foot cotton rows per treatment from both fields. No statistical comparisons are present in this figure, and all treatments weigh more than the control in both fields. As mentioned in the methodology section, the treatment plot has skipped rows; in contrast, control rows do not have skip rows. With the increase in row spacing, the competition of plants for nutrients and sunlight will decrease, which could cause a higher yield on the treatment side. Similarly, Field 1 has a higher yield in every treatment than Field 2, which could be due to differences in soil nutrient level, planting date, and soil moisture.

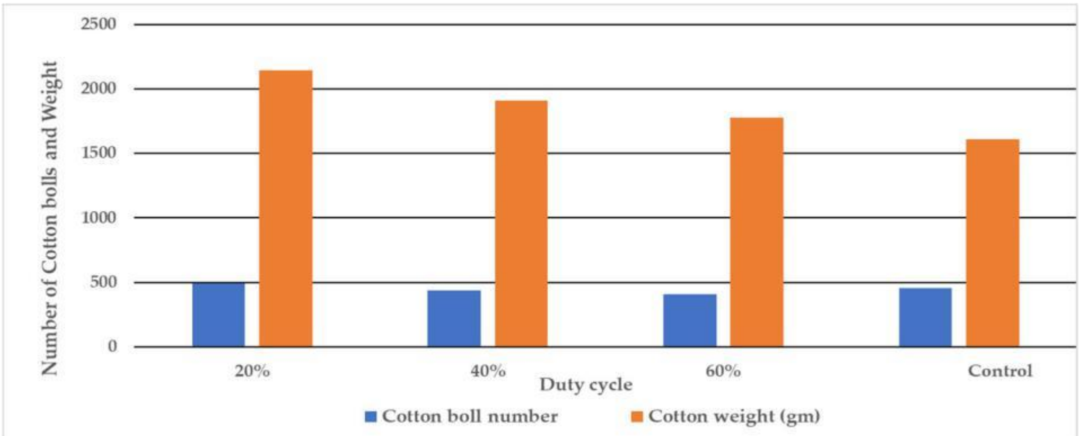

Figure 11: Average cotton boll and weight data of field 1

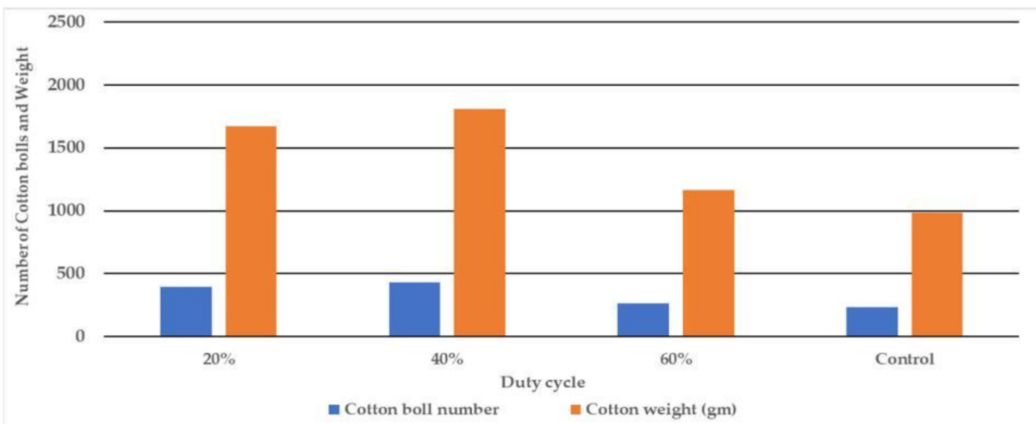

Figure 12: Average cotton boll and weight data of field 2

2.5 DISCUSSIONS

The results for Figure 9 showed that the duty cycles and the defoliation rate combination of using UGV and specialized spraying system has a huge potential to apply precision agriculture technology. The results showed that chemical penetration is just as important as spray volume.

2.6 CONCLUSIONS

The combination of using UGV and a specialized spraying system has a huge potential to apply precision agriculture technology. This preliminary work showed an unexpected result. Although the assumptions that more chemicals should result in a higher defoliation rate, results on these experiments showed that higher duty cycles (high volumes) do not result in higher defoliation rates. For example, in Field 1, the treatments and control have insignificant effects on day 4 but showed that on days 16 to 20, the control showed a higher defoliation rate than the treatments. Note that the 40% treatment is not statistically different from the rest of the treatment and control on day8 and 12. In contrast, in Field 2, the 20% duty cycle has a higher defoliation rate on days 4, 8, and 12 compared to other treatments, although not significant. The results showed that chemical penetration is more important as compared to volume, as shown in the results of Figures 9 and 10. Overall, these preliminary results for both field experiments showed that defoliation can be achieved using a smaller amount of defoliant chemicals, as long as coverage is adequate on the cotton plants.

Droplet characteristics (droplet distribution, density, and potential droplet drift) were not significant across the treatments. Therefore, the 20% duty cycle was sufficient to defoliate based on the results of the field experiment. Higher spacing in treatment rows provides a better opportunity for nutrients and sunlight and thus results in higher yields than control rows. Additional experiments are needed to validate these results further and although this work is focused on cotton, the technology developed can also be applied to other agrochemicals in agricultural crops.

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CHAPTURE THREE

EFFECT OF CONTROL SPRAYING ON COTTON FIBER QUALITY

3.1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a very important industrial crop (Chalise et.al.,2022). It is a perennial crop which has indeterminate growth habits. However, in most parts of the United States of America (USA), it is grown as an annual crop with the application of growth regulators (Wright et.al.,2022). Cotton has a long history of cultivation and domestication (Smith et.al.,1999) and a significant role in the U.S. economy because it is the third largest producer of cotton and is the top leader of the cotton export market in the world (Avelar et.al.,2020). Cotton is grown primarily in 17 southern-States collectively known as the "Cotton Belt." Among them, Texas is the largest producer contributing approximately 40 percent of USA cotton, then followed by Georgia, Mississippi, and Arkansas. The USA produces approximately 20 million cotton bales and cotton contributes nearly 7 billion USD to the economy (USDA, 2023). Even though South Carolina is not a top cotton-producing state, cotton is one of the main cash crops of this state.

Defoliation is the process of leaf removal from cotton mainly because of maturity, senescence, and injury. In defoliation, water-conducting tissue remains alive until the leaf drops. Defoliation differs from desiccation. Defoliation is a physiological phenomenon in which abscission layer is formed between the petiole and stem, then plant enzymes, such as cellulase and pectinase, digest the cell wall and middle lamella of the abscission zone, which causes leaves to separate from the stem, and eventually fall from the plant. Plant hormones play a role in the development of abscission layers, such as abscisic acid and ethylene encourage the development of the layers, whereas auxin discourage it (Ayala et.al.,2001). Defoliation is a natural phenomenon, but untimely leaf drop requires spraying of chemical defoliants. Before harvest, cotton defoliation is a preparatory work for mechanical cotton harvesting and it is done approximately two weeks before the expected harvest time. Defoliation has a great role in increasing the harvester efficiency, minimizing the fiber trash content, drying of dew, and increase the fiber quality (Xin et.al.,2018).

Depending on the mode of action, the defoliants are herbicide or hormone. In herbicide, the plant leaf is injured which cause ethylene production, and that encourages leaf drop (Gwathmey et.al.,2016). Some examples of herbicide defoliants are carfentrazone-ethyl, thidiazuron, diuron, and tribufos. For the herbicide defoliant, the chemical penetration and spraying pattern play an important role as it does not move within the plant. Therefore, it is critical for all leaves to receive the chemical for a successful leaf drop. However, hormone defoliants encourage ethylene production and inhibit auxin transport in the plant, which stimulates leaf abscission (Weicai et.al.,2016). In the USA, hormone defoliants, such as tribufos, dimethipin, and ethephone, are widely used (Snipes et.al.,1992; Jones et.al., 2021). These defoliants do not directly influence boll opening thus, they must be applied in combination with a boll opener, to provide satisfactory defoliation and opening of immature bolls (Du et.al., 2014; Du et.al.,2013). Poor defoliation can lower the fiber quality while defoliating too early lowers yield and micronaire (Karademir et.al.,2007). As leaves are the major source of carbohydrates production through photosynthesis, early defoliation can interfere the production and movement of energy from leaves to the cotton boll (Ritchie et.al.,2007). Therefore, cotton defoliation is recommended when 60% of bolls are opened to avoid loss in yield and fiber quality (Snipes etal.,1994). However, Karademer et al., 2007 reported that defoliation can also be done after 40% boll opening without compromising yield and fiber quality. Many factors affect the yield and fiber quality of the cotton; among them include timing of defoliant application, types of chemicals used, and spraying technologies are some major factors.

With the recent advances in agriculture, new technologies have been adopted, such as the application of artificial intelligence (Liu et.al.,2020), plant disease detection (Alatawi et.al.,2022; Annabel et.al.,2019), soil, crop, weed, and disease management (Eli-Chukwu et.al.,2019). Cotton growers can also adopt these technologies, especially for defoliation and mechanical harvesting. Conventional boom sprayers are widely used for defoliant application (Weicai et.al.,2016). Similarly, using an unmanned aerial vehicle for cotton defoliation has also been increasing recently (Liao et.al.,2020; Chen et.al., 2022). Likewise, the crop duster is another concept of agriculture spraying in which chemicals are applied in powdery form using aerial vehicles (unmanned or manned aircraft) (Hoogerwerf, 2010; Subramaniam et.al., 2012). However, in all systems of chemical application, the spraying is done horizontally downward from the top, and a minimum of defoliant droplets reaches the lower canopy of the plant due to high wind turbulence (in the case of drone) and interlocking of branches and leaves on upper canopy of the plant. But for successful defoliation, each leaf must receive the defoliant as chemicals do not move within the plant (Jones et.al.,2021). Therefore, to address this research gap, we are developing a new spraying system using unmanned ground vehicles and pulse width modulation technology

(Neupane et.al.,2023). The development of autonomous spraying technology would encourage the development of new sprayer industries and the unmanned ground vehicle industries, together with the need for the global development of an agricultural system with broad market prospects and brings about huge economic, social, and ecological benefits.

Fiber quality is very important for cotton production. There are two methods mainly used for cotton fiber quality measurement: high volume instrument (HVI) and Advanced Fiber Information System (AFIS). The HVI system was developed with the aim of replacing manual fiber quality measurement methods by developing the instrumental fiber quality measurement method (Kelly et.al.,2018). HVI measures fiber parameters such as upper half mean length (UHML), uniformity index (UI), strength, elongation, trash, reflectance, and yellowness (color grade). HVI is faster and more cost effective than other methods; however, HVI is insufficient to explain the fiber length's total variation within the sample, such as the shortest fibers (Kelly et.al.,2018). AFIS is another system that can measure higher fiber length variation as compared with length variation captured by HVI method (Sayeed,2020). In AFIS, firstly, the fibers are individualized and then presented to an electrooptical sensor aerodynamically for the measurement of different fiber quality parameters (Bragg and Shofner, 1993). In contrast, in the case of HVI, the fiber length measurement is based on the principle of fibro gram and based on a quick assessment of a bundle of fiber (Hertel, 1940).

The use of robotics has been widely increasing in various sectors such as medical (Bogue 2011), business (Goudzwaard et.al., 2019; Jang and Lee, 2020), and agriculture (Lytridis et.al., 2021). To our knowledge, no studies thus far have addressed the autonomous ground spraying platform for cotton defoliation covering the whole canopy of the plant. Thus, this study's results concerning the effect of defoliant application through the autonomous robotic platform and pulse width modulation on yield and fiber quality parameters analyzed by High Volume Instruments (HVI) and Advanced Fiber Information System (AFIS) separately and provide new references and bases for further improving the cotton defoliant spraying technique. Therefore, the study was conducted to evaluate the effect of different duty cycles (defoliant rate) on cotton fiber quality parameters.

3. 2. MATERIALS AND METHODS

3.2.1. THE UNMANNED GROUND VEHICLE (UGV) AND SPRAYER UNIT

The autonomous platform (Husky A200, Clearpathrobotics, Ontario, CA) at the Sensor and Automation Laboratory was used for this research (Figure 1). For the navigation purpose, the platform is equipped with an Inertial Measuring Unit (UM7, CH Robotics, Victoria, Australia), Global Positioning System (Swiftnav, Swift Navigation, CA, USA), motors, encoders, and laser scanner (UST-10LX, Hokuyo, Osaka, Japan).

The sprayer unit (Model #1598042, County Line, USA) is a 94 L 2-nozzle trailer sprayer with a built-in 12V diaphragm 9.5 L/min pump. According to the specification, the rated pressure of the pump was 482 KPa. The sprayer was retrofitted with 6 nozzles (Model #625147-001, Capstan Ag Systems Inc, Kansas, USA), and all valves, O-rings, flynut, and other sprayer parts was provided by Wilger Inc. (Wilger Industries, SK, Canada). The nozzle from the bottom to the top was designated as first, second, and third nozzles on both sides. An aluminum extrusion was used to hold the nozzles, and the third nozzle was positioned at an angle of 40 degrees. Three hex screws can adjust the extrusion holding the third nozzle. This is intended for crop height changes during the field test. The distance between the first and second nozzles was based on the spread of the tip used, while the third was based on the height of the crop. Some other characteristic parameters of UGV and the sprayer unit are presented below in Tables 1 and 2, respectively.

Table 6: UGV and spraying parameters used in research field.

Parameter (UGA)	
External dimensions (mm)	990x 670x 390
Internal dimensions (mm)	296x 411x 155
Weight (kg)	50
Max payload (kg)	75
Speed (m/s)	1

Parameter (Spraying unit)	
Nozzle types	Hollow conical nozzle
Nozzle number	six
Pressure (kpa)	414
Nozzle height from ground (cm)	38, 84, and 145
Flowrate	0-100%
Tank capacity (L)	94

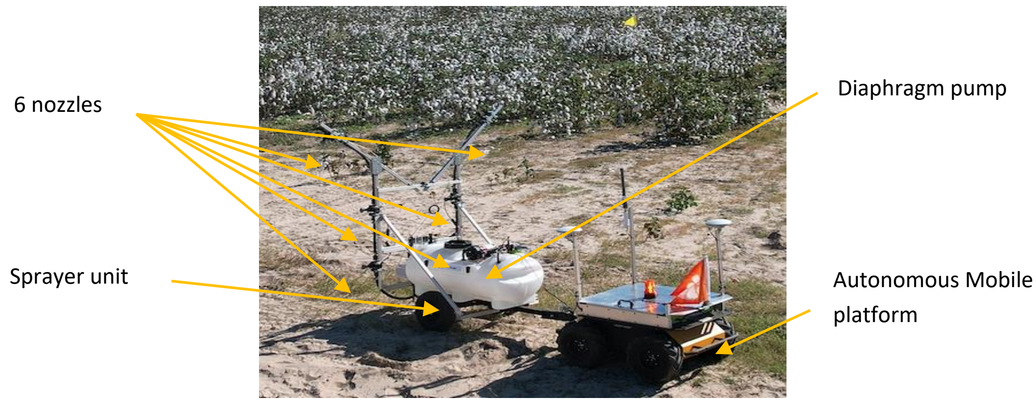

Figure 13: UGV equipped with sprayer unit.

3.2.2. CHEMICAL DEFOLIANTS

A mixture of two defoliant and one boll opener was used for defoliation which is presented below (table 3). All the chemicals applied were supported by Edisto research and education center, and the same chemical composition is generally used by farm crew for defoliation at the station farms.

Table 7: Information on chemicals used for the research.

Product Formulation	**Active Ingredient**	**Rate**	**Remarks**
Folex 6 EC	tribufos	454 g/38 L	Cotton defoliant
Free fall SC	thidiazuron	91 g/38 L	Cotton defoliant
Super boll	ethephon	907 g/38 L	Plant regulator

3.2.3. EXPERIMENTAL FIELD, COTTON CULTIVARS, AND PLANTING SCHEDULE

The experiment was carried out in Edisto Research and Education Centre (EREC) research fields at Blackville SC, USA and field trials was conducted in two field at the research farm (Field 1: 33.347, -81.319; Field 2: 33.353, -81.310). The cotton was planted for many years in the experimental field. Delta pine cotton cultivars (DP 2038B3XF and DP 2055B3XF) were planted in the field 1 and field 2, respectively. In Field 1, cotton was planted in early May of 2022 in six rows for research treatment and two rows for control treatment and field was further divided into two plots. In Field 2, cotton was planted in late May of 2022. Similar to field 1, there were six rows for research treatment and two rows for control treatments, but field 2 has single plot and was smaller than in Field 1. Thus, there were 16 and 8 cotton rows in Fields 1 and 2, respectively. The typical cotton row spacing in the research farm range was 97 ~ 114 cm. However, research plot used in this research practiced skip row (i.e., cotton was planted by skipping one row) to facilitate the movement of autonomous sprayer. Thus, the actual row spacing for the research field was 193 ~ 229 cm, whereas, in the control plot, it was 97 ~ 114 cm. The management practices followed the South Carolina Cotton Grower's Guide (Jones et.al.,2021).

3.2.4. EXPERIMENTAL DESIGN AND TREATMENTS

Completely randomized experimental design (CRD), with 4 replications in Field 1 and 2 replications in Field 2 was used. The sprayer system was set up at the Sensor and Automation Lab using the sprayer controller developed by the same lab. The volume output of each nozzle was tested at a different duty cycle (20%, 40%, 60%, 80, and 100%) by measuring the water output volume from each nozzle in 20 seconds. This preliminary test was made to study if each nozzle would generate the same volume with the same duty cycle settings. Based on the preliminary test result, three duty cycles were selected as a treatment for the research field (20%, 40%, and 60%), and a conventional tractor-mounted boom sprayer was a control treatment. In this research, the 20% duty cycle represents 20% of the nozzle orifice opening. Generally, spraying in the grower's field is done without a spray controller where the nozzle orifice is 100% open during spraying.

3.2.5. DATA COLLECTION AND ANALYSIS

A total of 120 plants (field 1=80 and field 2= 40) were randomly selected. Before the treatment application the selected plants were tagged with red thread to recognize the same plant for multiple data collection. For the control treatment, the conventional tractor mounted sprayer was use for spraying chemical on the other side of the research field. Same chemical defoliant was used in research plot and control plot. The spraying was done approximately 20 days before the harvesting date in both fields.

To study the cotton yield and fiber quality, cotton bolls from 3m (10 foot) length row were harvested manually, as shown in Figure 2. Approximately 300 gm of seed cotton per sample was selected for ginning (figure 2), which was done in one of the laboratories at the center (figure 3). The data on lint turnout and the seed was taken. The cotton fiber of approximately 65 gm per sample (figure 3) was sent to the Cotton Incorporated Laboratory for high volume instrument (HVI) and advanced fiber information system (AFIS) analysis (USTER AFIS PRO 2). One‑way ANOVA and Tukey test were done to study treatment effects and mean separation using statistical software (R version 4.1.2 (2021-11-01), The R Foundation for Statistical Computing Platform, Vienna, AT).

Figure 14: Manual cotton harvesting and sampling of cotton for ginning.

Figure 15: Cotton ginning and cotton lint sampling for quality analysis

3.3 RESULTS AND DISCUSSION

3.3.1. FIBER QUALITY ANALYZE BY HIGH VOLUME INSTRUMENT (HVI)

The defoliation timing, strategy, and leaf pubescence characteristics can impact the efficacy of defoliation and the fiber quality parameters (Byrd et.al., 2016; Faircloth et.al., 2004). There were several works on cotton fiber quality assessment (Johnson et.al., 2002; Bourland et.al., 2010; Clay et.al., 2006; Balkcom et.al., 2010); however, no information is available on the effects of defoliant dosage with the application of cotton defoliation from the side covering the whole canopy of the plant (i.e., bottom, middle, and upper). This work focused on the cotton fiber quality assessment of the newly developed sprayer prototype which can autonomously run and sprayer defoliants in between the cotton rows covering whole canopy of the plant. The study indicates that defoliants dosage (20%, 40%, and 60% duty cycle) had no significant effect on cotton fiber quality in both fields (Tables 8) except the Micronaire in field 2 (Table 8), which has significant results. Therefore, this showed that the defoliants could be applied safely at either of the three duty cycles without affecting these cotton fiber quality parameters. However, applying a 20% duty cycle will significantly reduce the use of chemicals therefore, it will be a good choice for cotton defoliation.

Table 8: Effect of defoliant dosage on fiber quality of field 1 and field 2 cotton analyze by high volume instrument (HVI)

Field#	**Treatment**	**Mic**	**UHML (mm)**	**Str (g tex^{-1})**	**Elo (%)**	**Rd**	**+b**	**Trash**	**SFI (%)**	**UI (%)**
1	20%	4.19[a]	1.12[a]	29.92[a]	6.83[a]	83.38[a]	7.28[a]	5.25[a]	8.75[a]	82.32[a]
	40%	4.30[a]	1.13[a]	30.05[a]	6.76[a]	83.35[a]	7.11[a]	8.37[a]	8.93[a]	82.31[a]
	60%	4.30[a]	1.12[a]	30.00[a]	6.60[a]	83.16[a]	7.35[a]	5.37[a]	8.46[a]	82.06[a]
	Control	3.96[a]	1.13[a]	29.95[a]	6.62[a]	84.00[a]	6.97[a]	10.75[a]	9.42[a]	81.92[a]

	20%	4.05^{a}	1.26^{a}	30.06^{a}	8.13^{a}	78.51^{a}	7.60^{a}	9.16^{a}	6.75^{a}	83.56^{a}
2	40%	3.83^{ab}	1.26^{a}	30.25^{a}	8.33^{a}	78.35^{a}	7.43^{a}	8.50^{a}	6.50^{a}	83.81^{a}
	60%	4.09^{a}	1.25^{a}	30.98^{a}	8.21^{a}	77.80^{a}	7.55^{a}	11.66^{a}	6.75^{a}	84.30^{a}
	Control	3.65^{b}	1.23^{a}	31.26^{a}	7.76^{a}	80.75^{a}	7.36^{a}	8.00^{a}	7.71^{a}	83.30^{a}

Legend: Mic – Micronaire

UHML - Upper half mean lengths

Str - Strength

Elo – Elongation

Rd – Reflectance

+b – Yellowness

SFI - Short fiber index

UI - Uniformity index

3.3.2. QUALITY PARAMETERS ANALYZES

Micronaire provides information on the thickness of the cotton fiber's cell wall, which indicates fiber fineness and maturity. Low micronaire values indicate fine and/or immature fibers; high values indicate coarse and/or mature fibers. The fineness factor in micronaire is considered more important for spinning, and fiber maturity is considered to have a significant effect on the dye-uptake process. Micronaire values between 3.8 and 4.2 were considered as desirable during the early 2000's (Valco,2002); however, the value has changed based on a 3-year study of fiber micronaire (2011, 2012, and 2014) showing an average of 4.74 and the maximum of 5.01 in the year of 2011 (Liu et al., 2016). Although the micronaire data from our research lies within the desirable range of early 2000's , it is less than South Carolina state average data of 4.35 and 4.39, respectively (Cotton Inc.,2023). Many factors affect the fiber micronaire including planting dates, cultivar, agronomy practice, crop load (Bange et.al.,2012), and weather (Luo et.al.,2016).

The upper half mean length (UHML) is average length of the upper half of the longest fibers which is equivalent to staple length. It is an important quality parameter as fiber fineness, and fiber tensile strength are closely related to UHML. The longer staples are usually finer and stronger than the shorter staples. The fiber properties, such as UHML are reported to be affected by compact yarn spinning processes (Gunaydin et.al.,2018).

The fiber strength in the HVI system is measured in terms of force in grams required to break one tex unit of fibers when clamping in between the two sets of jaws. The data on the strength is insignificant across the treatments in both fields (Tables 8). According to the classification of cotton published by Cotton Incorporated, the fiber is within the strong category based on strength (range is 29-30) except for the control fiber in field 2 which falls in the very strong category.

Fiber elongation is very important for the spinning and textile industry because of its direct relation with the tendency for fiber break. A positive correlation was reported between individual fiber elongation and tenacity (Mathangadeera et.al.,2020). In both Fields, the elongation of the fiber is statistically insignificant.

The reflectance (Rd) and yellowness (+b) determines the color grade of the cotton fiber. Reflectance denotes the brightness of the fiber, whereas yellowness indicates the degree of pigmentation. Planting time and harvesting time have a significant role in the fiber color grade (Çopur et.al.,2018). Similarly, a significant effect of reflectance and yellowness was reported on some yarn properties (Üreyen and Kadoglu,2006). The HVI color chart for American upland cotton ranges from 4 to 18, and the yellowness (or pigmentation) increases with an increase in value of +b. Likewise, the reflectance ranges from 40 to 90; the higher the value, the whiter (light) will be the fiber color.

Higher trash content in fiber negatively affects the fiber quality, and depending on the particle size, it can cause yarn breakage and may worsen the spinning stability. As in the delivered bale condition, the trash content of raw cotton is nearly in the range of 1–7% (Peyravi et.al.,2014). The trash in both fields is insignificant across the treatment. Therefore, we can apply any duty cycle safely for defoliation from the perspective of trash content.

The presence of excess amounts of short fibers in cotton is not good for the spinner and can cause many problems, such as excess waste, weaken yarn strength, and more yarn defects (Thibodeaux et.al.,2008). Both fields have an insignificant result on short fiber index within the fields. However, if we compare the data between two fields, field 2 has a lower SFI value than field 1.

The ratio between the mean length of the fiber and the upper half mean length is known as the uniformity index of cotton fiber. In field 1, the value of UI is in the range of 80-82, which is defined as average UI, and in field 2, the range is 83-85, which is defined as high UI according to the US cotton fiber chart (Cotton USA and Cotton Inc., 2022). The cultivar is an important determining factor for the uniformity index (Armijo et.al.,2019). Besides cultivar, some production practices could also reduce uniformity, such as early defoliation and harvesting methods (Armijo et.al.,2019). Similarly, post-harvest handling methods, such as ginning could also have significant effect on uniformity index and other quality parameters (Daget and Tesema,2022). In our research, harvesting was done manually in both fields; however, the defoliation was done two weeks earlier in field 1, which might have cause for the lower uniformity compared to field 2. But at the same time, we need to consider the planting time which is almost two weeks late in field 2 as mentioned on methodology section. Likewise, cotton cultivars were different which may have been a major source for the differences in UI between the fields.

3.3.3. FIBER QUALITY ANALYZE BY ADVANCE FIBER INFORMATION SYSTEM (AFIS)

The advance fiber information system (AFIS) is one of the techniques used to study cotton fiber quality in which fibers are cleaned and individualized using an internal mini card. It uses electro-optical sensors to analyze fibers, neps, and trash via high velocity air flow. Material passing through the sensor tube interrupts light imposing on the sensors and algorithms. The direct measurements of the dimensions of fiber and other particles are recorded based on the degree and time of light interruption passing the sensors (Calhoun et.al.,1997). The AFIS generates data on 20 different variables which are discussed below.

A. INFORMATION ON NEPS PARAMETER

Neps are the entangled and knotted fibers that are formed during cotton harvesting or the ginning process. Approximately 5-20 fibers found to be knotted together to form a single neps. Harvesting methods have a significant role in neps formation; manually harvested cotton results in fewer neps than mechanically harvested. The existence of neps in a cotton bale is unavoidable. A cotton bale with about 100 to 200 fiber neps per gram is considered the best-case scenario, whereas 200 to 350 neps/g considers the normal range (Elmogahzy,2023). The cotton in each field was manually harvested. Nep size in field 1, and Nep/gm in field 2 had non-significant results (Table 9). Similarly, the control had statistically higher nep/gm in field 1, and higher nep size in field 2. In both fields, Nep/gm is within the best to manageable range.

Table 9: Effect of defoliant dosage on fiber quality analyze by AFIS (Neps parameter)

	Field 1				***Field 2***			
Treatments	**Nep Size**	**Nep/gm**	**SCN (cnt/g)**	**SCN size**	**Nep Size**	**Nep/gm**	**SCN (cnt/g)**	**SCN size**
20%	654.87[a]	163.62[b]	9.00[a]	1132.12[a]	637.16[b]	178.66[a]	5.16[a]	1124.66[a]
40%	666.12[a]	160.62[b]	10.37[a]	1252.12[a]	646.83[ab]	192.66[a]	6.33[a]	1110.33[a]
60%	634.25[a]	138.50[b]	5.87[a]	1154.00[a]	650.83[ab]	212.66[a]	6.50[a]	1152.66[a]
Control	647.00[a]	236.25[a]	9.50[a]	1066.75[a]	670.33[a]	229.00[a]	9.83[a]	1246.66[a]

B. INFORMATION ON LENGTH PARAMETER

The AFIS is a count-based system, and the values are given on a number basis which are actual measurements, whereas values given on a weight basis are calculated. In the table10, (n) represents the number basis, and (w) represents weight basis length measurements.

Fiber length is critical as it greatly influences the end use of fiber and the process needed for fiber transformation (Krifa, 2006). Also, the AFIS analysis for cotton fiber length and diameter provides a close estimation of fiber behavior in the spinning process (Zurek et.al.,1999). In both fields, the fiber length (number basis) is statistically similar between the treatments (Table 10), and the control has the lowest mean length. However, a different result is observed on the weight basis measurement where 60% duty cycle has the lowest mean length in field 1, and no difference in length was observed in field 2. In the literature, there is some mention regarding weight basis measurement as “length- biased distribution” (Krifa,2006). Therefore, the fiber length property in this paper will be calculated according to number-based results. Zurek et al., (1999) mentioned that the selection of improved fiber length distribution was accomplished by AFIS method for their cotton breeding research, and the range of fiber length in their research was 18.8 mm to 24.6 mm, which is close is the length observed in our research (Kelly et.al., 2012).

The measurement of short fiber content (SFC) is very important from a spinning perspective, as excessive amounts of short fiber can result in production inefficiencies and deteriorate the textile quality (Thibodeaux et.al.,2008). The SFC was found to influence most of the yarn properties, such as yarn strength, irregularity, and frequency of thick and thin defects. This is justified by the strong correlation with each of the three measures of short fiber content (Thibodeaux et.al.,2008). In field 1, 60% duty cycle was found to have lower SFC as compared to other treatments. Similarly, in field 2, 60% and 40% duty cycles

Table 10: Effect of defoliant dosage on fiber quality cotton analyze by AFIS (Length parameter)

Field#	Treatment	L(n)	L(n) CV%	SFC (n)%	L (5%)	L(w)	L(w) CV%	UQL (w)	SFC (W)
1	20%	0.81^{ab}	43.33^{ab}	21.76^{ab}	1.34^{ab}	0.96^{ab}	37.17^{a}	1.17^{a}	8.81^{ab}
	40%	0.82^{a}	44.87^{a}	22.47^{ab}	1.37^{a}	0.97^{a}	35.48^{ab}	1.20^{a}	8.98^{ab}
	60%	0.81^{a}	42.31^{ab}	20.56^{b}	1.34^{ab}	0.96^{ab}	33.81^{b}	1.16^{ab}	8.32^{a}
	Control	0.77^{b}	45.37^{a}	25.00^{ab}	1.33^{ab}	0.93^{ab}	36.22^{a}	1.15^{b}	10.65^{a}
2	20%	0.86^{a}	47.00^{a}	22.13^{b}	1.51^{a}	1.05^{a}	36.48^{a}	1.32^{a}	8.51^{b}
	40%	0.84^{ab}	47.40^{a}	23.13^{ab}	1.49^{ab}	1.03^{ab}	36.90^{a}	1.30^{ab}	9.05^{ab}
	60%	0.86^{a}	46.58^{a}	22.40^{b}	1.49^{ab}	1.04^{a}	35.95^{a}	1.30^{ab}	8.71^{b}
	Control	0.81^{b}	48.45^{a}	25.60^{a}	1.45^{b}	1.00^{b}	37.55^{a}	1.27^{b}	10.31^{a}

(L= length, L (CV%) = Coefficient of variation of fiber length in %, SFC= Short (<0.5 inch) fiber content in %, UQL= Upper quartile length

C. INFORMATION ON TRASH PARAMETER

Trash measures the amount of non-lint material in cotton, such as leaves and bark. The major causes of trash are crop management, harvest, and post-harvest ginning. The presence of trash in cotton fiber quality was reported to degrade the quality of HVI and AFIS length measurements (Morais et.al.,2020). The total (cnt/g), trash size, dust, trash (cnt/g), and VFM variables are statistically not significant across the treatments in both fields (Table 11).

Table 11: Effect of defoliant on fiber quality cotton analyze by AFIS (Trash parameter)

Field#	Treatments	Total (cnt/g)	Trash size	Dust	Trash (cnt/g)	VFM
1	20%	82.62[a]	315.75[a]	315.75[a]	12.37[ab]	0.28[a]
	40%	129.20[a]	328.87[a]	328.87[a]	20.87[a]	0.48[a]
	60%	75.50[a]	322.50[a]	322.50[a]	12.25[ab]	0.27[a]
	Control	109.75[a]	373.50[a]	373.50[a]	22.00[a]	0.51[a]
2	20%	149.66[a]	317.00[a]	126.83[a]	22.50[a]	0.44[a]
	40%	151.66[a]	308.83[a]	129.66[a]	21.66[a]	0.43[a]
	60%	132.00[a]	306.00[a]	113.16[a]	18.66[a]	0.38[a]
	Control	117.83[a]	356.33[a]	95.66[a]	22.16[a]	0.46[a]

D. FIBER FINENESS, MATURITY RATIO, AND IMMATURE FIBER CONTENT (IFC)

The fiber fineness determines the stiffness or softness of fabric, twisting property during yarn formation, strength, and uniformity of a yarn and neps formation (Ramey,1982). Likewise, fiber maturity is also determined by fiber wall thickness, and immature fibers have a minimum wall thickness, possibly due to interruption or retardation of secondary cell wall cellulose biosynthesis during cotton fiber development. The higher proportion of immature fiber deteriorates the fiber quality by decreasing breaking strength and increasing neps (Kim et.al.,2021). Similarly, the fiber maturity ratio is very crucial property and is directly proportional to the degree of wall thickening. Thus, immature fibers have a very small maturity ratio with little or no secondary wall thickening (Paudel et.al., 2013). In field 1, there is no significant effect of treatment on the fineness, IFC, and mat ratio whereas in field 2, treatments had no effect on IFC and maturity ratio; however, fineness is significant with the 60% duty cycle having the higher fiber fineness than the other treatments (Table 12).

Table 12: Effect of defoliant dosage on fiber maturity ratio, fineness, and immature fiber content

Treatments	***Field 1***			***Field 2***		
	Fine (m tex)	**IFC (%)**	**Mat ratio**	**Fine (m tex)**	**IFC (%)**	**Mat ratio**
20%	165.87[a]	6.31[a]	0.86[a]	158.66[ab]	7.38[a]	0.84[a]
40%	160.37[a]	6.51[a]	0.86[a]	158.00[ab]	7.43[a]	0.83[a]
60%	167.37[a]	5.83[a]	0.88[a]	161.83a	7.50[a]	0.84[a]
Control	163.00[a]	6.97[a]	0.84[a]	156.66[ab]	7.25[a]	0.83[a]

4. CONCLUSIONS

The results from this study demonstrated that the autonomous ground sprayer across different duty cycles (i.e., 20%, 40%, or 60%) could be used for cotton defoliation without affecting the fiber quality. The defoliant dosages in this study did not significantly affect most of the fiber quality parameters. Meanwhile, some parameters showed significant results. In field 1; nep/gm, length (Ln), L (5%), SFC, trash content, and in field 2; micronaire, nep size, length (Ln), L (5%), SFC, and fiber fineness were significant. In the big picture, the fiber quality parameters were better using the newly developed sprayer (i.e., on the research plot) compared to the control plot where defoliation was done by a conventional tractor mounted boom sprayer. Therefore, the combination of using UGV and a specialized spraying system has significant potential for sprayer-based precision technology in the agricultural sector. In addition, these results could guide further study of autonomous ground sprayers and this technology for not only for cotton, but also for other agricultural crops.

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CHAPTER FOUR

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

A new cotton defoliation sprayer was developed with the application of robotics and pulse width modulation technology to solve the problem of poor bottom defoliation. Two field trials were conducted at Edisto Research and Education Centre, Clemson University, Blackville in 2022 and the research was focused to study droplets characteristics & defoliation rate and yield & fiber quality at different duty cycles (pulse width). The research is innovative and novel as no research has been conducted on side spraying for cotton defoliation previously.

From the result of the study, it can be concluded that:

For the satisfactory defoliation of the cotton plant, using the defoliant at a 20% duty cycle is recommended. However, the use of defoliant will not have its effect if there is rain after its spraying and when there are consecutive freezing nights for two days. With the freezing temperature for the two consecutive days, the leaves die before the formation of abscission layer between the petiole and stem and the spraying do not have any use. The planting time, time of defoliant application and crop varieties may bring the difference in the rate of defoliation in cotton. It was found that double spaced cotton in a row gave the higher yield facilitating the better uptake of nutrients and sunlight. The use of defoliant has been found to improve nep/gm, length (Ln), L (5%), SFC, trash content, micronaire, nep size, length (Ln), L (5%), SFC, and fiber fineness.

In overall, the prototype of new control sprayer showed promise for effective defoliation while using less chemicals which has huge benefits for human health, reduced production cost, and sustainable environment.

Future Recommendations

Although these results showed that the protype of control sprayer used in this research is a suitable for cotton defoliation, follow up research is needed to validate the result of current research. Similarly, in this research three duty cycles (20%, 40%, and 60%) were used so the future research should examine other duty cycles, such as 10%, 30%, and 50%, to quantify the impact on cotton defoliation. Likewise, a new study on selective defoliation can be done to support the concept of selective cotton harvesting in future.

APPENDIX A

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The Next Generation of Cotton Defoliation Sprayer

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Abstract: Chemical spraying is one of the most important and frequently performed intercultural agricultural operations. It is imperative to select the appropriate spraying technology as a selection of ineffective one leads to the wastage of a considerable volume of applied chemicals to the non-target area. Many precision technologies have been developed in the past few decades, such as image processing based on real-time variable-rate chemical spraying systems, autonomous chemical sprayers using machine vision and nozzle control, and use of unmanned aerial and ground vehicles. Cotton defoliation is a natural physiological process, but untimely and inadequate leaf defoliation by natural process hinders the mechanical cotton harvest. Induced defoliation is practiced by applying defoliants to address the issue with the natural process of defoliation. This paper covers spraying technologies in agriculture, cotton plants, cotton defoliation, new defoliant spraying systems, and the recent field test. The new spraying system attached to an autonomous mobile robot aims to improve the delivery of defoliant chemicals by adding a spray unit on the side of the plant. Preliminary results of the water-sensitive paper test at the field showed adequate penetration with low flow rates. This is a huge development as there is a huge potential to save on the cost of applying defoliant chemicals.

Keywords: cotton production; defoliation chemical; intelligent spray; robotics

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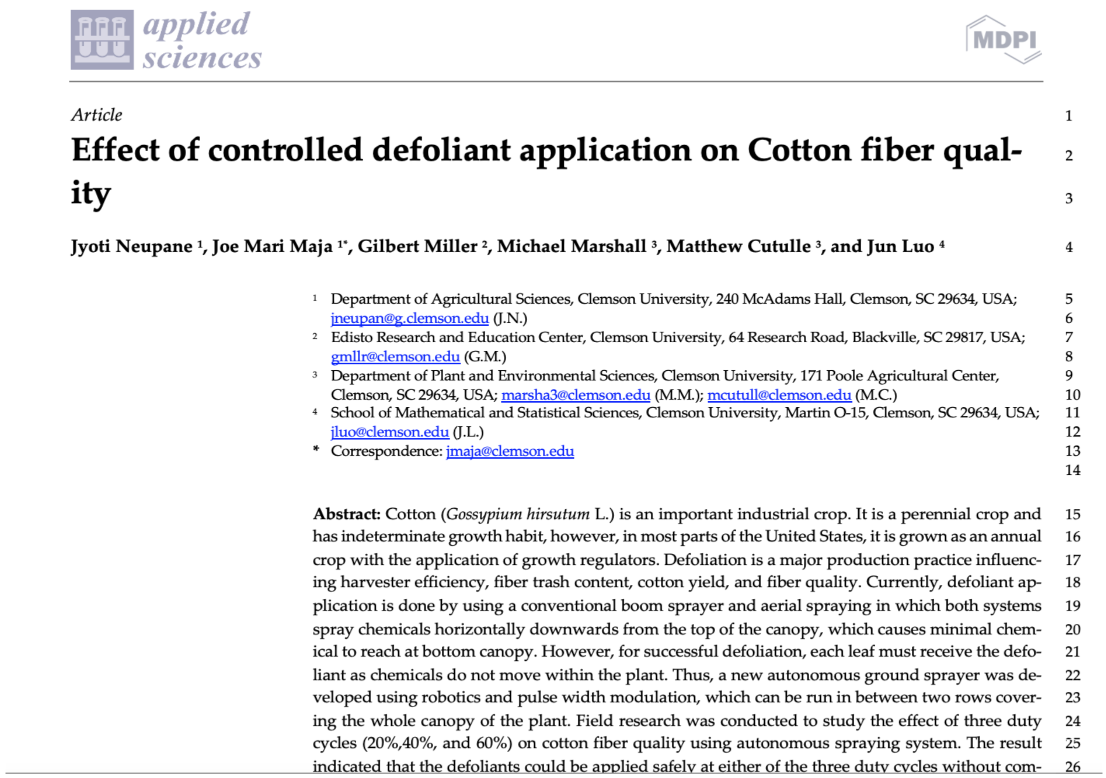

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Article

Effect of controlled defoliant application on Cotton fiber quality

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Abstract: Cotton (*Gossypium hirsutum* L.) is an important industrial crop. It is a perennial crop and has indeterminate growth habit, however, in most parts of the United States, it is grown as an annual crop with the application of growth regulators. Defoliation is a major production practice influencing harvester efficiency, fiber trash content, cotton yield, and fiber quality. Currently, defoliant application is done by using a conventional boom sprayer and aerial spraying in which both systems spray chemicals horizontally downwards from the top of the canopy, which causes minimal chemical to reach at bottom canopy. However, for successful defoliation, each leaf must receive the defoliant as chemicals do not move within the plant. Thus, a new autonomous ground sprayer was developed using robotics and pulse width modulation, which can be run in between two rows covering the whole canopy of the plant. Field research was conducted to study the effect of three duty cycles (20%,40%, and 60%) on cotton fiber quality using autonomous spraying system. The result indicated that the defoliants could be applied safely at either of the three duty cycles without com-

- The supplementarily material about automatic cotton defoliation sprayer can be viewed at: Video S1: UGV Cotton Defoliation Sprayer during field test (**https://youtu.be/i8SamBbH3N4**).