BIODIVERSITAS
Volume 25, Number 5, May 2024
Pages: 2063-2073

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d250524

Identification of chili varieties (*Capsicum annum*) tolerance to root cutting based on stress selection indices and morphological traits planted in lowland area

SARLIN KUSUMANINGRUM[1], ENDANG SULISTYANINGSIH[1,♥], RUDI HARIMURTI[1], KUMALA DEWI[2]
[1]Graduate School of Agriculture, Faculty of Agriculture, Universitas Gadjah Mada. Jl. Flora, Bulaksumur, Sleman 55281, Yogyakarta, Indonesia. Tel.: +62-858-7854-8282, ♥email: endangsih@ugm.ac.id
[2]Laboratory of Plant Physiology, Department of Tropical Biology, Faculty of Biology, Universitas Gadjah Mada. Jl. Teknika Selatan, Sekip Utara, Sleman 55281, Yogyakarta, Indonesia

Manuscript received: 19 February 2024. Revision accepted: 15 May 2024.

Abstract. *Kusumaningrum S, Sulistyaningsih E, Harimurti R, Dewi K. 2024. Identification of chili varieties (*Capsicum annum*) tolerance to root cutting based on stress selection indices and morphological traits planted in lowland area. Biodiversitas 25: 2063-2073.* Root cutting is a potential technique for inducing root growth to increase chili yield. A set of four lowland chili varieties were evaluated under root cutting to identify tolerant variety. Stress selection indices such as stress tolerant level (TOL), Stress Susceptible Index (SSI), Stress Tolerance Index (STI), Yield Stability Index (YSI) and morphological traits responses were employed in screening of the variety. The research was arranged in randomized complete block design factorial, where the first factor was the lowland chili varieties ('Tanjung', 'Lembang-1', 'Tanjung-2', 'Ungara'), and the second factor was period of root cutting (0, 8, and 0 + 8 weeks after transplanting and no root cutting). The results showed that 'Kencana', 'Lembang-1', 'Ungara' were identified as the tolerant group under root cutting treatment and 'Tanjung-2' was identified as the intolerant group based on chili yield and stress selection indices. The tolerant group had chili yield increment under root cutting (0, and 8 WAT), which related to high root morphological traits (root diameter, root length, root surface area, and root dry weight density). Root cutting at 8 WAT gave the highest chili yield in tolerant group. The increased root growth in the tolerant group was contributed to promote shoot morphological traits (leaf number, leaf area, and plant height). Root cutting treatment in the intolerant group caused chili yield decrement, which was related to no increment of the root and shoot morphological traits. It was concluded that root cutting treatment at 8 WAT on tolerant group ('Kencana', 'Lembang-1', 'Ungara') can be used to increase chili yield in lowland areas.

Keywords: Cutting, intolerant, lowlands, root, tolerant

Abbreviations: FWF: Fresh Weight of Fruit, NL: Number of Leaves, PH: Plant Height, RCBD: Randomized Completely Block Design, RD: Root Diameter, RL: Root Length, RSA: Root Surface Area, RWD: Dry Weight of Root Density, SSI: Stress Susceptibility Index, STI: Stress Tolerance Index, TOL: Tolerance, WAT: Week After Transplanting, YSI: Yield Stability Index

INTRODUCTION

Chili is a vegetable commodity widely cultivated in highlands with tropical climates, such as Indonesia. The area of chili cultivation in highland tropical regions of Indonesia, reaches 57,552 ha, which is wider than that of the lowland areas (87,657 ha) (Irjayanti et al. 2023). The expansion of chili cultivation proceeded from lowlands to highlands to fill continuous demands. However, lowland chili cultivation (6.33 t ha^{-1}) has a lower productivity than highland cultivation (11.79 t ha^{-1}) (Irjayanti et al. 2023). Lowland areas feature high temperatures, which affect the decrease in assimilate production due to an increase in respiration and transpiration (Timlin et al. 2006). The production of shoot assimilates is influenced by roots, which contribute to the supply of water and nutrients (Tajima 2021). According to Van Noordwijk and De Willigen (1987), an agricultural policy law states the remarkable dependence of the total growth of shoots depends largely on root development. Maize crops with improved root systems can increase economic yields (Guo et al. 2022). Bektas et al. (2023) also reported linear wheat yields with plant root biomass. The increase in root growth is one of the efforts to increasing shoot growth and plant production, and it can be achieved through root cutting (Gao et al. 2018).

Root cutting is one of the techniques used to induce root growth to increase root capacity (Jeong et al. 2021). The root cutting treatment causes plants to mainly allocate assimilates to roots for growth due to the loss of root biomass (Magaña-Hernández et al. 2020). Plants that are tolerant to root cutting have higher mean yield and relative yield performance. Evaluation of the yield stability can use tolerance indices such as stress tolerance level (TOL), Stress Tolerance Index (STI), Yield Stability Index (YSI), and Stress Susceptibility Index (SSI). These indices are a yield stability parameter, which are based on how much yield reduction under loss of root biomass conditions (Kumar et al. 2014). TOL shows differences in relative yield, while YSI shows evaluate genotype stability under root cutting and control. STI shows plant tolerance, and SSI measures the yield stability that apprehends the changes in both potential and actual yield under loss of root biomass condition (Kumar et al. 2014). Identification of yield stability can be supported through root and shoot morphology. Root morphology such as root diameter, root length, root surface area, and number of lateral roots plays an important role in supporting shoot growth and plant yield (Mwangoe et al. 2022). Based on previous research, it showed that an increase in root surface area as a result of root growth causes optimal nutrient uptake (Kesumawati et al. 2021). Root cutting by 50% in *Helianthus tuberosus* L. increased root biomass and plant economic yields (Gao et al. 2018). Budiarto et al. (2019) reported that root cutting in citrus plant can increase the translocation of assimilates to the root, and the fibrous root density. Mashamaite et al. (2020) also reported that root cutting in *Moringa oleifera* L. seedlings can increase plant height, and number of leaves. The response of plants to root cutting is influenced by period of plant cultivation (Werner et al. 2001). Root cutting in seedlings of *Celosia argentea* L. can increase shoot and root biomass (Ning et al. 2021). Root cutting can also be performed during plant ridging. Ridging is conducted to avoid pest attacks, and loosen soil, which increase nutrient absorption, by roots and strengthen plants (Dewi et al. 2023). The important traits associated with stress tolerant indices and morphological plants can identify tolerant variety under root cutting treatment. Multivariate analysis such as cluster analysis and principal component analysis can be used to cluster variety with similar characteristics and identify tolerant variety (Pandey et al. 2021). Therefore, identification of lowland chili varieties tolerance to root cutting using stress selection indices and morphological traits is required to determine some traits increasing chili yield. The adaptive lowland chili varieties (*Capsicum annum* L.), which include 'Lembang-1', 'Kencana', 'Tanjung-2', and 'Ungara' can be used as an evaluation material for identification tolerance level under root cutting treatment.

MATERIALS AND METHODS

Materials and experimental site

This research was carried out in Tridharma Field Experimental Unit, Faculty of Agriculture, Bantul, Yogyakarta, Indonesia (latitude: 7°50′24.87″S and longitude: 110°24′29.99″E). Materials used in this research were chili varieties planted in lowland areas. Those are, namely 'Lembang-1', 'Kencana', 'Tanjung-2', 'Ungara'.

Research design

The reseach was arranged in randomized complete block design with factorial treatment with three blocks as replications. The first factor was period of root cutting, consiting of transplanting (0 weeks after transplanting (WAT)), ridging (8 WAT), transplanting + ridging (0 + 8 WAT), and no root cutting (control/normal condition). The second factor was lowland chili varieties, namely 'Lembang-1', 'Kencana', 'Tanjung-2', 'Ungara'.

Experimental procedure

Nursery and transplanting

The seedbed of chili plants was prepared that used husk charcoal, soil, and organic fertilizer at a ratio of 1:1:1 inserted into a 50 g nursery plastic. A nursery plastic filled with chili seeds was placed in a germination tray (30×30×15 cm). It was placed in alternate dark and light condition. After seven days, the chili seedlings were readied for transplantation after four perfectly opened leaves. Transplanting was carried out, including the preparation of planting media containing soil:husk:cow manure with a ratio of 3:1:1 in polybags with a size of 35×35 cm. Polybags filled with planting media were arranged with an interspacing of 35×20 cm. Seedlings with four opened leaves were transplanted into the polybags. Next, the seedlings were planted at a depth of 5 cm or until the base of stem had been covered by soil.

Root cutting treatment

Root cutting was carried out on 50% of lateral roots after seedling transplantation (0 WAT) and ridging (8 WAT), whereas no root cutting was performed for the control. Root cutting at 0 WAT began with the measurement of the length of lateral roots. Then, 50% of the lateral roots were cut on both sides and weighed to determine their root fresh weight. After root cutting, the seedlings were transplanted into the polybags. Root cutting at 8 WAT was carried out on as much as 50% of lateral roots located on both sides, with soil being cut to a depth of 10 cm. After root cutting, the plant was transferred to another polybag, and soil was added to cover the roots.

Plant management

The plants were watered at field capacity once every 3-4 days. Fertilization was carried out in the vegetative phase (2 WAT) using 300 kg ha^{-1} urea, 600 kg ha^{-1} SP-36, and 300 kg ha^{-1} KCl. Fertilizers at generative stage (6 WAT) were used P_2O_5 and $CaCO_3$ + B as much as 3-5 g L^{-1} and 3 g L^{-1}, respectively. Weed control was accomplished manually. Yellow traps with petrogenol compounds were used to suppress the presence of fruit flies. Harvesting was conducted gradually every 3-4 days until the chilis were 80% ripe. 'Kencana', 'Lembang-1', 'Tanjung-2', and 'Ungara' were harvested 12, 15, 13, and 16 times, respectively. Harvesting was completed until fruits produced by the plant can be consumed.

Data observation

Yield and Stress selection indices

The economic yield can be observed through the fresh weight of fruit (FWF) per plant. The FWF was measured using analytical scales until 16 WAT. The FWF was used to calculate stress selection indices caused by root cutting treatment. The tolerant indices under root cutting treatment were measured using stress tolerance level (TOL), Stress Tolerant Index (STI), Stress Susceptibility Index (SSI), and Yield Stability Index (YSI). TOL was used to describe yield reduction under root cutting and without root cutting and stress conditions (root cutting) (Fischer and Maurerac 1978).

$$\text{Stress tolerance level (TOL)} = Y_{nc} - Y_c$$

Where: STI was used to describe the relative performance of chili varieties under stress conditions (root cutting) compared with normal conditions (without root cutting) (Fischer and Maurerac 1978).

$$\text{Stress tolerant index (STI)} = \frac{Y_{nc} \times Y_c}{(\bar{Y}_{nc})^2}$$

Where: SSI was suggested by Fischer and Maurerac (1978) for a yield stability measurement based on changes in potential and actual yield under stress condition. SSI can be evaluated plant tolerance under stress conditions (root cutting). SSI more and less than 1 indicates above and below-average susceptibility to the root cutting treatment.

$$\text{Stress susceptibility index (SSI)} = \frac{1 - Y_c/Y_{nc}}{1 - \bar{Y}_c \,/\, \bar{Y}nc}$$

Where: YSI was indicated the power of stability that indicated a good level of TOL to stress conditions (Fischer and Maurerac 1978).

$$\text{Yield stability index (YSI)} = \frac{Y_{nc}}{Y_c}$$

Where: Yc refers to the mean FWF with root cutting, and Ync denotes the FWF without root cutting (control). $\bar{Y}s$ and $\bar{Y}p$ are the mean FWF of all varieties of chili under root cutting and without root cutting. STI >1, SSI <1, TOL >1, and YSI >1 were indicated that plants showed tolerance in the root cutting treatment.

Morphological traits

Root morphology measurement was carried out at 12 WAT. The total Root Length (RL) and root surface area (RSA) were measured using a meter video camera (Delta-T Device Ltd, UK) integrated with WinDWAS software (Delta-T Device Ltd, UK). Prior to measurent, the video camera was calibrated with a ruler measuring 10 cm. After tool calibration, the roots were stretched to prevent them from overlapping and placed on the scanner table. RL and RSA can be measured by selecting the object menu on the monitor screen. The tool measures objects based on predetermined colors. In the first step, the color of roots was marked as the object for measurent. Then, all the root parts to be measured were selected by grabbing the mark. For RL measurement, the screen menu was selected, followed by the measure function. Afterward, RL and RSA data obtained automatically. The root dry weight were determined after dried in oven with temperature of 80°C for 24 h until a constant weight. The root dry weight density (RWD, mg root cm^{-3} soil) was calculated by dividing the root dry weight (mg) by the soil volume (10 kg = 10,000 cm^3) (Kamran et al. 2018).

Shoot morphology measurement was carried out at 12 WAT. The Number of Leave (NL) was used to describe leaf growth. The NL was calculated using a hand tally counter at 12 WAT. Leaf area (cm^2) was measured using leaf area meter (MK2, Delta-T Device Ltd. Serial No. CB380495, 220 V, 50 Hz, UK) with the assistance of WinDIAS software (Delta-T Devices Ltd, UK). The leaves were arranged on a glass and then passed over the scanner for leave visualization and measurement of the leaf area. The number listed on the monitor was subtracted from the standard value used to produce leaf area data in squared centimeters (cm^2). Plant height (cm) was measured from stem base to the highest stem at 10 WAT.

Data analysis

All data were analyzed using the mean ± standard deviation. The grouping based on stress indices and morphological traits were analyzed through the principal component analysis and cluster analysis. Pearson correlation analysis was used to determine the relationship of fresh weight of fruit and morphology traits on tolerant and intolerant groups. SAS version 9 software programs (SAS Institute Inc. 2002), OriginPro 2023, and Microsoft Excel version 2021 were used in the analyses.

RESULTS AND DISCUSSION

Fresh weight of fruit and stress selection indices

Fresh weight of fruit

Root cutting is a potential technique for inducing root and shoot growth, dry matter allocation, and yield improvement (Jing et al. 2017). Plant varieties that show tolerant in response to root cutting have a positive correlation with yield components. The increase in yield can occur due to an increase in sink demand, which promotes the assimilate translocation toward the fruits (Huang et al. 2021). The results to economic yield of chili under root cutting was related on Fresh Weight of Fruit (FWF) (Figure 1.C) (Hou et al. 2020). The FWF in 'Kencana', 'Lembang-1', and 'Ungara' was higher than 'Tanjung-2' under root cutting treatment (Figure 1.A). The positive response of 'Kencana' and 'Lembang-1' observed as the increases in FWF by 16.17, 25.92, 30.66, and 33.76%, respectively under root cutting at 0 and 8 WAT (Figure 1.A). All root cutting treatments on 'Ungara' increased the FWF by 27.59, 31.74, and 24.36%, respectively at 0, 8, and 0 + 8 WAT (Figure 1.A). Conversely, on 'Tanjung-2' decreased FWF by 7.57-34.58% in all root cutting treatments (Figure 1.A). Thus, root cutting at 8 WAT can increase FWF of 'Kencana', 'Lembang-1', and 'Ungara', on the contrary of 'Tanjung-2'. The increase in economic yield occurs due to an increase the photosynthates translocation to the fruit. In maize, root cutting can reduce water consumption through reduction of transpiration and increase photosynthetic activity to promote seed filling (Umar et al. 2019). The decrease transpiration is offset by an increase water use efficiency, which enable roots to continue transporting sufficient amounts of water after cutting; as a result, the water potential of leaves is close to those of plants without cutting (Mashamaite 2020). The same finding was observed from *Ziziphus jujube* Mill., which exhibited an increased crop economic yield due to the increased cutting; as a result, water use efficiency was increased (Jin et al. 2019).

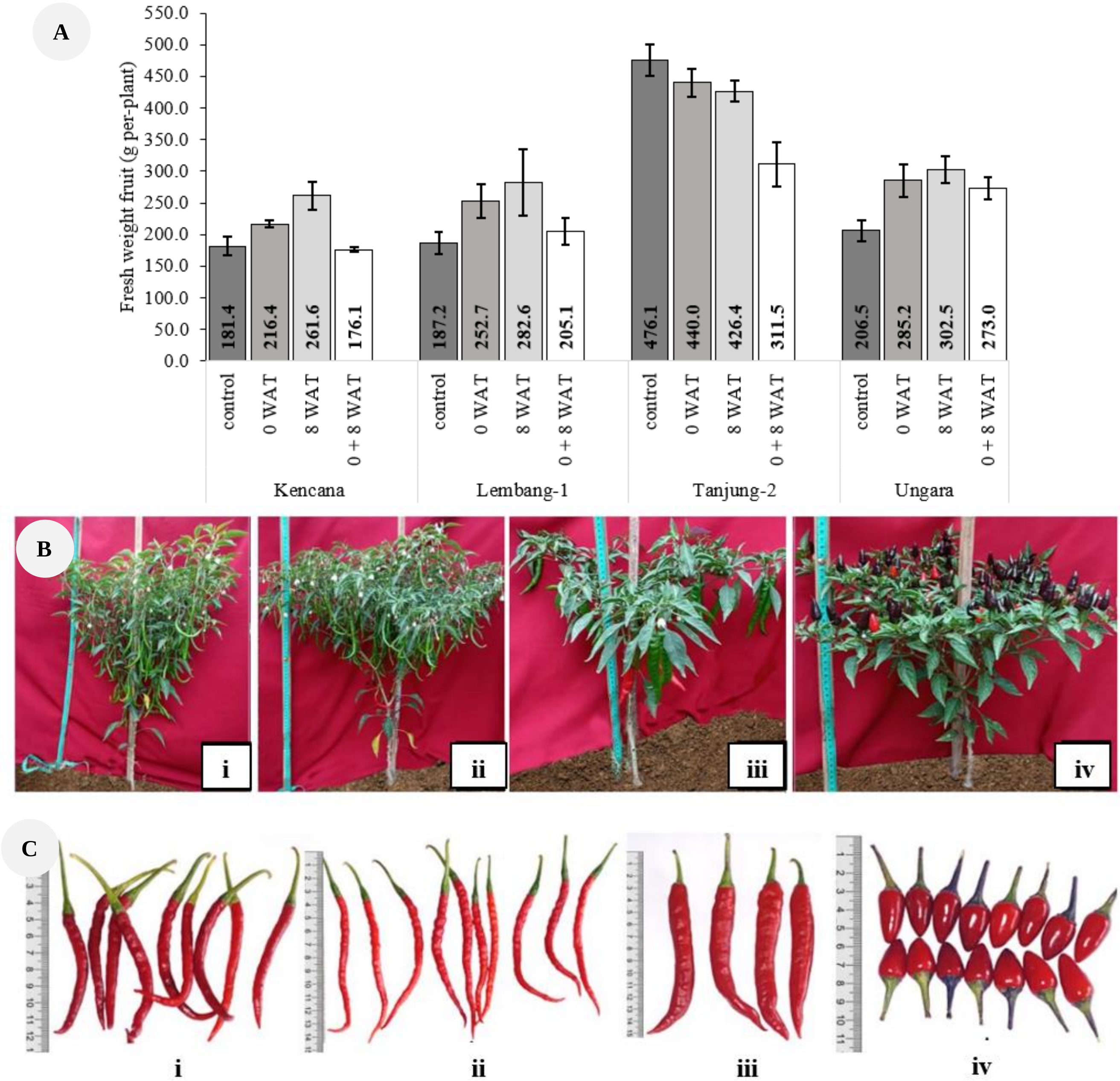

Figure 1. Fresh weight fruit (g) (A), Chili plant (B), Chili fruit (C) of four lowland varieties at 16 WAT. Note: the numbers presented are the means ± standard deviation. (i) 'Kencana', (ii) 'Lembang-1', (iii) 'Tanjung-2', (iv) 'Ungara'

Stress selection indices

The stress tolerance indices and relative yield can be evaluated using TOL and STI. In general, crop production is the main selection characteristic for determining the level of stress TOL (Padjung et al. 2021). 'Kencana', 'Lembang-1', and 'Ungara' displayed tolerance to root cutting. 'Kencana' increased TOL values of 35.1 and 80.3, respectively (Figure 2.A) under root cutting at 0 and 8 WAT. 'Lembang-1' under root cutting at 0, 8, and 0 + 8 WAT confirmed by the increase in TOL values (65.6, 95.5, and 17.9, respectively) (Figure 2.A). 'Ungara' had TOL of 78.7, 96.1, and 66.5, respectively under root cutting at 0 WAT, 8 WAT, and 0 + 8 WAT (Figure 2.A). Lower value of TOL in 'Tanjung-2' indicated the high stress to root cutting conditions. Various studies used STI to select stress-tolerant genotypes. An increase in STI values indicates high yield and stress tolerance (Lamba et al. 2023). Genotypes with a high STI generally present high yield differences under stress and optimal conditions (Permanasari et al. 2023). STI can reveal the relative performance of a plant under stress conditions compared with under optimal conditions. Tolerant and intolerant varieties had STI values >1 and STI <1, respectively. Root cutting at 8 WAT resulted the highest STI, such as 'Kencana', 'Lembang-1', and 'Ungara' at 1.29, 1.44, and 1.70, respectively (Figure 2.B). 'Tanjung-2' had STI <1 in all root cutting treatments (Figure 2.B). YSI is useful for distinguishing tolerant and susceptible genotypes. A high

YSI genotype indicates a high tolerant and more absolute individual comparison of production under stress and optimal conditions (Pertiwi et al. 2022). YSI values are classified as follows: >0.6, highly stable in root cutting; 0.41-0.60, stable in root cutting; 0.20-0.40, moderately stable in root cutting; <0.20, susceptible to root cutting (Rosmaina et al. 2019). An increase in YSI indicates an increase in plant TOL to stress conditions. The highest YSI obtained during root cutting at 8 WAT, such as 'Kencana', 'Lembang-1', 'Ungara' at 1.44, 1.51, and 1.47, respectively, whereas 'Tanjung-2' at 0.90 (Figure 2.D). Kumar et al. (2014) suggested that stress susceptibility index assess the reduction in yield caused by stress compared to optimal conditions. Lower SSI values indicate the lower differences in yield between non-stress and stress condition. SSI is a measure of yield stability. Genotypes with low SSI values (less than 1) can be considered to be tolerant because they exhibited smaller yield reductions under stress compared with optimal conditions. SSI values are classified as follows: highly tolerant (SSI <0.50), tolerant (SSI: 0.51-0.75), moderately tolerant (SSI: 0.76-1.00) and susceptible (SSI >1.00). On the basis 'Kencana', 'Lembang-1', and 'Ungara' had SSI under root cutting (8 WAT) at 0.24, 0.19, and 0.08, respectively (Figure 2.C). Based on these stress tolerance indices indicators, 'Kencana', 'Lembang-1', and 'Ungara' were tolerant to root cutting, whereas 'Tanjung-2' was intolerant. A major factor in the decline in yield was the limited supply of metabolic energy to sustain growth (Abdelhaleim et al. 2022).

Principal component analysis and cluster analysis

The grouping of tolerant and intolerant chili varieties under root cutting treatment based on stress tolerance indices were determined using the results of principal component analysis and cluster analysis (Figures 3.A and 3.B). The result of principal component analysis explained stress tolerance indices of the chili varieties. A total of two Principal Components (PCs) were resulted from the analysis with total contribution to the variation of 100%. The first component variant (PC1) contributed to stress tolerance indices TOL (0.510), YSI (0.506), STI (0.475), and SSI (0.506) for 95.5% of the total variability, and the second component variant (PCA 2) contributed 4.5% of the total variability (Figure 3.A). Based on positive direction of the loading plot (PC1) used to describe TOL, YSI, STI, and SSI that indicate the tolerant variety under root cutting treatments. Based on the PC1 grouping, 'Ungara', 'Kencana', and 'Lembang-1' belong to the tolerant group, and 'Tanjung-2' belong to the intolerant group. The result of cluster analysis based on chili yield and morphological plant showed that 55.60% similarity value was obtained between tolerant and intolerant groups, with tolerant group showing 65.69% similarity value (Figure 3.B).

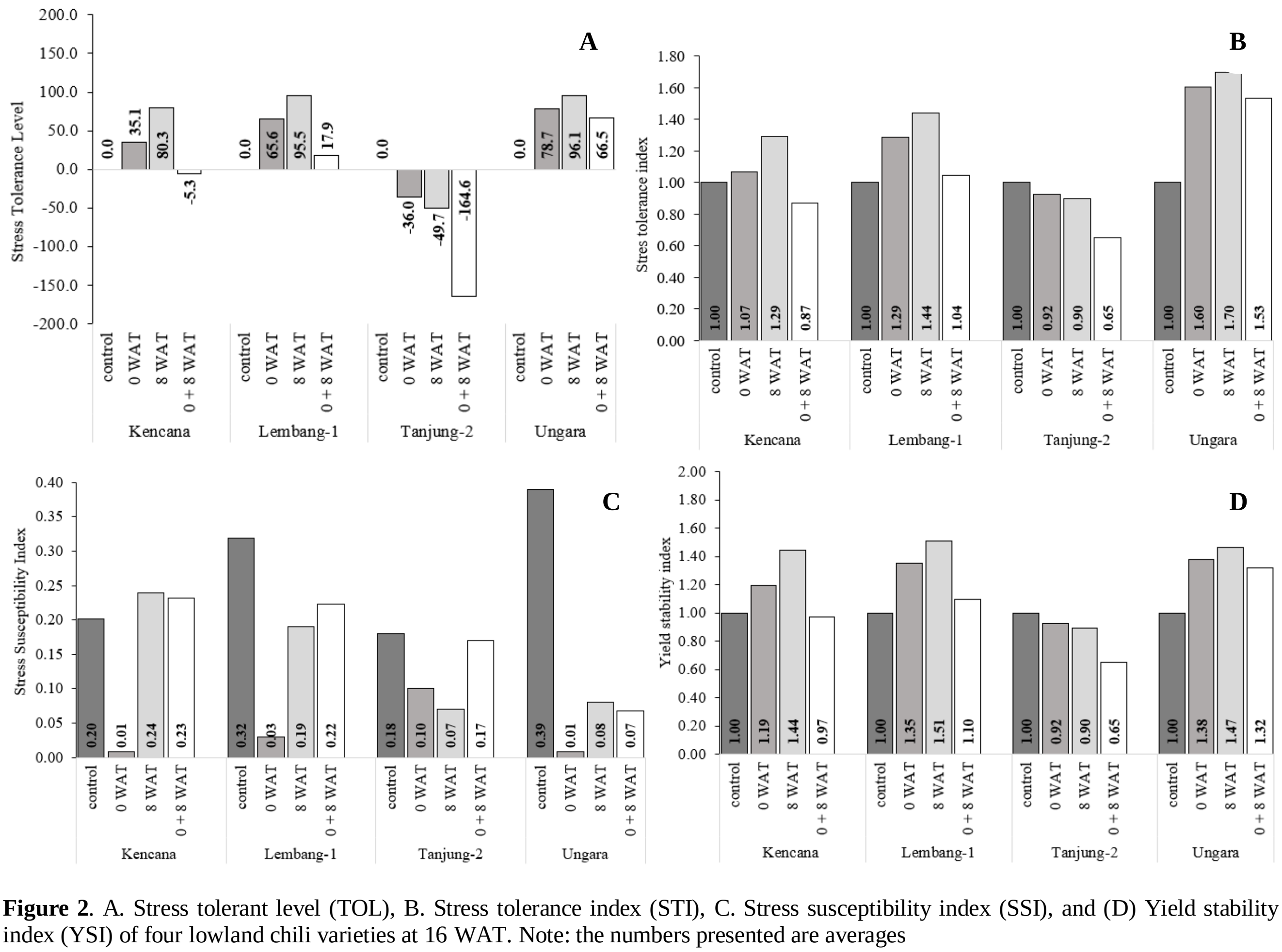

Figure 2. A. Stress tolerant level (TOL), B. Stress tolerance index (STI), C. Stress susceptibility index (SSI), and (D) Yield stability index (YSI) of four lowland chili varieties at 16 WAT. Note: the numbers presented are averages

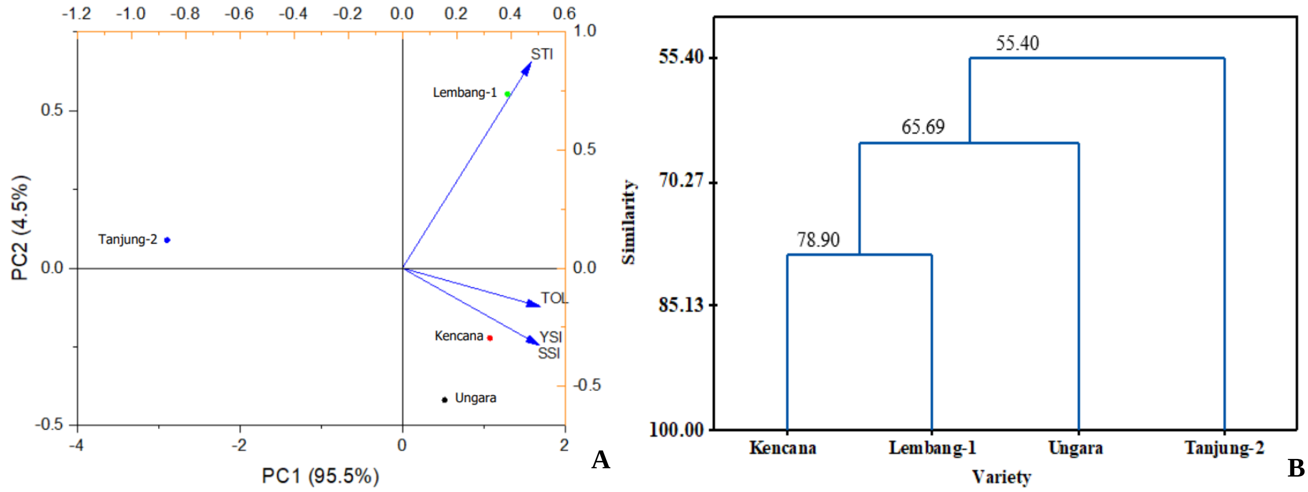

Figure 3. A. Principal component analysis, and B. Cluster analysis based on stress indices and morphological traits. Note: TOL: Tolerance, STI: Stress tolerant index, SSI: Stress susceptibility index, and YSI: Yield stability index

Morphological traits

Root morphology (root dry weight density, root diameter, root length, and root surface area)

The tolerant variety under root cutting was increased root morphology. The architecture root system that includes RL and RSA is an important plant trait for obtaining soil resources (Sakya et al. 2023). Root Weight Density (RWD) is one of the essential parameters used for the evaluation of roots morphology. RL can indicate root growth, and RSA shows the root absorption area in exploration of water and nutrients. Our data showed that root cutting at 8 WAT intolerant groups such as 'Kencana', 'Lembang-1', and 'Ungara' could increase RWD by 37.89, 47.30, and 56.81%, respectively (Figure 4.D). All root cutting treatment in the intolerant variety ('Tanjung-2') could increase RWD (Figure 4.D). Thus, the RWD recovery of tolerant varieties from root cutting was greater than of intolerant varieties. Root cutting causes changes in root strength in absorption of dry matter in chili seedlings (Kesumawati et al. 2021). Kamran et al. (2018) suggested the improved RWD is linked with the increased assimilate partitioning towards the roots rather than shoot, resulting in improved root architecture and greater root dry weight. From our results, we assumed that for higher economic yield depends on higher root activity and greater root surface area, which can help plants to efficiently absorb and translocate nutrients from the deeper soil. A crop with deeper root system can explore a large volume of soil. The large surface area can efficiently exploit limited soil volume. Biomass partitioning is a mechanism that plants use to overcome limitations that inhibit growth, and it can ultimately affect plant growth. Plants allocate large amounts of assimilates to organs that experience a great degree of competition (Mašková and Herben 2018). An increase in root biomass in soil volume can increase nutrient capacity and efficiency (Shamuyarira et al. 2022).

The root diameter can promote water and nutrient absorption capacity. The root diameter of tolerant group, namely 'Kencana', 'Lembang-1', and 'Ungara' could increase by 14.63, 35.00, and 34.29%, respectively under root cutting at 8 WAT (Figure 4.C). All root cutting treatment on intolerant variety ('Tanjung-2') could decrease root diameter (Figure 4.C). According to Schneider et al. (2021), an increase root diameter in corn accelerates root penetration in compact soils, and root diameter contributes to maximize root assimilate in poplar (Jing et al. 2017). A decrease in root diameter can limit root penetration and root growth. The small root diameter in cucumbers can reach more resources and minimize assimilate for root system (Jeong et al. 2021). According to Rieger and Litvin (1999), a smaller root diameter in soybeans had a larger root conductivity, which can optimize water and nutrient absorption.

The root length affects optimization of nutrient and mineral absorption. When considerable amounts of nutrients are leached out, long roots can reach the leached nutrients. The tolerant group under root cutting showed an increase root length. Root cutting at 8 WAT on 'Kencana', 'Lembang-1', and 'Ungara' increased 34.51, 30.16, and 30.62%, respectively (Figure 4.B). All root cutting treatment on intolerant variety ('Tanjung-2') could decrease root length (Figure 4.A). The long roots of *Moringa oleifera* L. plant can reach distant resources (Valdés-Rodríguez and Pérez-Vázquez 2019). The increase root growth due to cutting involves the bipetal transport of auxins synthesized by meristematic shoots for lateral root initiation (Jansson et al. 2021). Lateral root initiation and xylem differentiation require the basipetal transport of auxins from young leaves or fruits to root tips to protoxylem pericyclic cells. The pericyclic cells initiated by anticlinal division develop into lateral root primordia. Then, as a result of periclinal division, lateral root primordia push the primary root cortex layer and begin to resemble the tip of an adult root with the presence of epidermis, cortex, endodermis layers. Kesumawati et al. (2021) reported that root cutting can stimulate a dense and compact root system, which increased the root growth of chili seedlings. An increase RL indicates the ability of a plant to survive in uncertain environmental conditions during planting. Changes in environmental conditions, such as the lack of water and high evaporation, enable roots to develop the ability to supply sufficient amount of water for shoot growth (Sheridan and Davis 2021).

According to Meychik et al. (2021), Root Surface Area (RSA) is related to root area contact with ions. The greater RSA could increase contact of roots with nutrient ions. The RSA of tolerant group, namely 'Kencana', 'Lembang-1', and 'Ungara' could increase by 28.68, 29.87, and 25.32%, respectively under root cutting at 8 WAT (Figure 4.B). The intolerant variety ('Tanjung-2') under root cutting at 0, 8, and 0 + 8 WAT reduced the RSA by 30.17, 10.64, and 15.78%, respectively (Figure 4.B). Root cutting can promote poplar root growth, which expands the absorption area (Jing et al. 2017). Root growth of chili seedlings due to cutting is caused by stimulation by the translocation of assimilate and transport of hormones from shoots (Kesumawati et al. 2021). The existence of a massive root system in wheat influences the access to water resources, which increases water absorption (Brunel-Saldias et al. 2020).

Shoot morphology (number of leaves, leaf area, and plant height)

Plant tolerance under root cutting treatment can be observed from shoot morphology (Figure 1.B). Plant height is one of the morphological traits, which can be used for selecting root cutting tolerance among crop varieties. In the study of Mwangoe et al. (2022), plant height is related to grain yield. In wheat, a decrease in plant height is reported to reduce photosynthesis and nutrient translocation. Reduced plant height has also been associated with increased partitioning of assimilates to the grain. In our research, plant height in tolerant variety, namely 'Kencana', 'Lembang-1', and 'Ungara' under root cutting at 8 WAT increased by 12.82, 24.95, and 3.47%, respectively (Figure 5.C). The intolerant variety ('Tanjung-2') under root cutting at 8 WAT and 0+8 WAT increased plant height by 9.47 and 10.31%, respectively (Figure 5.C). The tolerant group ('Kencana', and 'Lembang-1') increased number of leaves by 23.60, and 24.95%, respectively (Figure 5.A), and leaf area by 30.85 and 33.25%, respectively (Figure 5.B) under root cutting at 8 WAT. Conversely, the tolerant variety ('Ungara'), and intolerant variety ('Tanjung-2') can not be increased number of leaves and leaf area under root cutting treatment. An increased shoot morphology indicates competition between vegetative and reproductive organs during assimilate accumulation. Another mechanism involved is the changes in assimilate translocation between roots and shoot, with a decrease in leaf assimilates observed due to their export from leave to roots in chili plants (Zakaria et al. 2020).

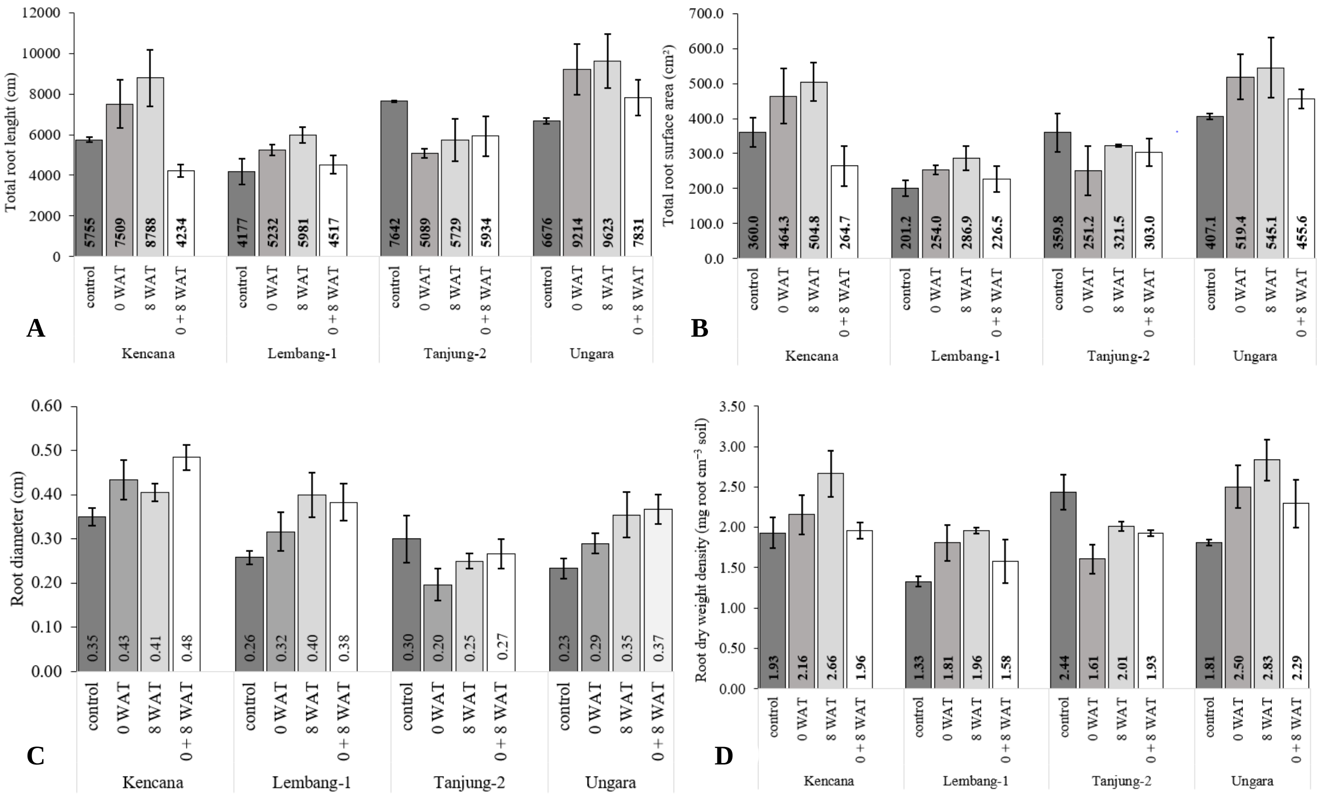

Figure 4. A. Total root length (g), B. Total root surface area (cm), C. Root diameter (cm), and (D) Root dry weight density (mg root cm^{-3} soil) of four lowland chili varieties at 12 WAT

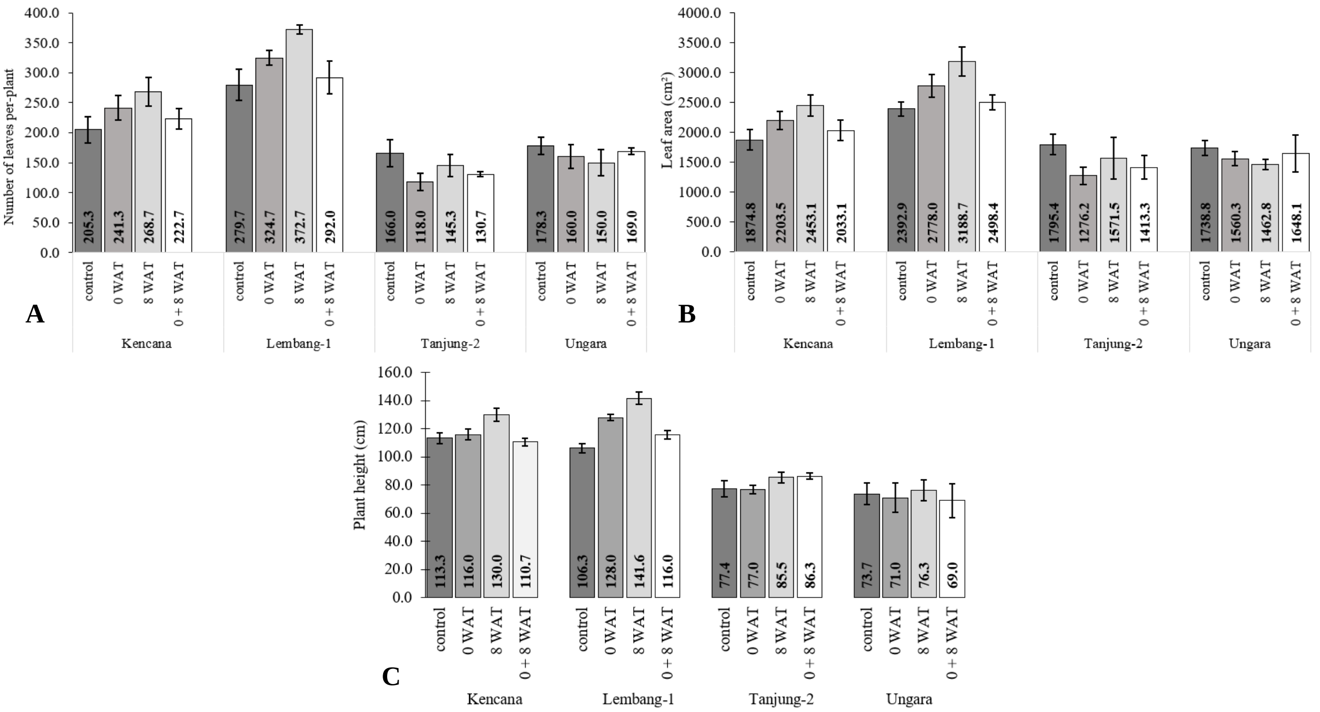

Figure 5. A. Number of leaves per plant, B. Leaf area (cm^2), and C. Plant height (cm) of four lowland chili varieties at 12 WAT. Note: the numbers presented are means ± standard deviation

Root cutting can further shift balance by decreasing shoot growth. Such a phenomenon can be observed because root cutting increases the need for root assimilates as a result of dry weight loss of roots, as had been observed in raspberries (Darnell et al. 2008). Root cutting causes a decrease in the assimilate content in leaves due to the export of assimilates from leaves to roots (Zakaria et al. 2020). In addition, root cutting reduces moisture absorption and inhibits shoot growth. Smaller leaf area in root cutting reduced water loss and maintained a balance between water absorption and transpiration. Moreover, plants subjected to root cutting lose some of their competitiveness and experience decreased ability to acquire and use resources compared with the controls. Root cutting can also shift the balance by decreasing shoot growth. In addition, the supply of assimilate to roots is disrupted due to competition with the fruit (Saure 2007). According to Zakaria et al. (2020), root cutting causes a decrease in sucrose content in leaves due to the decreased rate of photosynthesis and export of assimilates from leaves to roots. Yan et al. (2023) observed that a decrease in the leaf area during root cutting occurs as a form of plant morphological adaptation to overcome root reduction.

Correlation analysis

The relationship of fresh weight fruit in tolerant group to root and shoot growth was divided into two mechanisms based on shoot morphology. The tolerant varieties ('Kencana', and 'Lembang-1'), which exhibited a leaf growth response, revealed an FWF positively related to RL (r = 0.41*) and RSA (r = 0.35*) (Figure 6.A). Increased root morphology under root cutting affected shoot morphology through NL (r = 0.61*) and LA (r = 0.62*) (Figure 6.A). This finding indicates that root cutting of tolerant varieties contributes to increased shoot growth by compensating for root loss. Plants with a strong root system produce a great NL, which can increase light interception for photosynthesis. A fast root growth rate occurs during cutting because roots use stored carbohydrate reserves and can increase sink activity for root growth, which increases the need for root sinks (Darnell et al. 2008). Massive root systems produced by root cutting can access water resources from deep layers of soil to replenish fruit and increase production. The tolerant variety ('Ungara') did not respond to leaf growth during root cutting. FWF of 'Ungara' after root cutting correlated with root morphology, such as RWD (r = 0.66*), RL (r = 0.38*), and RSA (r = 0.47*) (Figure 6B). However, FWF did not correlate with NL and LA. According to Zakaria et al. (2020), root cutting causes a decrease in sucrose content in leaves due to the decreased rate of photosynthesis and export of assimilates from leaves to roots. Saure (2007) reported that a high economic yield lessens the translocation of assimilates to leaves. Ma et al. (2010) reported a relationship exists between root efficiency and high yields in wheat plant, because root cutting leads to an availability of photosynthates for increased shoot and yield production. The compensation of root biomass due to cutting affects left development for photosynthetic activities and production of assimilate for plant growth. According to Sun et al. (2023), an increase in leaf area of maize can indicate a widening canopy, which lessens the light that passes through the lower layer of shoot. The decrease in light passing through the shoot is due to the increased light interception in canopy (Cahyo et al. 2021). Tafes and Alemayehu (2020) also suggested that in wheat, increased leaf growth due to canopy widening can increase crop dry matter production.

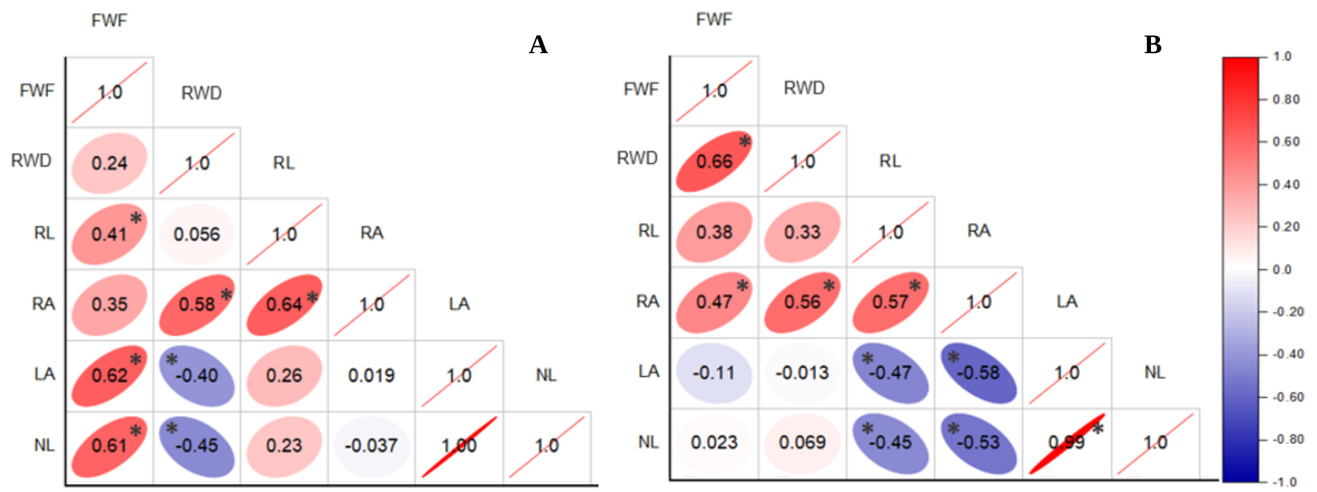

Figure 6. Pearson correlation analysis of the tolerant group: A. 'Kencana', and 'Lembang-1'; B. 'Ungara'. Note: FWF: Fresh Weight of Fruit, RL: Root Length, RSA: Root Surface Area, RWD: Root Dry Weight Density Root, LA: Leaf Area, NL: Number of Leaves. *: indicate statistically significant correlations at P <0.05

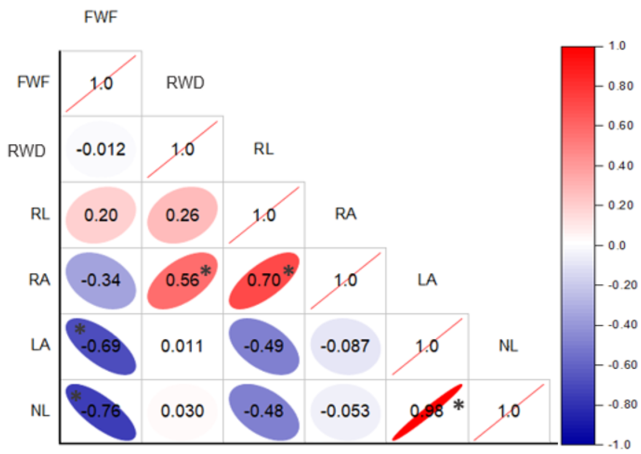

Figure 7. Pearson correlation analysis of intolerance group ('Tanjung-2'). Note: FWF: Fresh Weight of Fruit, RL: Root Length, RSA: Root Surface Area, RWD: Root Dry Weight Density Root, LA: Leaf Area, NL: Number of Leaves. *: indicate statistically significant correlations at P <0.05

Latifah et al. (2021) reported that in tomato plants, yield growth is influenced by growth of vegetative organs, such as leaves, and dry weight plants. According to Dong et al. (2019), in Chinese fir, root cutting affected the balance of shoot and root growth because it altered the availability and allocation of assimilate partitions, which resulted in an increase in biomass demand for root growth due to cutting. Du et al. (2012) mentioned that poplar plants can coordinate shoot and root growth, which can be proven from its ability to restore root growth after root cutting. Similar to the research of Yan et al. (2023), root cutting in corn plants can reduce root growth, with a control mechanism for balancing shoot and root growth. The FWF in the intolerant group did not correlate with root morphology. Compared with shoot, FWF was negatively correlated with LA (r = −0.69*), the NL (r = −0.76*) (Figure 7). Thus, an increase in fruit growth of intolerant variety could be observed through the reduced growth of leaves. Restriction of root growth in chili caused a decrease in assimilate content translocated from leaves to roots (Zakaria et al. 2020). Thus, assimilate partition in fruits was also limited, which decreased the FWF. The root system affects the ability of plants to obtain resources underground. A low root growth after root cutting of plants indicates that roots lose some of their competitiveness and experience a decrease in the ability to obtain and use resources compared with the control (Ma et al. 2010).

In conclusion, three of four lowland chili varieties ('Kencana', 'Lembang-1', 'Ungara') were identified as the tolerant group under root cutting treatment based on chili yield and stress selection indices. The tolerant chili had low stress susceptibility index under root cutting treatment, but high stress tolerance level, stress tolerance index, and yield stability index. The tolerant chili could increase root morphological traits (root diameter, root length, root dry weight density, and root surface area). Improvement root morphological traits under root cutting treatment at 8 WAT maintained shoot morphological traits (number of leaves, leaf area, and plant height) in 'Kencana', 'Lembang-1', 'Ungara'. Morphological traits enhancement under root cutting at 8 WAT increased fresh weight of fruit in 'Kencana', 'Lembang-1', 'Ungara' by 30.66, 33.76, and 31.74%, respectively. It was concluded that root cutting treatment at 8 WAT on tolerant group ('Kencana', 'Lembang-1', 'Ungara') can be used to increase chili yield in lowland areas.

ACKNOWLEDGEMENTS

The authors would like to thank to the Directorate General of Higher Education, Indonesia for funding this research under the management of the Universitas Gadjah Mada, Yogyakarta, Indonesia based on project number 5712/UN1.DITLIT/DIT-LIT.

REFERENCES

Abdelhaleim MS, Rahimi M, Okasha SA. 2022. Assessment of drought tolerance indices in faba bean genotypes under different irrigation regimes. Open Life Sci 17 (1): 1462-1472. DOI: 10.1515/biol-2022-0520.

Bektas H, Hohn CE, Lukaszewski AJ, Waines JG. 2023. On the possible trade-off between shoot and root biomass in wheat. Plants 12 (13): 2513. DOI: 10.3390/plants12132513.

Brunel-Saldias N, Ferrio JP, Elazab A, Orellana M, del Pozo A. 2020. Root architecture and functional traits of spring wheat under contrasting water regimes. Front Plant Sci 11: 1-14. DOI: 10.3389/fpls.2020.581140.

Budiarto R, Poerwanto R, Santosa E, Efendi D. 2019. A review of root pruning to regulate citrus growth. J Trop Crop Sci 6: 1-7. DOI: 10.29244/jtcs.6.01.1-7.

Cahyo AN, Murti RH, Putra ETS, Nuringtyas TR, Fabre D, Montoro P. 2021. Assessment of factual measurement times for chlorophyll-a fluorescence in rubber (*Hevea brasiliensis*) clones. Biodiversitas 22 (6): 3470-3477. DOI: 10.13057/biodiv/d220656.

Darnell RL, Alvarado-Raya HE, Williamson JG. 2008. Root pruning effects on growth and yield of red raspberry. HortScience 43 (3): 681-684. DOI: 10.21273/HORTSCI.43.3.681.

Dewi IK, Bahri S, Sumarmi. 2023. The effect of three ridges on the growth and production of three varieties of baby corn (*Zea mays* L.). Jurnal Agrotek Tropika 11 (1): 79-88. DOI: 10.23960/jat.v11i1.5782. [Indonesian]

Dong T, Duan B, Korpelainen H, Niinemets U, Li C. 2019. Asymmetric pruning reveals how organ connectivity alters the functional balance between leaves and roots of Chinese fir. J Exp Bot 70 (6): 1941-1953. DOI: 10.1093/jxb/erz013.

Du ZY, Xing SJ, Ma BY, Liu FC, Ma HL, Wang QH. 2012. Effects of root pruning on the growth and rhizosphere soil characteristics of short-rotation closed-canopy poplar. For Syst 21 (2): 236-246. DOI: 10.5424/fs/2012212-02634.

Fischer RA, Maurer R. 1978. Drought resistance in spring wheat cultivars grain yield responses. Aust J Agric Res 29 (5): 897-912. DOI: 10.1071/AR9780897.

Gao K, Zhu T, Wang L, Gao Y. 2018. Effects of root pruning radius and time on yield of tuberous roots and resource allocation in a crop of *Helianthus tuberosus* L. Sci Rep 8: 4392. DOI: 10.1038/s41598-018-22586-1.

Guo S, Liu Z, Zhou Z, Lu T, Chen S, He M, Zeng X, Chen K, Yu H, Shangguan Y, Dong Y, Chen F, Liu Y, Qin Y. 2022. Root system architecture differences of maize cultivars affect yield and nitrogen accumulation in southwest china. Agriculture 12 (2): 209. DOI: 10.3390/agriculture12020209.

Hou X, Zhang W, Du T, Kang S, Davies WJ. 2020. Responses of water accumulation and solute metabolism in tomato fruit to water scarcity and implications for main fruit quality variables. J Exp Bot 71 (4): 1249-1264. DOI: 10.1093/jxb/erz526.

Huang Y, Ciais P, Santoro M, Makowski D, Chave J, Schepaschenko D, Abramoff RZ, Goll DS, Yang H, Chen Y, Wei W, Piao S. 2021. A global map of root biomass across the world's forests. Earth Syst Sci Data 13 (9): 4263-4274. DOI: 10.5194/essd-13-4263-2021.

Irjayanti AD, Wibowo AS, Stiyaningsih H, Putri IM, Gitaningtyas OP, Areka SK, Suprapti W, Nurfalah Z. 2023. Statistics of horticulture 2022. BPS Statistics Indonesia. [Indonesian]

Jansson C, Faiola C, Wingler A, Zhu XG, Kravchenko A, de Graaff MA, Ogden AJ, Handakumbura PP, Werner C, Beckles DM. 2021. Crops for carbon farming. Front Plant 12: 1-12. DOI: 10.3389/fpls.2021.636709.

Jeong HW, Lee HR, Kim JY, Kim GG, Na CI, Hwang SJ. 2021. Assessment of growing media and fertigation for production of root pruning splice-grafted cucumber seedlings. Hortic Sci Techol 39 (3): 294-304. DOI: 10.7235/HORT.20210026.

Jin S, Wang Y, Wang X, Bai Y, Shi L. 2019. Effect of pruning intensity on soil moisture and water use efficiency in jujube (*Ziziphus jujube* Mill.) plantations in the hilly loess plateau region, China. J Arid Land 11: 446-460. DOI: 10.1007/s40333-019-0129-z.

Jing DW, Liu FC, Wang MY, Ma HL, Du ZY, Ma BY, Dong YF. 2017. Effects of root pruning on the physicochemical properties and microbial activities of poplar rhizosphere soil. PLOS ONE 12 (11): e0187685. DOI: 10.1371/journal.pone.0187685.

Kamran M, Wennan S, Ahmad I, Xiangping M, Wenwen C, Xudong Z, Siwei M, Khan A, Qingfang H, Tiening L. 2018. Application of paclobutrazol affect maize grain yield by regulating root morphological and physiological characteristics under a semi-arid region. Sci Rep 8: 4818. DOI: 10.1038/s41598-018-23166-z.

Kesumawati E, Amalia R, Fitrizal, Rahmawati M. 2021. The effect of pruning type on old seedling of chili pepper (*Capsicum annuum* L.) plants to the growth and yield. IOP Conf Ser: Earth Environ Sci 667: 012031. DOI: 10.1088/1755-1315/667/1/012031.

Kumar S, Dwivedi SK, Singh SS, Jha SK, Lekshmy S, Elancezhian R, Singh ON, Bhatt BP. 2014. Identification of drought tolerant rice genotypes by analysing drought tolerance indices and morpho-physiological traits. Sabrao J Breed Genet 46: 217-230.

Lamba K, Kumar M, Singh V, Chaudhary L, Sharma R, Yashveer S, Dalal MS. 2023. Heat stress tolerance indices for identification of the heat tolerant wheat genotypes. Sci Rep 13: 10842. DOI: 10.1038/s41598-023-37634-8.

Latifah E, Krismawati A, Saeri M, Arifin Z, Warsiati B, Setyorini D, Prahardini PER, Subagio H, Sihombing D, Antarlina SS, Widaryanto E, Ariffin, Maghfoer MD, et al. 2021. Analysis of plant growth and yield in varieties of tomato (*Solanum lycopersicum* L.) grafted onto different eggplant rootstocks. Intl J Agron 2021: 1-11. DOI: 10.1155/2021/6630382.

Ma SC, Li FM, Xu BC, Huang ZB. 2010. Effect of lowering the root/shoot ratio by pruning roots on water use efficiency and grain yield of winter wheat. Field Crops Res 115 (2): 158-164. DOI: 10.1016/j.fcr.2009.10.017.

Magaña-Hernández E, Zuloaga-Aguilar S, Cuevas-Guzmán R, Pausas JG. 2020. Variation in plant belowground resource allocation across heterogeneous landscapes: implications for post-fire resprouting. Am J Bot 107 (8): 1114-1121. DOI: 10.1002/ajb2.1521.

Mashamaite CV, Dube ZP, Phiri EE. 2020. Chemical root-pruning of *Moringa oleifera* for improved seedling growth. S Afr J Bot 129: 155-160. DOI: 10.1016/j.sajb.2019.04.003.

Mašková T, Herben T. 2018. Root:shoot ratio in developing seedlings: How seedlings change their allocation in response to seed mass and ambient nutrient supply. Ecol Evol 8 (14): 7143-7150. DOI: 10.1002/ece3.4238.

Meychik N, Nikolaeva Y, Kushunina M. 2021. The significance of ion-exchange properties of plant root cell walls for nutrient and water uptake by plants. Plant Physiol Biochem 166: 140-147. DOI: 10.1016/j.plaphy.2021.05.048.

Mwangoe J, Kimurto PK, Ojwang PP. 2022. Identification of drought tolerant finger millet (*Eleusine coracana*) lines based on morpho-physiological characteristics and grain yield. Afr J Plant Sci 16 (4): 47-60. DOI: 10.5897/ajps2022.2225.

Ning W, Li W, Pi W, Xu Y, Cao M, Luo J. 2021. Effects of decapitation and root cutting on phytoremediation efficiency of *Celosia argentea*. Ecotoxicol Environ Saf 215: 112162. DOI: 10.1016/j.ecoenv.2021.112162.

Padjung R, Farid M, Musa Y, Anshori MF, Nur A, Masnenong A. 2021. Drought-adapted maize line based on morphophysiological selection index. Biodiversitas 22 (9): 4028-4035. DOI: 10.13057/biodiv/d220951.

Pandey BB, Ratnakumar P, Usha KB, Dudhe MY, Lakshmi GS, Ramesh K, Guhey A. 2021. Identifying traits associated with terminal drought tolerance in sesame (*Sesamum indicum* L.) genotypes. Front Plant Sci 12: 739896. DOI: 10.3389/fpls.2021.739896.

Permanasari I, Sulistyaningsih E, Kurniasi B, Indradewa D. 2023. Morphophysiological and yield traits of soybean varieties tolerant of intercropping with maize. Biodiversitas 24 (7): 3872-3880. DOI: 10.13057/biodiv/d240726.

Pertiwi MD, Sulistyaningsih E, Murti RH, Purwanto BH. 2022. Identification of high-temperature tolerance of some potato varieties based on stress tolerance indice and cluster analysis. Agric 34 (1): 79-88. DOI: 10.24246/agric.2022.v34.i1.p79-88.

Rieger M, Litvin P. 1999. Root system hydraulic conductivity in species with contrasting root anatomy. J Exp Bot 50 (331): 201-209. DOI: 10.1093/jxb/50.331.201.

Rosmaina, Parjanto, Sobir, Yunus A. 2019. Screening of *Capsicum annuum* L. genotypes for drought tolerance based on drought tolerance indices. Sabrao J Breed Genet 51: 205-224.

Sakya AT, Sulistyaningsih E, Purwanto BH, Indradewa D. 2023. Evaluation of zinc efficiency and some of nutritional and physiological responses of tomatoes cultivars. J Plant Nutr 46 (18): 4420-4437. DOI: 10.1080/01904167.2023.2241495.

Saure MC. 2007. Root pruning - a poorly understood management practice in fruit trees. Intl J Fruit Sci 7 (2): 43-56. DOI: 10.1300/J492v07n02_05.

Schneider HM, Strock CF, Hanlon MT, Vanhees DJ, Perkins AC, Ajmera IB, Sidhu JS, Mooney SJ, Brown KM, Lynch JP. 2021. Multiseriate cortical sclerenchyma enhance root penetration in compacted soils. Proc Natl Acad Sci 118 (6): e2012087118. DOI: 10.1073/pnas.2012087118.

Shamuyarira K, Shimelis H, Figlan S, Chaplot V. 2022. Path coefficient and principal component analyses for biomass allocation, drought tolerance and carbon sequestration potential in wheat. Plants 11 (11): 1407. DOI: 10.3390/plants11111407.

Sheridan RA, Davis AS. 2021. Characterizing the utility of the root-to-shoot ratio in Douglas-fir seedling production. Forests 12 (12): 1745. DOI: 10.3390/f12121745.

Sun X, Li X, Jiang W, Zhao M, Gao Z, Ge J, Sun Q, Ding Z, Zhou B. 2023. Integrated management practices for canopy-topsoil improves the grain yield of maize with high planting density. Plants 12 (10): 1-17. DOI: 10.3390/plants12102000.

Tafes B, Alemayehu Y. 2020. Physiological growth indices of durum wheat (*Triticum turgidum* L. Var. durum) as affected by rates of blended and nitrogen fertilizers. Am J Life Sci 8 (4): 52-59. DOI: 10.11648/j.ajls.20200804.12.

Tajima R. 2021. Importance of individual root traits to understand crop root system in agronomic and environmental contexts. Breed Sci 71 (1): 13-19. DOI: 10.1270/jsbbs.20095.

Timlin D, Rahman SML, Baker J, Reddy VR, Fleisher D, Quebedeaux B. 2006. Whole plant photosynthesis, development, and carbon partitioning in potato as a function of temperature. Agron J 98 (5): 1195-1203. DOI: 10.2134/agronj2005.0260.

Umar M, Ahmad S, Haider ST, Naz S. 2019. Effect of pruning to improve yield and fruit quality of 'Kinnow' mandarin plants under high density plantation. Hortic Sci Technol 2: 85-89. DOI: 10.46653/jhst190203085.

Valdés-Rodríguez OA, Pérez-Vázquez A. 2019. Seedling characteristics of three oily species before and after root pruning and transplant. Plants 8 (8): 258. DOI: 10.3390/plants8080258.

Van Noordwijk M, De Willigen P. 1987. Agricultural concepts of roots: From morphogenetic to functional equilibrium between root and shoot growth. Netherlands J Agric Sci 35 (4): 487-496. DOI: 10.18174/njas.v35i4.16707.

Werner T, Motyka V, Strnad M, Schmülling T. 2001. Regulation of plant growth by cytokinin. Proc Natl Acad Sci 98 (18): 10487-10492. DOI: 10.1073/pnas.171304098.

Yan M, Zhang C, Li H, Zhang L, Ren Y, Chen Y, Cai H, Zhang S. 2023. Root pruning improves maize water-use efficiency by root water absorption. Front Plant Sci 13: 1023088. DOI: 10.3389/fpls.2022.1023088.

Zakaria NI, Ismail MR, Awang Y, Megat WPE, Berahim Z. 2020. Effect of root restriction on the growth, photosynthesis rate, and source and sink relationship of chilli (*Capsicum annuum* L.) grown in soilless culture. BioMed Res Intl 2020. DOI: 10.1155/2020/2706937.