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Effect of Different Waterlogging Regimes on Growth, Some Yield and Roots Development Parameters in Three Fiber Crops (*Hibiscus cannabinus* L., *Hibiscus sabdariffa* L. and *Corchorus olitorius* L.)

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Abstract: The objective of this study was to investigate the effect of different waterlogging regimes on growth, yield and roots development in three fiber crops. Three fiber crops kenaf (*Hibiscus cannabinus* L.), roselle (*Hibiscus sabdariffa* L.) and jute (*Corchorus* olitorius L.) were subjected to waterlogging for 45, 60, 75, 90 and 105 days, as well as a well-drained subject (control). The waterlogging regimes had a significant effect on plant height, stem diameter, leaf area, biomass production, root growth and aerenchyma tissue formation. The crops subjected to waterlogging for longer periods were more affected in their growth characteristics: *H. cannabinus* had a higher plant height, stem diameter, leaf area, biomass production and root growth less than *H. sabdariffa* and *C. olitorius*. Aerenchyma tissue developed in adventitious roots of three fiber crops species. The fiber crops subjected to waterlogging regimes decreased fiber yield by 11.9-51.2% compared to the control. *H. cannabinus* produced the highest fiber yield after 45 days of waterlogging duration. This results is due to the higher growth and roots development of *H. cannabinus* than the other two fiber crops.

Key words: Adventitious root, *Corchorus olitorius*, growth, *Hibiscus cannabinus*, *Hibiscus sabdariffa*, waterlogging

INTRODUCTION

Among abiotic stresses, extremes of water availability, waterlogging is a major problem limiting production and productivity of the most crops. The primary stress factor induced by waterlogging is reduction in soil oxygen availability. Oxygen deficiency periods can trigger functional and developmental responses that promote acclimation to hypoxic or anoxic conditions. Low oxygen concentrations lead to long-term morphological adaptations (Geigenberger, 2003). The production of a pre-rice crop during the dry-wet transition period may increase of farmer's income in the Northeast area of Thailand. The early rains in the dry-wet transition period can be used to successfully grow upland crops such as fiber crops, because rice seedlings can be transplanted later in the wet season. As these fiber crops are often grown in the dry-wet transition period as pre-rice crops, waterlogging and excessive soil moisture often cause damage on these plants. Moreover, waterlogging stress can reduce growth and yield depending in the plants and the duration of waterlogging (Robert, 1991; Linkemer *et al*., 1998; Setter and Waters, 2003).

Formation of new adventitious roots is one of the major adaptive responses of plants under waterlogged conditions (Bacanamwo, 1999; Mano and Omori, 2007). Additionally, aerenchyma is developed in the cortex of new and existing roots of some plant species, which is also thought to increase waterlogging tolerance (Armstrong *et al*., 1991). Actually, in flood-tolerance species, such as mangrove (*Kandelia candel*) (Ye *et al*., 2003) and Tartary buckwheat (*Fagopyrum tataricum*) (Matsuura *et al*., 2005) and through the formation and development of adventitious roots (Chen *et al*., 2002; Singh and Singh, 2003) and through developing aerenchyma in roots (Colmer, 2003; Drew *et al*., 2000).

Thus, survival and reproduction of plants under waterlogged conditions depend on their ability to transport of oxygen from aerial to hypogeal organs. Diffusion of atmospheric oxygen results in the maintenance of root aerobic respiration and nutrient

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absorption (Jackson and Drew, 1984; Justin and Armstrong, 1987; Naido *et al*., 1992; Baruch and Merida, 1995; Jackson and Armstrong, 1999). When waterlogging occurs regularly, we would expect selection for plant species able to respond with anatomical modifications that allow sustained growth and adventitious root development. The objective of this study was to investigate the effects of different waterlogging regimes on growth and yield as well as on development of adventitious roots and the formation of aerenchyma in the three fiber crops (namely, *H. cannabinus* L., *H. sabdariffa* L. and *C. olitorius* L.).

MATERIALS AND METHODS

A pot experiment was conducted in a greenhouse at the Field Crop Research Station of Khon Kaen University in Khon Kaen, in Thailand (16°28'N and 102°48'E), from March to August 2005. The mean annual air temperature in the greenhouse was 16.4 to 20.2°C at night and 24.3 to 35.9°C in the daytime. The sandy loam soil had following characteristics: 4.75 pH (1:2.5 w/v water), 0.52% organic matter content (Walkley and Black, 1934), 245 mg kg^{-1} total N (Bremner, 1960), 14 mg kg^{-1} available P (Bray II extraction, Bray and Kurtz, 1945) and 35 mg kg^{-1} exchangeable K (1 N ammoniumacetate pH 7 extraction, Schollerger and Simmon, 1945). The soil were dried, sieved to remove undecomposed plant materials and filled in plastic pots (height = 38 cm; diameter = 37.5 cm) with 30 kg. Three tropical fiber crops, *H. cannabinus* (Kenaf, cv. KhonKaen 60; KK60), *H. sabdariffa* (Roselle, Thai kenaf, cv. NonSoong 2; NS2) and *C. olitorius* (Jute, cv. KhonKaen 1; KK1), were used as plant material in this study. Five seeds were sown per plastic pots and fertilized with chemical compound (15-15-15 for N-P_2O_5-K_2O) at the rate of 156 kg ha^{-1} at 3 cm depth. The seedlings were later thinned to one plant per pot at the two-leaf stage to obtain plants with uniform growth vigor. Hand weeding was done 30 Days after Sowing (DAS) instead of pesticides.

In this experiment, the treatment of waterlogging were as follows 45 days (105 DAS through harvest), 60 days (90 DAS through harvest), 75 days (75 DAS through harvest), 90 days (60 DAS through harvest) and 105 days (45 DAS through harvest) and well-drained as the control. In this experiment soil moisture of all the plots was maintained at container capacity for optimal growth throughout the growing season excluding the waterlogging regimes treatment when standing water maintained at 10 cm above soil surface.

At harvest (150 DAS), plant height, stem diameter, leaf area and dry weight of leaves, bark, wood, shoots and fiber yield were recorded (Ogbonnaya *et al*., 1998). Plant height from the soil level to the terminal bud of the main stem was measured with a ruler. Stem diameter was measured at 10 cm from soil level using a vernier. Leaf area was measured with a leaf area meter (LI-COR 3100, LI-COR, Lincoln, NE). Dry matter production was determined after carefully uprooting the plants from the pot and separating them into leaves, bark, wood and shoots. The bark was separated from the central wood core by peeling. The plants were oven-dried at 80°C for 48 h before recording dry weight. The stems were soaked in water for 15 days in a plastic pots and separate fiber from the stem by hand. The fibers were dried at 80°C for 48 h and measured dry weight of fiber yield.

Roots were taken from above and below the soil surface to be dry weighed at harvest. Samples were fixed using formalin-acetic acid-ethanol solution (FAA). Aerenchyma tissue was observed in randomly selected samples from adventitious roots at harvest and then freehand cross-sections method of adventitious root were made to examine root anatomy at 5 cm from the root tip along the root axis followed with staining by toluidine blue O (0.01%) (Lux *et al*., 2005) for light and fluorescence microscopy (BX-51, Olympus) equipped with a CCD digital camera (VB7000, Keyence).

The study was arranged a 6×3 factorial in a completely randomized design with four replications. Waterlogging regimes were factor A and species were factor B. Parameters such as growth, yield, development of adventitious roots and aerenchyma formation in three fiber crops (namely, *H. cannabinus*, *H. sabdariffa* and *C. olitorius*) were examined with reference to waterlogging regimes. The results for all the parameters were subjected to Analysis of Variance (ANOVA) by means of Statistic 8 software (Statistic Analytical Software, 2003). The treatment means were compared on the basis of least significant difference at 0.05 probability level.

RESULTS

Waterlogging effect on plant height: Both fiber crop species and waterlogging regimes significantly affected on plant height and the interaction between the two factors was observed. The *H. cannabinus* gave the highest value (270.8 cm) plant height, followed by *H. sabdariffa* and *C. olitorius* (Table 1). The plant height of fiber crops was reducing percentage according with the regime of waterlogging compared with the control. The crops subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days reduced plant height by 1.4, 7.2, 11.3, 24.7 and 38.9% of the control, respectively (Table 1). The

Table 1: Effect of different waterlogging regime and fiber crop on plant height, stem diameter and leaf area at harvest

Effect	Plant height (cm)	Diameter (cm)	Leaf area (cm^2)
Fiber crops (F)			
H. cannabinus	270.8a	2.22a	8381.7a
H. sabdariffa	256.5b	2.01b	7845.8a
C. olitorius	222.7c	1.83c	5574.8b
Waterlogging regimes (W)			
Control	290.4a	2.27a	11228.5a
Waterlogged 45 days	286.3a	2.17ab	8438.7b
Waterlogged 60 days	269.5b	2.10b	7406.1bc
Waterlogged 75 days	257.5b	2.03b	6749.0cd
Waterlogged 90 days	218.8c	1.91c	5204.0d
Waterlogged 105 days	177.5d	1.65d	4578.7d
F-test			
Fiber crops (F)	**	**	**
Waterlogging regimes (W)	**	**	**
F×W	**	**	**
CV (%)	4.38	3.28	16.48

**Significant at p<0.01. Mean followed by the same letter at the same column was not significantly different according to Least Significant Difference (LSD)

interaction between fiber crop species and waterlogging regimes was shown in Fig. 1a. *Hibiscus* cannabinus subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days reduced plant height by 0.4, 7.8, 9.7, 23.1 and 32.8% of the control, respectively and 1.6, 6.2, 12.1, 26.3 and 34.7% in *H. sabdariffa* and 6.4, 11.4, 15.9, 27.7 and 52.7% in *C. olitorius* (Fig. 1a). The *H. cannabinus* had a higher value (307.5 cm) plant height than *H. sabdariffa* and *C. olitorius* when 45 days of waterlogging regimes treatment. The lowest value (130.0 cm) plant height was observed for 105 days of waterlogging regimes in *C. olitorius*.

Waterlogging effect on stem diameter: Fiber crop species and waterlogging regime treatments affected on stem diameter and the interaction between fiber crop species and waterlogging regimes. The *H. cannabinus* gave the highest value (2.22 cm) stem diameter, followed by *H. sabdariffa* and *C. olitorius* (Table 1). Waterlogging stress reduced percentage the stem diameter, depending on duration. The crops subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days reduced stem diameter by 4.4, 7.5, 10.6, 15.9 and 27.3% of the control, respectively (Table 1). For the interaction between fiber crop species and waterlogging regimes was shown in Fig. 1b. *Hibiscus cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased stem diameter by 3.8, 7.5, 9.5, 11.1 and 18.1% of the control, respectively and 3.8, 8.5, 12.2, 18.1 and 29.0% in *H. sabdariffa* and 6.2, 6.8, 9.8, 18.7 and 36.3.% in *C. olitorius* (Fig. 1b). Regarding the duration of waterlogging, *H. cannabinus* had a larger value (2.33 cm)

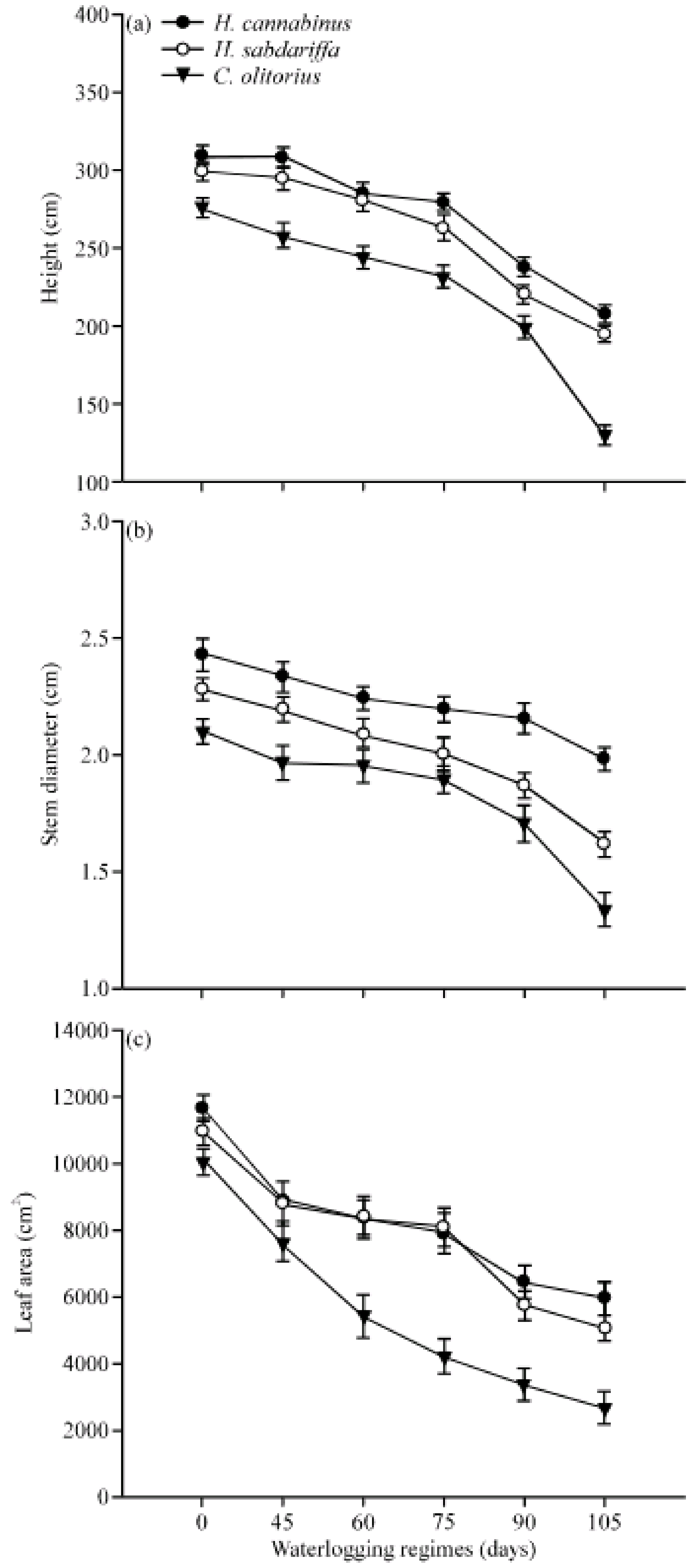

Fig. 1: (a) Plant height, (b) stem diameter and (c) leaf area of three fiber crops (*H. cannabinus*, *H. sabdariffa* and *C. olitorius*) at harvest of different waterlogging regimes. Vertical bars on symbols indicate ±SE

stem diameter than the other two species after 45 days of waterlogging treatment and *C. olitorius* had the smallest value (1.34 cm) stem diameter after 105 days of waterlogging treatment.

Waterlogging effect on leaf area: Fiber crop species and waterlogging regimes treatments significantly affected on leaf area and the interaction between fiber crop species and waterlogging durations. The *H. cannabinus* gave the larger value (8381.7 cm^2) leaf area, followed by *H. sabdariffa* and *C. olitorius* (Table 1). In the study, the leaf area of the whole plant was decreased to 24.8, 34.0, 39.9, 53.7 and 59.2% of the control after 45, 60, 75, 90 and 105 days of waterlogging, respectively (Table 1). The three fiber crops subjected to waterlogging showed a lower leaf area than that of the control. For the interaction between fiber crop species and waterlogging regimes was shown in Fig. 1c. *Hibiscus cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased leaf area by 29.6, 33.7, 37.3, 48.9 and 52.8% of the control, respectively and 26.5, 29.8, 32.4, 51.8 and 57.7% in *H. sabdariffa* and 24.4, 46.1, 58.0, 66.4 and 73.1% in *C. olitorius* (Fig. 1c). Regarding the regimes of waterlogging, *H. cannabinus* had a larger value (8900.9 cm^2) leaf area than the other two species after 45 days of waterlogging and *C. olitorius* had the smallest value (2705.5 cm^2) leaf area per plant after 105 days of waterlogging.

Waterlogging effect on aboveground biomass: Aboveground biomass was affected by fiber crop species and waterlogging regimes treatments and the interaction between fiber crop species and waterlogging regimes. The *H. cannabinus* gave the highest value aboveground biomass, followed by *H. sabdariffa* and *C. olitorius* (Table 2). The waterlogging regimes had effect on aboveground biomass, which was reducing percentage by waterlogging according with the regimes of the treatments compared with the control. The crops subjected to the treatment for 45, 60, 75, 90 and 105 days reduced leaf dry weight to 30.4, 38.1, 41.2, 57.2 and 60.3% compared to the control, respectively. In waterlogging treatments, wood, bark and shoot dry weight decreased to 15.4, 23.5, 33.6, 44.1 and 65.8%, 14.9, 23.9, 40.1, 51.8 and 62.6% and 16.4, 22.8, 35.7, 46.2 and 65.6% of the control, respectively (Table 2). For the interaction between fiber crop species and waterlogging regimes was shown in Fig. 2. *Hibiscus cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased leaf dry weight to 27.7, 28.4, 34.2, 44.5 and 51.2% of the control, respectively and 27.1, 28.4, 29.9, 50.0 and 50.3% in *H. sabdariffa* and 37.6, 64.2, 66.5, 84.1 and 87.4% in *C. olitorius* (Fig. 2a). The wood dry matter of *H. cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased 3.4, 9.6, 17.2, 28.6 and 47.2% of the control, respectively and 9.2, 11.8, 15.9, 28.4 and 64.9% in *H. sabdariffa* and 35.3, 51.3, 70.8, 78.1 and 87.3% in *C. olitorius* (Fig. 2b), as well as the bark dry matter decreased 5.0, 7.3, 23.4, 37.5 and 51.1% in *H. cannabinus* and 15.6, 25.6, 29.3, 41.9 and 52.0% in *H. sabdariffa* and 25.3, 40.9, 70.4, 78.6 and 86.8% in *C. olitorius* (Fig. 2c). In addition, the shoot dry matter of *H. cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased 3.8, 9.0, 18.9, 31.0 and 49.4% of the control, respectively and 7.9, 11.2, 18.8, 30.7 and 61.5% in *H. sabdariffa* and 39.1, 49.9, 71.4, 78.8 and 87.5% in *C. olitorius* (Fig. 2d). The *H. cannabinus* had a higher value aboveground biomass production than *H. sabdariffa* and *C. olitorius* when 45 days of waterlogging regimes treatment. The lowest value aboveground biomass production was observed for 105 days of waterlogging regimes in *C. olitorius*.

Table 2: Effect of different waterlogging regime and fiber crop on aboveground biomass at harvest

	Weight (g)			
Effect	Leaf dry	Wood dry	Bark dry	Shoot dry
Fiber crops (F)				
H. cannabinus	15.4a	104.42a	36.45a	140.54a
H. sabdariffa	14.1a	94.17b	31.50b	128.17b
C. olitorius	6.7b	52.45c	20.19c	72.07c
Waterlogging regimes (W)				
Control	19.4a	120.22a	43.34a	164.90a
Waterlogged 45 days	13.5b	101.73b	36.89b	137.79b
Waterlogged 60 days	12.0bc	92.00b	32.98b	127.31bc
Waterlogged 75 days	11.4c	79.77c	25.98c	106.09d
Waterlogged 90 days	8.3d	67.18d	20.88cd	88.73e
Waterlogged 105 days	7.7d	41.17e	16.23d	56.74f
F-test				
Fiber crops (F)	*	**	**	**
Waterlogging regimes (W)	**	**	**	**
F×W	**	**	**	**
CV (%)	16.27	7.13	6.58	7.92

*Significant at $p<0.05$, **Significant at $p<0.01$. Mean followed by the same letter at the same column was not significantly different according to Least Significant Difference (LSD)

Waterlogging effect on root growth: Both fiber crop species and waterlogging regimes treatment affected on root growth and the interaction between fiber crop species and waterlogging regimes. In waterlogging treatments for 45, 60, 75, 90 and 105 days decreasing percentage belowground root dry weight by 50.5, 59.8, 66.8, 84.4 and 86.6% compared to the control, respectively and the *H. cannabinus* gave the highest value belowground root dry weight, followed by *H. sabdariffa* and *C. olitorius* (Table 3). For the interaction between fiber crop species and waterlogging regimes was shown in Fig. 3. *Hibiscus cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased belowground root dry weight by 26.5, 41.9, 47.1, 82.3 and 82.9% of the control, respectively and 63.9, 67.4, 76.9, 82.8 and 84.4% in *H. sabdariffa* and 66.6, 73.8, 80.7, 89.0 and 93.9% in *C. olitorius* (Fig. 3a). Moreover, adventitious roots emerging on the stem base increased with the

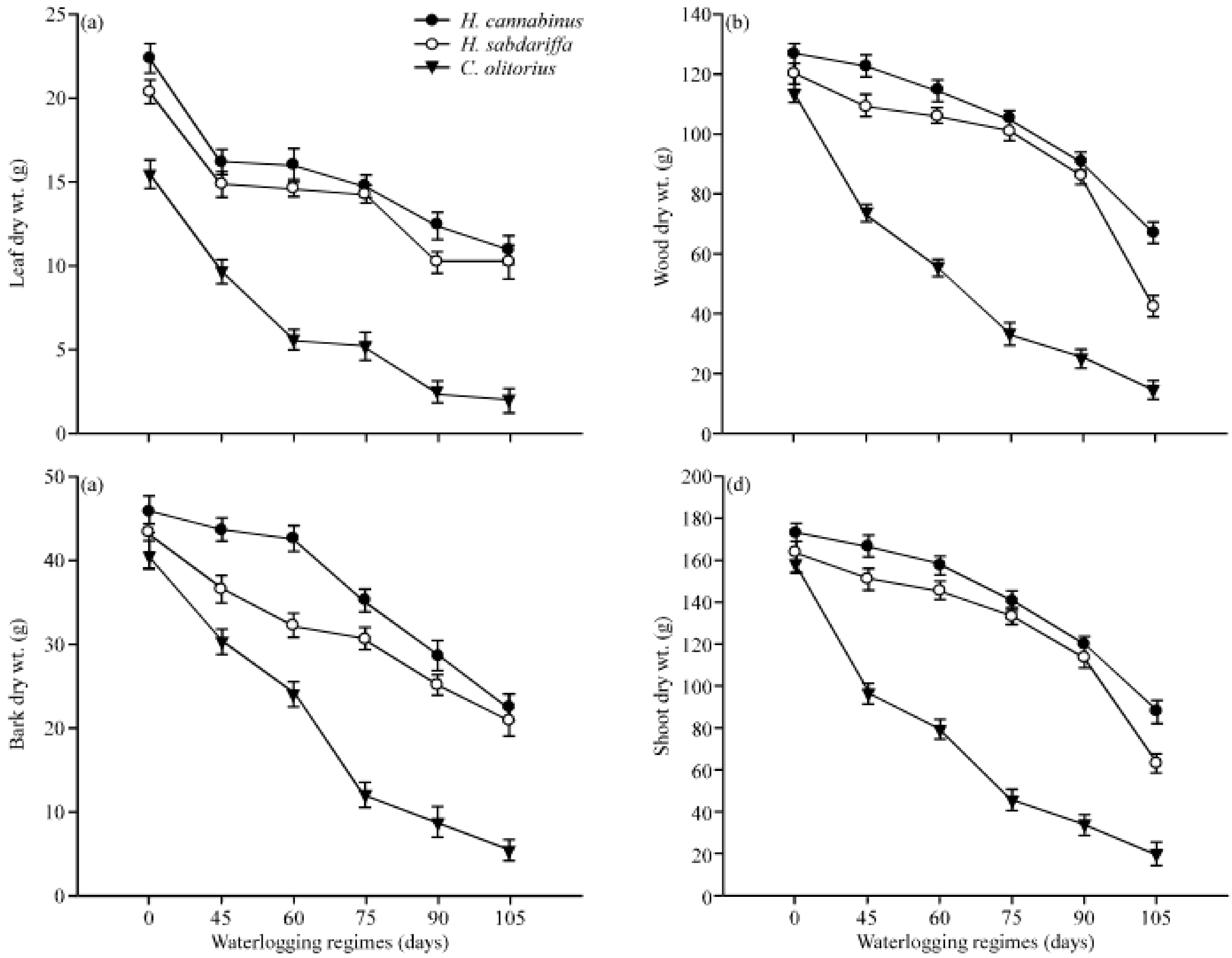

Fig. 2: Effect of waterlogging regimes on dry matter production of (a) leaf, (b) wood core, (c) bark and (d) shoot of three fiber crops at harvest. Vertical bars on symbols indicate ±SE

Table 3: Effect of different waterlogging regime and fiber crop on belowground root and adventitious root dry weight, lateral root number and tap root length at harvest

Effect	Belowground root dry wt. (g)	Adventitious root dry wt. (g)	Lateral root number ($plant^{-1}$)	Tap root length (cm)
Fiber crops (F)				
H. cannabinus	24.8a	20.2a	87.9	28.5
H. sabdariffa	14.9b	13.3b	80.4	25.2
C. olitorius	11.9c	6.6c	77.2	24.0
Waterlogging regimes (W)				
Control	41.0a	0.0e	113.6a	32.3a
Waterlogged 45 days	20.3b	9.8d	105.3ab	30.6a
Waterlogged 60 days	16.5cb	14.3c	95.1bc	28.0ab
Waterlogged 75 days	13.6c	18.0b	84.0c	28.0ab
Waterlogged 90 days	6.4d	22.6a	63.4d	24.1b
Waterlogged 105 days	5.5d	15.3c	29.5e	12.4c
F-test				
Fiber crops (F)	**	**	ns	ns
Waterlogging regimes (W)	**	**	**	**
F×W	**	**	**	ns
CV (%)	27.9	25.28	28.74	32.82

**Significant at p<0.01, ns: Non-significant. Mean followed by the same letter at the same column was not significantly different according to Least Significant Difference (LSD)

regimes of waterlogging, while no adventitious root was formed on the control plants (Fig. 3b). The adventitious roots under waterlogging were 20.2 g in *H. cannabinus*, 13.3 g in *H. sabdariffa* and only 6.6 g in *C. olitorius*. From the result, the adventitious roots dry matter in *H. cannabinus*, *H. sabdariffa* and *C. olitorius* increased depending on the waterlogging regime (Table 3). Regarding the regimes of waterlogging, *H. cannabinus*

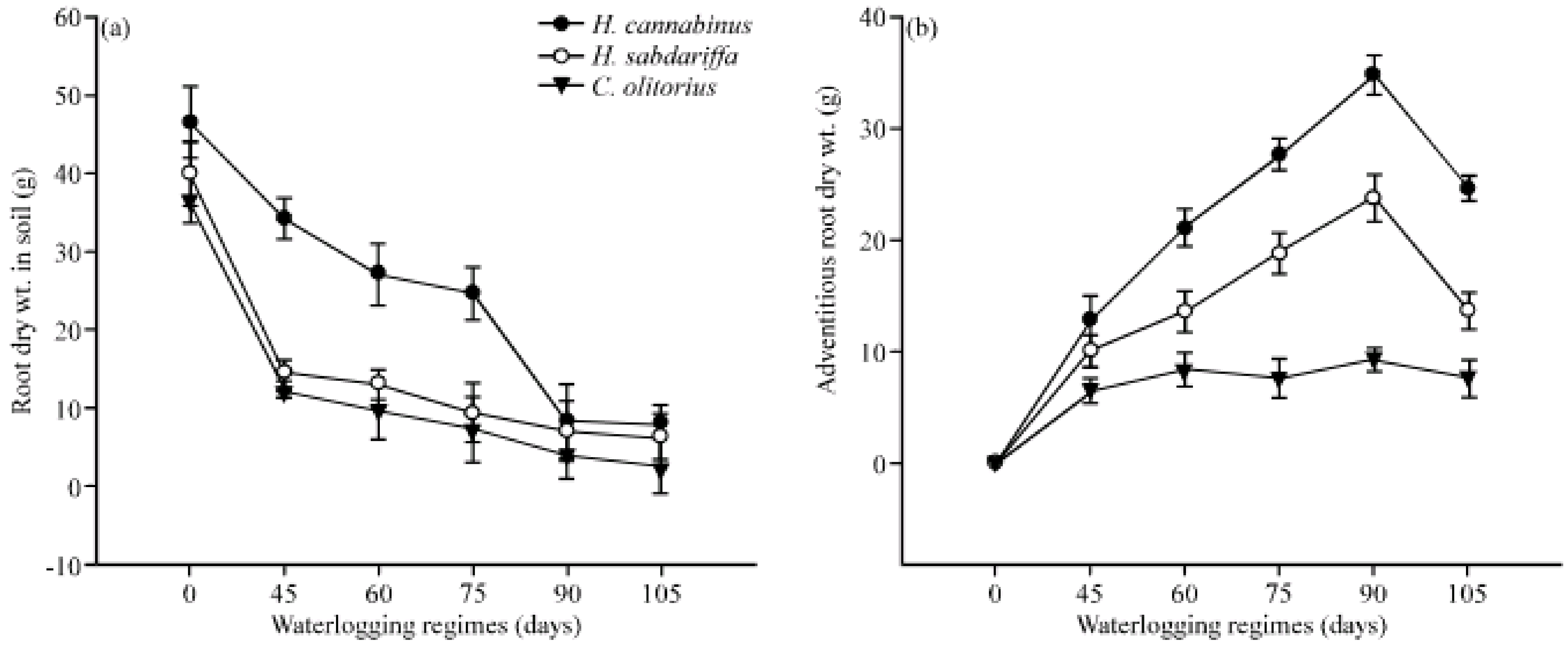

Fig. 3: Effect of waterlogging regimes on root in soil and adventitious roots dry weight of three fiber crops at harvest. Vertical bars on symbols indicate±SE

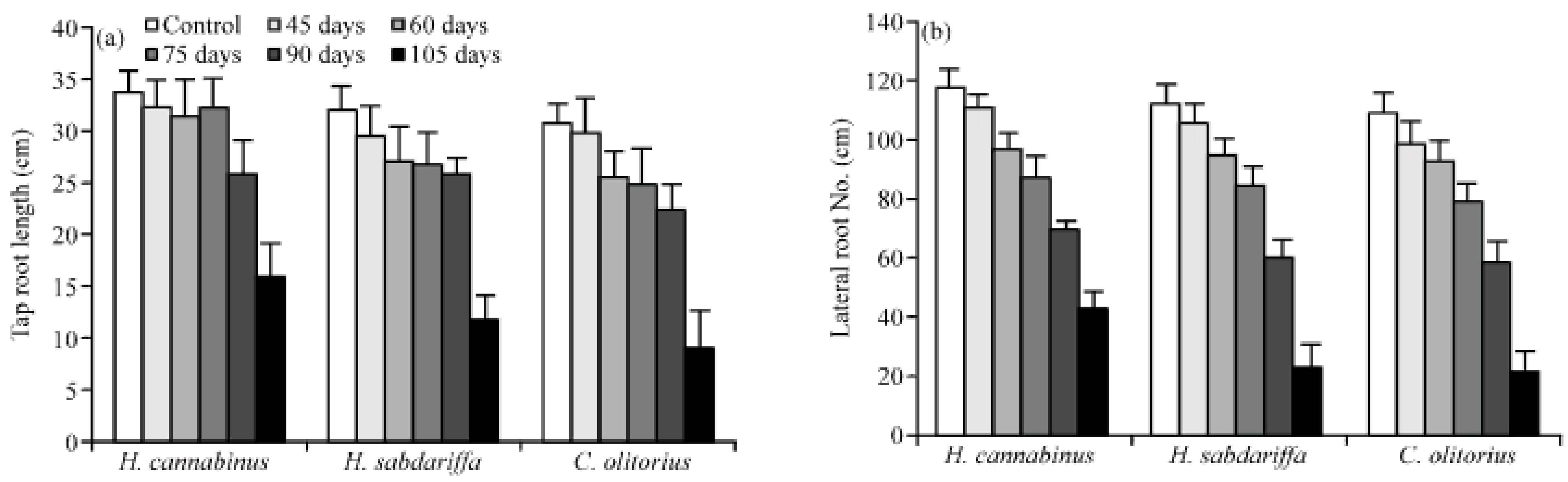

Fig. 4: Tap root length and lateral root number of three fiber crops at harvest as influenced by different regimes of waterlogging. Vertical bars on symbols indicate SE

had a higher value (34.8 g) of adventitious root than the other two species after 90 days of waterlogging. The lowest value (6.5 g) of adventitious root biomass was observed for 45 days of waterlogging regimes in *C. olitorius*.

Tap root length and lateral root number were also significantly affected by waterlogging regimes, but fiber crop species was not significantly. The interaction between fiber crop species and waterlogging regimes in lateral root number, but not interactions in tap root length. In waterlogging regimes for 45, 60, 75, 90 and 105 days decreased by 5.3, 13.3, 13.3, 25.4 and 61.6% compared to the control, respectively, in tap root length and decreased by 7.3, 16.3 26.1, 44.2 and 74.0% compared to the control, respectively, in lateral root number (Table 3). *H. cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased tap root length by 3.9, 6.8, 4.5, 23.2 and 52.4% of the control, respectively and 7.2, 14.8, 15.4, 24.8 and 62.6% in *H. sabdariffa* and 5.1, 19.3, 21.2, 28.8 and 70.9% in *C. olitorius* (Fig. 4a). Moreover, *H. cannabinus* decreased 6.1, 17.4, 25.6, 40.8 and 63.1% of the control, respectively and 6.4, 15.9, 25.2, 46.5 and 79.4% in *H. sabdariffa* and 9.6, 15.5, 27.3, 45.5 and 8.1% in *C. olitorius* (Fig. 4b). The interaction between fiber crop species and waterlogging regimes in the lateral root number was shown in Fig. 4b. *Hibiscus cannabinus* produced the highest lateral root number after 45 days of waterlogging and *C. olitorius* produced the lowest fiber after 105 days of waterlogging.

Waterlogging effect on aerenchyma development: In this experiment, cross sections of adventitious roots showed that aerenchyma or air space developed in all fiber crops. Aerenchyma formation is an adaptive response of *H. cannabinus*, *H. sabdariffa* and *C. olitorius* to waterlogging stress. Aerenchyma tissue developed in adventitious roots when the *H. cannabinus* were subjected to waterlogging for 45, 60, 75, 90 and 105 days (Fig. 5a-f), similarly in *H. sabdariffa* and *C. olitorius* (data not shown).

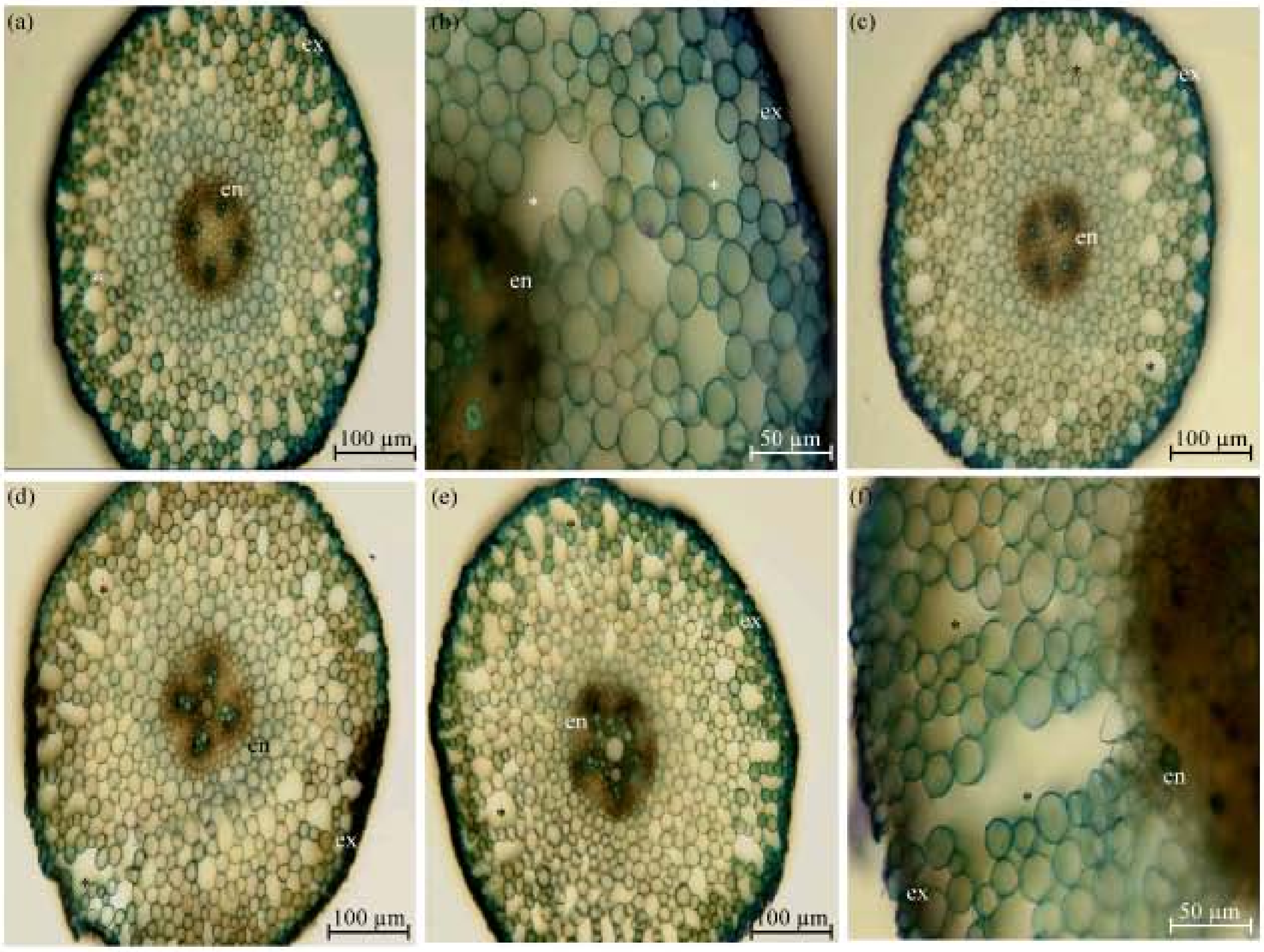

Fig. 5: Light microscopy of root cross-sections at 50 mm from the root tip of adventitious roots; *H. cannabinus* grown in soil waterlogging of (a, b) 45 days, (c) 60 days, (d) 75 days, (e) 90 days and (f) 105 days waterlogged treatments. The bars indicate 100 µm in a, c, d and e and 50 µm in b and f. Asterisks (*) indicate air space or aerenchyma structures in the root cortex. en: Endodermis, ex: Exodermis

Images of lateral roots in the soil of the three fiber crops grown in waterlogged conditions show that only *H. cannabinus* and *H. sabdariffa* formed apparent aerenchyma tissue (Fig. 6a, c, e). In the lateral roots, aerenchyma tissue was not observed under non-waterlogged (Fig. 6a, g). Moreover, the presence of cells with thickened lignin and/or suberin walls was observed in the external cortex of fiber crops (Fig. 6b, d, f, h).

Waterlogging effect on fiber yield: Fiber crop species and waterlogging regime treatments affected on the fiber yield and the interaction between fiber crop species and waterlogging regimes. The *H. cannabinus* gave the highest (17.08 g) fiber yield dry weight, followed by *H. sabdariffa* and *C. olitorius*, which fiber yield was 17.1 g in *H. cannabinus*, 15.1 g in *H. sabdariffa* and only 10.5 g in *C. olitorius* (Table 4). The waterlogging regime treatment of 45, 60, 75, 90 and 105 days had decreased fiber yields, at 11.9, 16.7, 29.4, 36.7 and 51.2% of the control, respectively (Table 4). For the interaction among fiber crop species and waterlogging regimes was shown in Fig. 7. *H. cannabinus* subjected to waterlogging treatment for 45, 60, 75, 90 and 105 days decreased fiber yield by 4.4, 7.3, 21.4, 28.6 and 40.8% of the control, respectively and 5.7, 12.9, 27.3, 31.4 and 52.1% in *H. sabdariffa* and 14.5, 36.0, 40.7, 55.2 and 65.1% in

Table 4: Effect of different waterlogging regime and fiber crop on fiber yield at harvest

Effect	Fiber yield (g)
Fiber crops (F)	
H. cannabinus	17.08a
H. sabdariffa	15.08b
C. olitorius	11.13c
Waterlogging regimes (W)	
Control	18.80a
Waterlogged 45 days	17.57a
Waterlogged 60 days	15.67b
Waterlogged 75 days	13.50c
Waterlogged 90 days	11.90d
Waterlogged 105 days	9.17e
F-test	
Fiber crops (F)	**
Waterlogging regimes (W)	**
F×W	**
CV (%)	6.14

**Significant at $p<0.01$. Mean followed by the same letter at the same column was not significantly different according to Least Significant Difference (LSD)

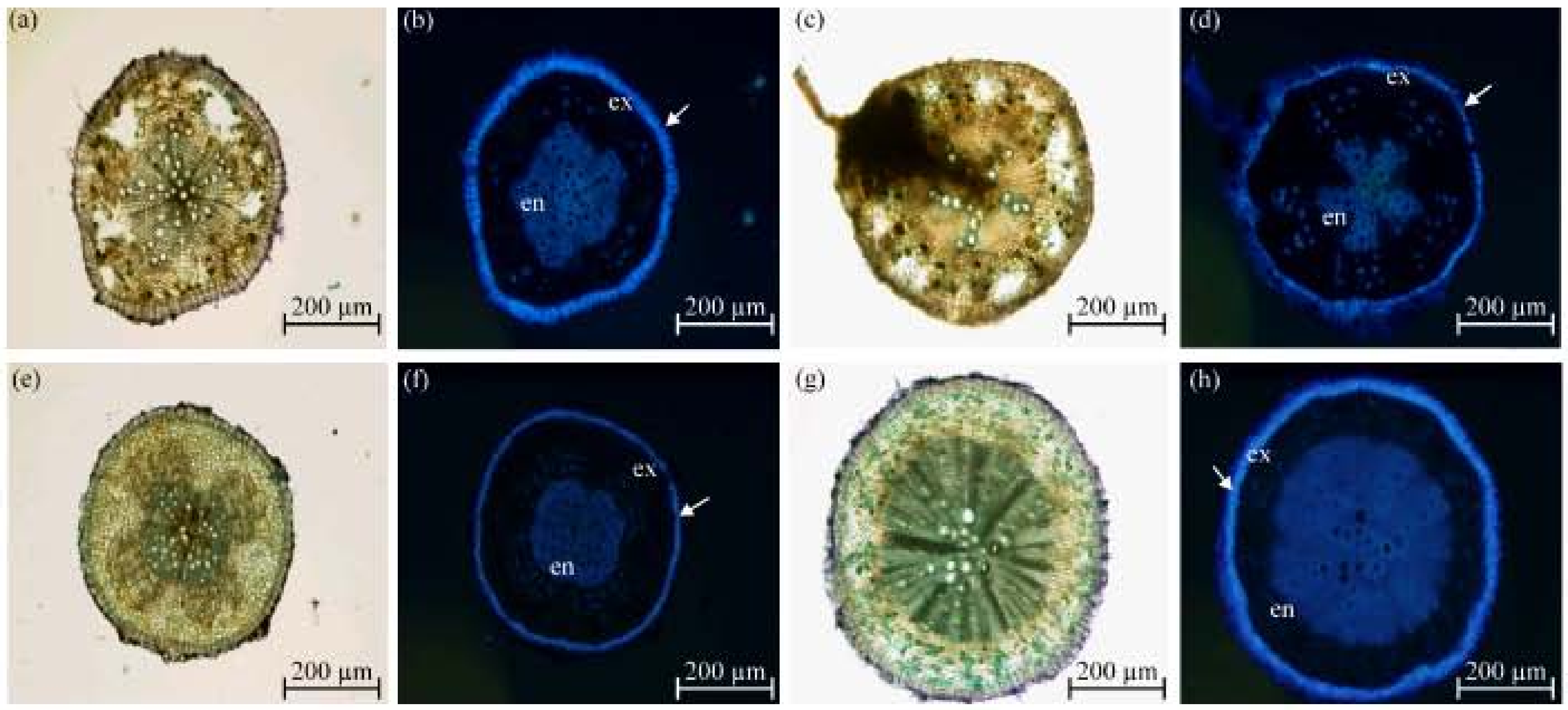

Fig. 6: Light microscopy images (a, c, e and g) and flourescent microscopic images (b, d, f and h) of cross section taken 50 mm below the root-shoot junction of 200-400 mm lateral roots at harvesting of: *H. cannabinus* (a , b), *H. sabdariffa* (c, d) and *C. olitorius* (e, f) grown in 75 days waterlogged treatment and *H. cannabinus* (g, h) grown under drained condition. The bars indicate 200 µm in A-H. Asterisks (*) indicate aerenchyma in the root and white arrow show lignin or suberin. en: Endodermis, ex: Exodermis

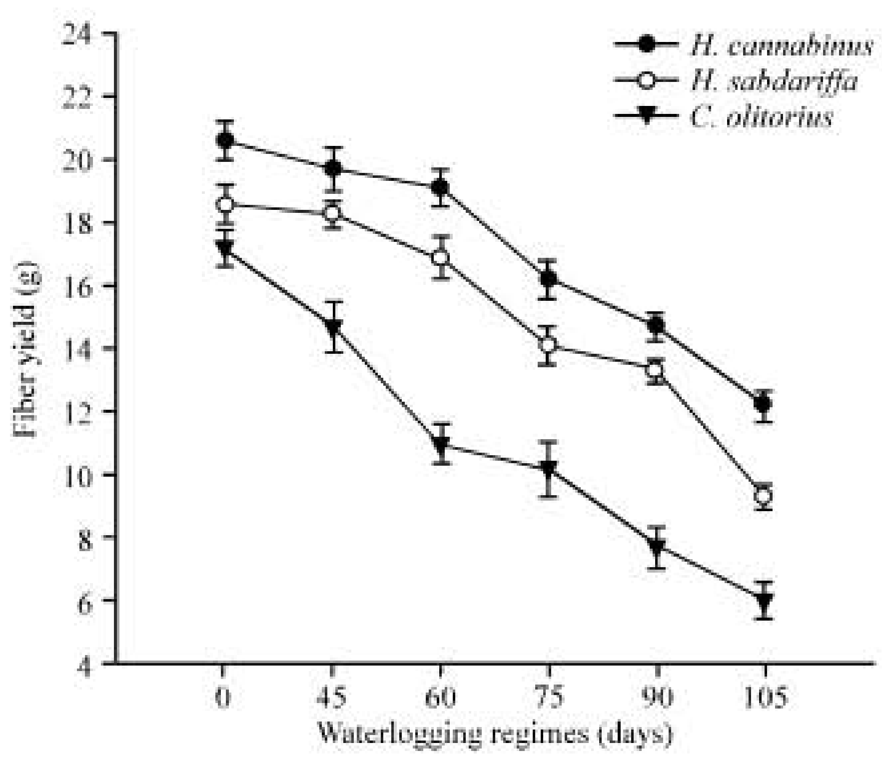

Fig. 7: Fiber yield of the three fiber crops at harvest as influenced by different waterlogging regimes. Vertical bars on symbols indicate±SE

C. olitorius (Fig. 7). *Hibiscus cannabinus* produced the highest (19.7 g) fiber yield after 45 days of waterlogging and *C. olitorius* produced the lowest (6.0 g) fiber after 105 days of waterlogging.

DISCUSSION

Waterlogging, even it continues for a short period, can cause considerable damages to the growth and yield. The present study clearly demonstrated that the longer-duration growth of fiber crop was severely reduced by a short-duration exposure to waterlogging. Our experiment has shown that crops subjected to waterlogging stress had reduced the plant height, the stem diameter and the leaf area of all three species and that waterlogging duration of 105 days was the most severity for the plant growth. In other crops, the parameter of plant height was reduced in response to flooding by 25-37% in soybean (*Glycine max*) (Githiri *et al*., 2006). In this study, the leaf area of the whole fiber crop was decreased to 24.8-59.2% of the control due to waterlogging. Similarly, the total leaf area was reduced by waterlogging to 76 and 34% of the control in Buckwheat (*Fagopyrum esculentum* Moench) and Tartary buckwheat or Tatar buckwheat (*Fagopyrum tataricum* (L.) Gaertn.), respectively (Matsuura *et al*., 2005). On the other hand, it was observed that waterlogging was reduced for all investigated parameters in this experiment.

According to Pezeshki and DeLaune (1998), Brown and Pezeshki (2000), Chen *et al*. (2002), Matsuura *et al*. (2005) and Yetisir *et al*. (2006), soil waterlogging also was reduced the growth and dry matter production of shoots as in some species such as Chinese Privet (*Ligustrum sinense*), perennial pepperweed (*Lepidium latifolium* L.), Tartary buckwheat (*Fagopyrum tataricum* L.) and Watermelon (*Citrullus lanatus*). Stem dry weight in Cacao (*Theobroma cacao* L.) was increased when the plant was subject to flooding for 15 and 30 days while it decreased under flooding for 45 and 60 days (Sena-Gomes and

Kozlowski, 1986). The present study shows similar results: shoot dry weight of three fiber crops decreased when waterlogged for 60-105 days. However, waterlogging regimes for 45 days in *H. cannabinus* gave results not different from those of the control while *H. sabdariffa* and *C. olitorius* were reduced in all waterlogging treatments.

Data recorded during our study suggest that longer regime of waterlogging stress higher reduction of shoot and root growth. Furthermore, it was understood that soil waterlogging reduced the yield of many crops (Belford, 1981; Musgrave, 1994; Collaku and Harrison, 2002). In our experiment, long periods of waterlogging reduced fiber yield more in the *C. olitorius* L. than in the *H. cannabinus* L. and the *H. sabdariffa* L. and it was clear that these three fiber crops can survive waterlogging for different regimes. On the other hand, it was found that the dry weight of adventitious roots increased depending on the regimes of waterlogging, which was accompanied by the damage or death of original roots but it was promoted development of adventitious roots. The dry weight of adventitious roots was different among species and *H. cannabinus* L. had more dry weight of adventitious roots than *H. sabdariffa* L. and *C. olitorius* L. Chen *et al*. (2002) reported that the amount of adventitious roots in perennial pepperweed (*Lepidium latifolium* L.) increased depending on the waterlogging regimes. These adventitious roots may have a positive role in supporting shoot growth during prolonged flooding (Jackson, 1985).

Moreover, root dry weight was reduced by flooding to 82% and 88% of the control in the tolerant and sensitive genotypes of Tatary buckwheat (*Fagopyrum tataricum* L.), respectively (Matsuura *et al*., 2005). Waterlogging reduced the root dry weight of Cacao (*Theobroma cacao* L.) by 9-81% of the non-waterlogged control in a greenhouse experiment, depending on waterlogging regimes (Sena-Gomes and Kozlowski, 1986). Likewise, as in our experiment, root dry weight was reduced to 5-61% of the non-waterlogged control. In addition, the length of lateral roots was significantly reduced by waterlogging for winter wheat (*Triticum aestivum* L.) and the number of nodal roots was 18-47% lower than in the drained plants (Huang *et al*., 1994).

In *H. cannabinus*, *H. sabdariffa* and *C. olitorius*, aerenchyma was developed in adventitious roots in response to waterlogging. Aerenchyma formation under waterlogging conditions is essential for the survival of plants grown in waterlog-prone soils as provides an interconnected system of air channels which enables gases to diffuse or ventilate from aboveground to belowground organs to maintain aerobic respiration and rhizosphere oxygenation (Jackson and Drew, 1984; Blom and Voesenek, 1996; Jackson and Armstrong, 1999; Vasellati *et al*., 2001). In *H. cannabinus*, *H. sabdariffa* and *C. olitorius*, aerenchyma was formed under waterlogging conditions. This characteristic is essential for the survival of plants grown in waterlog-prone soils. In *H. cannabinus*, aerenchyma was more developed compared with *H. sabdariffa* and *C. olitorius*. Such development of aerenchyma in adventitious roots, depending on tolerance for the waterlogging, indicated that aerenchyma was developed in adaptation to soil waterlogging, which is consistent with results from previous studies (Jackson and Armstrong, 1999; Niki and Gladish, 2001; Chen *et al*., 2002; Setter and Waters, 2003; Shimamura *et al*., 2003; Shuwen *et al*., 2006). Moreover, *H. cannabinus* formed the aerenchyma in cortex of the taproot under waterlogging condition. The formation of aerenchyma in *H. cannabinus* roots at seedling stage may contribute to the waterlogging tolerance (Changdee *et al*., 2008).

The strategy of aerenchyma development in response to flooding may involve a tradeoff between maintaining physiological function and the need to reduce tissue respiration. While aerenchyma systems can benefit the plants in terms of facilitating oxygen transport and increasing metabolic efficiency, their formation also presents certain costs. Eliminating cortex tissue can impede root functions such as water and mineral uptake and transport (Moog, 1998). Hence, the aerenchyma in *H. cannabinus* develops maximally only under waterlogging conditions. Apparently, the aerenchyma formation is too costly unless a plant is confronted with hypoxia from flooding stress or nutrient shortage, necessitating the need for reduced plant tissue and concomitant reduced metabolic demands. Moreover, in our experimental fiber crops we observed lignin and/or suberin tissues. Lignification and suberization of hypodermal cell walls both contribute to preventing root collapse and function as a barrier to prevent oxygen loss and to exclude soil toxins which can be frequently found in flooded soils (Koncalova, 1990; Armstrong *et al*., 1991; Peterson, 1992).

In conclusion, the effect of different regimes of waterlogging is described in three fiber crops. Soil waterlogging decreased the plant height, stem diameter, leaf area, leaf and shoot and root dry weight located in the soil of the non-waterlogged (control). In addition, waterlogging regimes reduced the tap root length and lateral root number. No adventitious roots developed in the non-waterlogging (controls) and adventitious root dry weight in the three fiber crops increased depending on the waterlogging regimes. The aerenchyma tissue formed in adventitious roots when *H. cannabinus*, *H. sabdariffa* and *C. olitorius* were subjected to waterlogging. The fiber crops subjected to waterlogging significantly decreased fiber yield by 51.2% compared to the control. The differences among the three fiber crops were for all traits, which *H. cannabinus* gave the highest value plant height, stem diameter, leaf area, biomass production and root growth, followed by *H. sabdariffa* and *C. olitorius*. These results suggest that the survival of these three fiber crops may depend on the waterlogging regimes.

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