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Oil content and economic water productivity of soybean cultivars under different water availability conditions

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ABSTRACT: *This research evaluated the yield, water productivity, and economic water productivity for the oil content of three soybean cultivars under different water conditions. The experiments were conducted in the 2017/2018 and 2018/2019 harvests. The experimental design consisted of a two-factor randomized block, with the first factor of 5 irrigation depths, based on the reference evapotranspiration (ET_O), plus the treatment without irrigation and the second factor was 3 soybean cultivars. Results reported oil yield and productivity were higher for the depths of 75% (crop 1) and 100% of ET_O (crop 2). For the evaluations of water productivity and economic water productivity, the highest results were obtained at the level of 50% in crop 1 and 25% and 50% in crop 2. Cultivar BRASMAX Ponta had the highest values for oil production and BRASMAX Valente for oil yield, in both crops. In Crop 1, the BRASMAX Valente cultivar had the highest results in water productivity and economic water productivity, and in Crop 2, the BRASMAX Ponta cultivar had the highest values. Supplemental irrigation favored the increase in oil production and oil productivity. For a more efficient and economical use of water, it is necessary to use smaller irrigation depths.*
Key words: *grain composition, water use efficiency, Glycine max (L) Merrill.*

Produção de óleo e produtividade econômica da água de cultivares de soja em diferentes disponibilidades hídricas

RESUMO: *O presente trabalho teve como objetivo avaliar o rendimento, produtividade da água e produtividade econômica da água para o teor de óleo de três cultivares de soja sob diferentes condições hídricas. Os experimentos foram conduzidos nas safras 2017/2018 e 2018/2019. O delineamento experimental constou de um bifatorial em blocos ao acaso, com o primeiro fator de cinco* lâminas de irrigação, com base na evapotranspiração de referência (ET_O)*, mais o tratamento sem irrigação e o segundo fator foram três cultivares de soja. Os resultados para o rendimento e produtividade de óleo foram maiores para as lâminas de 75% (safra 1) e 100% da ET_O (safra 2). Nas avaliações de produtividade da água e produtividade econômica da água os maiores resultados foram obtidos na lâmina de 50% na safra 1 e 25% e 50% na safra 2. A cultivar BRASMAX Ponta apresentou os maiores valores para produção de óleo e a BRASMAX Valente para produtividade de óleo, em ambas as safras. Na safra 1, a BRASMAX Valente obteve os maiores resultados na produtividade de água e produtividade econômica da água e, na Safra 2, foi a BRASMAX Ponta que apresentou maiores valores. A irrigação suplementar favoreceu o incremento na produção de óleo e a produtividade de óleo. Para o uso mais eficiente e econômico da água é necessário a utilização de menores lâminas.*
Palavras-chave: *composição do grão, eficiência do uso da água, Glycine max (L) Merrill.*

INTRODUCTION

Soybean (*Glycine max L.*) is considered a major food crop in the global grain market, and the main factors determining its nutritional value are its oil and protein contents (AYDINSAKIR, 2018), which average approximately 20% and 40%, respectively.

Soybean oil is one of the most widely consumed vegetable oils globally, whereby, increasing it is of great interest. As genetic factors have the greatest influence over soybean nutritional composition, genetic improvement programs have been the focus of much research aimed at maximizing oil content (SILVA et al., 2021). Thus, studies showed significant variability among cultivars for oil content in the grain (FARIA et al., 2018; FLAJŠMAN et al., 2019). Nevertheless, environmental factors also have a significant impact on soybean nutritional composition. As soybean is grown in various regions of the world under vastly different climates, research on the effects of abiotic environmental factors on grain quality and productivity is necessary (MERTZ-

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HENNING et al., 2018). Among these factors, water availability is considered one of the most important, as water stress resulting from either deficit or excess, can cause significant reduction in crop productivity (WIJEWARDANA et al., 2019). Furthermore, water stress also affects the economic and environmental costs related to water use and productivity, as well as soybean quality parameters such as oil and protein contents (AYDINSAKIR, 2018).

Numerous studies have evaluated the effect of water availability on oil content in the soybean grain and results are controversial. Thus, in some cases, oil content in the grain decreased with increasing irrigation amount (AYDINSAKIR, 2018; KRESOVIĆ et al., 2017; WIJEWARDANA et al., 2019). Conversely, other studies reported a positive relationship between irrigation amount and oil content (CANDOĞAN & YAZGAN, 2016; MERTZ-HENNING et al., 2018; NAGY & PEPÓ, 2019).

Irrigation is primarily used to meet crop water demands in different climatic scenarios, specifically in regions where water scarcity prevails, or where precipitation is insufficient or poorly distributed throughout the crop cycle (GAJIĆ et al., 2018). As grain quality is directly associated with water availability, understanding the performance of soybean cultivars in response to this factor is fundamental. Supplementary irrigation aiming efficient water management reportedly results in higher crop yields while minimizing the use of water resources (CANDOĞAN & YAZGAN, 2016).

Effective irrigation management involves an efficient use of water resources, satisfactory economic returns, adaptation to climate change, and control of irrigation based on meteorological forecasts throughout the crop cycle (PAREDES et al., 2017).

The economic productivity of water and water use efficiency are indicators that allow a rational evaluation of the cost benefit ratio for irrigation (HAN et al., 2018), and to maximize the ratio between grain quality and water consumption.

In view of the above, this study evaluated the yield, water productivity, and economic productivity of water for oil content of three soybean cultivars under different irrigation conditions.

MATERIALS AND METHODS

The experiments was conducted using the harvests of the 2017/2018 (crop 1) and 2018/2019 (crop 2) growth seasons in the experimental fields of the Polytechnic College of the Federal University of Santa Maria (UFSM), Santa Maria, Rio Grande do Sul (RS), Brazil (29° 42’ 55.7” S 53° 44’ 21.4” W; elevation 120 m). According to the Köppen-Geiger classification, the climate of the region is Cfa (humid subtropical climate), with well-defined seasons (ALVARES et al., 2013). According to INMET, the average annual precipitation in the region is 1450 to 1650 mm, and the average temperature is 18 °C – 20 °C.

Soil samples for chemical and physical analyses were obtained following the protocols described by ARRUDA et al. (2014). Samples were analyzed at the Soil Analysis Laboratory of UFSM, where soil macro- and micro-nutrient were determined. After chemical analysis, fertilization was performed using the amounts recommended by the Fertilization and Liming Manual for RS and SC (2016).

Soybean seeds used for growing crops 1 and 2 were sown on 14/12/2017 and 23/11/2018, respectively. The experimental design consisted in a two-factor randomized blocks design; the first factor was irrigation, with six irrigation treatments, namely, the 0% control, and 25%, 50%, 75%, 100%, and 125% of the reference evapotranspiration, (ET_O). The second factor was soybean cultivar, including, NS 6909 PRO RR (NS 6909), BRASMAX Ponta IPRO 7166 RSF (BMX Ponta), and BRASMAX Valente RR 6968 RSF (BMX Valente).

For application of irrigation treatments, a fixed conventional sprinkler-type irrigation system was used, which consisted of a 92-m long main line and 24 lateral lines, each 24-m long, laid at 4 m intervals. The sprinklers were distributed along the lateral lines with a spacing of 4 m and at a height of 1.5 m.

A uniformity test (ISO 15886-3:2021) performed with a duration of 2 h allowed us to determine an irrigation application rate of 11.5 mm h^{-1}, and a value of 82% for Christiansen’s uniformity coefficient (BERNARDO et al., 2019). Irrigation was applied at 7 day intervals, when precipitation of the period fell below the water demand of the crop. Irrigation management was based on reference evapotranspiration (ET_O) calculated by the Penman-Monteith-FAO equation (ALLEN et al., 1998. Meteorological data used for calculation of ET_O at the study site were obtained from the automatic weather station of the National Institute of Meteorology at UFSM. The data collected daily included: rainfall (mm), maximum and minimum temperatures (ºC), relative ambient humidity (%), wind speed (m s^{-1}) and solar radiation (kJ m^{-2}).

The irrigation requirement was determined according to Eq. 1:

$$NI = ETo - P_{ef} \quad (1)$$

where NI is the irrigation requirement (mm); ET_O is the reference evapotranspiration for the seven-day period (mm); and P_{ef} is the effective precipitation (mm) determined by the method described by MILLAR (1988), which considers soil textural class, slope of the area (%) and vegetation cover. At the study site, the proportion of rainfall lost through runoff was estimated at 30% of the total precipitation.

Irrigation was conducted according to Eq. 2:

$$Ti = \frac{Ln}{Lr \cdot Ua} \cdot 100 \quad (2)$$

where Ti is the irrigation time (h); L_n is the irrigation depth (mm); L_r is the reference water supply rate (mm h^{-1}); and U_a is the uniformity rate of application (%).

Plants were collected at the end of the cropping cycle from a 4.5 m² effective area and subsequently threshed and the grain harvested was cleaned of impurities, weighed, and corrected to 13% moisture content.

Soybean oil was extracted using petroleum ether solvent in a Soxhlet extractor according to the procedure described in the Analytical Standards of the Adolfo Lutz Institute (1985). The oil yield was calculated by multiplying the oil content of the grain by the grain yield.

To determine water productivity, we adapted the methodology used by ADEBOYE et al. (2015), which determines the relationship between the total volume of water supplied (effective precipitation + irrigation water) and the total oil yield Eq. 3.

$$PA = \frac{Y}{I + P_{ef}} \quad (3)$$

where PA is water productivity (kg ha^{-1} mm^{-1}); Y is oil productivity (kg ha^{-1}); I is the amount of irrigation water applied (mm); and P_{ef} is the amount of effective precipitation (mm).

In turn, economic water productivity was determined using Eq.

$$PEA = \frac{p.Y}{I + P_{ef}} \quad (4)$$

where PEA is the economic productivity of water (US\$ ha^{-1} mm^{-1}); p is the average price of crude soybean oil (US\$ kg^{-1}); I is the amount of irrigation water applied (mm); and P_{ef} is the amount of effective precipitation (mm).

For the market price of crude soybean oil, the average prices of the Chicago exchange subsequent to the crop harvest in the month of April were obtained, with values of 0.63 and 0.61 US\$ kg^{-1} in the years 2018 and 2019, respectively.

Results were subjected to analysis of variance (ANOVA) at 5% probability of error using the Sisvar 5.6 program (FERREIRA, 2011). If an interaction between cultivar and irrigation rate was observed, regression analysis and maximum technical efficiency were performed. If no interaction between the two factors was detected, a comparison of means was performed using the Tukey test for qualitative data (soybean cultivar) and regression analysis and maximum technical efficiency for quantitative data (irrigation depth). Regression analysis was performed using SigmaPlot 11.0 software.

RESULTS AND DISCUSSION

Figure 1 shows the values for effective precipitation, irrigation, maximum and minimum temperatures, and evapotranspiration throughout both crop cycles under study. Total effective precipitation was only slightly greater in crop 2 (374.55 mm) than in crop 1 (369.18 mm).

Total water requirement of soybeans throughout the crop cycle reportedly varies between 450 and 700 mm (DOORENBOS; KASSAM, 1979); therefore, supplementary irrigation was necessary in both years of the study, as total rainfall was not sufficient to meet the water demand based on reference evapotranspiration, and rainfall did not present a uniform distribution over either crop cycle. The total number of irrigation events was seven and six for crops 1 and 2, respectively.

Using simulation models, TANG et al. (2018) evaluated the need for soybean irrigation in the Mississippi region, and observed that the irrigation demand of the crop during the growth cycle varied between 0 to 257 mm during periods of normal precipitation. Consistently, the required irrigation supplementation for soybean crops at the study site was 132 (2017/18 crop) and 135 mm (2018/19 crop), according to OLIVEIRA et al. (2020). In agreement with the results reported by these authors, the irrigation requirement for 100% water supplementation was 121.12 (crop 1) and 120.68 mm (crop 2), with a total rainfall of 369.18 and 374.55 mm, respectively.

The average values of oil production and oil yield in relation to the different irrigation treatments for the two years of the study are shown in figure 2. As there was no interaction between irrigation and cultivar in these evaluations, regression analysis was performed for irrigation treatments. The highest soybean-oil contents were 21.39% and 20.28%, for the 75% ET_O (crop 1) and 100% ET_O (crop 2) irrigation treatments, respectively. Furthermore, the lowest contents were observed without irrigation in both crops, with values of 17.73% and 17.47%, respectively. These findings

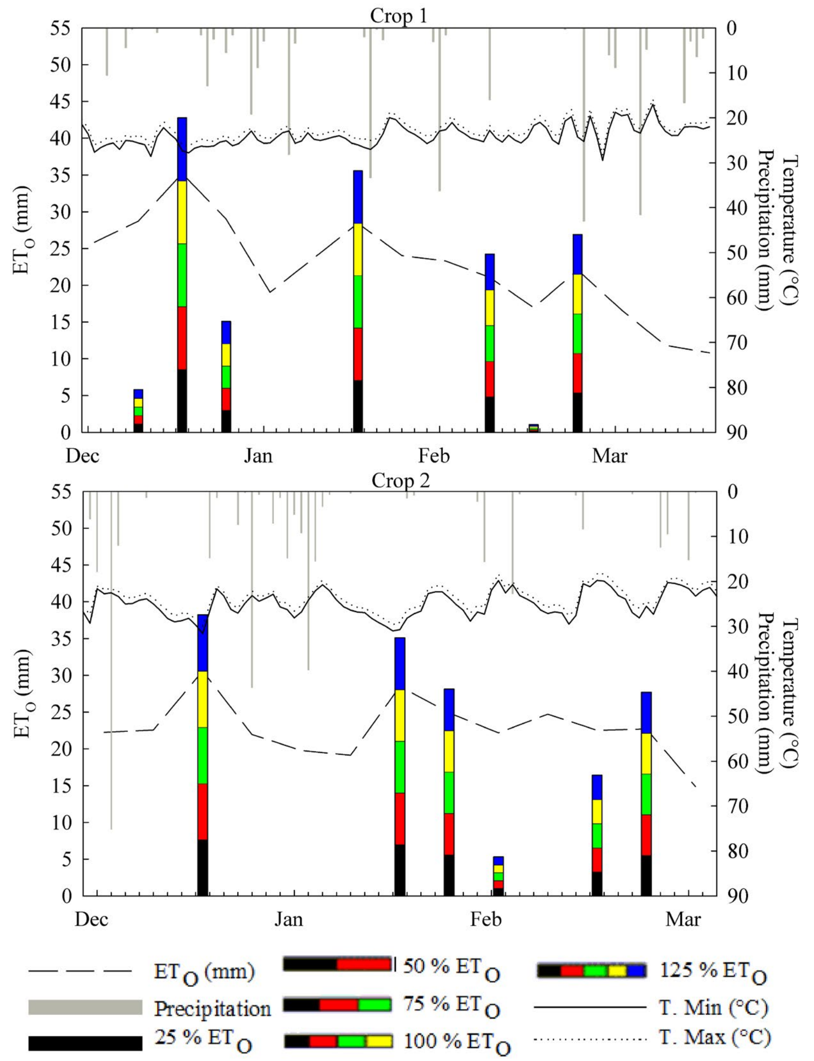

Figure 1 - Effective precipitation, irrigation amount, maximum and minimum temperatures and evapotranspiration throughout the crop cycle for crops 1 and 2.

differ from those reported by AYDINSAKIR et al. (2021) for a two-year study in which non-irrigated soybeans showed a significantly higher oil content than irrigated ones. In the same study, mean values of oil content were below 20% for all treatments. Additionally, AYDINSAKIR (2018) reported soybean oil contents ranging from 18.2% to 22.3% and, again in this case, the highest values were observed in the non-irrigated treatment. Intriguingly, KRESOVIĆ et al. (2017) observed the highest values for oil content both without irrigation and with full irrigation across all years of their study.

Conversely, MERTZ-HENNING et al. (2018)representing an important protein and oil source. Although genetic variability in the chemical composition of grains is seen in soybean, the mean levels of proteins have remained stagnant or, in some cases, have decreased over time, arousing concern in the agricultural industry. Furthermore, environmental conditions influence the chemical composition of grains. Thus, the present study evaluated the effect of water deficit (WD observed lower average oil contents in soybean plants subjected to water stress during the reproductive period. Our measurements for

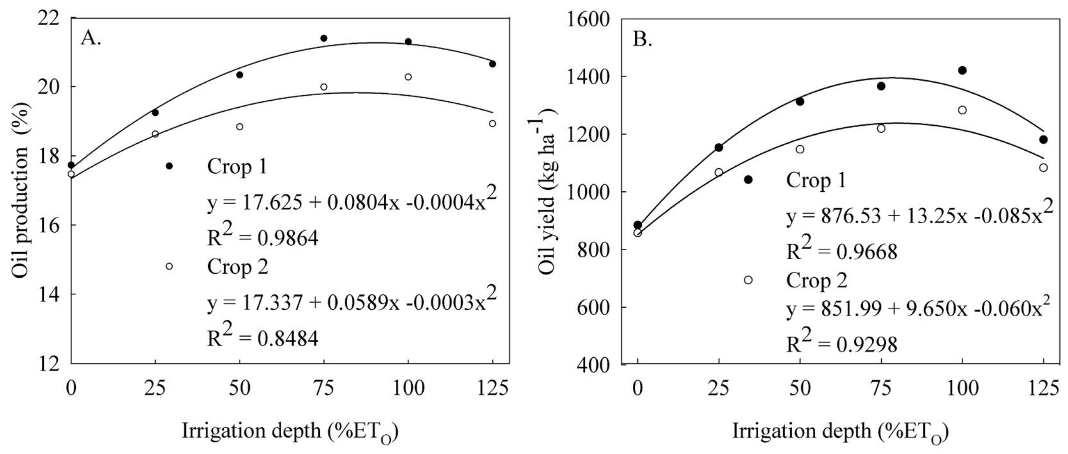

Figure 2 - Oil production (%) (A.) and oil yield (kg ha^{-1}) (B.) for the different irrigation treatments in crops 1 and 2.

oil productivity had low average values at a 0% ET_O irrigation rate, with values of 884.65 kg ha^{-1} for crop 1, and 857.70 kg ha^{-1} for crop 2. The highest values for oil yield were 1,420.97 (crop 1, 75% ET_O) and 1,283.44 kg ha^{-1} (crop 2, 100% ET_O). Consistently, supplemental irrigation applied to oilseed crops during periods of increased crop water demand, such as flowering and grain filling can reportedly increase oil productivity (MOHTASHAMI et al., 2020).

As for the evaluation of water productivity and economic productivity of water, according to the analysis of variance at 5% probability of error, no interaction was observed between irrigation treatment and cultivar. The pattern observed for these evaluations was the same for the two crops studied, with the lowest values observed for the 125% ET_O irrigation treatment, with a water productivity of 2.27 and 2.06 kg ha^{-1} mm^{-1} and an economic productivity of water 1.44 and 1.94 US\$ ha^{-1} mm^{-1}, in crops 1 and 2, respectively (Figure 3).

In the first year of study, the highest values for water productivity and economic productivity of water were obtained under 50% ET_O, with 3.05 kg ha^{-1} mm^{-1} and 1.94 US\$ ha^{-1} mm^{-1}, respectively. Conversely, in the second crop, the highest average values were observed for the 25% and 50% of ET_O irrigation treatments, in which case, water productivity was 2.64 kg ha^{-1} mm^{-1} and economic productivity of water was 1.61 US\$ ha^{-1} mm^{-1}.

Severe water stress can reduce economic water productivity for sunflower oil production by up to 20% (MORADI-GHAHDERIJANI et al., 2017). Similarly, in this study, such reduction was 13.18% for the three soybean cultivars, when the treatments that obtained the highest values under the non-irrigated treatment were compared, and 21.81% relative to the 125% ET_O irrigation treatment, which showed the highest reduction.

Table 1 shows the average values of oil production, oil yield, water productivity and economic productivity of water for the three cultivars studied. No significant interaction was detected between cultivar and irrigation treatment for any of the measured variables.

Cultivar NS 6909 showed the lowest average values for all variables and differed significantly from the other cultivars tested. The only exception to this was the oil content values of crop 2, in which case there was no significant difference among cultivars.

Cultivar BMX Ponta showed the highest total oil production values in both harvests; although, it differed significantly from the other two cultivars only in the first harvest and only from cultivar BMX Valente in the second harvest. In turn, cultivar BMX Ponta did not differ significantly from cultivar BMX Valente for oil yield, water productivity or the economic productivity of water; although, it showed the highest values for water productivity and economic productivity of water in crop 2.

As for the evaluation of oil productivity, BMX Valente showed the highest average values

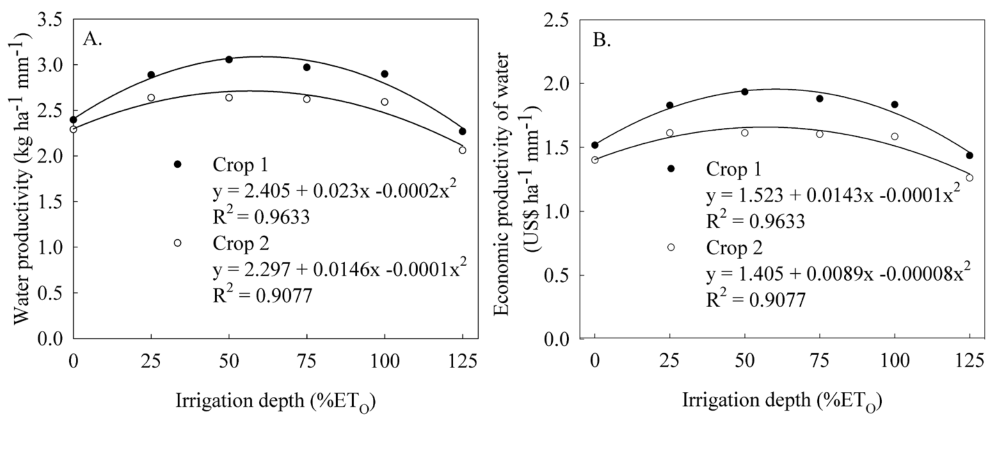

Figure 3 - Water productivity (kg ha $^{-1}$mm^{-1}) (A.) and economic productivity of water (US\$ ha^{-1} mm^{-1}) (B.) for the different irrigation treatments.

in both harvests, but was not statistically different from BMX Ponta. Finally, Valente BMX showed the highest values for water productivity and economic productivity of water in the first harvest but, again, did not significantly differ from BMX Ponta.

Working with seven soybean cultivars, FARIA et al. (2018) observed that cultivars showed significant differences in oil content (ranging between 20.7% and 26.7%) and productivity (ranging between 574 and 1,072 kg ha^{-1}) across four sowing dates and at two locations. Consistently, JUNIOR et al. (2017) measured oil content values of four soybean cultivars that ranged between 17.8% and 20.3% over three sowing seasons. Additionally, analyzing six soybean cultivars, Flajšman et al. (2019) measured oil contents between 16.7% and 22.1%, and a high oil yield of 918.9 kg ha^{-1}.

CONCLUSION

Irrigation rates of 75% and 100% ET_O favored an increase in oil content in the three soybean cultivars under study herein. The cultivar BMX Ponta showed the highest total oil production values in both harvests.

Our data further confirmed that water supplementation is necessary for a greater oil yield. Intermediate irrigation rates of 25% and 50% showed the best results for efficient irrigation and, consequently, a greater economic productivity of water.

Table 1 - Oil production (%), oil productivity (kg ha^{-1}), water productivity (PA, kg ha^{-1} mm^{-1}) and economic water productivity (PEA, US\$ ha^{-1} mm^{-1}) for the different cultivars.

Cultivars	-----------------------------Crop 1-----------------------------				----------------------------Crop 2--------------------------------			
	Oil production	Oil productivity	PA	PEA	Oil production	Oil productivity	PA	PEA
NS 6909	19.38c*	1,114.91b	2.51b	1.59b	18.83ab	1,018.43b	2.27b	1.39b
BMX Ponta	20.82a	1,252.06 a	2.83a	1.79a	19.54a	1,136.77 a	2.59a	1.59a
BMX Valente	20.12b	1,292.46 a	2.90a	1.84a	18.69b	1,146.94 a	2.55a	1.56a
**CV (%)	4.29	12.59	12.88	12.88	5.43	12.47	13.32	13.32

*Average values within columns, followed by different lowercase letters differ significantly from at 5% probability of error as per Tukey's test.
**CV = coefficient of variation.

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DECLARATION OF CONFLICT OF INTEREST

The authors declared that there are no conflicts of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception of the study and to the preparation of the manuscript. All authors reviewed the manuscript and approved the final version.

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