



## Article

# 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 defoliant 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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## 1. Introduction

Chemical spraying is one of the most important and frequently performed intercultural operations in agriculture [1]. Based on the target, chemical pesticides are classified as herbicides, insecticides, and fungicides to kill weeds, insects, and pathogens, respectively [2]. Similarly, some chemicals are used to accelerate the harvesting process, such as harvest aids and defoliant [3]. Even though using agrochemicals can effectively enhance crop production, it significantly impacts production cost, human health, and the environment [4]. Pesticide resistance is another major problem due to the overuse of chemicals [5]. During the green revolution, more agrochemicals were used to achieve targeted production, which created environmental degradation, human health effects, and high yields [6,7].

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 [6]. 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 of America rank 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 [8].

### 1.1. Spraying Technologies

It is imperative to select the appropriate spraying technology, as a selection of an ineffective one leads to the wastage of a considerable volume of applied chemicals in the non-target area. Advancements in new technologies in precision agriculture, such as the use of sensors, artificial intelligence, and unmanned vehicles contributed to the growth of 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. where they found 20~50% of applied chemical liquid recycled with the application of tunnel sprayer on a vineyard [9]. The above statement is supported by Jamar et al. as their study also found on an average 30% recycling of spraying volume which contributed to more environmental sustainability compared with traditional machines. Tunnel sprayer found to suitable for dwarf trees using traditional hydraulic nozzles [10].

A tower sprayer that sprays chemicals horizontally with airflow direction is suitable for taller plants. Tower air conveyor sprayers were found to have greater advantages on the distribution of air and pesticides through the trees, which help to minimize the loss of pesticides during spraying [11] but the airspeed, airflow, and power should consider properly as these factors significantly affects the penetrations of spray using tower sprayers in orchard [12]. Cannon air blast sprayers with cylindrical outlets create high air velocity jets to break spray mixture into finer droplets and have good canopy penetration, especially in the orchards such as blueberry which spray across the tops of several rows of blueberry resulting in high field capacity and minimum mechanical damage to developing fruits [13]. Similarly, the air-assisted spraying technology is used in cereal production to control insect pests [14].

Ultra-low volume (ULV) sprayers are very effective for controlling pests and insects in cotton plants [15]. Reduced fluid application rate, drift, and wastage are the primary objectives of ULV. Likewise, electrostatic techniques are emerging technology in agriculture. The concept behind it is the retention of particle charge, optimizing the deposition field. Some of the examples of this concept are air-assisted electrostatic spray, aerodynamic electrostatic spray, postharvest electrostatic sprays, and electrostatic pollination [16].

Conventional tractor-mounted boom sprayers spray on the upper sides, which is ineffective for controlling sucking insects as those insects' shelter on the bottom side of the leaves. The agrochemical application of conventional sprayers result in the wastage of applied chemicals, as it applies the agrochemicals at a uniform rate, resulting in off-target losses, economic losses, and environmental hazards. With advancements in technology, new concepts of variable rate of spraying technologies have been promising to apply the chemicals exactly to the required location.

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 [17] autonomous chemical sprayer using machine vision and nozzle control [18], use of unmanned aerial vehicle [19,20], and electrical robots [21].

Esau et al. reported that a machine vision smart sprayer for spot-application of agrochemical in wild blueberry resulted in an 11.6% saving of fungicide application along with a significant increase in the health of plant and harvestable yield [22]. Llorens et al. and Asaei et al. reported saving of more than 50% spraying volume with machine vision variable rate application as compared to constant rate conventional sprayer in orchards [23,24]. Through the use of machine learning, high spectral images have been increasing their ability to achieve precise and accurate action. Similarly, the use of unmanned vehicles is also increasing for multiple purpose. In agriculture, the application of unmanned aerial vehicle (UAV) is not only limited to spraying, but it is widely being use for mapping, planting, crop monitoring, and harvesting (Figure 1). Despite of many advantages it has some significant limitations such as battery and flight time [25]. In cotton, researchers

are using unmanned aerial vehicles to spray chemicals, predict application volume using remote sensing images [26].

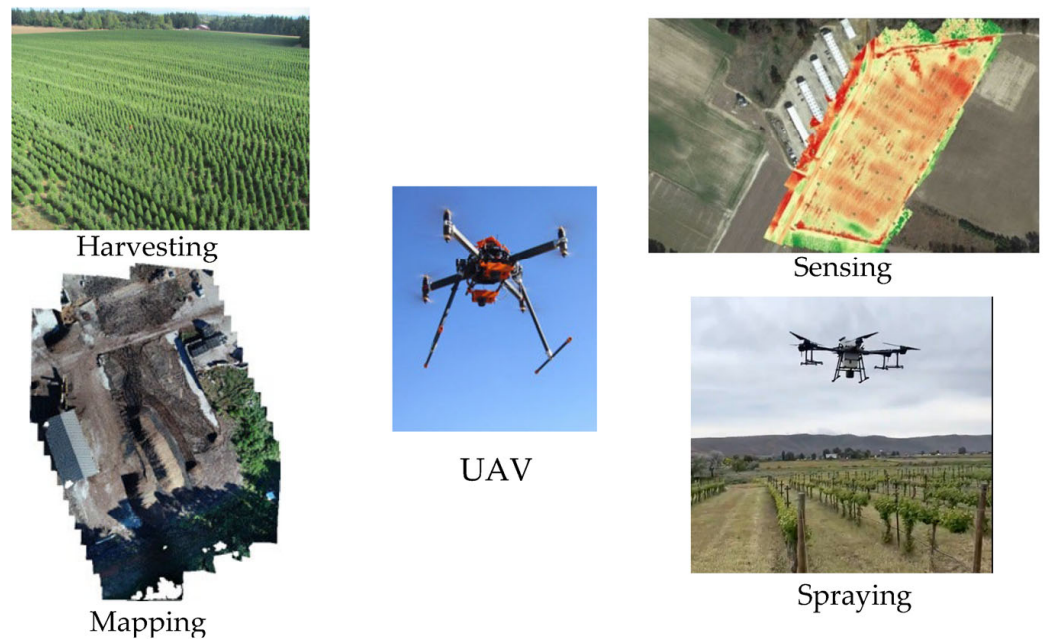


Figure 1. Multiple application of UAV in Agriculture.

Moreover, the use of unmanned ground vehicles is also increasing in agriculture. Mobile robots which mainly composed of two system: hydraulic subsystem with liquid tank and electrical system with pump, pressure regulator, electric flux regulator, flow rate meter, and electric on/off valves [21]. The robots are sometime referring 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 also have multiple application such as scouting, spraying, weeding, and harvesting (Figure 2) [27].



Figure 2. Mobile robots' different applications in Agriculture.

### 1.2. Cotton

Cotton (*Gossypium hirsutum*), a member of the *Malvaceae* family, is a tropical shrub [28]. 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 the evidence suggest its emergence roughly before 12.5 million years [29]. 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 dispersion.

*G. arboretum* is cultivated in some cotton markets leading countries such as India and Pakistan [30]. Likewise, *G. herbaceum* is cultivated in Africa and Asia on a small scale, whereas recently, the cultivation of tetraploid cultivars such as *G. barbadense* has been increasing in several regions of Asia and America due to its long, strong, and fine fibers [31]. 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 is dominated by the modern cultivar of *G. hirsutum* (i.e., upland cotton) [29].

Cotton, which is considered 'White gold', before the industrial revolution, the market was only restricted to domestic within a small region. Later, after the establishment of many textile companies and intercontinental markets, cotton became one of the major 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 U.S., especially in the upper southern part of the county, such as the Carolinas and Georgia, contributed to becoming the top cotton exporter in the world. The cotton industry primarily defines the U.S. position in the world economy. The United States is the world's third largest cotton producer after China and India [29].

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 another by-product. It is also believed to have some medicinal uses. In ancient times, people used its young shoot, leaves, and flowers to cure diseases such as asthma, convulsion, and skin diseases [32]. Cotton seed products include hulls, kernels, and linters. Hulls mainly provide the raw materials for rubbers and plastics, and the kernel provides raw materials for soap, glycerin, refined oil, animal feed, and fertilizers, whereas linters provide materials for the textile industry [33]. Because of its diversified uses, the cotton plant significantly influences the world economy even though it is not a food crop.

### 1.3. Physiology and Growth Pattern

An understanding of the growth habit of cotton is very crucial for its better management. It has indeterminate growth habits. Cotton is a perennial plant and favorable condition such as high rainfall, nitrogen fertilization, and fertile soil encourages high vegetative growth as compared to reproductive growth. From the economic perspective, reproductive growth is very important so application of growth regulator to achieve desirable vegetative and reproductive growth is beneficial [34]. The maximum growth of cotton occurs between 40 and 80 days after emergence (DAE). Likewise, canopy coverage also follows a similar pattern, such as height, in relation to days after emergence [35]. This result is also supported by Sun et al. work on cotton growth analysis using LiDAR [36].

At the vegetative stage, most of the carbohydrates produced are used for root and leaf development, but once the plant reaches the reproductive stage, the transport of carbohydrates shifts to developing fruits [37]. 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 set it apart from vegetative branches, which have a straight growth habit. Cotton leaves' photosynthetic capacity varies with age, reaching a

maximum value about 20 days of leaf age. Low fertility and water stress cause premature aging of the cotton leaf canopy, which further reduces the photosynthetic capacity and subsequently reduces the yield of the crop [37].

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 stable length, it begins maturing, or thickening, which happens because of the deposition of additional layers of cellulose [38]. The economic part of cotton is its fiber. Historically, growers used to harvest cotton boll manually which very tedious work and inconvenient for commercial production. Later, the concept of defoliation came to make harvesting more efficient. 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.

#### 1.4. Cotton Defoliation

Defoliation is the shedding of leaves by natural or artificial phenomena. Cotton defoliation is a natural physiological process, but untimely and inadequate leaf defoliation by natural process hinders the mechanical cotton harvest [39]. Therefore, induced defoliation is practiced by applying defoliant to facilitate mechanical harvesting [40]. Cotton defoliation is a major factor influencing mechanical harvesting, fiber quality, and the costs of cotton cultivation [41].

The importance of defoliation in cotton has been realized with increased mechanical/autonomous harvesting [42]. Several factors, such as plant condition, atmospheric temperature, and moisture during defoliant's application influence the success of cotton defoliation [43]. The defoliation practice accelerated boll opening and thus higher yield [44]. Historically, calcium cyanamide dust was first used as defoliant to promote aeration and thus reduce the boll rots in 1938 [45]. Chemical application is important from a production perspective and the most dangerous agricultural operation [46]. Therefore, we should apply chemicals precisely to minimize costs and their adverse impacts on environments and living beings.

Generally, chemical defoliant are applied through ground-based or aerial-based vehicles such as tractor-mounted boom sprayer, unmanned aerial spraying (drone spraying), and unmanned ground sprayer (robots spraying). Each system has its own merits and demerits and selection of these system depend on available technology, economic budget, cultivated area. Pivot attached sprayer system and conventional tractor-mounted sprayer resulted in better defoliation than chemigation [47]. However, UVA spraying system found to have significantly higher pesticides utilization rate, agronomic properties, yield, and fiber quality of cotton as compared to tractor-mounted boom sprayer [48]. Conventional spraying systems resulted in higher losses of chemical due to off target application. Thus, to tackle this problem many advance technologies such as pulse width modulation technology [49], LiDAR-guided system [50], unmanned aerial vehicles [51], unmanned ground vehicles such as mobile robots [52], 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, US farmers usually use a boom sprayer. The same boom sprayer is used for pesticide and fertilizer applications. A study compared an air-sleeve sprayer with a hydraulic nozzle sprayer 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 [53]. As large machinery such as tractors cause soil compaction, mechanical crop damage, and yield losses [54], the use of unmanned aerial vehicles (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 aids (defoliants and boll opener) was reported to increase defoliation and boll opening rates [55] 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 [54,56]. There are few reasons why aerial applications used for defoliations are not very common in the US. This is due to the Federal Aviation Authority (FAA) policy on using 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 [57]. For ground-based, it is apparent that manual spraying is still being used especially in India. The most popular sprayer unit is the mobile backpack (MBP), an air-assisted sprayer [58].

### *1.5. 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 [59]. The application of PWM has been increasing in agriculture mainly to improve the efficiency of pesticide application with higher precision [60]. Moreover, the nozzle flow rate can be controlled by using PWM, which can significantly reduce pesticide consumption, off-target drift losses, environmental risk, and production cost [61]. Although lower PWM results in a lower flow rate and minimizes the chemical use, we need to ensure the desired droplet size, distribution, and coverage. Only minimizing chemical use by ignoring 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 non-venturi type of nozzles to optimize and homogenize the spray droplet size across spray application [62].

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  $\pm 10\%$  of the target rate for each PWM duty cycle most of the time [63]. The application of PWM can be found in various crops such as apples [49], vines [64], and Palmer amaranth [65]. However, minimal studies about the application of PWM have been found for row crops such as cotton.

Boatwright et al. reported that intelligent spraying technology have higher efficiency in controlling disease and pests with reduced spray volume and drift in peach orchards compared to conventional air blast systems [66]. Likewise, Chen et al. used drones equipped with sensors and multispectral cameras to generate a defoliation prescription map using RGB and multispectral images [56]. 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, the large number of works has been conducted on conventional boom sprayer and UAV spraying; however, very limited study has been conducted on application of unmanned ground vehicle together with pulse width modulation technology for cotton defoliation.

### *1.6. Defoliation Time*

The timing of the defoliant application plays a significant role in cotton yield because premature defoliation reduces yield and late defoliation can deteriorate fiber quality due to bad weather [34]. Gormus et al. concluded that early application of defoliants significantly reduces seed cotton yield, boll number per plant, micronaire, and fiber length [67]. Various methods have been used to determine the time of defoliants application on cotton. Traditionally, counting nodes above the cracked boll (NACB), and calculating the percentage of the open boll methods were used which 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, is considered safe for defoliation [34].

Early application of defoliant (prior to 60% open boll) found to decrease yield and fiber quality thus Snipes and Baskin suggested to apply defoliant when 60% of boll are open [68]. However, it is important to consider variety of cultivated cotton as cultivar effect can be significant and the timing can be different for different cultivar [69].

However, there are no clear-cut guidelines for the perfect timing of defoliants application. 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 it is considered as physiological cutout [70].

According to COTMAN program when the NAWF = 5 and HU = 472 consider as appropriate time for defoliation. 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. However, Bynum and Cothren findings contradict COTMAN's recommendation based on their experiment [71]. 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 than compared to COTMAN recommendation (i.e., NAWF = 5 and 472 HU). Similarly, Clay et al. studied 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 [72]. The highest defoliation was found at 830 HU. Moreover, lint yield and gin turnout were found to be highest in early defoliation but fiber qualities except the fiber strength were insignificant to the defoliation timing. The HU accumulation can differ from one location to another based on their weather condition 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.

### 1.7. Defoliant and Factors Affecting Defoliation

The defoliants and harvest aids are categorized into two groups based on their nature of action: herbicidal and hormonal. Herbicidal defoliants injure the plant, causing it to produce ethylene in response which promotes leaf abscission [73]. Some examples of herbicidal defoliants are Carfentrazone-ethyl, Thidiazuron, diuron, and Tribufos. In the case of the herbicidal defoliant, for a successful leaf drop, each leaf should encounter the chemical, as chemical penetration and evenness of the spray play a significant role in defoliation [74]. In contrast, hormonal defoliants enhance ethylene production and inhibit auxin transport in the plant, encouraging leaf abscission [73]. The hormonal defoliants are generally more sensitive to temperature and crop conditions than herbicidal defoliants [75]. 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 [76].

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. found to have a significant effect of nitrogen and harvest aid on defoliation efficiency and cotton yield [76]. With rising N levels, the defoliation and boll opening percentages were significantly reduced and 150 kg N/ha together with 900 + 3000 g ai ha<sup>-1</sup> of Thidiazuron + Ethephon was recommended for good cotton yield and efficient defoliation [76]. Weather factors that influence harvest-aid performance are temperature, relative humidity, seasonal rainfall, and the occurrence of precipitation shortly following application. High seasonal night temperatures promote crop maturity and susceptibility to defoliation. Harvest aid work best when nighttime temperatures are 15.5 degrees Celsius or higher [34]. In general, herbicidal type defoliants such as tribufos (S, S, S, -tributyl phosphonodithioate)

have lower minimum temperatures (12.7–15.6 °C) than hormonal types (15.6–18.3 °C) such as ethephon and thidiazuron (N-phenyl-N'-1,2,3- thiadiazol-5-ylurea) [76]. Defoliation occurs twice as quickly at 35 degrees Celsius than it does at 25 degrees Celsius because the rate of activity doubles with a 10-degree Celsius increase in temperature [76]. Defoliation was 17% with no adjuvant at five days after treatment (DAT) when day/night temperatures 29.5/21 degree Celsius, 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-degree Celsius day/night temperature under all treatments at 5 DAT [77].

In general, excessive watering before and during defoliation can result in more vegetative growth of plants. Whereas extremely dry condition during defoliant application may hinder the defoliant activity. Terminating the irrigation at least 24 days before the defoliation resulted in good defoliation with single application of defoliant [78].

Plant characteristic such as leaf area index was found to have a significant effect on droplet deposition and defoliation rate [79], but the distribution of droplet depends on several factors which affects the defoliation. Plant characteristics (e.g., height, leaf area, and density) and spraying technology (spraying volume, nozzle types, pressure, and vehicle speed) influence the droplet coverage and distribution in the plant canopy [80].

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 gradually increases with the increase in the 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  $\mu$ m) was found. However, the average deposition of coarse droplet found greater when the flight height was 2 or 3 m [81]. The upper leaves intercept droplets and reduce the number of droplets available to deposit onto the lower parts of the leaf canopy [82]. Zhu et al. reported that spray deposition decreased dramatically from the top to the bottom of the canopy throughout the growing season [83]. This statement is also supported by Meng et al., who found the lowest droplet coverage on the bottom half of the cotton [84].

The main objective of this work is to evaluate the new spraying system developed by studying the droplet characteristics and defoliation at the different treatment levels and how does this affect the yield.

## 2. Materials and Methods

### 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 with 6 rows and 2 groups.



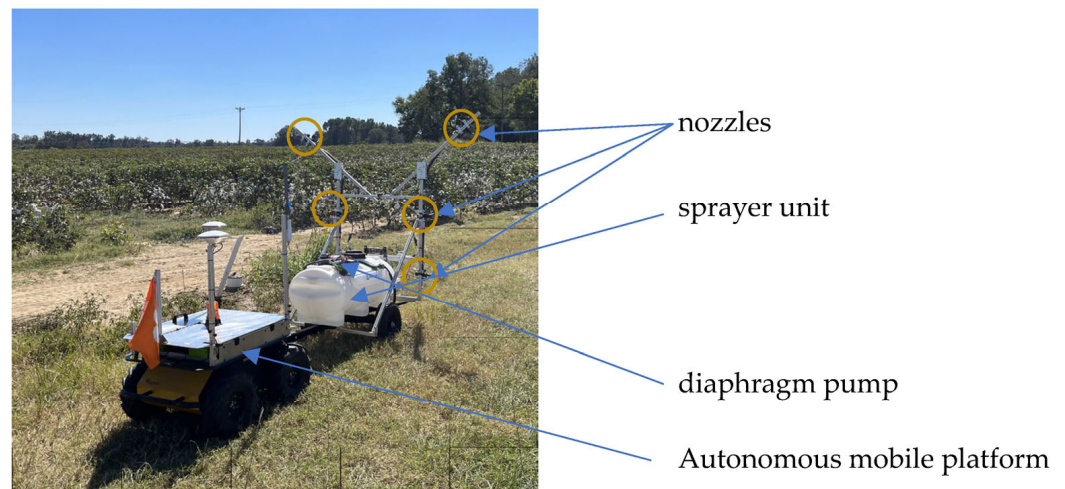
In Field 2, cotton was planted in late May of 2022 and has a smaller size as compared to Field 1 (Figure 4). Six rows were selected with length ranging from 21 m to 27 m. Cotton on both fields were planted by skipping one row (skip row) to facilitate the movement of the mobile robot.



**Figure 4.** Cotton planted in Field 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 (see Figure 5). The mobile platform is lightweight and powerful enough 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.



**Figure 5.** Autonomous mobile platform with the pull behind sprayer.

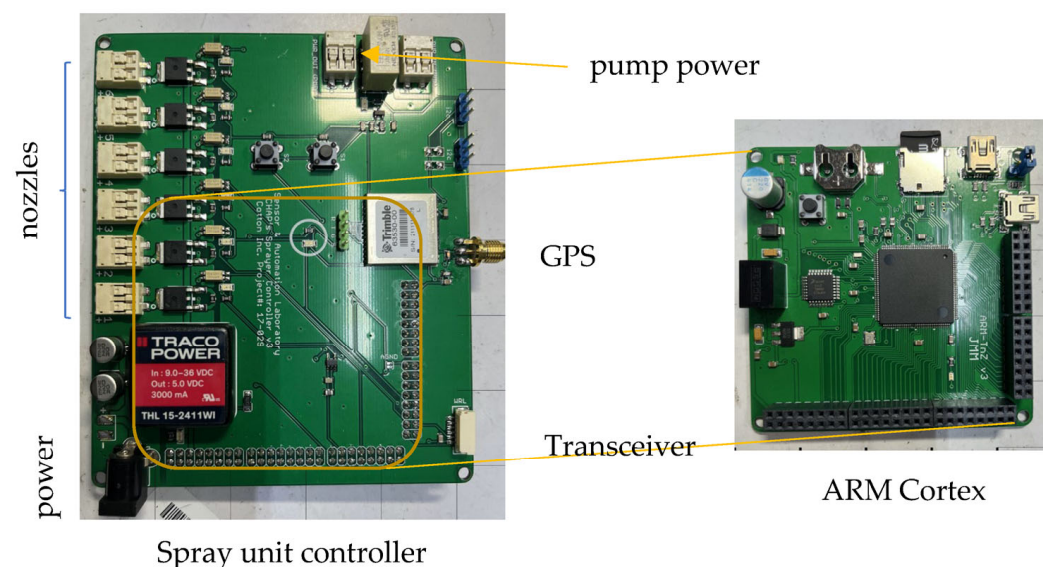
The sprayer unit (Model #1598042, County Line, Austin, TX, USA) is a 94 L 2-nozzle trailer sprayer with a built-in 12V diaphragm 9.5 L/min pump. The rated pressure of the pump based on the specification was 482 KPa. The sprayer was retrofitted with 6 nozzles (Model #625147-001, Capstan Ag Systems Inc, 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.

### 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., Kaohsiung, 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.



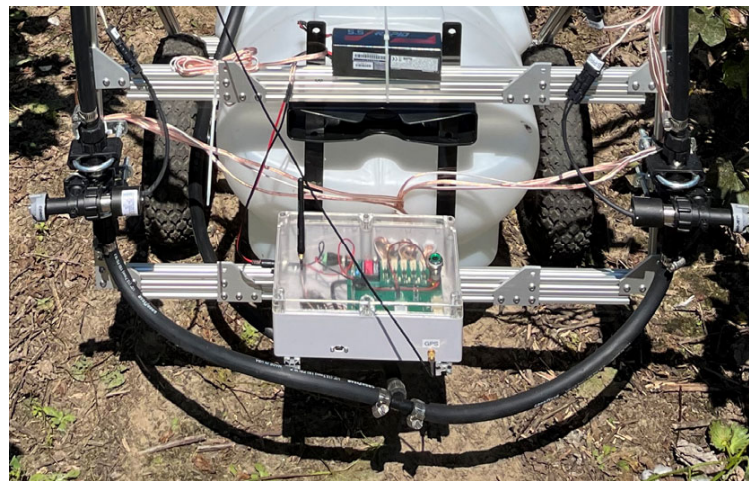
**Figure 6.** Sprayer controller developed for this project.

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.

#### 2.4. 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 12 May 2022, while the second field was planted on 25 May 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 used for this 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  |

#### 2.5. 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 0th, 4th, 8th, 12th, 16th, and 20th days after treatment application (DAT). The defoliation rate was calculated using Equation (1):

$$\text{Defoliation Rate} = \frac{lfc_n - lfc_{n+1}}{lfc_n} \times 100 \quad (1)$$

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.

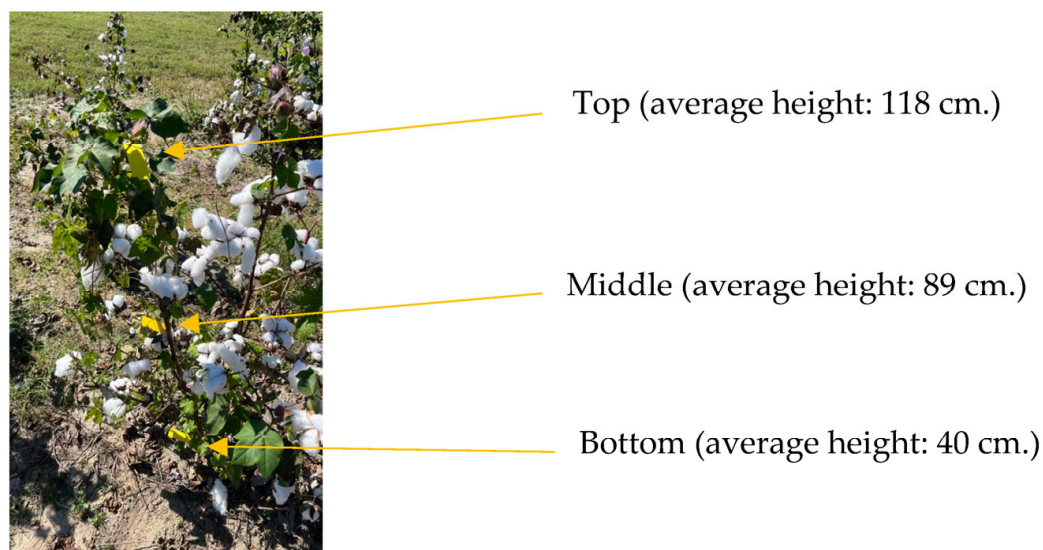


Figure 8. WSP placement during the field sprayer test.

### 3. Results and Discussion

#### 3.1. Defoliation Rate

Overall, the control has higher mean defoliation (Figure 9). Here control represents the current practice in which spraying was conducted using the conventional tractor-mounted sprayer. There is no significant difference in defoliation across the three treatment levels, meaning a 20% duty cycle does the same results as a 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 do 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 could be attributed that even with less volume of defoliants (20%) is enough to defoliate the plants if the chemicals were sprayed from top to bottom. This is a very promising result as there are no study yet on cotton defoliation that sprayed the side of the cotton. This means that farmers can reduce the use of defoliants and focus on the delivery of the chemicals.

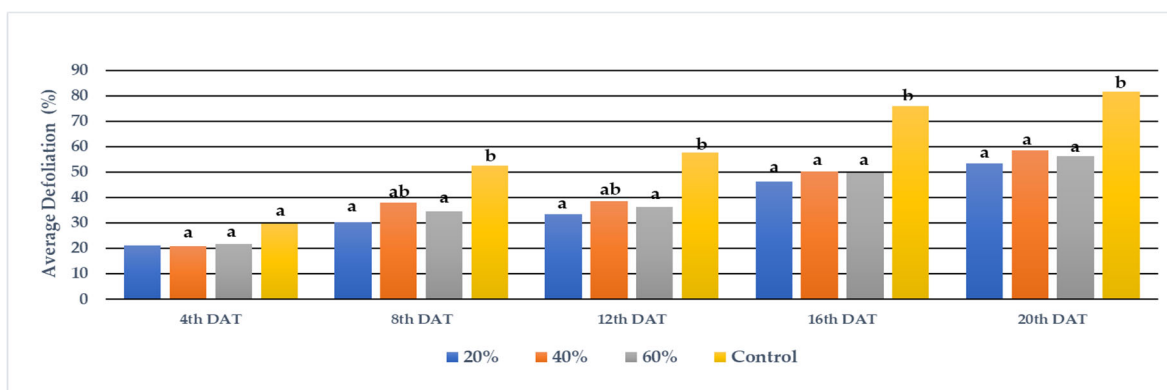


Figure 9. Average defoliation percentage on different days after defoliant application in Field 1.

Moreover, during the spraying on the research plot with the new sprayer, 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.

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.

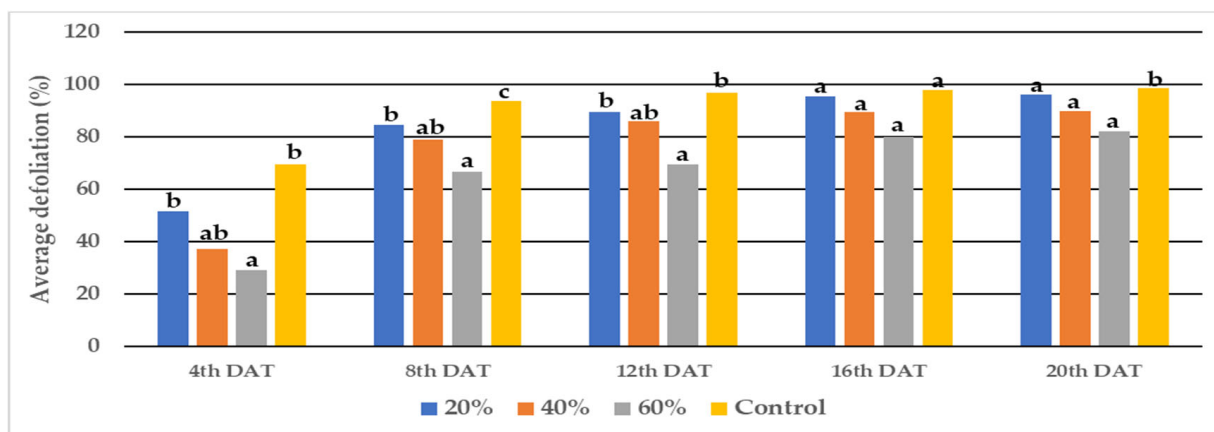


Figure 10. Average defoliation percentage on different days after defoliant application (Field 2).

### 3.2. 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 (\*  $p \leq 0.05$ , \*\*  $p \leq 0.01$ ).

| 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 (\*\*  $p \leq 0.01$ ).

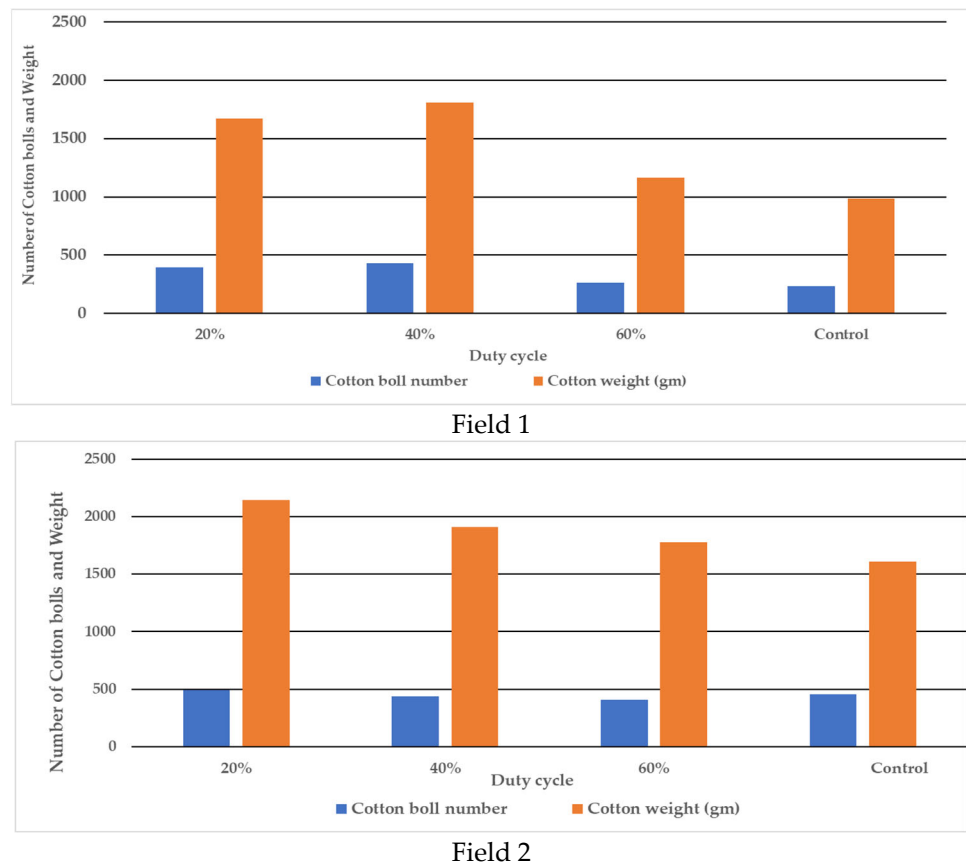
| Source                 | Degree of Freedom | Sum of Squares | Mean of Squares | F-Value | p-Value   |
|------------------------|-------------------|----------------|-----------------|---------|-----------|
| Treatment (duty cycle) | 2                 | 60,365         | 30,183          | 2.557   | 0.08457   |
| Block (Canopy height)  | 2                 | 146,508        | 73,254          | 6.206   | 0.0032 ** |
| Interaction            | 4                 | 46,643         | 11,661          | 0.988   | 0.41978   |
| Residuals              | 72                | 849933         | 11,805          |         |           |

**Table 5.** ANOVA analysis for drift potential (\*\*  $p \leq 0.01$ ).

| 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         |         |            |

### 3.3. 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 for both fields across treatments.

#### 4. Discussions

The results for Figure 9 showed that the duty cycles and 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 important as compared to volume.

#### 5. 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 the 4th day, but showed that on the 16th to 20th days, 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 the 8th and 12th day. In contrast, in Field 2, the 20% duty cycle has a higher defoliation rate on the 4th, 8th, and 12th days 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 fields showed that defoliation can be achieved even with a smaller amount of defoliant chemicals, as long as it is delivered properly to the cotton plants. Delivery of the defoliant chemicals is more important than volume.

Droplet characteristics (droplet distribution, density, and potential droplet drift) were insignificant across the treatments. Therefore, using only a 20% duty cycle is enough to defoliate based on the result 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. More 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 agricultural crops.

**Supplementary Materials:** The following supporting information can be viewed at: Video S1: UGV Cotton Defoliation Sprayer during field test (<https://youtu.be/i8SamBbH3N4> accessed on 24 January 2023).

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