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Implementing Digital Multispectral 3D Scanning Technology for Rapid Assessment of Hemp (*Cannabis sativa* L.) Weed Competitive Traits

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Abstract: The economic significance of hemp (*Cannabis sativa* L.) as a source of grain, fiber, and flower is rising steadily. However, due to the lack of registered herbicides effective in hemp cultivation, growers have limited weed management options. Plant height, biomass, and canopy architecture may affect crop–weed competition. Greenhouse experiments conducted at the joint Clemson University Coastal Research and Education Center and USDA-ARS research facility at Charleston, SC, USA used 27 hemp varieties, grown under controlled temperature and light conditions. Weekly plant scans using a digital multispectral phenotyping system, integrated with machine learning algorithms of the PlantEye F500 instrument, (Phenospex, Heerlen, Netherlands) captured high-resolution 3D models and spectral data of the plants. Manual and scanner-based measurements were validated and analyzed using statistical methods to assess plant growth and morphology. This study included validation tests showing a significant correlation ($p < 0.001$) between digital and manual measurements ($R^2 = 0.89$ for biomass, $R^2 = 0.94$ for height), indicating high precision. The use of 3D multispectral scanning significantly reduces the time-intensive nature of manual measurements, allowing for a more efficient assessment of morphological traits. These findings suggest that digital phenotyping can enhance integrated weed management strategies and improve hemp crop productivity by facilitating the selection of competitive hemp varieties.

Keywords: high-throughput phenotyping (HTPP); hemp (*Cannabis sativa* L.); leaf area; leaf angle; plant architecture; crop–weed competition; hemp weed management; weed-competitive traits

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1. Introduction

Hemp (*Cannabis sativa* L.), an annual herb in the Cannabaceae family, is distinct from other plants that are also referred to as "hemp," such as *Musa textilis* (Manila hemp, abaca), *Agave sisalana* (sisal hemp), *Hibiscus cannabinus* (kenaf), and *Crotalaria juncea* (sunn hemp), due to its unique botanical characteristics and applications [1,2]. Hemp is valued for its diverse uses, with more than 50,000 products derived from its stems, flowers, and seeds [3–6]. Historically, hemp was cultivated for the strength of its fiber, making it an excellent candidate for paper, rope, and canvas production. Hemp can also be manufactured into cloth, animal bedding, composite wood products, insulation, carpeting, plastics, stucco

and mortar, and fiberglass alternatives in the aviation and automotive industries. Seeds can be processed into hemp oil and seed cake, which can be used in the production of animal feed, personal hygiene products, and technical goods like oil paints and printing inks. All the aforementioned uses are derived from one of three types of industrial hemp in production: fiber, grain, or flower. In practice, hemp is rarely grown exclusively as a grain crop; rather so-called "dual purpose" hemp varieties are used to produce fiber and flower/grain from a single crop/production system [5].

The demand for hemp derived products has created an economic opportunity for United States (US) growers. A recent congressional report estimated US hemp product sales at $700 million per annum [4], with a tremendous opportunity for growth predicted [6]. Cannabis criminalization under the 1970 Controlled Substances Act (CSA) prevented US farmers from legally growing the crop until 2018, when the Farm Bill formally declared industrial hemp distinct from marijuana [7]. The prior US prohibition against Cannabis, along with criminalizing the growing of the crop, also banned research on best agronomic practices in hemp, including the development of recommendations for the control of competing vegetation. Cannabis' long legal history has resulted in a significant knowledge gap with respect to integrated weed management (IWM), hindering growers' abilities to maximize crop yields.

Weeds are problematic in all types of hemp production, and weed control is needed to prevent crop failure, maximize yield potential, increase harvestability, and reduce habitat for other pests such as insects and pathogens [8–10]. Research on hemp in coastal South Carolina, USA indicated that failing to control weeds can significantly reduce flower bud yield. The study identified a critical weed-free period of 2 to 4 weeks following transplanting as crucial for maximizing hemp yield. [11]. Plant size and architecture of the crop canopy are important characteristics that influence the critical weed-free period (CWFP) [12]. Therefore, there is a need to evaluate hemp varieties exhibiting different types of growth with respect to size and branching habits, which can identify their ability to compete against weeds in multiple weed infestation scenarios.

The determination of which plant traits contribute to the weed-competitiveness of a crop is often not readily apparent; in most instances, it is likely that a combination of various attributes are involved. In general, crops that exhibit rapid development and that effectively reduce the quality and quantity of light within the crop canopy tend to possess a higher level of competitiveness [13,14]. Other characteristics that have been observed to influence the weed-competitive ability of crop plants include rapid germination and emergence, rapid accumulation of biomass, leaf area index, leaf angle, and light penetration [15,16].

Most traditional phenotyping technologies are labor intensive, subjective, time consuming and destructive to plants. Therefore, high-throughput plant phenotyping (HTPP) using a non-destructive image-based machine vision is progressing rapidly. Machine vision-based plant phenotyping can estimate single plant traits or crop canopy for thousands of plants in the field. Hence, adoption of HTPP is an efficient strategy to accelerate the understanding of crop plant traits relating to competitiveness. Specifically, HTPP enables testing of large numbers of plant morphological parameters in a timely and cost-efficient manner and generates knowledge that can guide subsequent field trials.

The purpose of this study was to comparatively assess the accuracy of determining morphological traits of selected hemp varieties with different growth habits by traditional methods and by digital phenotyping. The study aimed to provide a non-destructive, high-throughput method for measuring morphological traits that can inform integrated weed management strategies. This study utilized a digital multispectral phenotyping system equipped with PlantEyeF500 (PE) 3D scanner (Phenospex, Heerlen, Netherlands) to evaluate several phenotypic traits related to hemp plant growth. The associations between plant phenotypic characteristics collected by the PE scanner and manual measurements may provide a simple selection criterion for more competitive hemp varieties. The PE platform used in this research serves as a contemporary phenotyping sensor. However, its appropriateness for specific crop species and experimental circumstances needs to be

thoroughly examined. This study was designed to rigorously assess the initial growth responses of a diverse set of hemp varieties, with the overarching goal of screening a broader population for potential weed competitiveness. The critical weed-free period, a pivotal early stage in crop development when the absence of weeds is essential for optimal growth, was a focal point of our investigation. The experiment aimed to be concluded before surpassing this crucial phase, ensuring that the findings would provide valuable insights into the selection of hemp varieties best equipped to maintain weed-free conditions during this vital period. This knowledge can serve as a basis for the development of tailored strategies for effective weed management in hemp cultivation.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

Greenhouse experiments were conducted at the Clemson University Coastal Research and Education Center greenhouse in Charleston, South Carolina (32.7941593, −80.0677777, altitude 4.26 m). The seeds of 27 hemp varieties were sown in square pots with a volume of 1.76 L (Greenhouse Megastore, Danville, IL, USA) that were filled with potting mix (Metromix 830 natural and organic, Sungro, Bellevue, WA, USA). The greenhouse trial followed a randomized complete block design (RCBD) with three replicates of each variety, ensuring random placement to avoid variability in greenhouse conditions. Pots were watered once per day, while fertilizers with an N-P-K ratio of 10-10-10 applied every 2 weeks at a rate of approximately 8–10 g per plant during each application, ensuring consistent hydration and nutrient supply for optimal growth. The average maximum/minimum or day/night temperatures were set to 26/22 +/−2 °C in greenhouse. The experimental conditions included an 18-h photoperiod with LED light (400–500 nm) and 6 h of darkness. The experiments were conducted twice, with trial 1 initiated on 15 March 2022, and trial 2 initiated on 21 September 2022.

2.2. Experimental Setup and Hemp Plants Scanning

Twenty-seven hemp varieties, including floral, fiber, and dual-purpose types, were included in a greenhouse trial as outlined in Table 1. During the experiment, pots arranged on tables in fixed positions were randomly allocated to their initial positions once and remained stationary throughout the trial, except for scanning procedures. After scanning, pots were replaced to their original fixed positions, ensuring consistency in spatial arrangement across scans. Hemp plants were scanned using a digital multispectral phenotyping system equipped with one PE scanner at weekly intervals for six weeks beginning three weeks after planting and when plants were approximately 9 cm tall. Experimental apparatus was designed to place four plants for each entry randomly and subjected to PE scanning to measure morphological characteristics (Figures 1 and 2). All plants were systematically placed at the center of the scanned surface during each scan. The PE scanner incorporated a 7-channel multispectral camera (between 400 and 900 nm). This novel hardware-based sensor fusion concept enables the conveyance of spectral information for every plant data point in the x-, y-, and z-axes with high resolution.

The PE scanner used in this study was pre-mounted on a mobile gantry, traveling along the y-axis. (Figure 1). Pots were placed on flat-top surfaces beneath the scanner mount, and the scanner was then moved along the y-axis over the plants (Figure 1). With the scan width adjusted to 65 cm, the scanner was mounted 100 cm above the pot's rim. A 25 cm tall metal barcode distinguished the start and end of each scan. Barcodes could be positioned between each plant for discrete measurement or on either side of a group of containers for averaged results. Before the initial scan, each pot was labeled, placed on the tables, and scanned in the same position and orientation at each time point. The PE scanner captured a 3D model of each plant. This scanner, when moving along the bench with plants, repeatedly passes a laser beam in the direction perpendicular to the movement, captures the light scattered by the objects, and constructs a 3D model of the objects using triangulation. The plants were scanned weekly for six consecutive weeks between 3 and

10 weeks after seeding (WAS). However, data are presented in detail focusing on the 3 and 10 WAS; these specific intervals were chosen to align with essential growth phases, early vegetative development and the beginning of the reproductive stage, respectively.

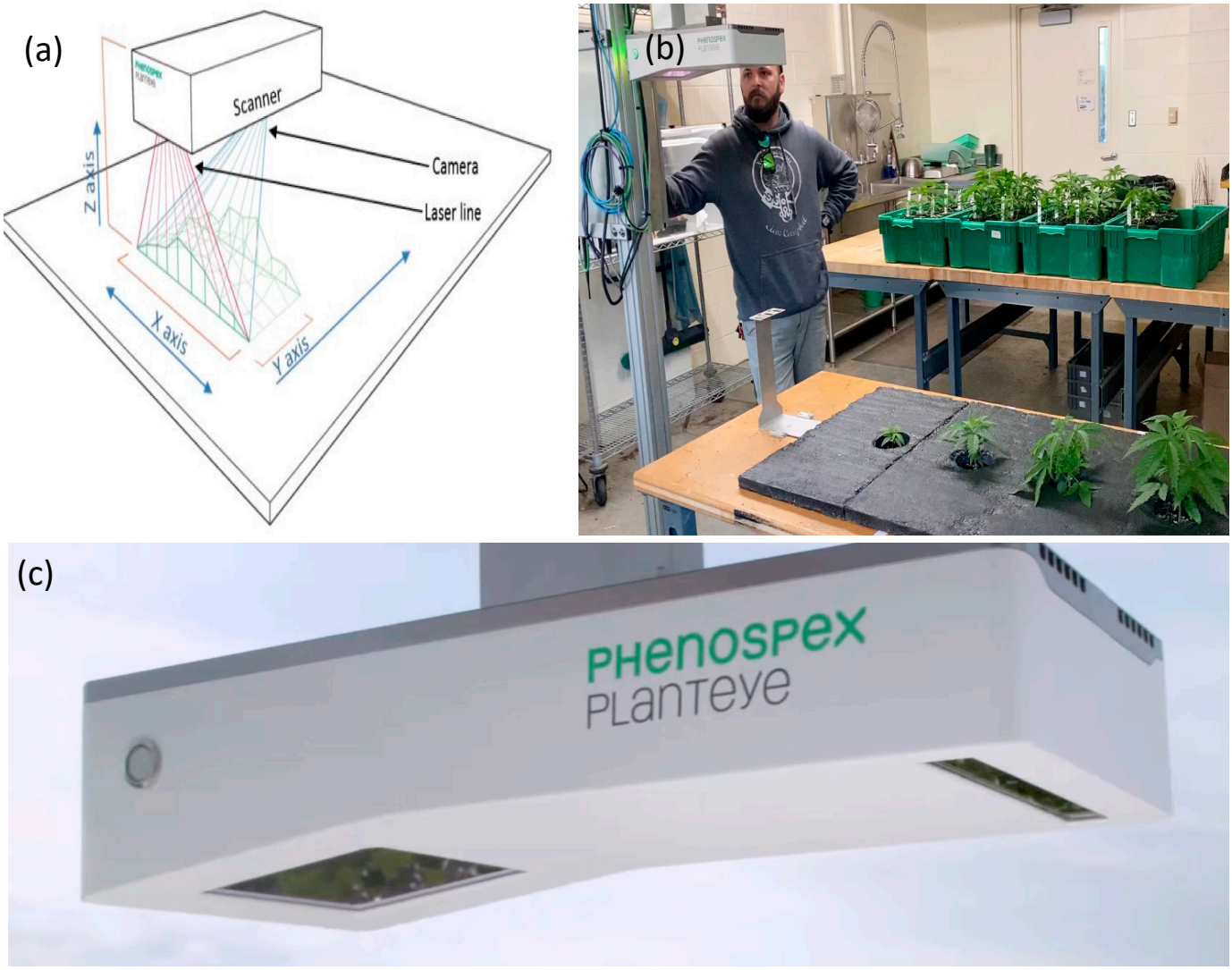

Figure 1. (**a**) Illustration of the Phenospex PlantEye3D triangulation scanner. The red lines represent the width and projection of the laser line, while the blue lines represent the projection and width of the camera. The green line/area indicates the crop stand. (**b**) The setup displays the moving position of the positioning system, with the 3D triangulation scanner securely mounted at designated location. (**c**) The enlarged image of Phenospex PlantEye3D F500 scanner.

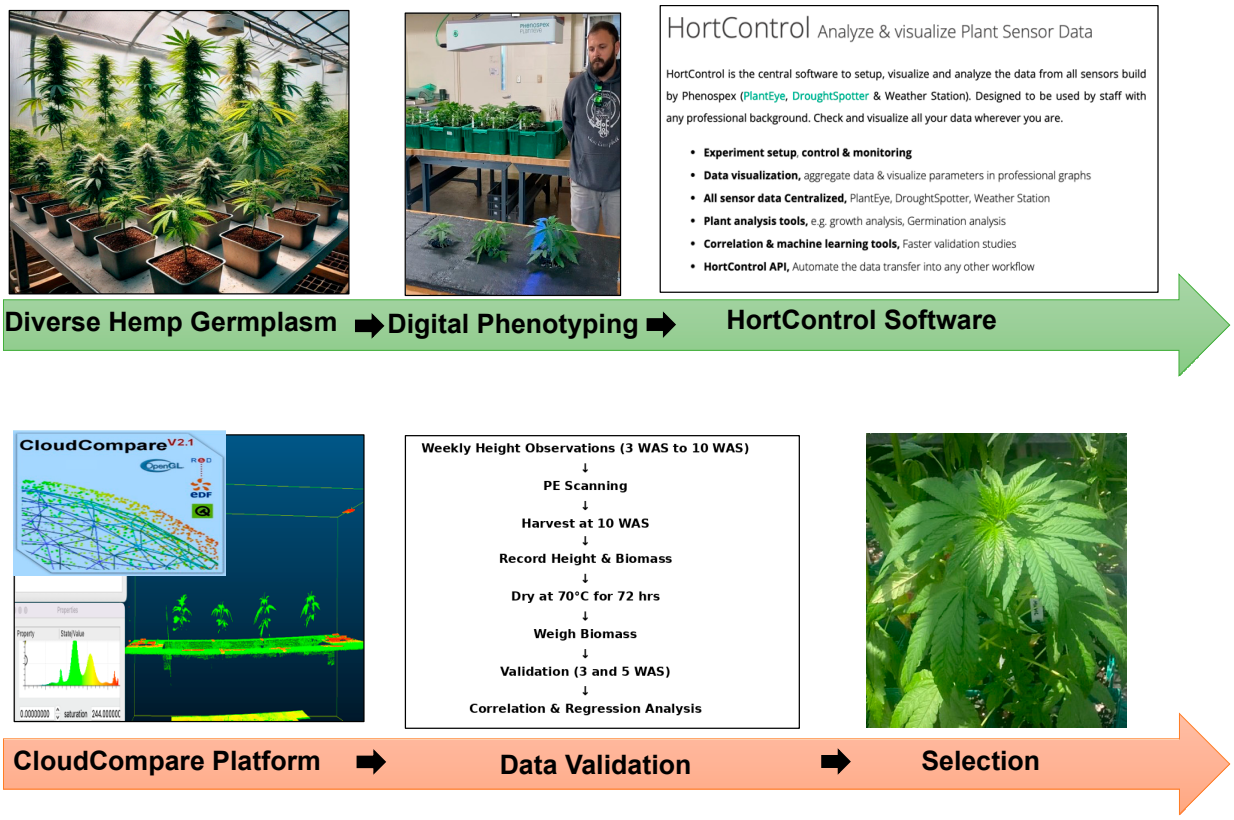

Figure 2. Workflow diagram for experimental steps in sequence.

Table 1. Hemp varieties (*Cannabis sativa* L.) categorized based on their primary usage types: floral, fiber, and dual-purpose (both floral and fiber production).

Varieties	Type (Fiber, Floral or Dual Purpose)
Arrowhead Abacus	Floral
Arrowhead Select	Floral
Bubbatonic	Floral
Hurricane Hemp	Floral
Hurricane Hemp: Florence	Floral
Lifter	Floral
Suver Haze	Floral
White CBG	Floral
Bialobrzeski	Fiber
Boxwine	Fiber
Boxwine 2.0	Fiber
Han-Ne	Fiber
Jinma	Fiber
Lara	Fiber
Puma	Fiber
Rincon	Fiber
Rogue	Fiber
Magic Bullet	Dual-purpose

Table 1. *Cont.*

Varieties	Type (Fiber, Floral or Dual Purpose)
Photo CBD	Dual-purpose
Abound	Dual Purpose
Anka	Dual Purpose
Ba0x Hybrid 2.0	Dual purpose
BaOx Hybrid	Dual purpose
BaOx Select	Dual purpose
Hlesia	Dual purpose
Hliana	Dual Purpose
Joey	Dual Purpose

2.3. Description of Remote Sensing Approach Using PlantEye

Data Collection: In this study, the PE sensor, mounted on a movable gantry system, was employed to scan hemp plants at weekly intervals. This setup enabled the capture of high-resolution spatial and spectral data across multiple spectral bands, including red (660 nm), green (550 nm), blue (450 nm), and near-infrared (800 nm). The high-resolution data collected by the PlantEye sensor facilitated detailed 3D reconstruction and spectral analysis of the plants, providing precise measurements of plant traits.

Data Preprocessing: To ensure the accuracy and reliability of the captured data, several preprocessing steps were undertaken. Adjustments were made for geometric and radiometric calibration to correct any spatial distortions and ensure accurate reflectance values. Noise reduction techniques, such as Gaussian and median filtering, were applied to remove environmental noise and enhance the quality of the captured data. Data normalization procedures were implemented to standardize the spectral data across different measurement sessions, ensuring consistency and comparability. Segmentation algorithms were used to differentiate plant material from the background, isolating the plant data for accurate trait analysis.

Data Analysis: Advanced algorithms and techniques were employed to analyze the preprocessed data, extracting meaningful insights into plant health and growth. Detailed 3D models of the plants were generated, enabling precise measurements of plant height, canopy structure, and leaf area. Spectral data was used to calculate vegetation indices such as the normalized difference vegetation index (NDVI) and green vegetation index (GVI), which are critical for assessing plant health and vigor. Time-series analysis tracked changes in plant traits over time, providing insights into growth patterns. Machine learning algorithms were used to develop predictive models for phenotypic traits. Regression models predicted plant height and biomass, while classification algorithms differentiated plant varieties.

Sensor Specifications: The PlantEye sensor has several key specifications that make it suitable for detailed remote sensing applications. The sensor provides millimeter-level precision for detailed 3D reconstruction of plant structures. It captures data in multiple spectral bands in the visible and near-infrared ranges, facilitating comprehensive spectral analysis. The sensor performs high-frequency scans, capturing dynamic changes in plant traits, and its wide field of view enables the capture of data from large areas or multiple plants simultaneously.

2.4. PE Data Collection, HortControl, and CloudCompare Software

The PE scanner, combined with HortControl (version 3.8) software measured plant height, 3D leaf area, projected leaf area, digital biomass, leaf inclination, leaf area index, light penetration depth, leaf coverage, greenness, and chlorophyll concentrations. Wavelength data combined with spectral indices, including normalized digital vegetation index (NDVI),

enhanced vegetation index (EVI), and photochemical reflectance index (PRI), among others. HortControl software also generates 3D point cloud data in PLY (polygon file format) files, capturing plant structures.

CloudCompare (version 2.6.1) software allows for exploration, analysis, and visualization of PLY files, as well as providing additional details. This data allows researchers to analyze crop structure, health, and growth patterns, optimize resource allocation, assess plant traits, monitor environmental changes, and develop autonomous farming systems. CloudCompare was utilized as a tool to verify and analyze PE scanned plants retrospectively. By importing PE generated point cloud data in PLY format, CloudCompare facilitated comprehensive visualization, quality assessment, precise measurements, comparison with reference data, annotation, and seamless exportation of results. This enabled a thorough examination of plant morphology, validation of scanning accuracy, and meticulous documentation of observations. The workflow diagram for all the steps in sequence is provided in Figure 2.

2.5. Manual Observations, Destructive Harvesting, and Data Validation

Manual observations of plant height were conducted on a weekly basis, starting from 3 WAS until 10 WAS. These observations were conducted concurrently with PE scanning. At 10 WAS, all plants were harvested destructively, marking the end of the experiment. Aboveground height and biomass of plants were recorded. For aboveground biomass, plants were clipped, and oven dried in a general protocol oven (Heratherm, Thermo Scientific, Waltham, MA, USA) at 70 °C for 72 h and weighed.

Multiple validation experiments were conducted for morphological characteristics (biomass and plant height). For validation, the manually measured and PE scanner height data taken 3 and 5 WAS were utilized and presented in the paper. Validation used linear regression, with the *y*-axis being the manually measured heights and the *x*-axis being the PE scanner height from Equation (1). The linear regression analysis of PE scanner estimated plant height vs. manually measured plant height showed the following relationships:

$$y = 0.1908 + 0.0975x \quad (1)$$

where y is the plant height taken manually, and x is the PE scanner's estimated plant height.

2.6. Statistical Analysis

Comparisons were made by correlation analysis between PE scanner and manually measured traits. The PE scanner derived and manually measured heights and biomass were used for correlation and linear regression analysis in JMP Pro 17.0 (SAS Institute Inc., Cary, NC, USA) to determine the relationship between derived height (y) with measured height (x). The PE height values from the 3 and 5 WAS were used for validation of the methods. The PE derived height and manually measured height for two time periods were subjected to the two-tailed *t*-test to test the null hypothesis that the difference between measured and derived height was zero. All data were examined for normal distribution with the Shapiro–Wilk and Anderson–Darling tests. Data were log-transformed when necessary to satisfy the assumptions of normality and variance. The transformed data were used for statistical interpretation, but the back-transformed data were presented. Data were pooled for both trials because there was no treatment by trial interaction. Individual treatment differences were examined using Fisher's protected least significant difference (LSD) multiple comparisons test and GraphPad Prism v9.0 (GraphPad Software, La Jolla, CA, USA) was used for statistical analysis and graphical interpretation.

3. Results

3.1. Digital Height Estimation

The PE scanner estimated the plant's height from the top of the pot to the top of the plant. At 3 weeks after seeding (WAS), manually measured plant heights ranged from 10.0 to 40.0 cm, while the PE scanner estimated heights ranged from 9.6 to 35.8 cm (Figure 3).

The average discrepancy between the PE estimated and manually measured heights was 0.26 cm. This slight difference was not statistically significant ($p > 0.01$) and could be attributed to the natural bending of the plant tip during scanning, which was held straight during manual measurements. The results of the two-tailed *t*-test confirmed no significant difference between the heights estimated by the PE scanner and the manually measured heights ($n = 81$, $p = 0.731$) (Figure 4). Overall, a highly significant positive correlation was observed between manually measured plant height and digitally PE scanner estimated height at 3 WAS and 10 WAS (Tables 2 and 3).

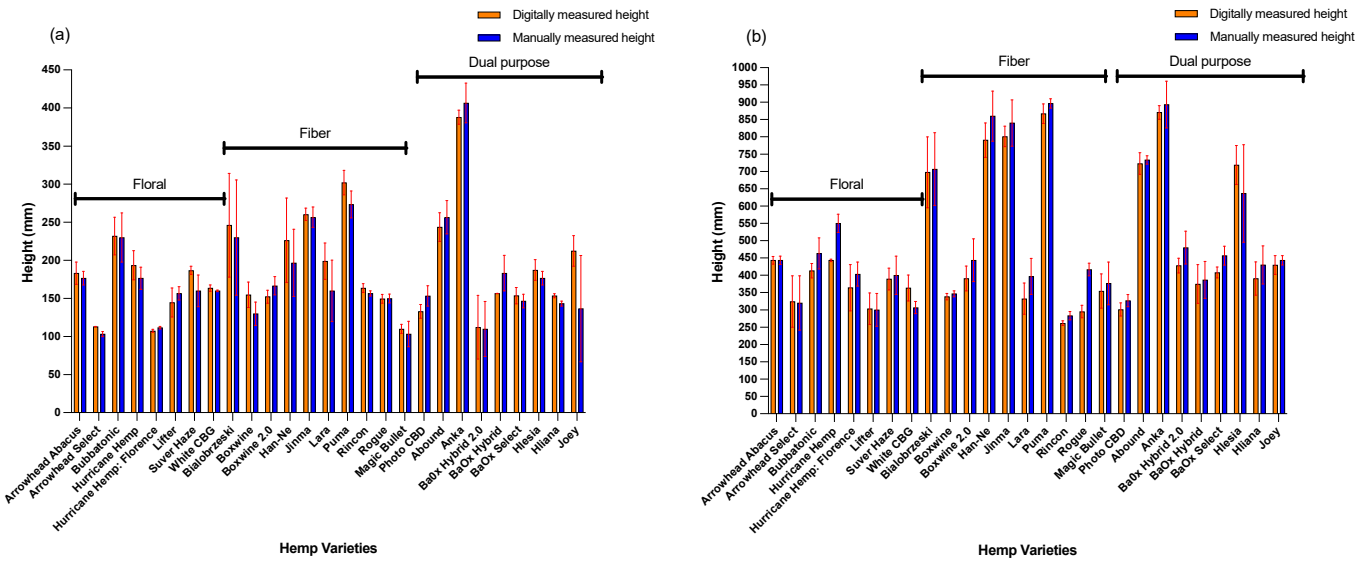

Figure 3. Comparison of digital and manual height of the different types of hemp varieties (Floral, fiber and dual purpose) taken 3 WAS (**a**) and 10 WAS (**b**).

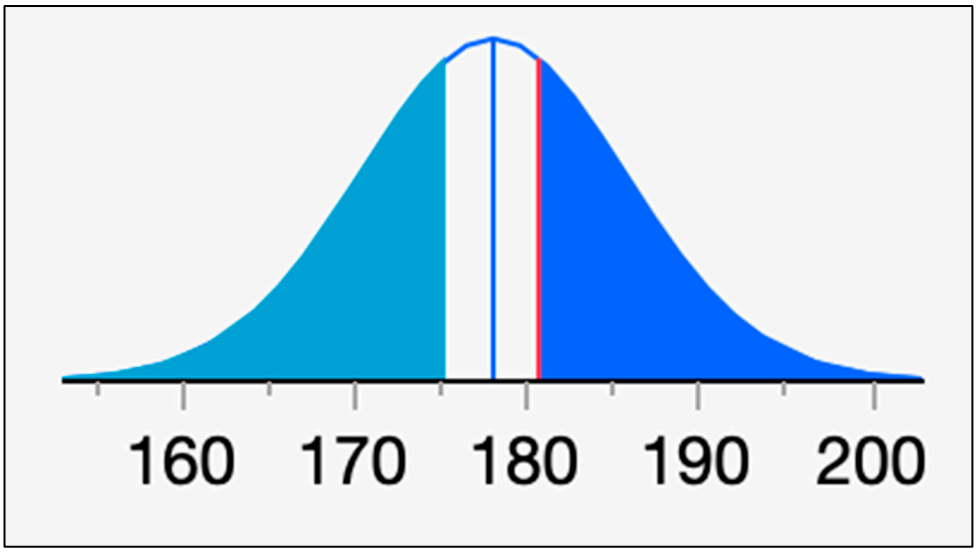

Figure 4. Distribution of PlantEye scanner-derived and manually measured hemp plant height of all data points ($n = 81$). To obtain the distribution curves, a two-tailed *t*-test was run on the PlantEye-derived and manually measured heights. The red line shows the mean height.

At 3 weeks after seeding (WAS), among floral hemp varieties, Bubbatonic and Hurricane Hemp were the tallest, with average heights of approximately 232 mm and 193 mm, respectively. In contrast, Arrowhead Select and Hurricane Hemp: Florence were observed with shorter digital heights of 113 mm and 107 mm, respectively. In the fiber hemp type,

Bialobrzeski, Jinma, and Puma displayed tallest digital heights with average of 246 mm, 260 mm, and 300 mm respectively, indicating their potential suitability for fiber production. Dual-purpose hemp varieties displayed a wide range of digital heights, approximately from 96 mm to 358 mm. Among dual-purpose hemp varieties, Anka demonstrated the tallest stature, with average digital height of approximately 358 mm, while Magic Bullet observed as the shortest variety with 96 mm height. Similar trends were followed when the data was taken at 10 WAS. Across all hemp types, visually represented in grouped graphs (Figure 3a,b), demonstrated a high degree of consistency between digital and manual height measurements. Fiber varieties tend to exhibit stronger growth in height over time compared to floral and dual-purpose types between the 3 WAS and 10 WAS. These findings underscore the substantial variability in hemp plant heights across different varieties and highlight the importance of selecting cultivars suited to specific agricultural objectives. Taller varieties may hold promise for fiber production, while shorter ones might find utility in floral yield or dual-purpose cultivation contexts.

Table 2. Correlation coefficients of morphological parameters of hemp varieties scanned after 3 weeks of seeding.

	Digital Biomass	Digital Height	Leaf Angle	Leaf Area Index	Light Penetration	Manual Plant Height
Digital biomass	1.00					
Digital height	0.72 *	1.00				
Leaf angle	0.04	−0.19	1.00			
Leaf area index	0.77 *	0.27	0.25	1.00		
Light penetration depth	0.61 *	0.71 *	0.01	0.44	1.00	
Manual plant height	0.59 *	0.90 *	−0.05	0.19	0.68 *	1.00

Values are presented as correlation coefficients, r, at 95% confidence level. * Represents significance ($p < 0.05$).

Table 3. Correlation coefficients of morphological parameters of hemp plants scanned 10 WAS (week after seeding).

	Digital Biomass	Digital Height	Leaf Angle	Leaf Area Index	Light Penetration Depth	Manual Plant Height	Fresh Biomass
Digital biomass	1.00						
Digital height	0.68 *	1.00					
Leaf angle	0.39	−0.06	1.00				
Leaf area index	0.74 *	−0.27	0.47	1.00			
Light penetration depth	0.64 *	0.79 *	−0.13	−0.11	1.00		
Manual plant height	0.15	0.94 *	−0.18	0.31	0.52 *	1.00	
Fresh biomass	0.89 *	0.69 *	0.08	0.67 *	0.62 *	−0.02	1.00

Values are presented as correlation coefficients, r, at 95% confidence level. * Represents significance ($p < 0.05$).

3.2. Method Validation of Digital Plant Height Estimation Techniques

To assess the reliability of the PE scanner in determining plant height, comparative analysis was conducted against standard manual measurement technique. The scatter plot in Figure 5a demonstrates the linear correlation between the manually measured plant heights (*y*-axis) and the heights derived from the PE scanner (*x*-axis) at 3 WAS. The best-fit line, represented by equation 1 ($y = 0.190 + 0.097x$), indicates a positive linear relationship with a coefficient of determination (R^2) of 0.88. This high R^2 value implies that the PE scanner-derived measurements can accurately predict the manually measured plant height. However, it is important to note that 88% of the variation in height was accounted for in this correlation analysis considering all data points ($n = 81$, $R^2 = 0.88$) at 3 WAS (Figure 5a). Few pots were observed with non-uniform growth, potentially attributable to factors such as inadequate germination. These pots exhibited the greatest deviation from the regression line. Upon exclusion of above-stated pots from the analysis, the remaining pots exhibiting

complete canopy cover demonstrated improved correlation between PE scanner-derived estimations and manual measurements (n = 75, R^2 = 0.946).

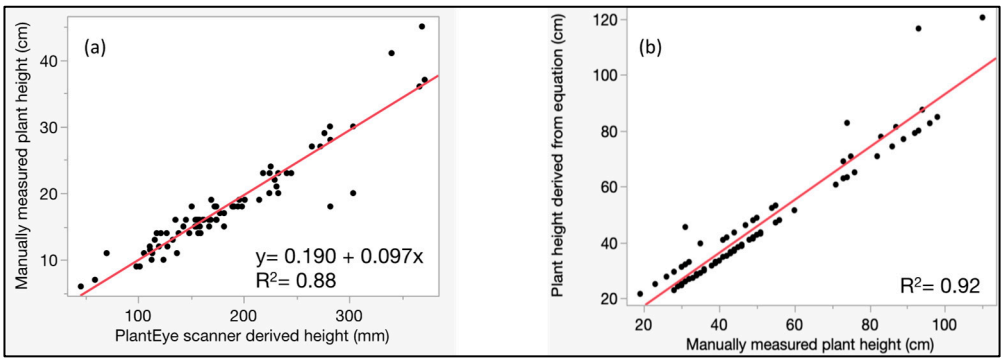

Figure 5. (**a**) Relationship between manually measured and PlantEye scanner-derived hemp plant height of all data points (n = 81). The relationship was derived by simple linear regression with manually measured height on the y-axis and PlantEye scanner derived height on the y-axis. (**b**) Relationship between manually measured plant height and derived height from regression equation at 5 WAS. The derived height from regression equation is on the y-axis and manually measured height is on the x-axis.

Figure 5b shows the correlation between manually measured plant heights at 5 WAS and the predicted heights derived from a regression equation 1 (y = 0.190 + 0.097x). The derived heights are plotted on the y-axis, while the manually measured heights are displayed on the x-axis. The resulting R^2 value of 0.92 suggests a strong correlation, indicating that the regression equation provides a highly reliable method for predicting plant height from manual measurements.

3.3. Leaf Area Index (LAI), Leaf Angle (LA), and Light Penetration Depth (LPD)

3.3.1. Leaf Area Index (LAI)

Weeds impede the development of new crop plants by shading and competing for soil nutrients and growing space. The leaf area index (LAI) is an important parameter for defining canopy structure, light use efficiency, and in predicting primary production. LAI is a dimensionless quantity, which represents the total one-sided area of leaf surface (m^2) per unit ground surface area (m^2) (Tables 4 and 5). In this study, LAI follows a near-linear relationship with digital biomass and height. Wide variations of LAI were observed among the varieties, with the LAI of 'Han-Ne' (0.140) being about four times higher than that of 'Joey' (0.033). Generally, 'Anka', 'Bialobrzeski', 'Bubbatonic', and 'Han-Ne' had the greatest LAI, followed by 'Hurricane Hemp', 'Hlesia', and 'Puma' with the least LAI.

Among all varieties, floral hemp, cultivated primarily for its flowers/buds, showed a range in LAI values, indicating differences in leaf density and canopy structure. For example, at 3 WAS, 'Bubbatonic' exhibited a relatively high LAI of 0.135, suggesting a dense canopy beneficial for capturing light efficiently at the early vegetative stage. By 10 WAS, 'Hurricane Hemp' showed a significant increase in LAI, pointing towards sustained leaf area development conducive to supporting floral production. Fiber hemp types are grown for their stalks and used in textiles and construction materials. These varieties tend to prioritize vertical growth, which was reflected in their LAI measurements. 'Han-Ne' had the highest LAI at 3 WAS (0.140), indicating robust early growth conducive to fiber production. By 10 WAS, 'Bialobrzeski' and 'Jinma' showed substantial LAI values, which could correlate with a denser canopy, potentially improving photosynthetic efficiency crucial for biomass accumulation necessary for fiber yield. Dual-purpose hemp varieties are versatile and used for both fiber and floral production. These types showed a significant range in LAI values at 3 and 10 WAS, reflecting their varied use. For instance, 'Anka' showcased a dramatic increase in LAI by 10 WAS (0.192), the highest among dual-purpose varieties, signifying its

potential for fiber and flower production due to its dense canopy. Conversely, 'Magic Bullet' and 'Photo CBD' had lower LAI values at 3 WAS, which could affect their early vegetative development and overall productivity. The observed LAI values across the different hemp types reveal intrinsic growth strategies and potential productivity outcomes based on their intended use. Floral varieties emphasize dense canopies early to support flower development, fiber types focus on vertical growth and leaf area to boost stalk biomass, and dual-purpose varieties balance these traits to support both ends.

Table 4. Morphological traits of the hemp varieties scanned with Phenospex PlantEye scanner 3 weeks after seeding.

Varieties	Type (Fiber, Floral or Dual Purpose)	Digital Biomass (cm^3)	Digital Height (mm)	Leaf Angle (°)	Leaf Area Index	Light Penetration Depth (mm)	Manual Plant Height (cm)
Arrowhead Abacus	Floral	3915 abc	183 bcde	54 ab	0.123 abcd	153.13 bc	17.67 bcde
Arrowhead Select	Floral	2035 abc	113 de	53 ab	0.1046 abcdef	104.88 bc	10.33 f
Bubbatonic	Floral	5436 ab	232 abcde	55 a	0.135 ab	185.69 abc	23.00 bc
Hurricane Hemp	Floral	4235 abc	193 bcde	51 abc	0.1283 abc	185.41 abc	17.67 bcde
Hurricane Hemp: Florence	Floral	777 c	107 e	51 abc	0.042 ef	42.27 c	11.17 ef
Lifter	Floral	1303 bc	144 cde	52 abc	0.051 def	49.93 c	15.67 cde
Suver Haze	Floral	2912 abc	166 bcde	51 abc	0.101 abcdef	160.57 abc	16.00 cde
White CBG	Floral	3231 abc	163 cde	53 ab	0.114 abcde	158.17 abc	16.00 cde
Bialobrzeski	Fiber	5121 ab	246 abc	56 a	0.125 abcd	232.87 ab	23.00 bc
Boxwine	Fiber	3372 abc	154 cde	55 a	0.126 abc	132.45 bc	13.00 ef
Boxwine 2.0	Fiber	2143 abc	152 cde	51 abc	0.081 abcdef	68.72 c	16.67 cde
Han-Ne	Fiber	5693 a	226 abcde	45 bc	0.140 a	110.28 bc	19.67 bcde
Jinma	Fiber	2910 abc	260 abc	48 abc	0.065 bcdef	128.33 bc	25.67 b
Lara	Fiber	1840 abc	165 bcde	47 abc	0.070 abcdef	163.16 abc	16.00 cde
Puma	Fiber	3625 abc	225 ab	51 abc	0.079 abcdef	140.44 bc	23.67 b
Rincon	Fiber	2092 abc	163 cde	55 a	0.074 abcdef	104.24 bc	15.67 cde
Rogue	Fiber	2155 abc	149 cde	49 abc	0.084 abcdef	124.3 bc	15.00 de
Magic Bullet	Dual purpose	739 c	96 e	52 abc	0.041 ef	34.74 c	10.33 f
Photo CBD	Dual purpose	1314 bc	133 cde	51 abc	0.057 cdef	53.25 c	15.33 cde
Abound	Dual purpose	3232 abc	243 abcd	54 ab	0.077 abcdef	120.54 bc	25.67 b
Anka	Dual purpose	5713 a	358 a	51 abc	0.094 abcdef	308.98 a	40.67 a
Ba0x Hybrid 2.0	Dual purpose	1938 abc	112 de	53 ab	0.0863 abcdef	74.37 c	11.00 f
BaOx Hybrid	Dual purpose	2498 abc	177 cde	55 a	0.078 abcdef	65.25 c	18.33 bcde
BaOx Select	Dual purpose	2815 abc	153 cde	51 abc	0.106 abcdef	139.09 bc	14.67 de
Hlesia	Dual purpose	2443 abc	187 bcde	52 abc	0.075 abcdef	182.38 abc	17.67 bcde
Hliana	Dual purpose	2446 abc	153 cde	53 ab	0.0923 abcdef	130.71 bc	14.33 ef
Joey	Dual purpose	1273 bc	212 bcde	43 c	0.033 f	88.17 bc	13.67 ef

Letters within each cell indicate statistically significant differences ($p < 0.05$) based on the least significant difference (LSD) test.

Table 5. Morphological traits of the hemp varieties scanned with Phenospex PlantEye scanner 10 weeks after seeding.

Varieties	Type (Fiber, Floral or Dual Purpose)	Digital Biomass (cm^3)	Digital Height (mm)	Leaf Angle (°)	Leaf Area Index	Light Penetration Depth (mm)	Manual Plant Height (cm)
Arrowhead Abacus	Floral	11,141 abc	443 d	44 ab	0.112 ab	419.76 a	44.33 cdef
Arrowhead Select	Floral	6296 abc	324 de	49 a	0.088 ab	198.93 bc	32.00 ef
Bubbatonic	Floral	5017 abc	413 de	46 a	0.055 ab	318.06 abc	46.33 cdef
Hurricane Hemp	Floral	8712 abc	443 d	48 a	0.088 ab	430.99 a	55.00 bcdef
Hurricane Hemp: Florence	Floral	5618 abc	364 de	46 ab	0.073 ab	350.00 abc	40.33 def
Lifter	Floral	4159 abc	303 de	47 a	0.061 ab	254.06 abc	30.00 f
Suver Haze	Floral	6916 abc	389 de	43 ab	0.077 ab	384.76 abc	40.00 def
White CBG	Floral	4815 abc	363 de	47 a	0.058 ab	346.30 abc	30.67 f
Bialobrzeski	Fiber	9932 abc	698 c	46 ab	0.231 a	259.01 abc	70.67 abcd
Boxwine	Fiber	7352 abc	338 de	51 a	0.097 ab	279.93 abc	34.67 ef
Boxwine 2.0	Fiber	3912 abc	391 de	45 ab	0.046 ab	260.03 abc	44.33 cdef
Han-Ne	Fiber	4788 abc	701 bc	45 ab	0.161 ab	187.41 c	96.00 a
Jinma	Fiber	7163 bc	801 abc	42 ab	0.051 ab	252.02 abc	84.00 ab
Lara	Fiber	5113 abc	332 de	47 a	0.068 ab	328.64 abc	39.67 def
Puma	Fiber	1675 c	867 ab	34 b	0.021 b	382.37 abc	91.67 a
Rincon	Fiber	2969 bc	261 e	48 a	0.051 ab	251.36 abc	28.33 f
Rogue	Fiber	4767 abc	295 de	45 ab	0.071 ab	291.88 abc	41.67 cdef
Magic Bullet	Dual purpose	5220 abc	354 de	49 a	0.065 ab	322.78 abc	37.67 ef
Photo CBD	Dual purpose	2800 c	301 de	46 ab	0.042 ab	201.65 bc	32.67 ef
Abound	Dual purpose	23,227 a	723 abc	45 ab	0.186 ab	374.64 abc	73.33 abc
Anka	Dual purpose	21,139 ab	871 a	44 ab	0.192 ab	292.15 abc	89.33 a
BaOX Hybrid	Dual purpose	7820 abc	428 de	46 a	0.081 ab	410.51 ab	48.00 cdef
BaOX Hybrid 2.0	Dual purpose	5122 abc	375 de	46 ab	0.066 ab	302.25 abc	38.67 def
BaOX Select	Dual purpose	8566 abc	408 de	47 a	0.093 ab	401.60 ab	45.67 cdef
Hlesia	Dual purpose	1158 c	819 abc	44 ab	0.013 b	241.52 abc	63.67 abcde
Hliana	Dual purpose	3599 bc	391 de	47 a	0.043 ab	239.57 abc	43.00 cdef
Joey	Dual purpose	10,207 abc	430 d	49 a	0.106 ab	421.87 a	44.33 cdef

Letters within each cell indicate statistically significant differences ($p < 0.05$) based on the least significant difference (LSD) test.

3.3.2. Leaf Angle (LA)

Leaf angle (LA) is a crucial trait in plant morphology, reflecting how leaves orient themselves in relation to the plant's stem. It affects the plant's ability to capture light, influencing photosynthesis, and can impact overall plant health and productivity. Leaf angle of all hemp varieties ranged from 43° to 55° (Tables 4 and 5). Among all varieties, Abound, Arrowhead Abacus, Arrowhead Select, Ba0x Hybrid 2.0, BaOx Hybrid, BaOx Select, Bialobrzeski, Boxwine, Boxwine 2.0, Bubbatonic, Hlesia, Hliana, Hurricane Hemp, Lifter, Magic Bullet, Rincon, and White CBG had the significantly greatest leaf angle (>51°), whereas Joey, Lara, and Han-Ne had the least leaf angle (43–49°). Among different hemp types, floral type generally displayed leaf angles ranging from about 51° to 55° at 3 WAS,

indicating a moderately upright orientation. At 10 WAS, the leaf angles remained consistent. Fiber varieties showed a broader range of leaf angles, from 45° to 56° at 3 WAS. Dual-purpose varieties exhibited leaf angles that were generally in line with those of floral and fiber types, showing a blend of characteristics.

3.3.3. Light Penetration Depth (LPD)

The light penetration depth (LPD) refers to the extent to which the laser scanner can penetrate through the plant's canopy. Consequently, plants with a high-density canopy will demonstrate a correspondingly low numerical value. The laser's ability to penetrate the canopy at its maximum depth is determined by analyzing the histogram along the *z*-axis, which is similar to the calculation of height. The LPD values were significantly correlated ($R^2 > 0.60$, $p < 0.001$) with digital biomass, digital plant height, and manual plant height (Tables 2 and 3). In general, tall varieties had a high LPD value, which indicates low plant density. The lower-height plant had a greater density and lower LPD values (Tables 4 and 5).

Significant differences in LPD across hemp varieties at critical growth stages, 3 and 10 WAS, were revealed in the study, indicating the dynamic nature of canopy development and its influence on agronomic outcomes. At 3 WAS, LPD values ranged from as low as 34.74 mm in the "Magic Bullet" (Dual purpose) variety, reflecting a denser canopy, to as high as 308.98 mm in the "Anka" (Dual purpose) variety, suggesting a more open canopy that could potentially enhance under-canopy light availability and influence subsequent growth stages. By 10 WAS, the LPD exhibited a notable increase, with "Joey" (Dual purpose) showing a substantial rise to 421.87 mm. In comparison, "Hlesia" (Dual purpose) reached 241.52 mm, demonstrating variability in canopy architecture evolution over time. These quantitative findings underscore the impact of genetic variation on canopy structure, with LPD ranging from 34.74 mm to 421.87 mm across the observed growth stages, highlighting the importance of variety selection in optimizing light distribution for improved photosynthetic efficiency and yield. Such insights are critical for developing tailored agronomic practices, such as weed management, that leverage canopy architecture dynamics to maximize crop productivity.

3.4. Digital Biomass

The plants' digital biomass was recorded in mm^3 values by a PE scanner, which represents the volume of the canopy, not of the plant. The method used for determining a plant's digital biomass involves multiplying its height by its three-dimensional leaf area. Digital biomass values were highly correlated with digital height, leaf area index, light penetration depth, and manual plant height ($p < 0.001$) (Tables 2 and 3). Significant correlation ($p < 0.001$) between digital biomass and manually measured biomass ($R^2 = 0.89$) as well between digital height and manually measured height ($R^2 = 0.94$) observed 10 WAS, indicated a high precision and usefulness of 3D multispectral scanning in measuring morphological traits. (Table 2). In the trial runs, various PE parameters showed a consistently highly significant correlation ($R^2 > 0.7$; $p < 0.001$) with manual/destructive biomass measurements. Similar correlations ($R^2 > 0.8$) in biomass recorded for various species and growth conditions have been observed [17,18].

This study presents a comprehensive analysis of digital biomass growth in hemp varieties (floral, fiber, and dual-purpose) measured at 3 and 10 WAS (Figure 6). Notably, dual-purpose varieties demonstrated remarkable growth efficiency, with "Abound" showcasing a significant increase in digital biomass to 23,227 cm^3 at 10 WAS, signifying its superior adaptability and growth potential. In contrast, leading fiber and floral varieties, "Bialobrzeski" and "Hurricane Hemp," recorded biomass accumulations of 9932 cm^3 and 8712 cm^3, respectively, indicating significant but comparatively lower growth capabilities. The contrast in growth trajectories among the varieties underscores the importance of strategic variety selection based on cultivation objectives. Weed competitiveness in hemp is multifaceted, encompassing rapid early growth to establish dominance, dense canopy

formation to suppress weed emergence, and the ability to sustain growth vigor in the presence of competitive pressure.

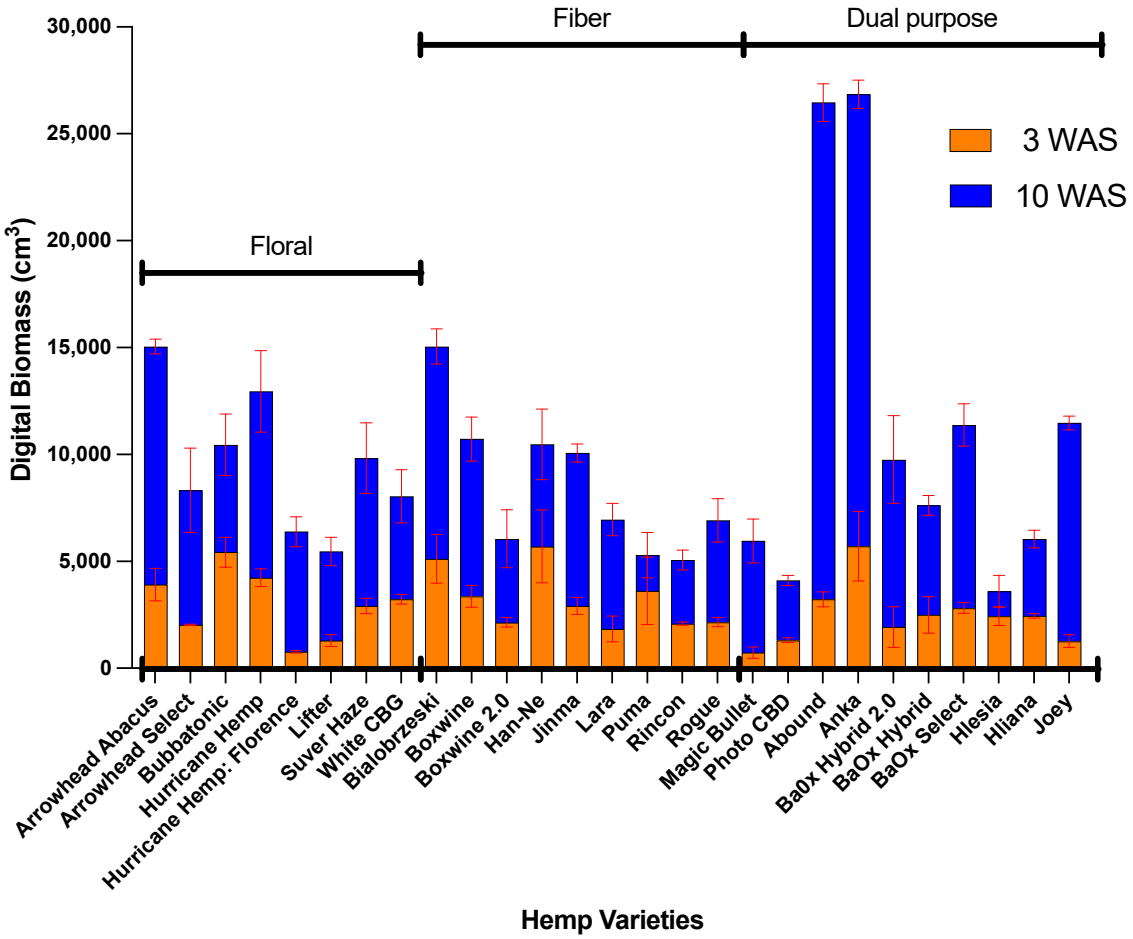

Figure 6. Digital biomass of the 27 hemp varieties taken 3 and 10 WAS (week after seeding).

Overall, digital biomass data reported that dual-purpose varieties, particularly "Abound" and "Anka," showed remarkable growth acceleration, significantly outpacing both floral and fiber varieties by the later growth stage. This suggests that dual-purpose varieties may have a higher overall growth efficiency, weed competitiveness, and potential yield, making them valuable for both fiber and floral yields, and potentially offering greater flexibility and economic returns for growers.

4. Discussion

Certain characteristics have been observed to have an impact on the competitive ability of crops such as rapid germination and emergence, rapid biomass accumulation, leaf area index, leaf angle, and light penetration. In this study, digital plant biomass, plant height, and plant 3D-leaf area (including leaf area index, leaf angle, and light penetration) were studied because weed competitiveness is often measured by these characteristics [15,16]. The PE scanner used in this research serves as an illustration of a contemporary phenotyping sensor. The utilization of the PE scanner has been documented in various studies to capture images of different plant species. For instance, this technology was used to estimate plant weight and leaf area in contrasting rapeseed genotypes with similar architecture based on linear correlations from one genotype [17]. The same technology was utilized to assess plant canopy traits affecting water use (leaf area, leaf area index, and transpiration) in peanut, cowpea, and pearl millet and found close agreement between scanned and observed leaf area data (R^2 between 0.86 and 0.94) [18]. This technology was also used

to image salt-stressed wheat plants and found a strong correlation (R^2 = 0.86) between PE-measured leaf area and manually measured leaf area [19]. In another research study significant correlations (R^2 = 0.87) between the actual fresh plant mass and digital biomass of different tomato cultivars were observed [20]. Similarly, this technology was used for imaging soyabean and found a strong correlation between the PE leaf area and observed leaf area (R^2 values ranging between 0.89 and 0.91) [21]. Another study utilized PE for detecting drought and salinity stress in basil plants and found a significant correlation between digital biomass and shoot fresh weight (R^2 = 0.90) [22].

The findings in this study are consistent with prior research results [18,21]. These earlier studies also identified a significant relationship between the parameters obtained using scanning techniques and the corresponding parameters seen directly for a range of different crops. While it is true that stronger correlations between the reference and PE technique are observed, it is important to acknowledge the constraints imposed by the age of the plants and their development trajectory, which might result in the overlapping of leaves. As stated in previous research [18], more investigation and data acquisition at several time intervals are necessary to authenticate the findings pertaining to the efficacy of scanner-based technologies in accurately estimating leaf area and digital biomass in large plants. The objective of this study was to assess the first growth responses of a diverse set of hemp varieties in order to screen a wider population to study potential weed competitiveness. The aim was to conclude the experiment before it progressed beyond the key stage of critical weed-free time. Taller fiber hemp varieties, such as Puma, may be suited for higher planting densities due to their dense canopies, aiding in weed suppression. Shorter floral and dual-purpose varieties may require lower planting densities but might contribute to weed control through canopy density. Optimizing planting densities based on variety height may enhance canopy closure, minimize weed competition, and improve overall crop yield.

The analysis presented in this study supports the efficacy of the PE scanner in replicating manual measurement results. The R^2 values confirm the high reliability of the PE measurement method. In the study, a strong relationship was identified between digital biomass and manually measured biomass, as well as between digital height and manually measured height. Also, significant correlations existed between all targeted traits except for leaf angle. LAI follows a near-linear relationship with digital biomass and height. Measuring leaf area is typical for crop–weed competition, as shading by either species depends on the relative total leaf area [23]. Crop varieties that rapidly grow and shade the soil surface are more competitive in suppressing weed growth than slow-growing varieties [24]. Also, leaf area can influence plant fitness and photosynthetic potential in intraspecific and interspecific competition since the final biomass yield depends on leaf area [25]. LAI is a better indicator than leaf area for light interception as it is the ratio of one-sided leaf area per ground area. The amount of light that reaches a plant determines a plant's ability to conduct photosynthesis and, ultimately, produce crop yield. Previous research on sweet potato shows that varieties exhibiting a bunched type of growth habit have less light penetration through the canopy compared to sweet potato varieties that exhibit a traditional vining type, hence are more weed competitive [12,26]. A reduction in light interception by plants due to crowding from neighbors and the importance of this reduction can differ based on the crop stage and crop species.

In this study, the primary focus was on assessing the height and biomass of the selected hemp varieties as key indicators of their growth responses and potential weed competitiveness. While manual measurements of other valuable traits such as LA, LAI, and LPD were not conducted due to their labor-intensive and time-consuming nature, our approach was grounded in practicality. Height and biomass, recognized as a reliable proxy for crop growth and development, provided a pragmatic balance between data depth and measurement feasibility. By prioritizing these metrics, the study efficiently identified significant variations in growth responses among the hemp varieties within the experimental design. Future research could explore automated or semi-automated

methods to incorporate a broader range of traits, potentially offering a more comprehensive understanding of hemp's weed competitiveness and other agronomic characteristics

5. Conclusions

These data suggest that 3D multispectral scanning is a precise and potentially valuable method for evaluating weed-competitive morphological features in hemp and other specialty crops. Moreover, multispectral analyses used in this study are non-destructive, rapid techniques with minimal error and human interference, which have a great potential to optimize hemp cultivar selection to aid in weed management. Crop-competitiveness in the presence of weed species is one of the key factors that determine crop performance. Scientists may obtain critical insights into the dynamics of competition and their effects on crop plants by evaluating key morphological parameters using PE technology. The integration of digital plant phenotyping from controlled environments, such as laboratories or greenhouses, into natural field settings can provide a comprehensive understanding of the morphological, physiological, and functional responses of plant communities. Moreover, investing in similar innovative approaches for assessing and selecting weed competitive traits in crop breeding and agricultural research may be crucial for addressing weed management challenges in crop production.

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