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Effects of Biochar on Growth, Response to Water Stress, and Post-Stress Recovery in Underutilized Vegetable *Hibiscus sabdariffa* from Malawi

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Abstract: Globally, *Hibiscus sabdariffa* L. (Malvaceae), commonly known as roselle or hibiscus, is a multipurpose vegetable crop. In Malawi, where it is referred to as 'Chidede' (Chichewa), it is recognized as an underutilized traditional plant with significant potential. Traditional vegetable production in Malawi is being promoted to enhance nutritional food security and climate change mitigation. Recently, biochar has become increasingly used to improve agricultural productivity through climate-smart technologies. To date, the influence of rice husk biochar (RHB) on *H. sabdariffa* remains underexplored. This study aims to evaluate the effects of RHB on the vegetative growth, response to water stress, and post-stress recovery of *H. sabdariffa* using a greenhouse pot experiment. Our findings indicate that biochar-amended soil enhanced plant height, stem thickness, and total leaf area by 16.5%, 12.0%, and 12.9%, respectively. Water stress significantly reduced all assessed growth parameters ($p < 0.05$) except total leaf area and average leaf area per plant. Under water stress conditions, biochar-treated plants were significantly taller ($p < 0.05$) and had a higher specific leaf area ($p < 0.05$), demonstrating a positive effect. A post-stress recovery analysis revealed that *H. sabdariffa* fully recovered in height and biomass, while partial recovery was observed for root collar diameter and compensatory recovery for total leaf area and average leaf area. Biochar-treated plants exhibited superior post-stress recovery compared to those grown in unamended soil. Overall, plants grown with biochar were taller and had a larger root collar diameter, higher stem and leaf fresh biomass, and greater total leaf area. These findings underscore biochar's potential as a sustainable soil amendment for enhancing growth and resilience in underutilized crops. Further studies should explore field experiments to access environmental heterogeneity and examine the diverse factors influencing biochar efficiency.

Keywords: *Hibiscus sabdariffa*; post stress; recovery; response; rice husk biochar; vegetable

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1. Introduction

Hibiscus sabdariffa L. is a versatile plant belonging to the family *Malvaceae* Juss. The genus *Hibiscus* comprises more than 300 species of annual or perennial herbs, shrubs,

or trees [1]. The species is native to India and Malaysia [2] and is known by different names [3], with specific cultures naming the plant differently [4]. *Hibiscus sabdariffa* is suited to warm and humid tropical climates, thriving at temperatures between 18 °C and 35 °C, with an optimum of 25 °C [5]. The species requires annual rainfall ranging between 1500–2000 mm and an elevation of between 0–600 m above sea level [4]. *Hibiscus sabdariffa* requires well-drained fertile soils but can tolerate moderately fertile sandy and loamy soils [6]. *Hibiscus sabdariffa* can grow in low-quality land and is moderately drought tolerant. This notwithstanding, extremes in temperature and rainfall at key phenological stages such as germination flowering and fruiting stages can negatively impact yield [7].

1.1. Hibiscus sabdariffa in Malawi

Hibiscus sabdariffa has been cultivated in Malawi for a long time, but its utilization is comparatively low. This species has immensely diverse uses, as presented in Figure 1; yet, in Malawi, most uses remains underexploited. Generally, there is a dearth of research on *Hibiscus sabdariffa* in Malawi, leading to calls for increased research attention to this crop [8]. Of the few studies done, one focused on hibiscus utility in winemaking [9], while another [10] evaluated the photoelectrochemical characterization of dyes. Recently, Chatepa et al. [11] compared extraction methods for phytochemicals and antioxidants from Malawi's *Hibiscus sabdariffa*. To date, very little has been done to understand the agroecological performance of the species in Malawi. The versatility of *Hibiscus sabdariffa* makes it a key crop for production prioritization as part of wider efforts to address various challenges, including malnutrition [12], rural poverty [13], and climate change [14]. The value of *Hibiscus sabdariffa* lies mainly in the biochemical composition of almost all plant parts and its tolerance to a wide and heterogeneous range of climatic environments.

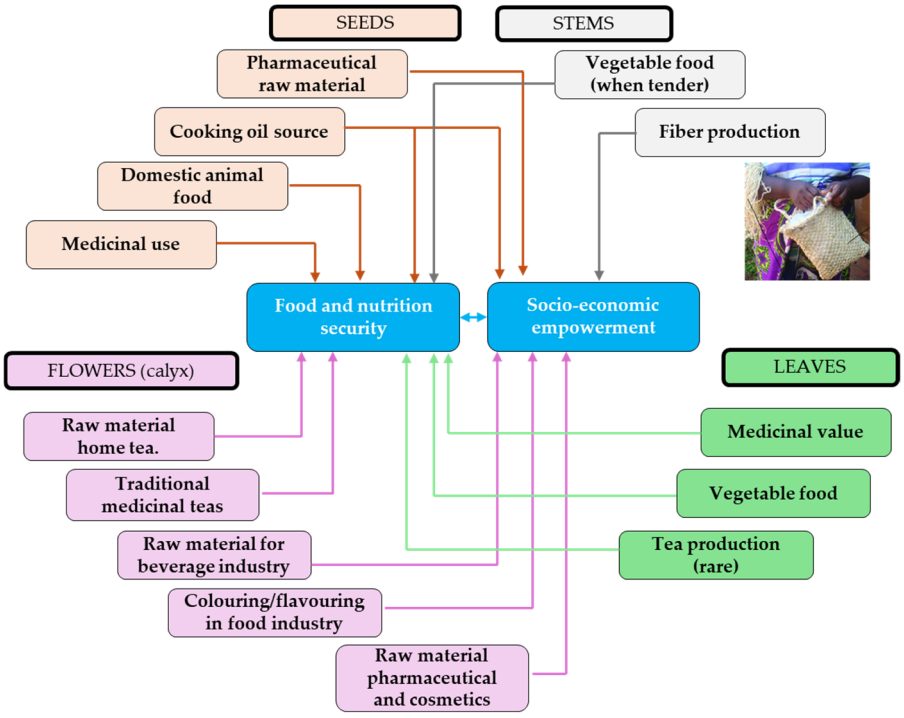


Figure 1. Utilization of various plant parts of *Hibiscus sabdariffa* and their potential to contribute to both food and nutrition security and the socio-economic wellbeing of communities.

1.2. Important Uses of Hibiscus sabdariffa

Hibiscus sabdariffa is a very versatile plant with a huge untapped potential in terms of improving community food nutrition security and climate change adaptation. All parts

of the plant are usable by humans. For example, *Hibiscus sabdariffa* leaves are consumed as a vegetable [15] and are reported to have high levels of essential elements, bioactive compounds, and vitamins but low amounts of antinutrients [16]. This makes it a good dietary addition that can contribute to food security [15] in Malawi. The calyx is used to prepare sauces, jams, juices, jellies, and syrups, and for food flavoring [17]. The attractive red color of the *Hibiscus sabdariffa* calyx is used as a coloring agent for various foods and drinks. El Bilali [15] found that poor households with access to *Hibiscus sabdariffa* have improved food and nutrition security. *Hibiscus sabdariffa*, due to its tolerance of extreme weather, is preferred over cereals [4] by farmers facing drought. In traditional medicine, the species is used as treatment for hypertension, cardiac diseases, stomachache, urine problems, skin diseases, and hair problems [18], among others. Recent animal-based clinical trials showed the potential of *Hibiscus sabdariffa* in treating conditions such as hypertension, dyslipidemia, obesity, anemia, antioxidants, inflammation, and kidney disease [19]. Economically, *Hibiscus sabdariffa* has export potential for Malawi. In Sudan, hibiscus fiber is a major export crop, second only to pearl millet [20]. In India, *H. sabdariffa* is an important fiber crop that serves as a major source of employment for women in rural communities, where they primarily manage its cultivation, along with other vegetables [4,21].

Irrespective of the value of the species, *Hibiscus sabdariffa* is considered an underutilized vegetable with great potential [22] in some societies and is recognized as a hunger crop [4]. Underutilized vegetable crops are not farmed commercially on a significant scale or traded widely [23] and are underrated in the context of their potential to provide economic and food security due to a lack of information regarding production practices [24]. Biochar use in producing such vegetables offers unique opportunities that are worth exploring. Despite the recognized benefits of biochar, there is limited research on its effects on water stress response and recovery in *Hibiscus sabdariffa*.

1.3. Study Rationale and Objectives

The motivation behind this research was diverse. First, the promotion of traditional vegetables requires sufficient knowledge of their agronomy. Secondly, crop response to water stress is one key aspect of plant production, especially in a climatically changing agricultural landscape. Water stress is one of the most serious threats to crop production and is expected to worsen due to climate change [25]. Thirdly, crop response to water stress intra- and inter-species variations [26] demand exploration. Therefore, understanding how different crops respond to water stress is critical in enabling farmers to produce climate-smart crops in a changing agroecosystem. The prevailing biochar experimentation and promotion as a soil amendment offers a unique opportunity. Evaluating biochar feasibility in production of underutilized traditional vegetables would contribute to calls for dietary diversification [27]. However, the reported effects of biochar are sometimes contradictory and exhibit species specificity. The few studies on *Hibiscus sabdariffa* growth mainly focused on the effects of biochar. There is a paucity of published reports regarding the effects of rice husk biochar amendment on growth, response to water stress, and stress recovery in *Hibiscus sabdariffa*. The objectives of this study were (1) to assess the effects of rice husk biochar on growth in *Hibiscus sabdariffa*, (2) to assess the effect of rice husk biochar on water stress in *Hibiscus sabdariffa*, and finally, (3) to assess the role of rice husk biochar amendment on post-stress recovery in *Hibiscus sabdariffa*. We hypothesize that biochar will enhance growth, water stress tolerance, and post-stress recovery through improved soil moisture retention and nutrient availability.

2. Materials and Methods

2.1. Experimental Setup and Design

The experiment was conducted in the greenhouse at Tokyo University of Agriculture, Japan; latitude: 35°38′27.76″ N and longitude: 139°37′56.22″ E, elevation: 40 m above sea level. The temperature in the greenhouse ranged between 22.4 °C and 34.3 °C. Relative humidity varied between 52.7% and 91.5%. Biochar was purchased from Ahmiya Green Service, Saitama, Japan, and the soil was purchased from Emata (Kamiishikawa, kanuma-shi, Tochigi-ken, Japan). The particle size distribution of the soil was used to classify its texture following the USDA soil textural classification system (Table 1). The soil contained 60.1% sand, 39.1% silt, and 0.8% clay, which classified it as sandy loam. Table 2 shows the physical and chemical properties of unamended soil, soil amended with rice husk biochar (RHB), and pure biochar. Key parameters measured included pH, electrical conductivity (EC), specific gravity, loss on ignition, total carbon, and total nitrogen. The biochar was highly alkaline pH (10.47) and had high carbon content (49.27%); its addition to soil slightly increased the soil's pH, electrical conductivity, and total carbon content. The specific gravity and nitrogen content decreased marginally in soil amended with biochar.

Table 1. Particle size distribution of soil used in the experiment.

Particle Size			
Sand (%)	**Silt (%)**	**Clay (%)**	**Textural Class (USDA)**
60.10	39.10	0.80	Sandy loam

Table 2. Physical and chemical properties for soil, soil and biochar mixture, and biochar used in the experiment.

Media	pH	EC (mS/m)	Specific Gravity (g/cm^3)	Loss on Ignition (%)	Total Carbon (%)	Total Nitrogen (%)
Soil	5.05	8.20	2.41	22.10	6.18	0.36
Soil + biochar	5.12	14.60	2.39	23.30	6.48	0.34
Biochar (RHB)	10.47	-	-	-	49.27	0.53

Hibiscus sabdariffa seeds were imported from Malawi. We used direct sowing in 3 liter pots. Two treatments were set up. Treatment 1 (Control) comprised only soil as a growing medium, and treatment 2 constituted a homogeneous mixture of soil and rice husk biochar (RHB). For treatment 2, an application rate of 20% (v/v) RHB to soil mixture was used. The later biochar application rate was based on the published literature. The 20% biochar application rate for this experiment was selected based on a previous reports [28–30], as it consistently promoted plant growth in the referenced studies.

Both soil and biochar were air-dried before use. The growing media were watered to field capacity before seeding. Planting was done on 23 June 2024, when 10–15 seeds were sown per pot. Germination was first observed three days after planting. Thinning was done soon after germination, leaving two plants per pot. Irrigation was done every two days. During each irrigation episode, field capacity was used as a proxy measure of uniformity.

A total of 40 plants were grown in each treatment, i.e., 20 replicates per treatment (20 grown in soil and 20 in rice husk biochar (RHB) and soil mixture). A further two replicates were grown as backups in case of unforeseen events with the main experiment. The experimental setup used a simple randomized design. The experiment period was split into phase 1, phase 2, and phase 3. In phase 1, plants from both treatments were watered

for 38 days, after which water was withdrawn from half of plants from each treatment to induce water stress. Phase 2 was the water stress period, which lasted for 14 days, at which point significant wilting was observed in old and mature leaves. The first data collection was done at the end of the stress period (52 days after planting). Phase 3 was the recovery phase, where watering resumed for previously stressed plants. The recovery period lasted 39 days. The second harvest and data collection were done at the end of the recovery period (91 days after planting) to compare growth between previously stressed plants and those that had not been exposed to stress. Figure 2 shows a schematic overview of the experimental setup.

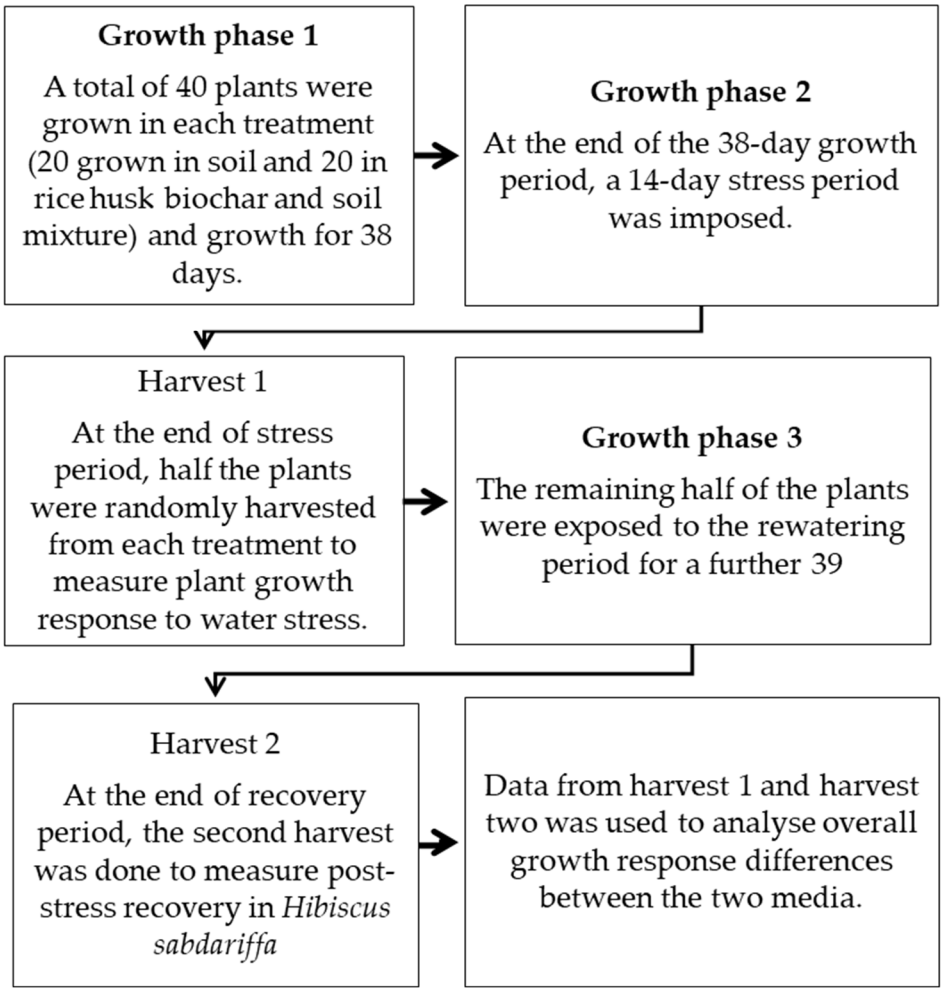


Figure 2. A flow chart of the greenhouse experimental setup during the three phases (phase 1 growth, stress period growth, and recovery periods growth).

At each harvest, plant height, number of leaves, leaf loss, root collar diameter, stem fresh weight, leaf fresh weight, leaf dry weight, plant dry weight, total leaf area, leaf area (mean), and leaf relative water content (mean) data were collected.

Leaf age numbering was based on the order of emergence. The first leaves (those accompanying germination) were numbered one and two. The third leaf to appear was numbered three and so on until leaf eleven. Based on this numbering approach, the first two leaves were the oldest and those at the shoot apex were the youngest. We also adopted and modified a broader leaf categorization (old, mature and young) by Albert et al. [31]. Leaves numbered 1–6 were classified as old, leaves 7–9 were classified as mature, and leaves 10 and 11 were categorized as young. These first two leaves had mostly abscised by the time of data collection, and hence, were not included in the leaf age analysis.

2.2. Leaf Area Measurement

We used a total of 110 leaves, 55 from each treatment, to measure leaf area. Leaf areas were measured using image analysis software Image J version 1.54i (National Institutes of Health, Bethesda, MD, USA). This involved placing whole leaves on white paper along a 30 cm ruler. Smartphone-captured leaf images were transferred into the computer for analysis. First, the leaves were uploaded to the software. Loading of known distance on the software, was done using the ruler on the image. For this study, 2 cm or 4 cm was utilized, depending on the leaf sizes. The scale of estimation was set on the analysis menu. The second step involved image modification (changing it to 8 bits and setting color thresholds). Leaf area was measured in the region of interest (ROI) manager under Tools in the analysis menu of the software.

2.3. Chlorophyll and Biomass Determination

A chlorophyll SPAD meter was used for chlorophyll measurements. Chlorophyll data were measured during the morning hours to minimize light intensity impact, as noted by [32]. Three SPAD values were taken per leaf, i.e., one per leaflet (an average of these was used as the value for the leaf). Four (4) mature healthy leaves (with no evidence of wilting and coloring) were measured per plant. A total of 9–10 plants were measured in each treatment. To determine plant biomass, leaf and stem biomass were determined separately and summed later to yield the total biomass. For fresh biomass, samples were measured immediately after harvesting. Dry biomass was obtained via oven-drying at 80 °C until constant weight. The dried plant material was weighed, and constant weight values were recorded.

2.4. Determination of Relative Water Content

Four fresh, fully expanded leaves were detached at 4:30 pm using a razor blade at the leaf base and immediately weighed to determine the fresh weight (FW). The cut leaves were immediately placed in a beaker with double-distilled water. The leaves were incubated in the dark at room temperature and in the dark for 24 h. The fully hydrated leaves were cleaned with tissue paper to remove water and weighed to measure turgid weight (TW). The leaves were then oven-dried at 80 °C for 24 h and measured to obtain dry weight (DW). All mass measurements were made using an analytical scale with precision of 0.0001 g. The relative water content was then determined using the formula given in [33]:

$$\mathrm{RWC} = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \times 100$$

where RWC is relative water content [%], FW is fresh weight of a leaf [g], DW is leaf dry weight of a leaf [g], and TW is turgid weight of a leaf [g].

2.5. Data Analysis

Data analysis and graphics were conducted using JASP version 1.54i and XLSTAT software annual version 2023.2.0. Both one-way and two-way analyses of variance (ANOVA) were used to assess the statistically significant differences among treatments and variables based on Tukey's HSD test ($p < 0.05$). Where data did not satisfy ANOVA assumptions, especially equal variance assumption, alternative tests were deployed. Pearson correlation was utilized to identify relationships between other variables that did not warrant ANOVA.

3. Results

3.1. Effect of Rice Husk Biochar Media on Growth

Nine growth-related variables were used to assess the effects of rice husk biochar (RHB) on *Hibiscus sabdariffa* growth. These were plant height, number of leaves (NL), root collar diameter (RCD), stem dry weight (SDW), leaf fresh weight (LFW), leaf dry weight (LDW), total leaf area (TLA), fresh aboveground biomass (FAGB), and dry aboveground biomass (DAGB) for soil and rice husk biochar (RHB). Table 3 shows the results regarding the effects of the growing media on *Hibiscus sabdariffa* growth. Plant height, root collar diameter, and total leaf area were significantly higher in RHB amended media at p = 0.01 0.05, and 0.05, respectively. Rice husk biochar positively influenced fresh and dry biomass and the number of leaves variables, but this was statistically insignificant.

Table 3. One way analysis of variance nine growth attributes (plant height, number of leaves (NL), root collar diameter (RCD), stem dry weight (SDW), Leaf fresh weight (LFW), leaf dry weight (LDW), total leaf area (TLA), fresh above-ground biomass (FAGB), and dry aboveground biomass (DAGB) for soil and rice husk biochar (RHB) grown *Hibiscus sabdariffa.* For each column, different letters (a, b) indicate significant differences in treatment means for each variable.

Media	Height (cm)	NL	RCD (mm)	SDW (g)	LFW (g)	LDW (g)	TLA (cm^2)	FAGB (g)	DAGB (g)
Rice husk biochar	31.70 a	12.60 a	5.24 a	1.56 a	8.86 a	1.78 a	253.1 a	13.8 a	3.36 a
STDEV	±3.68	±2.61	±1.10	±0.73	±3.37	±0.59	±61.71	±5.63	±1.24
Soil	27.21 b	12.13 a	4.68 b	1.37 a	7.89 a	1.66 a	224.14 b	12.18 a	3.03 a
STDEV	±2.19	±2.86	±0.95	±0.60	±2.25	±0.44	±41.23	±4.01	±0.92
p	0.00	0.43	0.02	0.23	0.15	0.33	0.02	0.15	0.23
F	10.45	0.63	5.69	1.46	2.17	0.96	5.80	2.07	1.47
(df)	(1.74)	(1.74)	(1.74)	(1.74)	(1.74)	(1.74)	(1.74)	(1.74)	(1.74)
ω2	0.111	0.00	0.06	0.01	0.02	0.00	0.06	0.01	0.01

Correlation of Growth Attributes in *Hibiscus sabdariffa*

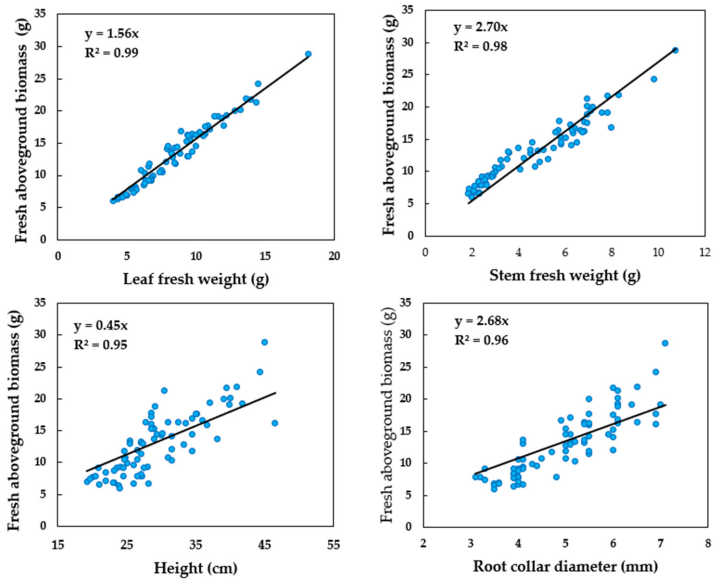
A correlation analysis of nine growth-related variables (Table 4) revealed significant correlation relationships among variables. Of interest were the correlations between fresh leaf weight and both fresh and dry aboveground biomass (r 0.963 and 0.947 respectively) and between fresh leaf weight and both fresh and dry aboveground biomass (r 0.980 and 0.967 respectively). Both fresh stem and leaf biomass in *Hibiscus sabdariffa* could adequately explain and predict above-ground biomass, as demonstrated with allometric models in (Figure 3). Of particular interest was the correlation shown between root collar diameter (RCD) and fresh and dry aboveground biomass (r 0.872 and 0.866 respectively). These can be used in non-destructive determination on biomass in *H. sabdariffa*. Height and biomass showed similar useful relationships (Figure 3A,B).

Table 4. The correlation coefficient of growth attributes in *Hibiscus sabdariffa* attributes (plant height, number of leaves (NL), root collar diameter (RCD), stem fresh weight (SFW), stem dry weight (SDW), Leaf fresh weight (LFW), leaf dry weight (LDW), total leaf area (TLA), fresh above-ground biomass (FAGB), and dry above-ground biomass (DAGB) for soil and rice husk biochar (RHB) grown Hibiscus sabdariffa.

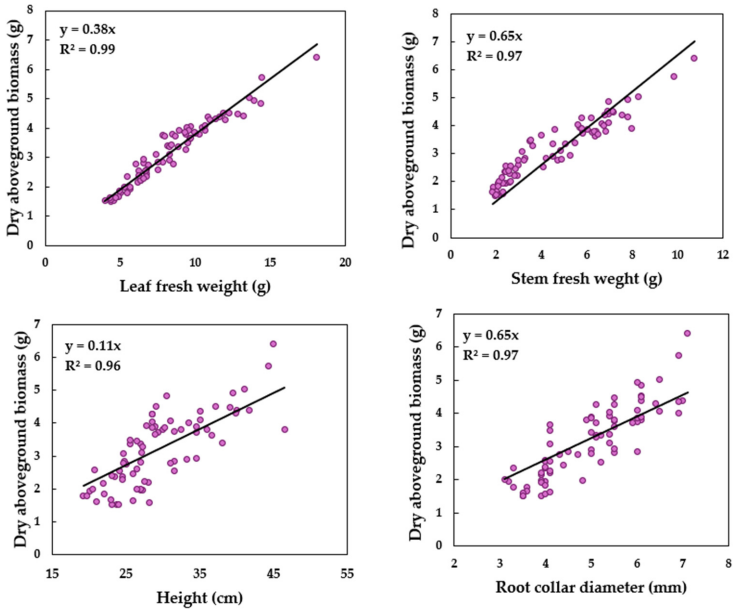
	Height (cm)	NL	RCD (mm)	SFW (g)	SDW (g)	LFW (g)	LDW (g)	TLA (g)	FAGB (g)	DAGB (g)
Height	1.00	0.72	0.82	0.88	0.86	0.74	0.52	0.541	0.82	0.78
NL	0.72	1.00	0.86	0.89	0.90	0.81	0.63	0.55	0.88	0.86
RCD	0.82	0.86	1.00	0.93	0.93	0.79	0.63	0.50	0.87	0.87

Table 4. *Cont.*

	Height (cm)	NL	RCD (mm)	SFW (g)	SDW (g)	LFW (g)	LDW (g)	TLA (g)	FAGB (g)	DAGB (g)
SFW	0.88	0.89	0.93	1.00	0.99	0.89	0.71	0.62	0.96	0.95
SDW	0.86	0.90	0.93	0.99	1.00	0.86	0.67	0.58	0.95	0.94
LFW	0.74	0.81	0.79	0.89	0.86	1.00	0.91	0.87	0.98	0.97
LDW	0.52	0.63	0.63	0.71	0.67	0.91	1.00	0.84	0.85	0.89
TLA	0.54	0.55	0.50	0.62	0.58	0.87	0.84	1.00	0.78	0.76
FAGB	0.82	0.87	0.87	0.96	0.95	0.98	0.85	0.78	1.00	0.99
DAGB	0.78	0.86	0.87	0.95	0.94	0.97	0.89	0.76	0.99	1.00



(**A**)



(**B**)

Figure 3. (**A**) Relationships among fresh aboveground biomass (FAGB) with fresh leaf weight, fresh stem weights, height, and root collar diameter in *Hibiscus sabdariffa* and associated allometric equations. (**B**) Relationships among dry aboveground biomass (DAGB) with fresh leaf weight, fresh stem weights, height, and root collar diameter in *Hibiscus sabdariffa* and associated allometric equations.

Based on Pearson *r*, the observed strong correlations among different growth variables are of interest in vegetable production. Figure 4 below shows how both fresh and dry aboveground biomass can be estimated from leaf fresh weight, stem fresh weight, height, and root collar diameter. While fresh and dry leaf and stem biomass are the best predictors of AGB ($r > 0.95$), the height-based and RCD-based estimation models allowed for continuous and non-destructive biomass assessments in *Hibiscus sabdariffa*.

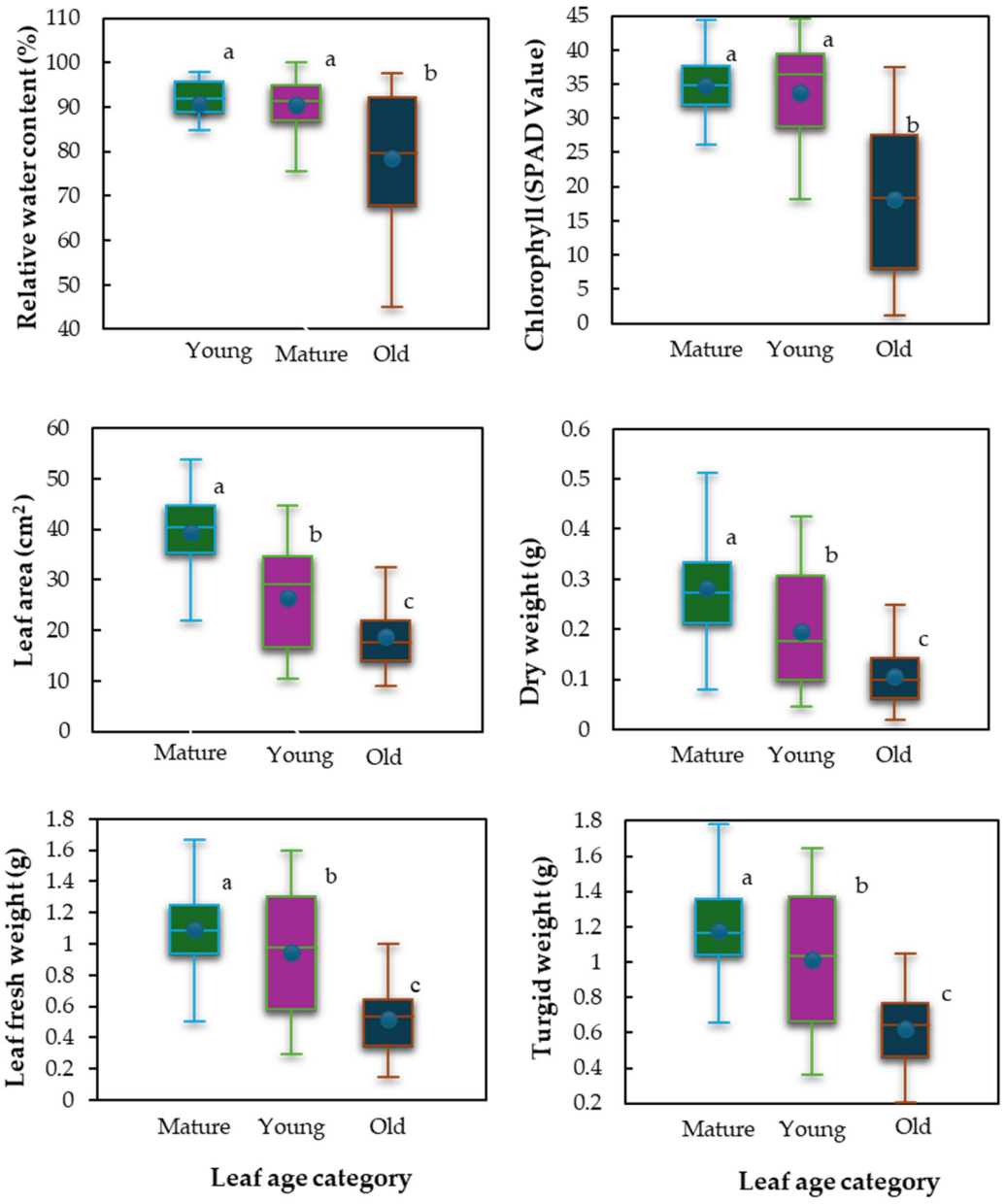


Figure 4. Age related differences in leaf attributes (relative water content, chlorophyll, leaf area, and leaf biomass) in *Hibiscus sabdariffa*. Note: in each graph, different letters (a, b, and c) for the three leaf categories denote statistically significant differences.

3.2. Effects of Stress on Growth in Hibiscus sabdariffa

Water stress effects were assessed on two levels: whole plant response and leaf response. The whole plant data included height, root collar diameter, number of leaves, and biomass. We sought to assess leaf age, and how five leaf attributes (chlorophyll, leaf length, leaf width, turgid weight dry weight, and leaf relative water content) changed due to water stress. Leaf growth and development is very sensitive to water stress [34].

The values for total leaf area and average leaf area were higher in non-stressed plants compared with the stressed plants. On a whole plant level, water stress had negative and significant effects on all parameters assessed except for total leaf area and average leaf area per plant (Table 5). A two-way ANOVA to check the effect of biochar on crop response to water stress (Table 5) showed significant interactions for height and specific leaf area. For height and average leaf area, a post hoc analysis showed that under stress, plants grown in biochar media were taller ($p < 0.001$) and had larger specific leave area (SLA) ($p < 0.05$) than those grown in soil.

Table 5. Effect of growing media (biochar and soil), and water stress and their interactions on growth of *Hibiscus sabdariffa* based on two-way ANOVA (df 1, 32).

Variable	Water Status		Growing Media		Water Status * Growing Media	
	F	***p*-Value**	***F***	***p*-Value**	***F***	***p*-Value**
Plant height	5.08	0.05	23.46	<0.00	6.11	0.02
Root collar diameter (RCD)	50.27	<0.00	25.47	<0.00	2.08	0.16
Number of leaves (NL)	5.41	0.05	1.49	0.23	0.31	0.58
Chlorophyll	13.75	<0.00	7.07	0.02	0.87	0.35
Leaf loss	10.00	0.00	6.40	0.02	0.40	0.53
Total leaf area (TLA)	3.35	0.08	0.89	0.35	0.01	0.75
Average leaf area	4.46	0.07	9.06	0.01	0.39	0.54
Specific leaf area	100.21	<0.00	5.31	0.05	7.58	0.01
Mean leaf relative water content	197.05	<0.00	0.79	0.38	0.33	0.57
Leaf fresh weight (LFW)	35.81	<0.00	0.23	0.63	0.27	0.61
Leaf dry weight (LDW)	38.32	<0.00	0.00	0.96	0.57	0.46
Stem fresh weight (SFW)	24.90	<0.00	5.43	0.05	0.00	0.95
Stem dry weight (SDW)	13.95	<0.00	4.62	0.05	0.00	0.99
Fresh above-ground biomass (FAGB)	22.59	<0.00	0.99	0.33	0.14	0.72
Dry above-ground biomass (DAGB)	31.54	<0.00	0.37	0.55	0.30	0.59

3.2.1. Leaf Response to Stress in *Hibiscus sabdariffa*

Overall, water stress was found to significantly reduce chlorophyll ($F = 13.76$, $p < 0.001$) (Table 5). This confirms previously reported results [35]. This study found that plants grown using biochar amended soils had significantly lower chlorophyll than those grown in soil, as shown in Table 4 ($F = 7.07$, $p < 0.05$). A two-way ANOVA revealed no significant interactions between media and water-stress plants ($p > 0.05$) in terms of chlorophyll, indicating that media had no influence on chlorophyl response to water stress. Stress negatively affected leaf fresh weight ($F = 10.88$, $p < 0.01$), leaf dry weight ($F = 26.47$, $p < 0.001$), and leaf relative water content ($F = 124.38$, $p < 0.001$). We also found that leaf age had a significant influence of all assessed leaf attributes. Old leaves showed low levels in all of the assessed attributes compared to mature and young leaves (Figure 4). Mature and young leaves showed statistically similar chlorophyll and relative water contents but significantly differed in terms of leaf area and biomass.

An age-specific analysis (Figure 5) showed progressive increases with leaf aging in all attributes. This was followed by stabilization and reduction (in younger leaves), except for relative water content.

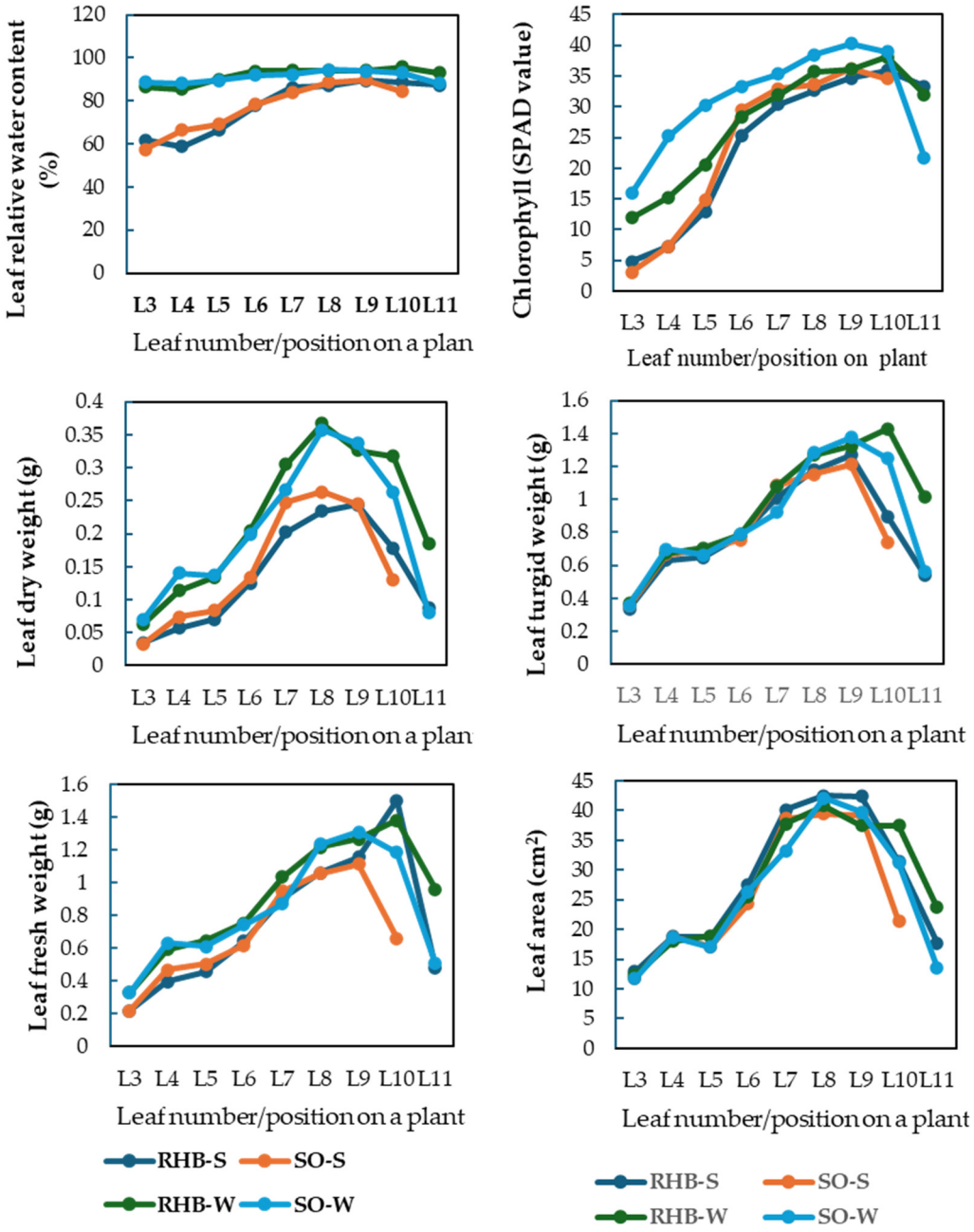


Figure 5. A comparison of leaf parameters with progressing age. Colours represent different media and water status as follows: Plants grown in stressed rice husk biochar media (RHB-S), stresses soil (SO-S), non-stressed rice husk biochar media (RHB-W) and non-stressed soil (SO-W).

3.2.2. Leaf Age Variations in Relative Water Content

Age-related variations in leaf relative water content have direct implications in terms of determining LRWC approaches. A pairwise comparison of LRWC was done to determine existing similarities among leaves of various ages. Table 6 shows a pairwise comparison of means using two sample *T*-test with leaves from the two media and the two stress conditions. Leaf pairs with significantly different LRWC are highlighted and bold.

Table 6. An age-specific comparison (of *p*-values) of leaf relative water content (LRWC) in *Hibiscus sabdariffa* under different media and water status conditions. Highlighted (in bold) are *p*-values where the means being compared are significantly different. Leaves are numbered from old to youngest based on emergence, with Leaves 1 and 2 being the first to emerge but having shed off at the time of data collection.

Rice husk biochar stressed leaves								
	Leaf 3	Leaf 4	Leaf 5	Leaf 6	Leaf 7	Leaf 8	Leaf 9	Leaf10
Leaf 3	1.000	0.494	0.310	**0.000**	**<0.0001**	**<0.0001**	**<0.0001**	**-**
Leaf 4	0.494	1.000	0.097	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**-**
Leaf 5	0.310	0.097	1.000	**0.006**	**0.000**	**<0.0001**	**<0.0001**	**-**
Leaf 6	**0.000**	**<0.0001**	**0.006**	1.000	**0.018**	**0.003**	**0.000**	**-**
Leaf 7	**<0.0001**	**<0.0001**	**0.000**	**0.018**	1.000	0.601	0.175	-
Leaf 8	**<0.0001**	**<0.0001**	**<0.0001**	**0.003**	0.601	1.000	0.353	-
Leaf 9	**<0.0001**	**<0.0001**	**<0.0001**	**0.000**	0.175	0.353	1.000	-
Soil-Stressed leaves								
	Leaf 3	Leaf 4	Leaf 5	Leaf 6	Leaf 7	Leaf 8	Leaf 9	Leaf10
Leaf 3	1.000	**0.017**	**0.003**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**-**
Leaf 4	**0.017**	1.000	0.307	**0.000**	**<0.0001**	**<0.0001**	**<0.0001**	**-**
Leaf 5	**0.003**	0.307	1.000	**0.002**	**<0.0001**	**<0.0001**	**<0.0001**	**-**
Leaf 6	**<0.0001**	**0.000**	**0.002**	1.000	**0.020**	**0.000**	**<0.0001**	**-**
Leaf 7	**<0.0001**	**<0.0001**	**<0.0001**	**0.020**	1.000	**0.001**	**<0.0001**	**-**
Leaf 8	**<0.0001**	**<0.0001**	**<0.0001**	**0.000**	**0.001**	1.000	0.357	-
Leaf 9	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.357	1.000	-
Rice husk biochar non-stressed leaves								
	Leaf 3	Leaf 4	Leaf 5	Leaf 6	Leaf 7	Leaf 8	Leaf 9	leaf 10
Leaf 3	1.000	0.721	0.277	**0.004**	**0.002**	**0.000**	**0.000**	**0.029**
Leaf 4	0.721	1.000	0.147	**0.001**	**0.001**	**0.000**	**0.000**	**0.018**
Leaf 5	0.277	0.147	1.000	**0.021**	**0.010**	**0.002**	**0.002**	0.064
Leaf 6	**0.004**	**0.001**	**0.021**	1.000	0.832	0.238	0.297	0.897
Leaf 7	**0.002**	**0.001**	**0.010**	0.832	1.000	0.285	0.359	0.968
Leaf 8	**0.000**	**0.000**	**0.002**	0.238	0.285	1.000	0.815	0.392
Leaf 9	**0.000**	**0.000**	**0.002**	0.297	0.359	0.815	1.000	0.441
leaf 10	**0.029**	**0.018**	0.064	0.897	0.968	0.392	0.441	1.000
Soil non-stressed leaves								
	Leaf 3	Leaf 4	Leaf 5	Leaf 6	Leaf 7	Leaf 8	Leaf 9	leaf 10
Leaf 3	1.000	0.859	0.761	0.161	0.108	**0.011**	**0.032**	0.056
Leaf 4	0.859	1.000	0.611	0.094	0.054	**0.004**	**0.014**	**0.025**
Leaf 5	0.761	0.611	1.000	0.237	0.163	**0.014**	**0.045**	0.078
Leaf 6	0.161	0.094	0.237	1.000	0.936	0.151	0.354	0.553
Leaf 7	0.108	0.054	0.163	0.936	1.000	0.081	0.302	0.504
Leaf 8	**0.011**	**0.004**	**0.014**	0.151	0.081	1.000	0.633	0.253
Leaf 9	**0.032**	**0.014**	**0.045**	0.354	0.302	0.633	1.000	0.642
leaf 10	0.056	**0.025**	0.078	0.553	0.504	0.253	0.642	1.000

Overall, plant leaves under water stress showed greater variability in LRC than well-watered plants. With stress, soil-grown plants showed high age-related variability in LRWC compared to plants grown with biochar (for soils, only leaves L8 and L9 showed same LRWC). Without stress, soil grown plant leaves had largely similar LRWC compared to leaves from plants grown with biochar. The distribution of LRWC in RHB-grown plants exhibited some stability among leaves of different ages both in stressed and non-stressed conditions. These findings have implications when sampling leaves for the determination

of LRWC. This result requires further inquiry, including an evaluation of which leaves could be representative of the actual water status of a plant of interest.

3.3. Effects of Biochar on Post-Stress Recovery

Two-way ANOVA was done to assess the effects of biochar amendment on *Hibiscus sabdariffa* post-stress recovery. Our results show that recovery was significantly affected by both previous stress and growing media (Table 7). No significant interactions were noted between growing media and stress recovery for all the variables, implying that media did not influence how previous stress affected recovery. Table 7 shows variables that showed significant differences in either growing media or stress status.

Table 7. Two-way ANOVA summary for selected variables that were affected either by water status (stress) or rice husk biochar application and the interaction between media and water status in *Hibiscus sabdariffa*.

Variable	Water Status (Non-Stressed vs. Post-Stress		Growing Media		Water Status * Growing Media	
	F	*p*-Value	*F*	*p*-Value	*F*	*p*-Value
Plant height	1.00	0.32	13.10	<0.00	0.05	0.82
Root collar diameter (RCD)	20.93	<0.00	22.28	<0.00	0.08	0.77
Total leaf area (TLA)	1.82	0.19	5.78	0.02	0.26	0.61
Average leaf area	10.96	0.00	2.31	0.14	1.86	0.18
Leaf fresh weight (LFW)	0.03	0.86	4.33	0.05	0.51	0.48
Stem fresh weight (SFW)	5.92	0.02	4.92	0.03	0.27	0.61
Stem dry weight (SDW)	8.99	0.01	5.41	0.03	0.67	0.42
Fresh above-ground biomass (FAGB)	0.52	0.48	4.79	0.04	0.45	0.51
Dry above-ground biomass (DAGB)	1.63	0.21	4.27	0.05	1.46	0.24

After post-stress recovery, significant differences were noted for larger root collar diameter and stem fresh weight in non-stressed plants compared to stressed plants, $F = 20.93$, $p < 0.001$; $F = 5.92$, $p < 0.05$ respectively. However, previously stressed plants had larger leaves than those that were never stressed ($F = 10.96$, $p < 0.01$). Regarding media, plants grown in biochar-amended soil remained taller than those in soils ($F = 13.10$, $p < 0.001$), with larger RCD ($F = 22.28$, $p < 0.001$), more stem fresh biomass ($F = 4.43$, $p < 0.05$), fresh leaf biomass ($F = 4.51$, $p < 0.05$), and higher total leaf area ($F = 5.77$, $p < 0.05$ compared to those grown in unamended soils. Figure 6 shows some graphical presentations of the two-way ANOVA for some assessed variables for visual clarity.

4. Discussion

4.1. Effects of RHB on Growth

Research on *Hibiscus sabdariffa's* response to biochar application has focused on biochar combined with other added nutrition [36]. In this study, we used pure (sole) biochar as a soil amendment. Our results show that sole RHB amended soils positively influenced growth of *Hibiscus sabdariffa* in nine plant growth related variables (height, number of leaves, leaf fresh weight, leaf dry weight, stem fresh weight, stem dry weight, fresh aboveground biomass, dry aboveground biomass, total leaf area, and root collar diameter). A similar study by Liu and colleagues [37] found that biochar application significantly and positively influenced shoot fresh weight but not dry weight. However, in Liu's study, fertilizer was added to all media, masking the effect of the biochar. The differences between our study

and that of Liu et al. could be explained by our reporting on how biochar affects plant growth and its underlying mechanisms.

Biochar influences plant growth via various mechanisms, as reviewed by Joseph et al. [38]. One key role of biochar involves nutrient cycling and microbial community enhancement. First, biochar influences the soil nitrogen (N) cycle by decreasing or increasing the soil inorganic N content via N adsorption or desorption by biochar [39]. Secondly, the liming effect of soil pH and its enhancement of microbial communities is the most important factor influencing plant growth [39]. Biochar further influences plant growth by increasing soil organic matter, soil water retention capacity, and soil aeration [40]. These are critical soil properties for enhancing plant growth. The positive effects of biochar are, however, dependent on other factors, such as soil type and whether biochar is combined with another substrate. In previous studies, biochar-related crop yield reductions were reported for alkaline soils [41] and fine-textured silty loam soil [42]. The exact mechanism behind our observed effects of biochar on *Hibiscus sabdariffa* could be attributed to several factors that await evaluation. Being an underexplored crop, we further sought to understand its overall growth patterns to facilitate future studies.

In plant growth studies, understanding growth attribute correlations is key, as these define groups of functionally and developmentally related traits [43]. Further, regression models derived from such correlations are useful in non-destructive sampling [44] and are particularly important for vegetable crops [45]. Here, we report on the significant correlations (Table 3) among various growth attributes in *Hibiscus sabdariffa*, confirming results reported by [46]. We further provide regression models that could be used to determine plant biomass non-destructively. Of note are models for predicting biomass from all measured attributes except height and total leaf area, which are comparatively less correlated with plant biomass. Relationships between total leaf area and biomass are known to vary depending on environmental factors [47]. Further studies are thus required to explain such variations in *Hibiscus sabdariffa*. Generally, the correlations presented here point to the possibility of the development of more non-destructive measurements for biomass, which are given in Figure 4.

4.2. Effects of Stress on Growth in Hibiscus sabdariffa

Water stress in *Hibiscus sabdariffa* has been reported to negatively affect height, relative gas exchange efficiency [48], flower number, and photosynthetic rate [49]. Most published reports focused on how the application of various chemicals, but not biochar, influences the response of *Hibiscus sabdariffa* to water stress [50–52]. In our study, we found that stress affected all growth attributes. We further found that biochar grown plants were taller and had higher specific leaf area compared with soil grown plants. This could mean that under stress, biochar supports growth. The exact mechanisms behind this remain to be determined.

The mechanisms behind biochar functionality in plants under stress are diverse and seem to be species specific and regulated by diverse mechanisms. The morphological, molecular, and physiological mechanisms regulating plants' responses to water stress have been widely studied [53–57]. Morphologically, some plants are preadapted to water stress via modifications of leaves, stems, and roots [58]. For non-adapted plants, stress response comprises the production of specific proteins, such as drought-induced proteins, or antioxidant enzymes [57], among others. The production of these molecules is genetically controlled and comprises diverse plant specific signal transduction pathways [55]. The role of biochar in plant response to stress is diverse. First, biochar slows the loss of soil efficient moisture and effectively changes the chlorophyll fluorescence parameters [59]. Further, biochar increases the level of enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity and net photosynthesis (P*n*) [59]. It also protects chlorophyll photosys-

tem (PS II) and membrane integrity, as evidenced by low membrane lipid peroxidation production (i.e., malondialdehyde (MDA)) in biochar grown plants. These mechanisms combine to significantly reduce damage and increase plant adaptability to water stress [59]. In *Hibiscus sabdariffa*, biochar supports water stress response by increasing anthocyanin levels [40]. Anthocyanins are key in controlling plant water loss by reducing stomatal transpiration and density [60]. Our study did not evaluate the physiological mechanisms regulating water stress response. Leaf growth and development can, however, offer some insights into whole plant responses to environmental cues.

4.2.1. Water Stress Effects on Chlorophyll, Leaf Loss, and Area in *Hibiscus sabdariffa*

Leaf growth and development are very sensitive to water stress [34]. Water stress causes leaf rolling, scorching, reduced leaf area [61], and significantly reduced chlorophyll in indigenous vegetables [62]. The extent of these impacts depends on stress duration, growing media, and crop's adaptability to stress. Stress-related reduction in chlorophylls in *Hibiscus sabdariffa* has been widely reported [35,46], yet little is known regarding the effect of biochar in this respect. This study found that plants grown in biochar had significantly lower chlorophyll levels than those grown in soil ($p < 0.05$), as shown in Table 5. The low chlorophyll under biochar could be due to the application rate. Guo and colleagues [63] reported on the biochar application rate and chlorophyll content in tomatoes, noting that rates beyond the optimal tended to reduce chlorophyll. In the case of *Hibiscus sabdariffa,* further research is required to determine the optimal application rate to support chlorophyll development.

In our study, leaf loss was found to be significantly higher in biochar-grown plants compared with soil-grown ones. Leaf loss is the most important drought resistance mechanism that plants have developed through evolution [64]. Premature leaf shedding is one of the strategies to avoid water loss under water stress [65]. Protective leaf shedding works by avoiding xylem embolism [65] and targeting older leaves [66]. Leaf loss is under genetic and hormonal control. Stress-related hormonal signaling pathways are triggered by water or extreme temperature stress and the accumulation of reactive oxygen species (ROS) [67]. How and why biochar grown plants lose high numbers of leaves in *Hibiscus sabdariffa* lies in a maze of factors whose isolation is beyond the scope of this work. Stress related reduction in leaf biomass has been reported for *Hibiscus sabdariffa* [68]. This scenario could be due to leaf sensitivity to stress. For example, leaf sensitivity to water stress causes plants to shed leaves, a response that impairs carbon assimilation and water and nutrient uptake, leading to carbohydrate shortage and reduced biomass accumulation [69].

In our study, the leaf area was not affected by either stress or media. Leaf area, at the onset of drought, cannot significantly change, since the area and its dimensions constitute an irreversible process [70]. Leaf area has been reported to remain unchanged under stress in other crops such as tomato [71]. In our study, an evaluation of leaf area showed a high but nonsignificant total leaf area ($p = 0.08$) and a significantly high average leaf area per plant in biochar- compared to soil-grown plants (Table 3). Specific leaf area, however, was significantly hindered in biochar grown plants ($p < 0.05$). Under stress, biochar grown plants also showed higher specific leaf area compared to soil grown plants ($p < 0.01$). Specific leaf area (SLA) is defined as the ration of leaf area to dry biomass [72]. This is important in plant growth modelling, as it determines how much new leaf area to deploy for each unit of biomass produced [73]. SLA is a highly plastic trait which is positively affected by increased nutrient supply [74]. The higher SLA observed in biochar-grown plants could have been due to the enhanced nutrient supply in the biochar media. The pattern and drivers for SLA in plants have been adequately reviewed elsewhere [75], but in *Hibiscus sabdariffa*, these are yet to be fully evaluated.

4.2.2. The Influence of Leaf Age on Response to Stress

Leaf age is a key attribute in plant growth and response to environmental changes. A plant's ability to undergo osmotic adjustments and sensitivity to water stress is partly dependent on the developmental stage or leaf age [76]. Leaf age affects a host of parameters, including chlorophyll, biomass, and adaptation in plants. In most plant-based experiments, leaf measurements are done on a sample within a plant depending on the parameter being measured. Usually, the leaves of a given age group are targeted. For example, when measuring leaf tissue tolerance to senescence, older leaves are recommended [77], while for the determination of leaf relative water content (LRWC), a suitable leaf age has not been specified. Most researchers make generic references to leaf age, for example, "fully expanded leaves" [78], while others are more specific, referring to equality in leaf size and age (youngest, "fully expanded leaves)", as in [79]. Other authors do not refer to age at all. Where biomass allocation is of concern, all plant parts are necessary [80], and leaves of all ages must be included. In this study, we sought to assess how different growth-related leaf attributes (biomass, leaf area, chlorophyll, and relative water content) vary with leaf age (Figure 4). We identified significant variations in leaf attributes with age. This exemplifies how these variations are masked when broader leaf categorizations (old, mature, and young) are used (Figure 5). LRWC fluctuations are more pronounced along the leaf age spectrum (Table 5) in *Hibiscus sabdariffa.* Our results show that the stability of LRWC is affected by growing media and water stress. These variations provide insights when using leaf traits as a unit of analysis.

4.3. Biochar Effects of Post-Stress Recovery

Research into water stress recovery in *Hibiscus sabdariffa* is scarce. What little exists has focused on how various soil amendments improve *Hibiscus sabdariffa* performance under drought conditions [46,50,81,82] but not recovery. Drought recovery is a plant's ability to resume growth and gain yield after exposure to severe water stress [83]. Post-stress recovery is recognized as a key element of crop adaptation to drought and climate change [84,85]. Our study showed growth recovery potential in *Hibiscus sabdariffa* for the parameters used, except for root collar diameter. Root collar diameter was significantly affected by water stress and did not fully recover after stress release. Meanwhile, the authors of [86] reported that stem diameter declined with increasing severity under water stress in *Hibiscus sabdariffa*. However, no study has reported on root collar diameter recovery status after water stress in *Hibiscus sabdariffa*. The observed limited post-stress recovery in stem diameter can be explained by the changes that occur in stems during water stress. Water stress-related moisture loss in stems is known to cause damaging processes, including xylem embolism [87], which is irreversible and has been reported to limit plant recovery from stress [88]. In this study, we also noted an increase in leaf area in recovering plants compared to non-stressed plants (Figure 6). A similar observation was made in *Populus* x *canadensis* where, after rewatering, the leaf area increased due to known 'compensatory growth' [89], resulting from significant stimulation of the individual leaf area expansion rate. In our study, the leaf area increase was coupled with a higher specific leaf area for rice husk biochar-grown plants compared with soil-grown plants. Since a specific leaf area depicts the leaf area required to produce a specific biomass amount, a high specific leaf area in rice husk biochar media indicates that leaf growth is uncoupled from biomass accumulation. The relationship between leaf area and growth in biomass is affected by how carbon is allocated to new leaves and root masses, reproduction, and respiration [90]. Due to variations in carbon demands by leaves and other organs, nonlinearity has been reported, not only between leaf area and leaf biomass [91], but also between leaf area and plant biomass [90]. However, the observed specific leaf area differences between the

two media we used require further inquiry, notably to elucidate the role of these media in biomass allocation in *Hibiscus sabdariffa*. Various post-stress recovery determinants and mechanisms have been reported that could explain our findings.

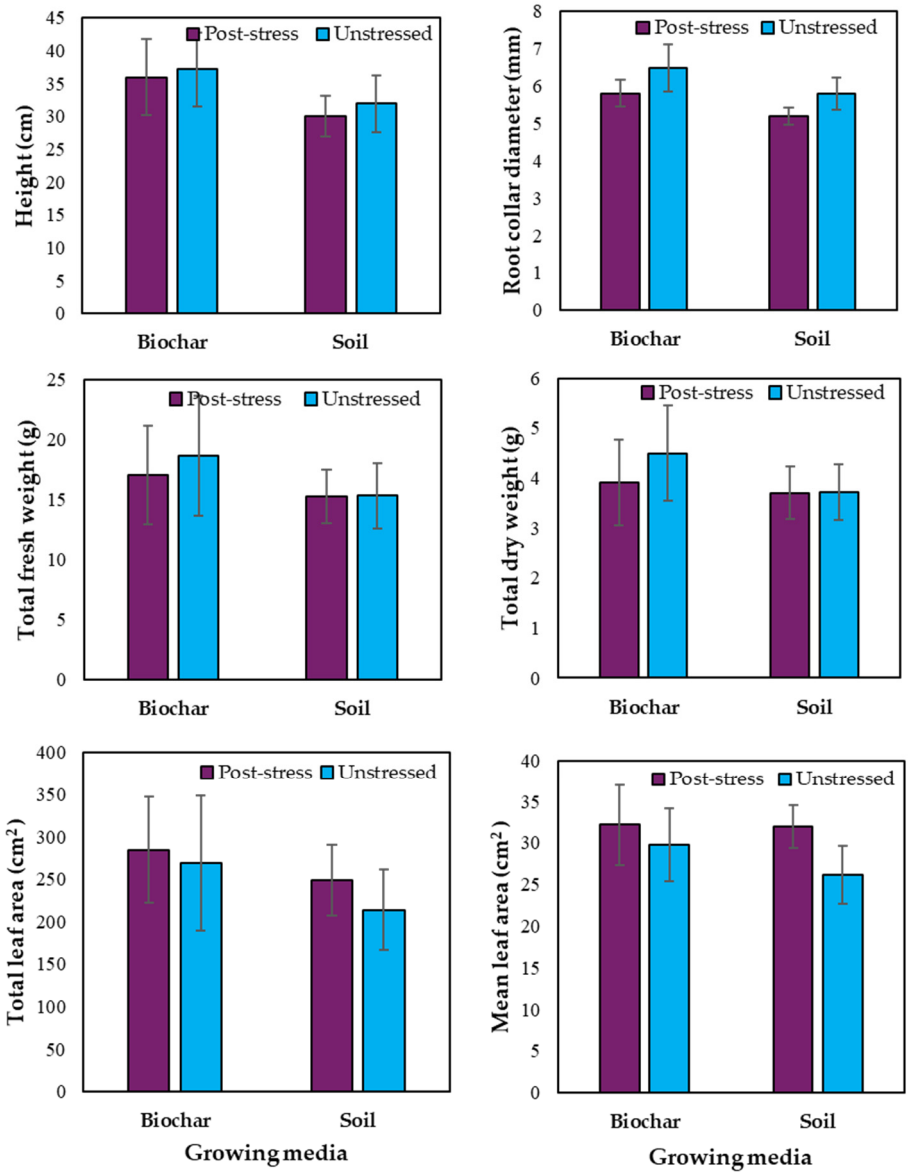


Figure 6. Post-stress recovery growth comparisons of plant height, root collar diameter (RCD), total fresh weight (TFW), total dry weight (TDW), total leaf area (TLA), and mean leaf area (MLA) in *Hibiscus sabdariffa* grown in soil and in rice husk biochar (RHB) amended soil.

Potential Post-Stress Recovery Mechanisms

Plant recovery from stress is affected by stress severity and associated functional impairment and damage to critical plant processes [92]. Stress severity also determines whether recovery is full, partial, or compensatory [92]. Water stress recovery mechanisms involve increasing cellular water potential to restore turgor, rapid changes in gene expression such as switching off the senescence-associated promoter (SAG12) gene [93], and down-regulation of the stress hormone abscisic acid (ABA). The latter mechanism ensures the restoration of stomatal conductance and leaf growth [94] after stress release. Biochar during stress recovery improves the leaf water potential and photosynthetic parameters [95], e.g., in maize, and increases water use efficiency, as observed in quinoa (*Chenopodium quinoa*) [96]. We could not find any published reports on post stress recovery

in *Hibiscus sabdariffa*. Our results show that stress recovery extent depends on the plant attributes, in agreement with [93], where the same was observed in tobacco. While we observed full recovery in height and biomass, partial recovery in root collar diameter, and potential compensatory recovery in total leaf area and average leaf area in *Hibiscus sabdariffa*, biochar application did not significantly influence recovery episodes (as shown in Table 7). Further studies are needed to elucidate post-stress recovery mechanisms and their ecological significance in *Hibiscus sabdariffa*.

4.4. Biochar Functionality Determinants, Trade-Offs and Implications for Farmers

Biochar use in vegetable production shows there is no one-size-fits-all approach. Biochar as a technology has its own production, quality, and upscaling limitations. Further, vegetable crop response is affected by a multitude of factors.

4.4.1. Biochar Functionality Determinants: A Brief

Biochar influences plant growth through its influence on soil pH, cation exchange capacity (CEC), nutrient availability, and microbiota diversity. Soil pH has long been known to influence plant growth by impacting nutrient mobility and availability [97]. However, an earlier study [98] noted that pH influence depends on both plants and soils. Biochar application increases soil pH and CEC at higher application rates. The authors of [99,100] reported that increasing soil pH affected the efficiency of biochar on plant growth and productivity. The overall impact of biochar depends on the soil's initial condition [99], suggesting that biochar influence of soil properties varies with soil type. Understanding both the biochar and soil properties will improve predictions of biochar application efficiency on soil improvement and crop productivity. Regarding soil biota, various mechanisms explaining biochar's role have been proposed [101]. In a recent study [102], it was reported that biochar application promotes microbial growth, diversity, community structure, and co-occurrence networks. These changes led to shifts in microbial species composition, abundance, and increased connectivity and stability. Biochar also improves microbial habitat potential by increasing labile active carbon sources [103]. Generally, the soil microbiome profile can be affected by soil type and land use. This scenario can potentially impact how biochar interacts with soil microbiota. To fully predict the response of *Hibiscus sabdariffa* to biochar application, an understanding of interactions among soil types, rice husk biochar (and biochar from other feedstocks), initial soil microbial community profiles, and crop ecophysiology is critical. Due to known differences in plant growth between greenhouse and field setups [104], further work involving field-based experiments is encouraged to account for temperature variations, heterogeneity in soil properties, and different cropping strategies.

4.4.2. Limitations and Trade-Offs of Biochar Application

Biochar utilization for crop production is heralded as a key to climate change adaptation. Its carbon sequestration ability makes biochar an effective negative emission technology (NET) for carbon dioxide removal [105]. Its role in agriculture, however, is dogged by inconsistent results [38]. To date, questions remain regarding the wide-scale applicability, feedstock sustainability, and potential long-term environmental impacts of biochar use. In most developing countries, widescale biochar utility is limited by policy, legal, institutional, technical, financial, and socio-economic barriers [106], particularly in developing countries like Malawi. Feedstock availability is a challenge that can threaten the feasibility of wider biochar usage. Waste use as a biochar feedstock provides one way to navigate feedstock feasibility challenges. In southern Africa, waste is disposed of rather irregularly. Landfill and incineration are expensive, and anaerobic decomposition from landfills releases the greenhouse gas methane [106]. Biochar-based waste recycling is thus a cost effective and

cleaner pathway. Such waste use broadens the feedstock base and could be supportive of wider biochar utilization.

Since new technology adoption is driven by tangible benefits, the current study has potential to contribute to the uptake of biochar as a soil amendment material. Feedstock availability and sustainability are considered to be deterrents to biochar adoption. Opponents of biochar production predict competition between feedstock staple food production [106]. This competition is viewed as a risk to community food and nutrition security. Evidence-based research and policymakers could help convince farmers of the need for biochar adoption [107]. Several potential long-term environmental impacts of biochar have been reported. Biochar production produces reactive nitrogen, dust, black carbon, and other gases which pose toxicity threat to both humans and the wider ecosystem [108]. Lu et al., [109] reported on the potential of biochar in enhancing soil erosion, although evidence to the contrary exists [110]. Such contradictions call for soil and broader ecosystem analyses of potential biochar impacts before widescale applications.

4.4.3. Study Implications on Malawi's Vegetables Farmers and Scientific Community

The key implications of this study for vegetable farmers revolve around four issues: rice husk biochar growth use feasibility, chlorophyll reduction, leaf loss under stress, and post-stress recovery capacity of *Hibiscus sabdariffa.* This study provides evidence to farmers regarding the benefits of deploying RHB as a climate-smart soil amendment technology. The lack of demonstratable evidence and delayed benefits have been attributed to failed long-term adoptions of some climate-smart technologies [111,112]. It is hoped this work will support the adoption of biochar technology. The reduction in chlorophyll under RHB is, however, a negative. Chlorophyll has been found to enhance vegetable acceptability and market value [113]. There is thus a need to understand and rectify the underlying mechanisms for low chlorophyll in RHB-grown *Hibiscus sabdariffa*. Leaf loss under stress is a normal reaction by plants, and while this is a negative, *Hibiscus sabdariffa* has been found to compensate for this with higher total leaf area upon post-stress recovery. The ability of *Hibiscus sabdariffa* to recover from water stress qualifies it as a climate-smart vegetable with the potential to support climate adaptation [26] in diverse agroecosystems.

5. Conclusions

Hibiscus sabdariffa is a plant whose full potential is yet to be exploited by farmers in Malawi and sub-Saharan Africa. The versatility of *Hibiscus sabdariffa* exposes a unique potential in improving the socioeconomic wellbeing of rural communities. This study has shown that biochar positively influences growth in *Hibiscus sabdariffa* by increasing biomass, leaf area, height, and stem diameters, even though water stress negatively impacted key growth attributes and biochar influence, i.e., *Hibiscus sabdariffa* height and leaf area responses. *Hibiscus sabdariffa* showed a remarkable capacity to recover from water stress. These responses provide preliminary and partial evidence for the use of this vegetable species as a climate smart crop. Further studies should focus on how biochar application may affect reproductive attributes (flowers and seeds) in *Hibiscus sabdariffa*. Differences in plant growth performance between greenhouse and field setups [104] necessitate further work involving field-based experiments to account for temperature variations, heterogeneity in soil properties, and different cropping strategies. Additionally, there is a broader need to evaluate ecosystem-wide limitations of biochar application.

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