Revista em Agronegócio e Meio Ambiente – RAMA
DOI: 10.17765/2176-9168.2024v17n.Especial.e12389
e-ISSN 2176-9168

Deficit irrigation management with magnetized water to improve mungbean (*Vigna radiata* L.) growth and production

Manejo da irrigação do déficit com água magnetizada para melhorar o crescimento e a produção do feijão mungo (Vigna radiata L.)

Marlon Firmo Martins[1], Leandra Matos Barrozo[2], Alan Mario Zuffo[3], Francisco Charles dos Santos Silva[4], Jorge González Aguilera[5], Fábio Steiner[6]

ABSTRACT: Deficit irrigation and magnetically treated water can be sustainable agronomic techniques to improve water use efficiency, plant development, and agricultural crop yield. A pot study was conducted to investigate the impact of distinct deficit irrigation regimes using magnetically treated and untreated water on mungbean development and grain yield [*Vigna radiata* (L.) R. Wilczek.] crops in the clayey soil of the Brazilian Cerrado. Mungbean plants were irrigated with magnetized water (MW) and non-magnetized water (N-MW) using four deficit irrigation regimes [20, 40, 60, and 80% of soil field capacity (FC)], considering a 2×4 factorial scheme, with four repetitions, conducted for 80 days. Plant growth rate, relative chlorophyll index, plant morphological traits, production components, and crop grain yield were measured. The results showed that the deficit irrigation regime of 60% and 80% of FC improves the rate of plant growth and development and grain yield of the mungbean crop. Although mungbean is considered a drought-tolerant crop, low soil water availability causes severe inhibition of plant growth and development and drastically reduces the crop's grain yield. Irrigation with magnetized water did not benefit mungbean crops' plant growth and development and grain yield. Plant growth rate, height, shoot dry matter, relative chlorophyll index, and number of grains per pod positively correlate with grain yield. In contrast, root length has a highly negative correlation with the grain yield of mungbean crops.

Keywords: Magnetism; Soil field capacity; Water stress.

RESUMO: A irrigação com água tratada magneticamente é uma técnica agronómicas sustentável para melhorar a eficiência do uso da água, o desenvolvimento das plantas e o rendimento das culturas agrícolas. Um estudo em vasos foi conduzido para investigar o impacto de diferentes regimes de irrigação deficitários usando água tratada e não tratada magneticamente no desenvolvimento e produtividade de grãos de culturas de feijão-mungo [*Vigna radiata* (L.) R. Wilczek.] em solo argiloso do Cerrado brasileiro. As plantas de feijão mungo foram irrigadas com água magnetizada (MW) e água não magnetizada (N-MW) utilizando quatro regimes de irrigação deficitários [20, 40, 60 e 80% da capacidade de campo do solo (FC)], considerando um fatorial 2×4. esquema, com quatro repetições, conduzidas por 80 dias. Foram medidos a taxa de crescimento das plantas, o índice relativo de clorofila, as características morfológicas das plantas, os componentes de produção e o rendimento de grãos da cultura. Os resultados mostraram que o regime de irrigação deficitário de 60% e 80% de FC melhora a taxa de crescimento e desenvolvimento das plantas e o rendimento de grãos da cultura do feijão mungo. Embora o feijão mungo seja considerado uma cultura tolerante à seca, a baixa disponibilidade de água no solo causa severa inibição do crescimento e desenvolvimento das plantas e reduz drasticamente o rendimento de grãos da cultura. A irrigação com água magnetizada não teve efeito benéfico no crescimento e desenvolvimento das plantas de feijão mungo e

---

[1] Discente de Agronomia da Universidade Estadual do Maranhão, Campus Balsas (MA).

[2] Doutora em Agronomia pela Universidade Federal da Paraíba. Docente do curso de Agronomia da Universidade Estadual do Maranhão, Campus Balsas, (MA), BR.

[3] Doutor em Agronomia (Fitotecnia) pela Universidade Federal de Lavras (UFLA). Docente do curso de Agronomia da Universidade Estadual do Maranhão, Campus de Balsa (MA).

[4] Doutor em Fitotecnia (Produção Vegetal) pela Universidade Federal de Viçosa. Docente de Agronomia da Universidade Estadual do Maranhão, Campus de Balsa (MA).

[5] Doutor em Genética e Melhoramento pela Universidade Federal de Viçosa (UFV). Docente do curso de Agronomia da Universidade Estadual do Mato Grosso do Sul (UEMS), Campus de Cassilândia, (MS).

[6] Doutor em Agronomia pela Universidade Estadual Paulista Júlio de Mesquita Filho (UNESP). Docente do curso de Agronomia da Universidade Estadual do Mato Grosso do Sul (UEMS), Campus de Cassilândia (MS).

no rendimento de grãos. A taxa de crescimento das plantas, a altura das plantas, a matéria seca da parte aérea, o índice relativo de clorofila e o número de grãos por vagem correlacionam-se positivamente com o rendimento de grãos. Em contraste, o comprimento da raiz tem uma correlação altamente negativa com o rendimento de grãos das culturas de feijão mungo.

Palavras-chave: Capacidade de campo do solo; Estresse hídrico; Magnetismo.

Autor correspondente: Leandra Matos Barrozo
E-mail: leandrabarrozo1@gmail.com

Recebido em: 01/03/2024
Aceito em: 21/05/2024

1 INTRODUCTION

Vigna radiata (L.) R. Wilczek. (Mungbean) is an important pulse crop for Brazil and the world. It is widely used in human food due to its high nutritional value, especially because its grain has a high protein, vitamin B, and iron content (Hou *et al*., 2019; Zhao *et al.*, 2022). Mungbean has a high production potential in Brazilian tropical conditions, and the area cultivated with this crop has increased enormously in recent years, mainly in Brazil's North, Northeast, and Midwest regions (Favero *et al.,* 2021; Noleto *et al.,* 2023). This rapid increase shows that Brazil has the potential to be one of the major producers and exporters of mungbeans in the global pulses sector.

The low production cost, short cycle, and adaptation to adverse conditions of temperature and soil water regime have contributed to the optimal plant development and high grain yields of the mungbean crop in Brazil (Sharma *et al.,* 2016; Barroso-Neto *et al.,* 2017; Akinyosoye *et al*., 2021; Singh *et al.,* 2021). Although some studies have reported that mungbean is a drought-tolerant crop, exposure of plants to severe drought stress can have a drastic negative effect on plant development and limit crop yield (Bangar *et al.*, 2019; Singh *et al.,* 2021). However, moderate and severe grain yield losses depend on the mungbean cultivar's genetic potential, the duration and intensity of stress, and the plant's developmental stage (Dutta; Bera, 2008; Ranawake *et al.,* 2011; Bangar *et al.,* 2019; Kumar*;* Ayachit; Sahoo, 2020). Drought stress affects the plants' morpho-physiological, biochemical, and molecular functions (Singh *et al.,* 2021). In mungbean, water stress significantly affects leaf area, stomatal conductance, shoot, and root system growth rate, shoot biomass production, and final yield (Farooq *et al.,* 2009; Ranawake *et al.*, 2011). Therefore, since the tropical Brazilian Cerrado region has an extraordinarily strong dry season during April and September, using agricultural practices that aim to supply part of the water requirement of mungbean fields is essential to ensure adequate productive performance of the crop.

Irrigation is essential for agriculture, as it helps to increase yields, improve quality, reduce risks of crop failure due to drought stress, and ensure food security. However, due to the significant increase in irrigated agriculture in the Brazilian Cerrado and the scarcity of water resources in many regions (Althoff; Rodrigues; Silva 2021; Silva *et al.,* 2021); irrigation management systems need to be used to increase water use efficiency. Strategies for rational water use include the deficit irrigation technique, which consists of applying irrigation depths lower than the crop's water needs (Abdelkhalik *et al.,* 2019; Guedes *et al*., 2023). In this context, adopting the deficit irrigation management technique can reduce the use of water and electricity and improve the efficiency of water resources without harming crop yield (Abdelkhalik *et al.,* 2019; Hayashi; Dogliotti, 2021; Zhou *et al*., 2022; Guedes *et al*., 2023). Indeed, Zhou *et al.* (2022) reported that deficit irrigation with a water supply of 65-75% of field capacity (FC) was optimal for the cultivation of woad (*Isatis indigotica* Fort.), resulting in greater water use efficiency and higher grain quality and yield. However, the impact of deficit irrigation management on the growth and yield of mungbean crops is still unknown.

In addition to deficit irrigation, another sustainable agricultural practice that can improve water use efficiency, irrigated water quality, and crop yield is the use of magnetized water (Doklega, 2017; Alemán *et al.,* 2022; Boix *et al.,* 2023; Aguilera *et al.,* 2023). Water is a polar molecule, and its physical-chemical properties can be modified when subjected to the effects of a magnetic field (Toledo; Ramalho; Magriotis*,* 2008). Magnetic water treatment reduces surface tension and increases viscosity, making the water molecule more stable with less molecular energy and more activation energy (Toledo; Ramalho; Magriotis*,* 2008; Cai *et al.,* 2009; Chibowski; Szcze, 2018). These changes in the physical-chemical properties of magnetically treated water result in better distribution and smaller spatial arrangement of macro-clusters of water molecules in the soil, facilitating their penetration through the cell wall and their absorption by root cells (Aguilera; Martín, 2016; Generoso *et al.,* 2017).

Furthermore, the reorganization of magnetically treated water molecules allows better use of essential nutrients dissolved in the soil solution (Doklega, 2017; Alemán *et al*., 2022), which can reduce the mineral fertilizer requirements in crops. The interaction of magnetically treated water with the physicochemical properties of the soil can also alter the ion exchange in the soil solution due to the redistribution and changes of space charges in the soil colloids (Generoso *et al.*, 2017; Zhou *et al.,* 2021; Alemán *et al.,* 2022).

Beneficial effects of magnetically treated irrigation water on seed germination, plant growth rate, and crop yield have been proven for some plant species, such as beet (*Beta vulgaris* L.) (Alemán *et al.,* 2022), common bean (*Phaseolus vulgaris* L.) (Boix *et al.,* 2023), potato (*Solanum tuberosum* L.) (Doklega, 2017), tomato (*Solanum lycopersicum* L.) (Aguilera; Martín, 2016), lettuce (*Lactuca sativa* L.) (Aguilera *et al.,* 2023) and cotton (*Gossypium hirsutum* L.) (Zhou *et al*., 2021). Therefore, magnetic treatment of irrigation water has shown to be an effective, beneficial, and promising technique to enhance agricultural production and, at the same time, be environmentally beneficial in the future. However, the effects of using magnetically treated water in a deficient irrigation management system on the growth and yield of mungbean crops are still incipient and unknown.

This study investigated the impact of different deficit irrigation regimes using magnetically treated and untreated water on the development and grain yield of *Vigna radiata* (L.) R. Wilczek. (mungbean) crops in a clayey soil of the Brazilian Cerrado.

2 MATERIALS AND METHODS

2.1 STUDY SITE AND PLANT GROWTH CONDITIONS

The trial was conducted under controlled conditions in Fortaleza dos Nogueiras, Maranhão, Brazil (07°08′83″ S, 45°56′45″ W, and altitude of 580 m), from August to October 2022, in 8-L plastic pots. The soil used in the trial was a clayey Oxisol collected from the plow layer in a Cerrado agricultural area. All soil chemical properties were determined using standard methods, and the main soil chemical characteristics are shown in Table 1.

Table 1. Soil chemical properties used in the experimental trial

pH	OM	P-resin	H+Al	Ca	Mg	K	CEC	V	B	Cu	Zn	Particle size		
												Sand	Silt	Clay
	g dm^{-3}	mg dm^{-3}			---------- mmol$_c$ dm^{-3} ----------			%		----- mg dm^{-3} -----				
5.2	38	34	42	49	21	4	116	64	0.4	0.4	0.6	330	214	456

OM: organic matter. CEC: cation exchange capacity. V: soil base saturation.

Field water capacity (FC) was estimated under free drainage conditions and controlled water rate application using the upper limit (inflection point) of the soil water retention curve as described by Silva *et al.* (2014). The difference between the total amount of water added and the amount of percolated water after 12 hours of free drainage corresponded to the value of the plant-available soil water capacity (i.e., FC), and the soil moisture content at FC was 432 g kg^{-1}. The soil was placed in 8 L pots and then fertilized with 50 mg N kg^{-1} [urea (45% N)] 200 mg P kg^{-1} [single superphosphate (18% P_2O_5, 25% CaO, and 12% S)], 100 mg K kg^{-1} [potassium chloride (60% K_2O)]. Each pot was filled with 10 kg of air-dried soil and sieved through a 5.0 mm mesh.

2.2. PLANT MATERIAL, TREATMENTS, AND IRRIGATION WATER MANAGEMENT

Seeds of the early cycle 'Ouro Verde' mungbean cultivar were sown in plastic pots. Four seeds were sown, and in the V_1 vegetative growth stage, the seedlings were thinned, keeping only one plant per pot. After sowing, all pots were irrigated until the soil moisture content reached 100% of FC (432 g kg^{-1}) to ensure adequate seedling emergence.

Afterward, the mungbean plants were irrigated with magnetized water (MW) and non-magnetized water (N-MW) and subjected to four deficit irrigation regimes (20, 40, 60, and 80% of soil FC), considering a factorial arrangement (2 × 4). Four replicates consisting of four 8-L pots containing one plant were used in this trial. Three replicate pots were used in the destructive analyses carried out during the crop development, including relative growth rate, root length, and shoot and root dry matter. The other replicate pot was used to evaluate the grain yield of the crop.

Magnetic water treatment was carried out using a magnetic field device composed of two permanent magnets manufactured by the National Center of Applied Electromagnetism (CNEA) in Santiago de Cuba, Cuba. This equipment has a non-uniform or heterogeneous static magnetic field between 20 and 200 mT. Water was directed to pass through the two-magnet magnetic field device using a 13 mm diameter polyvinyl chloride tube. The magnetically treated water was placed in test tubes and then applied to their respective treatments in the pot experiment.

An irrigation interval every three days was established. The plants were maintained under different deficit irrigation regimes with MW or N-MW throughout the crop's entire growth and development cycle (80 days). Soil water availability was controlled every three days using the gravimetric method (Imakumbili, 2019), and plant-available soil water content was adjusted by adding MW and N-MW after weighing the pot. The soil water content corresponding to 80, 60, 40, and 20% FC was 346, 259, 173, and 86 g kg^{-1}, respectively.

2.3 MEASUREMENT OF PLANT GROWTH AND GRAIN YIELD

At 20, 40, and 60 days after the start of the deficit irrigation regimes imposed at the V1 vegetative growth stage, plant height (PH) and total dry matter (TDM) were determined. The PH was determined using a tape measure, considering the distance from the soil surface to the apical meristem. Plants were separated into shoots (leaves + stems) and roots, oven-dried at 65 °C for three days and then weighed. The TDM was obtained from the sum of all the plant organs (leaves, stems, and roots). The PH and TDM data recorded in each treatment between the 20 and 60-day period were used to calculate the absolute and relative growth rates, respectively.

The absolute growth rate (AGR) was calculated according to Equation (1) proposed by Evans (1972):

$$AGR\ (cm\ day - 1)\ =\ (PH2 - PH1)/(T2 - T1) \tag{1}$$

Where AGR is the absolute growth rate in height (cm day^{-1}); PH2 and PH1 are the plant height between two successive assessments in each treatment (in centimeters); and, T2 and T1 are the time interval between two successive assessments (set at forty days in this study).

The relative growth rate (RGR) was calculated according to Equation (2), as proposed by Evans (1972):

$$RGR\ (g\ g - 1\ day - 1)\ =\ [ln(TDM2) - ln(TDM1)]/(T2 - T1) \tag{2}$$

Where RGR is the relative growth rate of whole plant dry matter (g g^{-1} day^{-1}); ln(TDM2) and ln(TDM1) are the total dry matter natural logarithms of the difference between two successive assessments; MST2 and MST1 are the total dry matter of two successive assessments in each treatment (in grams); and, T2 and T1 are the time interval between two successive assessments (set at forty days in this study).

At 40 days, the relative chlorophyll index (RCI), stem diameter (SD), and root length (RL) were also measured. The RCI was measured using a portable chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd., Japan). Two measurements were taken between the edge and the main nerve of the fully expanded leaves in the middle third of the plant. The SD was measured at 5 cm from the base of the stem using a digital caliper. The RL was measured using a tape measure, considering the length of the longest roots.

At 80 days, at crop maturity, the plants were harvested, and then the production components [number of pods per plant (NPP), number of grains per pod (NGP), and mass of one thousand grains (1,000-G)] and grain yield (GY) were determined. The grains were threshed, cleaned, and weighed, and the GY was estimated after correcting grain weights for 13% moisture.

2.4 EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

The experiment was conducted in a randomized block design, in a 2 × 4 factorial scheme: plants irrigated with magnetized water (MW) and non-magnetized water (N-MW) and four deficit irrigation regimes (20, 40, 60, and 80% of the soil FC), with four repetitions. All measured data were recorded in Excel® 2022 (Microsoft 365™ Corporation, Redmond, WA, USA) and examined by analysis of variance (ANOVA) using the Agroestat® 1.1 software for Windows (São Paulo State University, Jaboticabal, SP, BRA) (Barbosa; Maldonado, 2015). Polynomial regression analysis was used for deficit irrigation levels, and significant equations with >80% coefficients of determination (F test, $p < 0.05$) were adjusted.

Canonical correlation analysis (CCA) was used to understand the interrelationship between sets (vectors) of independent (magnetized and non-magnetized water and deficit irrigation regimes) and dependent (plant growth traits and grain yield) variables. These analyses were performed using Rbio 140 software for Windows (Federal University of Viçosa, Viçosa, MG, BRA) (Bhering, 2017).

3 RESULTS AND DISCUSSION

The analysis of variance showed that the effect of using magnetized water was insignificant ($p > 0.05$) on any of the plant growth and production traits. In contrast, the effect of deficit irrigation regimes was significant on all plant growth and production traits except on dry root matter. The interaction between the use of magnetized water and deficient irrigation regime did not report significant effects on the mungbean crop's growth characteristics and grain yield (Table 2).

Table 2. Result of the analysis of variance (F value) for the effects of the use of magnetized water and deficit irrigation regimes on the growth and production characteristics of mungbean crops

Plant traits [1]	Causes of variation				CV (%)
	Magnetized water (MW)	Deficit irrigation (DI)	Interaction (MW × DI)	Block	
	F value				
AGR	0.15^{NS}	56.08^{**}	0.04^{NS}	0.50^{NS}	9.70
RGR	0.19^{NS}	56.45^{**}	0.05^{NS}	0.86^{NS}	2.89
PH	0.15^{NS}	56.23^{**}	0.04^{NS}	0.51^{NS}	9.69
SD	0.20^{NS}	6.87^{**}	0.20^{NS}	1.45^{NS}	1.95
RCI	3.10^{NS}	44.91^{**}	1.20^{NS}	1.09^{NS}	3.66
SDM	0.00^{NS}	86.27^{**}	0.12^{NS}	1.36^{NS}	6.82
RDM	0.08^{NS}	2.58^{NS}	0.85^{NS}	1.59^{NS}	11.65
RL	1.80^{NS}	57.13^{**}	0.80^{NS}	0.42^{NS}	8.49
NPP	2.51^{NS}	9.51^{**}	0.73^{NS}	0.94^{NS}	17.42
NGP	0.00^{NS}	24.08^{**}	14.35^{NS}	1.00^{NS}	14.35
1,000-G	0.11^{NS}	5.42^{**}	0.26^{NS}	2.20^{NS}	0.70
GY	2.13^{NS}	35.20^{**}	1.22^{NS}	2.01^{NS}	19.89

[1] AGR: Absolute growth rate; RGR: relative growth rate; PH: plant height; SD: stem diameter; RCI: relative chlorophyll index; SDM: shoot dry matter; RDM: root dry matter; RL: root length; NPP: number of pods per plant; NGP: number of grains per pod; 1,000-G: mass of one thousand grains; GY: grain yield. **: significant at the 1% level by the F test; ns: not significant; CV: coefficient of variation.

The reduced soil water capacity available to plants resulted in a lower AGR and a lower RGR of the mungbean crop (Figures 1A, B). Although mungbean is considered a drought-tolerant crop, our results show that plant growth is drastically inhibited when plants are exposed to deficit irrigation regimes. Singh *et al.* (2021) and Bangar *et al.* (2019) also reported that exposure of mungbean plants to severe drought stress inhibited plant growth and development and limited the crop's grain yield. Damage caused by severe drought stress is related to the loss of water status of mesophyll cells, which significantly reduces the plant's photosynthetic rate and water use efficiency (Dutta; Bera, 2008; Bangar *et al.,* 2019; Singh *et al.*, 2021). Furthermore, plants exposed to severe drought stress have smaller leaf areas to reduce the rate of leaf transpiration and water losses (Bangar *et al.,* 2019). Therefore, the lower photosynthetic rate associated with the loss of cell turgor and the smaller leaf area results in the lower daily growth rate of mungbean plants, as observed in this study.

Increasing the level of deficit irrigation regime resulted in progressive reduced plant height and stem diameter of mung bean plants (Figure 1C;D). Plants irrigated with 60% and 80% of FC have greater shoot height and greater stem diameter when compared to plants irrigated with 20% and 40% of FC. The greater shoot growth of the plants with the application of the highest levels of irrigation (60% and 80% of FC) was due to water being the largest constituent of plant tissues, acting in the transport of inorganic and organic solutes, cell turgidity, stomatal mechanism, in addition to being essential for plant growth through cell expansion (Pohlmann *et al.*, 2022). In turn, the lower availability of soil water in the deficit irrigation regimes of 20% and 40% FC limited the shoot growth of mungbean plants, especially because water plays a key role in the photosynthesis process (Ranawake *et al.*, 2011). Coutinho *et al.* (2022) also reported that reduced soil water availability inhibited the shoot growth of mungbean plants, which caused a reduction in stem diameter.

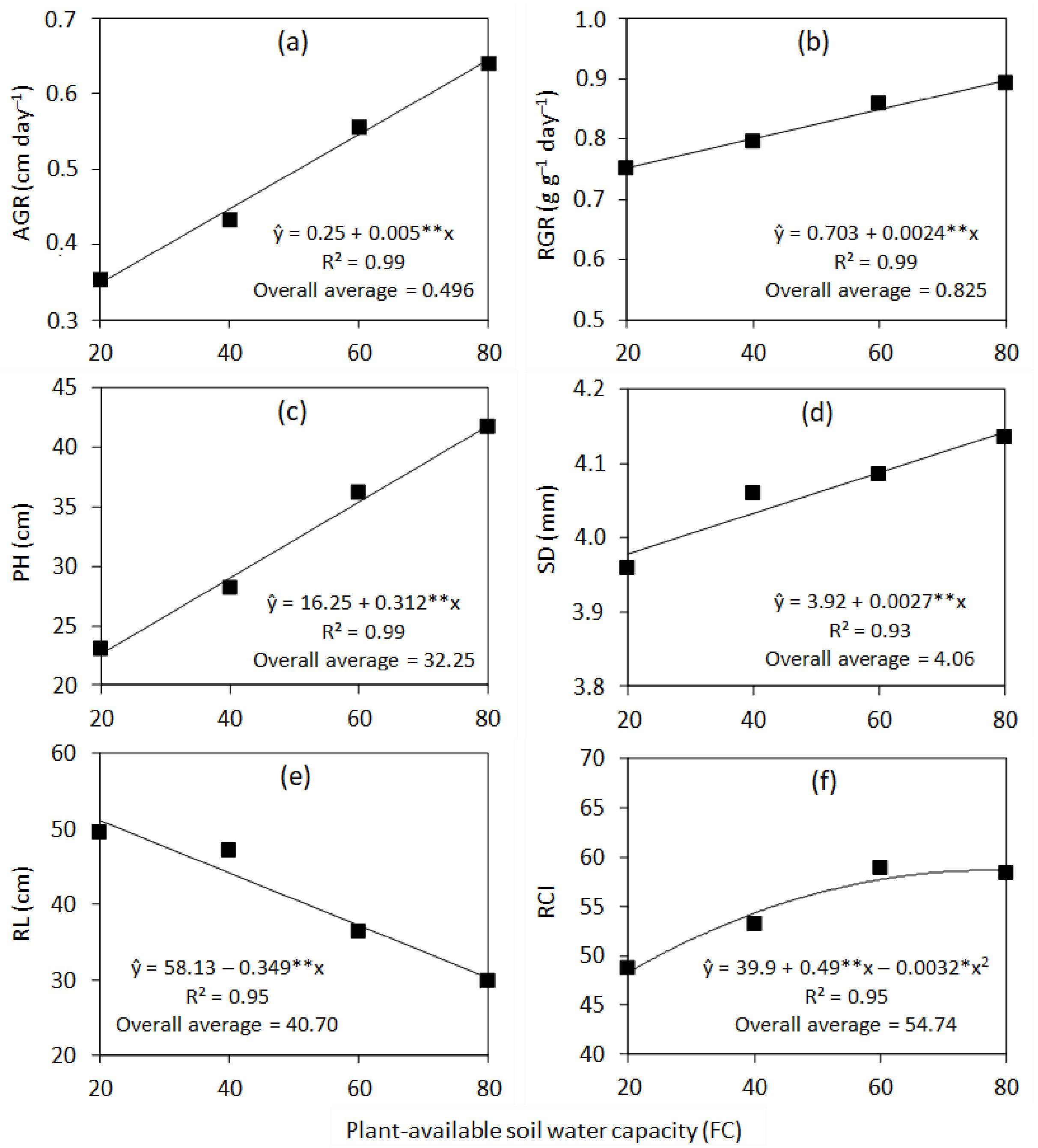

Figure 1. Effects of deficit irrigation regimes based on field water capacity (FC) on growth characteristics of the mungbean plants [*Vigna radiata* (L.) R. Wilczek.]: (**a**) Absolute growth rate – AGR; (**b**) relative growth rate – RGR; (**c**) plant height – PH; (**d**) stem diameter – SD; (**e**) root length – RL; and (**f**) relative chlorophyll index – RCI

Increasing the level of deficit irrigation increased the root length of mungbean plants (Figure 1E). Longer roots were obtained in 20% and 40% irrigation regimes of FC, while greater soil water availability resulted in shorter roots. The availability of soil water directly influences the growth of the root system. Under high soil water availability, the root growth rate tends to be lower to optimize the plant's physiological metabolism and reduce energy expenditure with the growth of a large root system (Boudiar *et al.,* 2020). In turn, in conditions of low soil water availability, the roots are directed to grow towards areas of the soil that remain moist since water is necessary to promote the turgidity of the root apices and cell expansion, and as a result, there is a longer root system in conditions of water restrictions (Boudiar *et al.,* 2020)

The highest values of the RCI were observed at the highest irrigation levels, in which the deficit irrigation regime of 60% and 80% resulted in the highest RCI values (Figure 1F). The most characteristic effects of plants exposed to water deficiency conditions are manifested through stomata closure due to the loss of turgor of plant cells (Ranawake *et al.,* 2011; Bangar *et al*., 2019). The closure of stomata decreases stomatal conduction, causing a reduction in the internal concentration of CO_2 and a decrease in the photosynthetic rate of plants, which is associated with the lower chlorophyll content of leaves that were degraded in conditions of lower soil water availability (Bangar *et al*., 2019).

The increase in soil water capacity available to plants resulted in a progressive increase in shoot dry matter of mungbean plants (Figure 2A). In contrast, root dry matter production was reduced with increased soil water capacity available to plants (Figure 2B). The low availability of soil water imposed by the irrigation regime of 20% of FC caused inhibition of the cell division process and a lower number of cells, indicated by the reduced size of the plants, which directly affected the accumulation of shoot dry matter of mungbeans (Bangar *et al.,* 2019; Singh *et al*., 2021). In turn, the increase in soil water availability provided better conditions for the physiological activities of plants, which led to greater development and accumulation of shoot dry matter (Figure 2A).

The increase in soil water availability provided by greater irrigation levels resulted in a progressive increase in the number of pods per plant (Figure 2C) and the number of grains per pod (Figure 2D). All crops have more critical periods for the occurrence of drought stress, and the reduction in water availability in the soil during these critical periods can cause a significant decrease in the number of reproductive organs (for example, flowers and pods). However, this reduction depends on the crop's duration, intensity, and stage of development (Farooq *et al.,* 2009; Ranawake *et al*., 2011). The increase in the number of pods per plant with higher irrigation levels is due to the better water status of the plants, resulting in an increase in the emission of flowers and pods per plant due to greater production of photoassimilates under favorable environmental conditions. These photoassimilates are necessary to improve grain filling and the productive potential of the crop (Ranawake *et al*., 2011). On the other hand, drought stress during the grain formation period can cause physiological changes in the plant, such as stomatal closure and loss of cell and leaf turgor, which impairs the production of photoassimilates and grain development (Farooq *et al.,* 2009).

The irrigation regime corresponding to 80% of FC resulted in the highest weight of a thousand grains compared to other deficit irrigation regimes (Figure 2E). In turn, the increase in soil water capacity available to plants resulted in a progressive increase in the grain yield of mungbean plants (Figure 2F). Grain weight and yield are factors directly associated with the number of pods per plant, the number of grains per pod, and the rate of photoassimilate translocation from leaves to grains. Therefore, increasing the plant's photosynthetic rate and improving flowering and fertilization of flowers are key factors for obtaining higher grain yields, which are directly affected by soil water availability. According to Ranawake *et al.* (2011), low soil water availability during the flowering and grain-filling stages causes a significant reduction in the grain yield of mungbean crops. This reduction in grain production results from increased respiration rate and lower production of photoassimilates under drought-stress conditions (Farooq *et al.*, 2009; Bangar *et al.*, 2019).

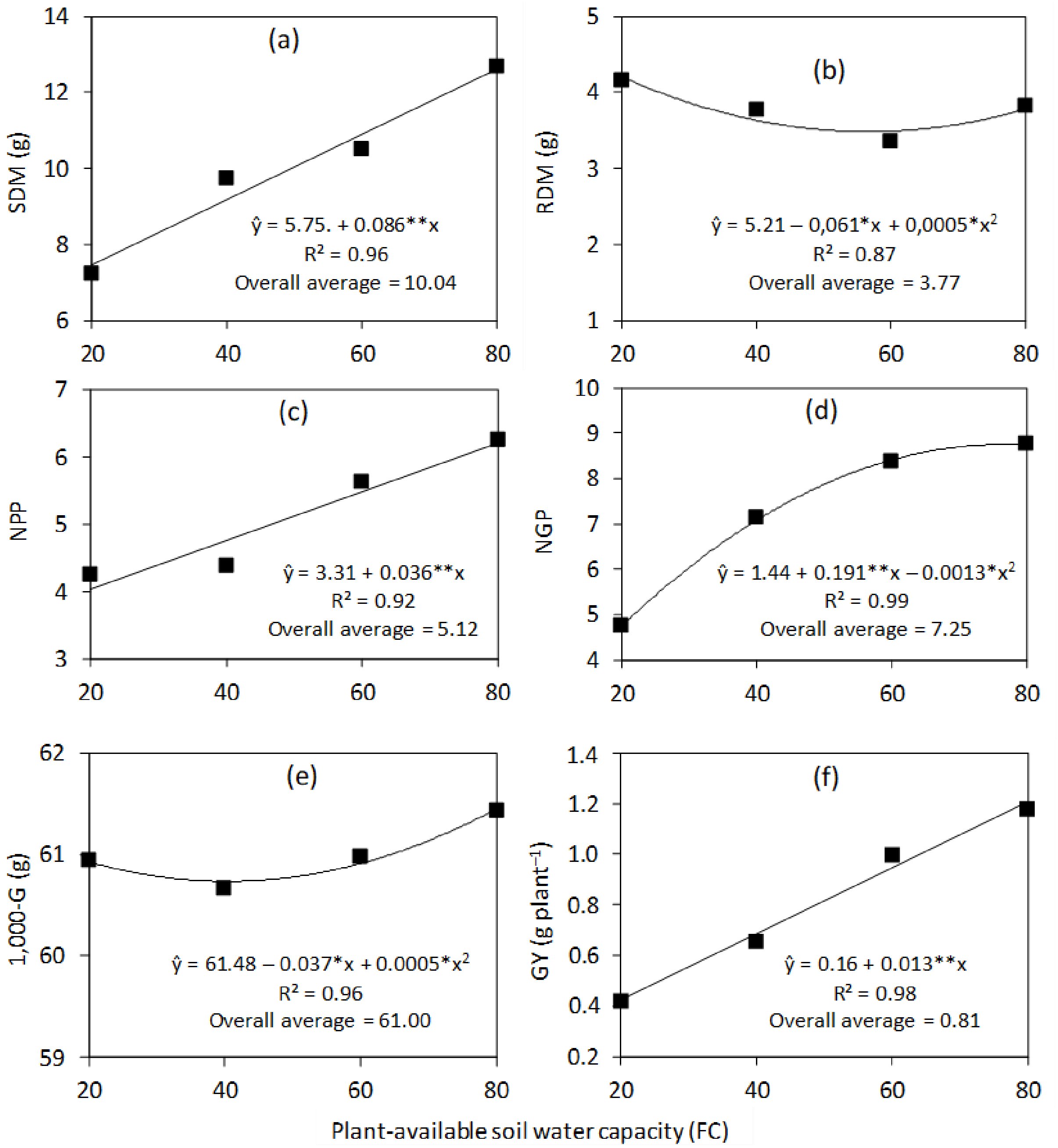

Figure 2. Effects of deficit irrigation regimes based on field water capacity (FC) on growth and production characteristics of the mungbean plants [*Vigna radiata* (L.) R. Wilczek.]: (a) shoot dry matter – SDM; (b) root dry matter – RDM; (c) number of pods per plant – NPP; (d) number of grains per pod – NGP; (e) mass of one thousand grains – 1,000-G; and (f) grain yield – GY

In the canonical correlation analysis, the distribution of variation factors was analyzed using canonical variables, in which the two main components represented 95% of the total variance (Figure 3).

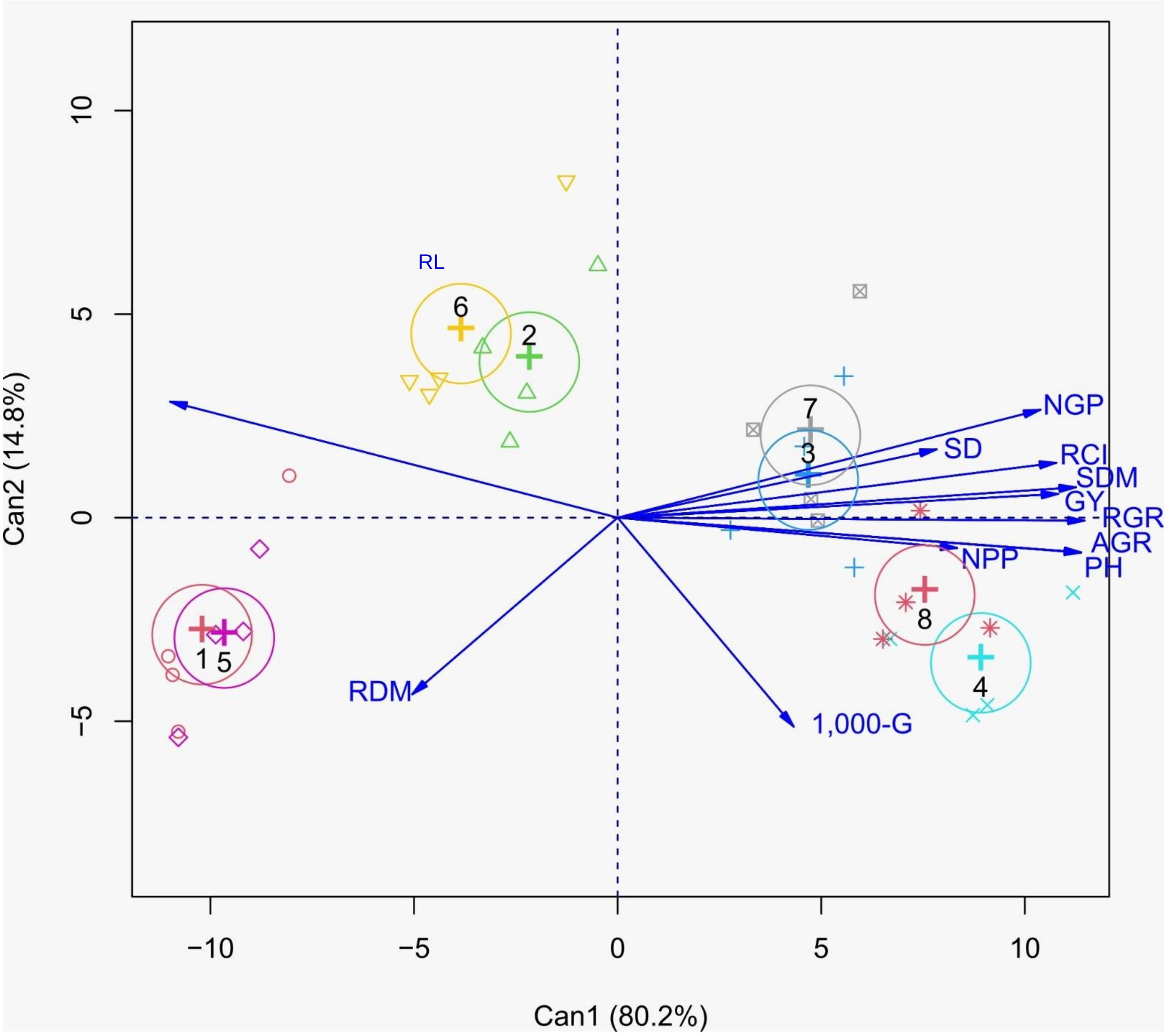

Figure 3. Canonical correlation analysis (CCA) between the growth and production characteristics of the mungbean plants [*Vigna radiata* (L.) R. Wilczek.] and deficit irrigation regimes with magnetized water (MW) or non-magnetized water (N-MW). The blue lines show the canonical correlation between the centroids of the first pair of canonical variables and the linear trendline.
AGR: Absolute growth rate; RGR: relative growth rate; PH: plant height; SD: stem diameter; RCI: relative chlorophyll index; SDM: shoot dry matter; RDM: root dry matter; RL: root length; NPP: number of pods per plant; NGP: number of grains per pod; 1,000-G: mass of one thousand grains; GY: grain yield. (T1) deficit irrigation regime with 20% of FC using N-MW; (T2) deficit irrigation regime with 40% of FC using N-MW; (T3) deficit irrigation regime with 60% of FC using N-MW; (T4) deficit irrigation regime with 80% of FC using N-MW; (T5) deficit irrigation regime with 20% of FC using MW; (T6) deficit irrigation regime with 40% of FC using MW; (T7) deficit irrigation regime with 60% of FC using MW; and (T8) deficit irrigation regime with 80% of FC using MW

Deficit irrigation regimes of 60% and 80% of FC with magnetized or non-magnetized water resulted in higher absolute growth rate, relative growth rate, plant height, shoot dry matter, stem diameter, number of pods per plant, number of grains per pod, relative chlorophyll index, thousand-grain mass, and grain yield (Figure 3). On the other hand, the highest root dry matter production and the greatest root length were obtained with deficit irrigation regimes of 20% and 40% of FC, respectively, using both magnetized and non-magnetized water (Figure 3). The availability of soil water influences the growth of the root system, and under conditions of low water availability, root growth has been improved to increase the root exploration area to regions of the soil that still have greater moisture (Boudiar *et al.,* 2020).

Highly positive and significant correlations were reported between NPP and GY, between GY and NGP, RCI, SDM, RGR, AGR, and PH; between NGP with RCI, SDM, RGR, AGR, and PH; between RCI with SDM, RGR, AGR, and PH; between SDM with RGR, AGR, and PH and between AGR with PH (Figure 4). Negative and significant correlations were reported between RL and GY, RCI, SDM, RGR, AGR, and PH. Therefore, these results indicate that selecting plants with greater production potential is possible based on the relative chlorophyll index measured using a portable chlorophyll meter.

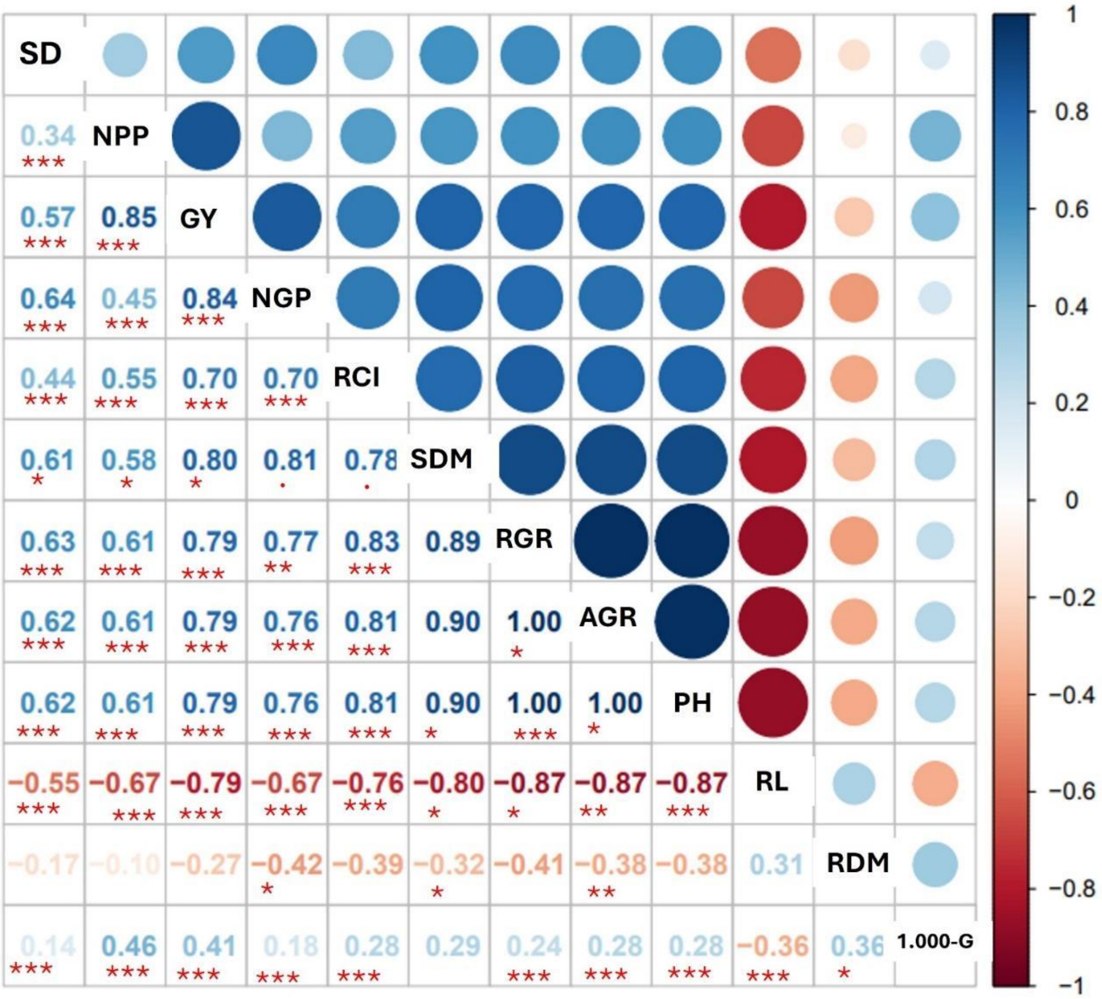

Figure 4. Pearson correlation coefficients (r) between growth and production characteristics of mungbean plants [Vigna radiata (L.) R. Wilczek.].
AGR: Absolute growth rate; RGR: relative growth rate; PH: plant height; SD: stem diameter; RCI: relative chlorophyll index; SDM: shoot dry matter; RDM: root dry matter; RL: root length; NPP: number of pods per plant; NGP: number of grains per pod; 1,000-G: mass of one thousand grains; and GY: grain yield

5 CONCLUSIONS

The deficit irrigation regime of 60% and 80% of field capacity improves the rate of plant growth and development and the grain yield of the mungbean crop.

Although mungbean is considered a drought-tolerant crop, low soil water availability causes severe inhibition of plant growth and development and drastically reduces the crop's grain yield.

Irrigation with magnetized water did not benefit mungbean crops' plant growth and development and grain yield.

Plant growth rate, height, shoot dry matter, relative chlorophyll index, and number of grains per pod positively correlate with grain yield. In contrast, root length has a highly negative correlation with the grain yield of mungbean crops

REFERENCES

ABDELKHALIK, A.; PASCUAL, B.; NÁJERA, I.; BAIXAULI, C.; PASCUAL-SEVA, N. Deficit irrigation as a sustainable practice in improving irrigation water use efficiency in cauliflower under Mediterranean conditions. **Agronomy**, v. 9, e732, 2019. https://doi.org/10.3390/agronomy9110732

AGUILERA, J. G.; SILVA, C. E. S.; SILVA, N. P.; BORGES, M. J.; RATKE, R. F.; ZUFFO, A. M.; BOIX, Y. F. Influência da água tratada magneticamente nas cultivares de alface conduzidas em sistema irrigado por gotejo. **Ensaios E Ciência**, v. 27, 1-5, 2023.

AGUILERA, J. G.; MARTÍN, R. M. Água tratada magneticamente estimula a germinação e desenvolvimento de mudas de *Solanum lycopersicum* L. **Revista Brasileira de Agropecuária Sustentável**, v. 6, n. 1, 47–53, 2016. https://doi.org/10.21206/rbas.v6i1.320

AKINYOSOYE, S. T.; AGBELEYE, O. A.; ADETUMBI, J. A.; UKACHUKWU, P. C. Selection for earliness and seed yield in mung bean accessions using REML/BLUP. **Pesquisa Agropecuária Brasileira**, v. 56, e02290, 2021. https://doi.org/10.1590/S1678-3921.pab2021.v56.02290

ALEMÁN, E. I.; HERNÁNDEZ, V. R. F.; DUBOIS, A. E. F.; BOIX, Y. F.; CUYPERS, A.; KINDELÁN, G. A.; AGUILERA, J. G.; ZUFFO, A. M.; RATKE, R. F.; GOES, R. J. Magnetically treated water influences soil properties, water absorption and nutrients in *Beta vulgaris* L. **Research, Society and Development**, v. 11, n. 7, e45111730203, 2022. https://doi.org/10.33448/rsd-v11i7.30203

ALTHOFF, D.; RODRIGUES, L. N.; SILVA, D. D. Assessment of water availability vulnerability in the Cerrado. **Applied Water Science**, v. 11, e176, 2021. https://doi.org/10.1007/s13201-021-01521-2

BANGAR, P.; CHAUDHURY, A.; TIWARI, B.; KUMAR, S.; KUMARI, R.; BHAT, K. V. Morphophysiological and biochemical response of mungbean [*Vigna radiata* (L.) Wilczek] varieties at different developmental stages under drought stress. **Turkish Journal of Biology**, v. 43, 58–69, 2019. https://doi.org/10.3906/biy-1801-64

BARBOSA, J.; MALDONADO, J. **Experimentação agronômica e AgroEstat**: sistema para análisesestatísticas de ensaios agronômicos. 2, Jaboticabal: Departamento de Ciências Exatas–UniversidadeEstadual Paulista (UNESP). 2015.

BARROSO-NETO, A. M.; MATOS, R. F.; PINHEIRO, M. S.; BERTINI, C. H. C. M.; DOVALE, J. C. Genetic variability and selection of extra-early cowpea progenies. **Revista Caatinga**, v. 30, 698–707, 2017. https://doi.org/10.1590/1983-21252017v30n318rc

BHERING, L.L. Rbio: A Tool For Biometric And Statistical Analysis Using The R Platform. **Crop Breeding and Applied Biotechnology**, v.17, 187-190, 2017. https://doi.org/10.1590/1984-70332017v17n2s29

BOIX, Y. F.; DUBOIS, A. F.; QUINTERO, Y. P.; ALEMÁN, E. I.; VICTÓRIO, C. P.; AGUILERA, J. G.; BETANCOURT, M. N.; MORALES-ARANIBAR, L. Magnetically treated water in *Phaseolus vulgaris* L.: an alternative to develop organic farming in Cuba. **Plants**, v. 12, n. 2, e340, 2023. https://doi.org/10.3390/plants12020340

BOUDIAR, R.; CASAS, A. M.; GIOIA, T.; FIORANI, F.; NAGEL, K. A.; IGARTUA, E. Effects of low water availability on root placement and shoot development in landraces and modern barley cultivars. **Agronomy**, v. *10*, e134, 2020. https://doi.org/10.3390/agronomy10010134

CAI, R.; YANG, H.; HE, J.; ZHU, W. The effects of magnetic fields on water molecular hydrogen bonds. **J. Mol. Struct.**, v. 938, 15–19, 2009. https://doi.org/10.1016/j.molstruc.2009.08.037

CHIBOWSKI, E.; SZCZE, A. Magnetic water treatment - a review of the latest approaches. **Chemosphere**, v. 203, 54–67, 2018. https://doi.org/10.1016/j.chemosphere.2018.03.160

COUTINHO, C. S.; ROCHA, E. S. N.; LOPES, D. I. S.; FREIRE, A. I. Evaluation of seedling growth of mungbeans on different substrates. **Research, Society and Development**, v. 11, n. 7, e58611730675, 2022. http://dx.doi.org/10.33448/rsd-v11i7.30675

DOKLEGA, S. M. A. Impact of magnetized water irrigation, soil mineral fertilization and foliar spraying with nanomaterial on potato plants. **Journal of Plant Production**, v. 8, n. 11, 1113–1120, 2017. https://doi.org/10.21608/jpp.2017.41123

DUTTA, P.; BERA, A. K. Screening of mungbean genotypes for drought tolerance**. Legume Research,** v. 31, 145–148, 2008.

EVANS, G. C. **The quantitative analysis of plant growth**. Blackwell Scientific, Oxford, 1972. 734p.

FAROOQ, M.; GOGOI, N.; BARTHAKUR, S.; BAROOWA, B.; BHARADWAJ, N.; ALGHAMDI, S. S.; SIDDIQUE, K. H. M. Drought stress in grain legumes during reproduction and grain filling. **Journal of Agronomy and Crop Science**, v. 203, n. 2, 81–102, 2009. https://doi.org/10.1111/jac.12169

FAVERO, V.O.; CARVALHO, R.H.; MOTTA, V.M.; LEITE, A.B.C.; COELHO, M.R.R.; XAVIER, G.R.; RUMJANEK, N.G.; URQUIAGA, S. *Bradyrhizobium* as the only rhizobial inhabitant of mung bean (*Vigna radiata*) nodules in tropical soils: a strategy based on microbiome for improving biological nitrogen fixation using bio-products. **Frontiers in Plant Science,** v. 11, e602645, 2021. https://doi.org/10.3389/fpls.2020.602645

GENEROSO, T. N.; MARTINEZ, M. A.; ROCHA, G. C.; HAMAKAWA, P. J. Magnetização da água e os parâmetros de transporte de fósforo no solo. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 21, n. 1, 9–13, 2017. https://doi.org/10.1590/1807-1929/agriambi.v21n1p9-13

GUEDES, W. A.; NOBRE, R. G.; SOARES, L. A. D. A.; LIMA, G. S.; GHEYI, H. R.; FERNANDES, P. D.; FERREIRA, A. P. N.; SILVA, A. A. R.; AZEVEDO, C. A. V.; SILVA, D. V.; MEDEIROS, J. F. Irrigation strategies with controlled water deficit in two production cycles of cotton. **Plants**, v. 12, n. 16, e2892, 2023. https://doi.org/10.3390/plants12162892

HAYASHI, R.; DOGLIOTTI, S. Water productivity in maize, at different levels of deficit irrigation in humid climate. **Agrociencîência**, v. 25, n. 1, e390, 2021. https://doi.org/10.31285/agro.25.390

HOU, D.; YOUSAF, L.; XUE, Y.; HU, J.; WU, J.; HU, X.; FENG, N.; SHEN, Q. Mung bean (*Vigna radiata* L.): bioactive polyphenols, polysaccharides, peptides, and health benefits. **Nutrients**, v. 11, n. 6, e1238, 2019. https://doi.org/10.3390/nu11061238

IMAKUMBILI, M. L. E. Making water stress treatments in pot experiments: An illustrated step-by-step guide. **Sokoine University of Agriculture: Morogoro**, Tanzania, 2019. 1–17 p. https://dx.doi.org/10.17504/protocols.io.2xdgfi6

KUMAR, S.; AYACHIT, G.; SAHOO, L. Screening of mungbean for drought tolerance and transcriptome profiling between drought-tolerant and susceptible genotype in response to drought stress. **Plant Physiology and Biochemistry**, v. 157, 229–238, 2020. https://doi.org/10.1016/j.plaphy.2020.10.021

NOLETO, M. P.; MENEZES-JÚNIOR, J. Â. N.; OLIBONE, D.; GOBBI, S. D.; PIVETTA, L. G.; SILVA, K. J. D. Adaptability and stability of mungbean genotypes in the Mid-North of

Mato Grosso, Brazil. **Ciência e Agrotecnologia**, v. 47, e012222, 2023. https://doi.org/10.1590/1413-7054202347012222

POHLMANN, V.; LAGO, I.; LOPES, S. J.; ZANON, A. J.; STRECK, N. A.; MARTINS, J. T. S.; CAYE, M.; BITTENCOURT, P. N.; SANTANA, V. F. K.; PORTALANZA, D. Tolerance to water deficit of bean cultivars. **Pesquisa Agropecuária Brasileira**, v. 57, n. 1, e02479, 2022. https://doi.org/10.1590/S1678-3921.pab2022.v57.02479

RANAWAKE, A. L.; DAHANAYAKA, N.; AMARASINGHA, U. G. S.; RODRIGO, W.; RODRIGO, U. T. D. Effect of water stress on growth and yield of mung bean (*Vigna radiata* L.). **Tropical Agricultural Research and Extension,** v. 14, 76–79, 2011.

SHARMA, L.; PRIYA, M.; BINDUMADHAVA, H.; NAIR, R. M.; NAYYAR, H. Influence of high-temperature stress on growth, phenology and yield performance of mungbean [*Vigna radiata* (L.) Wilczek] under managed growth conditions. **Science Horticulture**, v. 213, 379–391, 2016. doi: https://doi.org/10.1016/j.scienta.2016.10.033

SILVA, A. L.; SOUZA, S. A.; COELHO-FILHO, O.; ELOY, L.; SALMONA, Y. B.; PASSOS, C. J. S. Water appropriation on the agricultural frontier in western Bahia and its contribution to streamflow reduction: revisiting the debate in the Brazilian Cerrado. **Water**, v. 13, e1054, 2021. https://doi.org/10.3390/w13081054

SILVA, B. M.; SILVA, É. A.; OLIVEIRA, G. C.; FERREIRA, M. M.; SERAFIM, M. E. Plant-available soil water capacity: estimation methods and implications. **Revista Brasileira de Ciência do Solo**, v. 38, n. 2, 464–475, 2014. https://doi.org/10.1590/S0100-06832014000200011

SINGH, C. M.; SINGH, P.; TIWARI, C.; PURWAR, S.; KUMAR, M.; PRATAP, A.; SINGH, S.; CHUGH, V.; MISHRA, A. K. Improving drought tolerance in mungbean (*Vigna radiata* L. Wilczek): morpho-physiological, biochemical and molecular perspectives. **Agronomy**, v. 11, e1534, 2021. https://doi.org/10.3390/agronomy11081534

TOLEDO, E. J. L.; RAMALHO, T. C.; MAGRIOTIS, Z. M. Influence of magnetic field on physical-chemical properties of liquid water. Insights from experimental and theoretical models. **Journal of Molecular Structure,** v. 888, 409–415, 2008. https://doi.org/10.1016/j.molstruc.2008.01.010

ZHAO, T.; MENG, X.; CHEN, C.; WANG, L.; CHENG, X.; XUE, W. Agronomic traits, fresh food processing characteristics and sensory quality of 26 mung bean (*Vigna radiata* L.) cultivars (Fabaceae) in China. **Foods**, v. 11, e1687, 2022. https://doi.org/10.3390/foods11121687

ZHOU, B.; YANG, L.; CHEN, X.; YE, S.; PENG, Y.; LIANG, C. Effect of magnetic water irrigation on the improvement of salinized soil and cotton growth in Xinjiang. Agric.

Water Management, v. 248, e106784, 2021.
https://doi.org/10.1016/j.agwat.2021.106784

ZHOU, C.; ZHANG, H.; LI, F.; WANG, Y.; WANG, Y.; WANG, Z. Deficit mulched drip irrigation improved yield and quality while reduced water consumption of Isatis indigotica in a cold and arid environment. **Front Plant Science**, v. 13, e1013131, 2022. https://doi.org/10.3389/fpls.2022.1013131