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Article

# Determination of the Permanent Wilting Point of *Physalis peruviana* L.

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**Abstract:** The soil–water potential limit, or permanent wilting point (PWP), of *Physalis peruviana* L. is not known. Thus, determining the PWP of *P. peruviana* in different soils is essential to plan crops and manage irrigation in order to optimize the use of water and electricity. The objective of this study was to determine the PWP for *P. peruviana* in sandy and sandy clay loam soils. In a greenhouse, *P. peruviana* plants were grown in pots with different types of soil and maintained at 80% of field capacity. At intervals of 10 days, the irrigation of three pots was stopped, and when the plants wilted, they were transferred to a dark chamber without a vapor pressure deficit to verify if they would return to turgidity. When turgidity was not recovered, the PWP was considered, and the soil matric potential was determined by the water retention curve method. In sandy soil, *P. peruviana* wilted, on average, 1.7 days faster than in sandy clay loam soil. Regardless of the soil, matric potential equivalent to PWP decreased throughout the *P. peruviana* crop cycle. For sandy soil, the matric potential equivalent to PWP of *P. peruviana* ranges from −180 kPa (equivalent to 12% of the estimated value with a moisture release curve) to −2266 kPa (151% of the estimated value). In sandy clay loam soil, this matric potential ranges from −665 kPa (44% of the estimated value) to −1611 kPa (107% of the estimated value). The results contribute to water management and calculation of available water for *P. peruviana*; however, different soil textures do not have a single matric potential equivalent to PWP.

**Keywords:** available water; soil texture; soil matric potential; water deficit



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## 1. Introduction

Water has been shown to be the most limiting input to crop growth and yield [1]. In addition, estimates of the effects of global climate change have indicated an increase in the occurrence of drought events [2,3]. If this is confirmed, the situation will worsen further, causing significant impacts on plant development and, consequently, on food production. Thus, the correct and efficient use of water resources requires a systemic approach of factors related to their availability and use in the social sphere [4], besides detailed planning and correct management of agricultural crops. In this context, the demand for studies on soil properties and on the limitations imposed on water absorption by plants under water scarcity conditions has become increasingly important [1]. These responses contribute to understanding crop behavior and will certainly support decision-making during irrigation management [5].

In general, water management consists in determining water requirements and the appropriate time of irrigation. There are several ways to manage irrigation, and climate-based and soil-based managements are the most used [5–7]. To perform irrigation management, precise information on various parameters related to crop, soil, equipment, and climate is needed. Knowledge of the soil moisture equivalent to the permanent wilting point (PWP) is essential for irrigation management, either soil-based or climate-based. The PWP is necessary to determine the lower limit of soil–water content that a plant can extract. This way, it is also possible to calculate the available water for agricultural crops and improve the efficiency of water resource utilization.

PWP is defined as the water content of a soil at which the leaves of a plant growing in that soil reach irreversible wilt, even if placed in a water vapor-saturated atmosphere [8]. This classic concept is derived from the pioneering studies of Briggs and Shantz [9], Richards and Weaver [10], and Veihmeyer and Hendrickson [11]. These authors determined wilting points for a wide variety of plant species grown in different soils. Their conclusion was that different species wilt at similar matric potentials, regardless of soil texture.

The standardization of this physiological wilting occurred after that, according to the procedure described by Furr and Reeve [12], who used sunflower (*Helianthus annuus* L.) as an indicator plant, which became known as the physiological method of PWP determination. However, after advances in the understanding of the relationship between plant wilting and soil–water content, the study conducted by Richards and Weaver [10] was crucial for the adoption of the already classic concept of PWP. Soil scientists define PWP as the water content retained in the soil at a matric potential (ÿ) of −1500 kPa (soil wilting point) [9].

Many years later, Gee et al. [13] in their research pointed out some problems in studies carried out in the past. The authors examined the assumption of sample equilibrium on a pressure plate and concluded that the hydraulic conductivities of samples at −1500 kPa are so low that they never equilibrate, even after many days on a plate. Measurements with thermocouple psychrometers showed that the actual potentials of the sampled water ranged from −660 to −990 kPa after 10 days in a porous plate at −1500 kPa pressure. To get an idea of the error in irrigation management, differences between the measured and estimated PWP values with a matric potential of −1500 kPa must be analyzed.

In addition to the above, the consideration that PWP is a static soil characteristic has also been contradicted in the literature, as it represents a simplification of processes that occur in the soil–plant–atmosphere continuum. Authors describe that the process of quantifying the permanent wilting point becomes more complex when it is verified that different plants respond differently to soil moisture [14–16]. This indicates that soil moisture alone is not an appropriate criterion for defining the availability of water to the plant. According to Van Lier and Gubiani [17], characteristics, such as root geometry and distribution as well as limiting water potential to roots, that are intrinsic resistances of plants associated with soil–water potential and conductivity of the soil near the roots determine the plant's capacity to absorb water at rates compatible with the atmospheric demand.

Recent studies have shown that the matric potential equivalent to PWP varies depending on the plant's phenological phase and soil texture [14,18–22]. Experimental results on soil matric potential at the beginning of wilting show a very high variability. Wiecheteck et al. [21] found PWP ranging from −1637 to −2417 kPa for wheat and barley plants cultivated in soils with different textures. Procópio et al. [19] found PWP values of −325, −283, −352, −206, and −336 kPa for soybean, common bean, *Euphorbia heterophylla*, *Bidens pilosa*, and *Desmodium tortuosum* in the pre-flowering stage, respectively. In the initial grain filling stage, for the same crops, these values were −251, −283, −259, −983, and −242 kPa, respectively. Coelho et al. [14] also found values below −1500 kPa for PWP.

This parameter has already been determined for several crops, but there is still incipient knowledge about this variable for some crops that have recently shown remarkable prominence in the agricultural market. A crop that stands out in this context is *Physalis peruviana* L., belonging to the *Solanaceae* family [23,24]. Known in Brazil as 'Fisális', *P. peruviana* has recently entered the ranking of small fruits and has shown great potential for the national and international market [25,26]. This crop is seen as an excellent alternative for cultivation, since it develops in several climates and soil types, besides showing good economic return [23].

Information about the need for water for *P. peruviana* is still scarce. Regarding *P. peruviana*'s PWP, there is no reference in the literature. Therefore, studies are necessary to determine PWP at different growth stages of *P. peruviana*. This information is essential for calculating available water in the soil and performing crop water management. Unfamiliarity with PWP may result in excessive water application, leading to hypoxia situations, nutrient leaching, and electrical energy waste [27]. This lack of information can also result in insufficient water application, reducing plant growth and yield [28]. Regardless of underestimating or overestimating PWP, it is evident that this error causes economic losses to farmers.

The fact that there are no references to *P. peruviana* is mainly because its commercial cultivation in Brazil started a few years ago [29]. Cultural practices and managements are often based on other crops of the same family, but with high yield, such as tomato (*Solanum lycopersicum*) [30,31], or even based on technical bulletins from other growing regions. Thus, establishing cultivation standards and adopting management techniques that enable yield gains are essential for *P. peruviana* to reach higher levels in the agribusiness production chain.

Based on the above, the hypothesis is that *P. peruviana*'s PWP differs from that established by a matric potential of −1500 kPa and that it varies in different growth stages and soil types. Therefore, in this study, water content and equivalent soil matric potentials to PWP were evaluated in different growth stages of *P. peruviana* in different soil types. The expectation is that the plant will exhibit lower matric potentials at the end of the cultivation cycle and in soils with lower water retention capacity.

## 2. Materials and Methods

### *2.1. Characterization of the Experiment and Experimental Design*

The experiment was carried out in a greenhouse from July to November 2020. The structure is located in the experimental area of irrigation and drainage, belonging to the Agricultural Engineering Department of the Federal University of Viçosa (DEA/UFV), in Viçosa–MG, Brazil, located at the geographical coordinates 20°45′ S, 42°52′ W, and 648 m altitude. Hourly data were collected for air temperature and relative humidity during the experimental period (Figure 1).

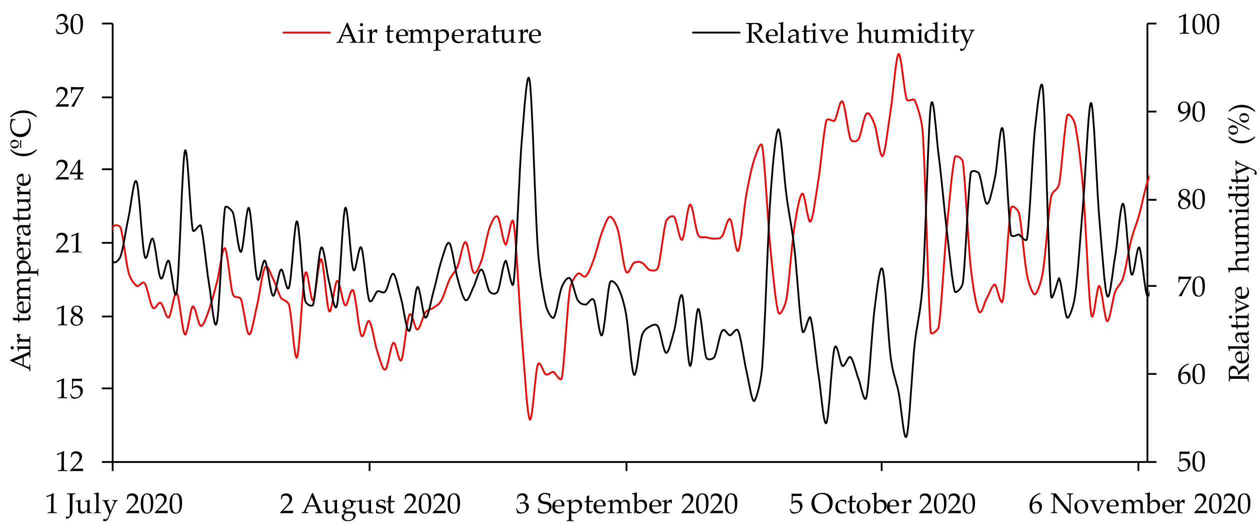


**Figure 1.** Climatic characterization inside the greenhouse during the experimental period. Daily variations in air temperature (°C) and relative humidity (%) in the cultivation cycle of *Physalis peruviana*. Viçosa–MG, DEA–UFV, 2020.

The experiment was conducted in a completely randomized design, with three replicates. The treatments were composed of *P. peruviana* plants grown in plastic pots, in two different types of soil, one of sandy texture and the other of sandy clay loam texture, according to the classification of Embrapa [32]. Samples were taken from different sites of the irrigation and drainage area to establish the textural differences. After the first laboratory confirmation, the demarcated points were chosen for collection. These soils were chosen because they were among those recommended for *P. peruviana* cultivation [33]. For the chemical and physical characterization of the soils, samples were collected in the 0–20 cm layer, the same layer used to collect soil and fill the pots. Macronutrients (P, H + Al, K, Ca, Mg) and particle-size composition were determined (Table 1). The analyses were carried out in the soil, plant tissue, and fertilizer analysis laboratory of the soil department of UFV.

**Table 1.** Physical–chemical composition of the soils used in the experiment.

| Textural Classification | | | | Sand | | | Silt | | | Clay |
|---|---|---|---|---|---|---|---|---|---|---|
| Sandy (SAN) | | | | 84 | | | 3 | | | 13 |
| Sandy Clay Loam (SCL) | | | | 57 | | | 13 | | | 30 |
| Soils | pH ($H_2O$) | P | K | H + Al | $Al^{+3}$ | $Ca^{+2}$ | $Mg^{+2}$ | CEC | V | OM |
| | | -- (mg $dm^{-3}$) -- | | ---------------- (cmol$_c$ $dm^{-3}$) ---------------- | | | | | (%) | (dag $kg^{-1}$) |
| SAN | 5.6 | 10.9 | 47 | 2.97 | 0 | 0.45 | 1.42 | 8.38 | 51.5 | 1.88 |
| SCL | 6.0 | 191.8 | 230 | 3.96 | 0 | 4.41 | 3.92 | 14.75 | 73.2 | 4.30 |

Sand, silt, and clay contents (dag $kg^{-1}$).

### 2.2. Preparation of Pots

The plants were cultivated in plastic pots with an upper width of 20 cm, a lower width of 16 cm, and a height of 20 cm, resulting in a volume of 5 L. These pots were filled with 3.6 kg of dry soil, for both the sandy soil and the sandy clay loam soil. Before filling the pots, the volumes collected from the two types of soil were pounded to break up clods, homogenized, air-dried, and passed through a 2 mm mesh sieve. Soon after, the soils were fertilized, respecting the requirements of each type of soil for correction.

Fertilization for *P. peruviana* was carried out according to the recommendation for tomato [33] because, in Brazil, there is still no specific fertilization recommendation for *P. peruviana*. For the sandy soil, 110 mg $dm^{-3}$ of P (single superphosphate, 20% $P_2O_5$), 80 mg $dm^{-3}$ of K (potassium chloride, 60% $K_2O$), and 40 mg $dm^{-3}$ of N (ammonium sulfate, 20% N) were used. For the sandy clay loam soil, no chemical corrections were necessary. In relation to acidity, it was also not necessary to apply correctives in either of the two soils used.

Five seeds of *P. peruviana* were planted in each pot. When the plants reached two pairs of complete leaves, thinning was performed, leaving only one plant per pot. The pots were arranged in the greenhouse at spacing of 1.5 m between rows and 1.5 m between plants.

### 2.3. Plant Material

The *P. peruviana* seeds used came from ripe fruits obtained from plantations located in the municipality of Diamantina, Minas Gerais. The fruits were cut, placed on sieves, and washed in running water to remove excess pulp. The seeds were extracted, arranged on trays with paper towel, and dried under ambient conditions (±25 °C) for 24 h. Before the experiment, tests were carried out to confirm the quality and viability of the seeds. Seed vigor analysis was performed with germination tests and seedling emergence analysis, following the procedures described in the rules for seed analysis [34]. Based on the results of these analyses, which showed that the seeds were viable and had a germination of 96%, the sowing operations were then performed. The tests were conducted at the seed analysis laboratory belonging to the agronomy department of the Federal University of Viçosa.

During the crop cycle, all lateral shoots that emerged during plant development were removed, keeping only the main branch. The cultivation row in the experiment was set up in the east–west direction according to the best position for the entry of solar radiation in the greenhouse. The plants were supported by bamboo stakes of about 3 to 5 cm in diameter and 1.50 m in height, with 0.5 m buried into the soil. The plants were tied with polypropylene strings along their development stage. The first tying was performed one month after transplanting, and the other ones every 25 days or as needed.

Pest control was carried out whenever necessary. Although the production is not organic, the products used were natural: biological insecticides (Dipel®) and repellent extracts (Neem oil).

### 2.4. Soil–Water Availability

The maximum water storage capacity of the soil was determined in each pot individually. After being filled with dry soil, the pots were saturated, sealed with a polyvinyl chloride (PVC) film, and suspended to drain excess water. After drainage stopped (24 h), the pots were weighed again, and the difference was considered to be the maximum soil–water retention capacity, according to the methodology described by Silva et al. [35].

Water replacement was carried out daily according to the gravimetric method, based on daily weighing with an electronic scale of 0.01 g accuracy, considering the daily increment of biomass of the plants. For this, each treatment had a "test" plant, on which the fresh matter measurements were performed. Water replacement was carried out so that soil moisture reached water availability levels corresponding to 80% of the maximum water retention capacity.

### 2.5. Determination of Permanent Wilting Point

The permanent wilting point (PWP) of *P. peruviana* was quantified at 10-day intervals. Along the entire cultivation cycle of *P. peruviana*, eleven determinations of PWP values were performed. Every 10 days, three pots of each type of soil were selected to be subjected to water deficit (Figure 2). Water replacement was not performed, and the soil reached the PWP during the desired stages.


**Figure 2.** (**A**) Morphological responses in hydrated plants (**B**) and plants under water deficit.

From this stage, at the first sign of wilting of the plants, the pots were transferred to a dark chamber with relative humidity close to 100% at the end of the day. At dawn, the return to turgidity of each plant was checked, adopting the criterion that, if at least one leaf recovered, the pot would be taken back to the greenhouse and continue to be maintained without irrigation, and so on, until there was no definitive return to turgidity. On this occasion, if the plant did not recover to its turgidity, the soil was considered to have moisture content equivalent to PWP.

After identifying that the soil had a moisture content equivalent to PWP, the pots were removed from the dark chamber, and the plants were cut close to the soil. Then, a soil sample (without roots) was collected in this pot and weighed on a precision scale [36]. This sample was taken to a forced air circulation oven and kept at a temperature of 105 ± 5 °C until reaching constant mass. These mass values were then used to determine the gravimetric water content. The matric potentials equivalent to PWP were calculated based on the moisture contents and water retention curves for the different soils (Figure 3).

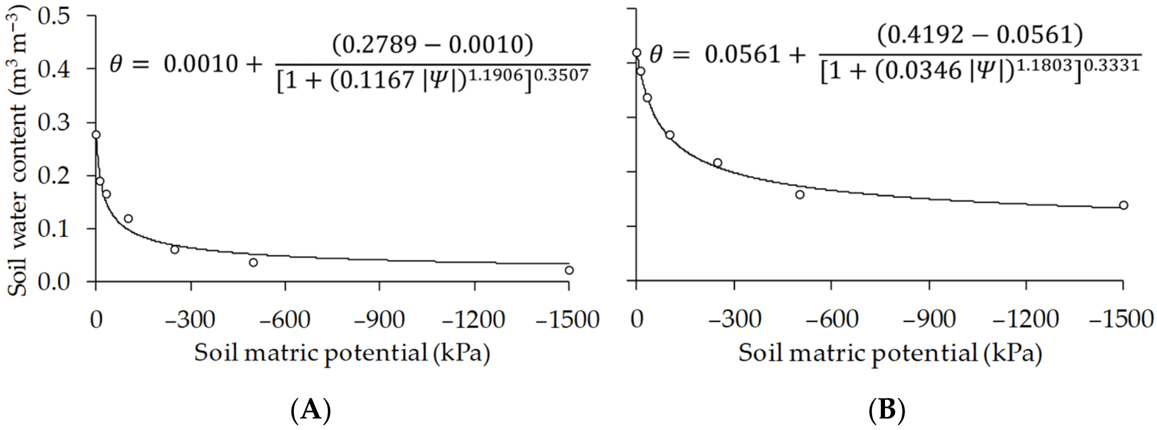


**Figure 3.** Water retention curves for sandy (**A**) and sandy clay loam (**B**) soils, fitted by the model of Van Genuchten [37].

To construct the soil–water retention curve, soil samples were subjected to matric potentials of −10, −33, −100, −250, −500, and −1500 kPa using Richard's pressure plate apparatus [38]. The mathematical model proposed by Van Genuchten [37], as shown in Equation (1) and Figure 3, was fitted to soil moisture data as a function of soil matric potentials.

$$\theta = \theta r + \frac{(\theta s - \theta r)}{[1 + (\alpha|\,\Psi|)^{n}]^{m}} \quad (1)$$

where $\theta$—soil volumetric water content, $m^3$ $m^{-3}$; $\theta r$—soil residual water content, $m^3$ $m^{-3}$; $\theta s$—soil saturation water content, $m^3$ $m^{-3}$; $\Psi$—soil matric potential, kPa; and $\alpha$, $n$, $m$—fitted parameters referring to the soil.

### *2.6. Statistical Analyses*

The quantitative factors were analyzed through regression, in which linear and quadratic models were tested. Model selection was based on the significance of the regression coefficients, using the *t*-test at 5% probability level, on the coefficient of determination ($R^2$) and on the biological phenomenon.

## 3. Results

After suppression of irrigation, the times required for the first signs of water deficit to appear in *P. peruviana* plants (characteristic wilt, with leaves rolled up from the edge to the midrib) varied according to phenological stage and soil texture. Figure 4 shows that, on average, these signs were observed three to eight days after the imposition of water deficit. The regression equations in Figure 4A,B indicates that the time for *P. peruviana* to wilt increased along the cultivation cycle.

In relation to the two types of soil, *P. peruviana* cultivated in sandy soil required a shorter time to wilt compared to the sandy clay loam soil. According to the regression equations, *P. peruviana* took three to six days to wilt in sandy soil (Figure 4A) and four to eight days to wilt in sandy clay loam soil (Figure 4B).

Figure 4C,D shows that *P. peruviana* was able to extract higher soil–water content as the cultivation cycle progressed. It is also verified that the plant was able to extract water at lower moisture contents when grown in sandy soil. The equations presented in Figure 3 were used to transform these moisture contents into soil matric potentials.

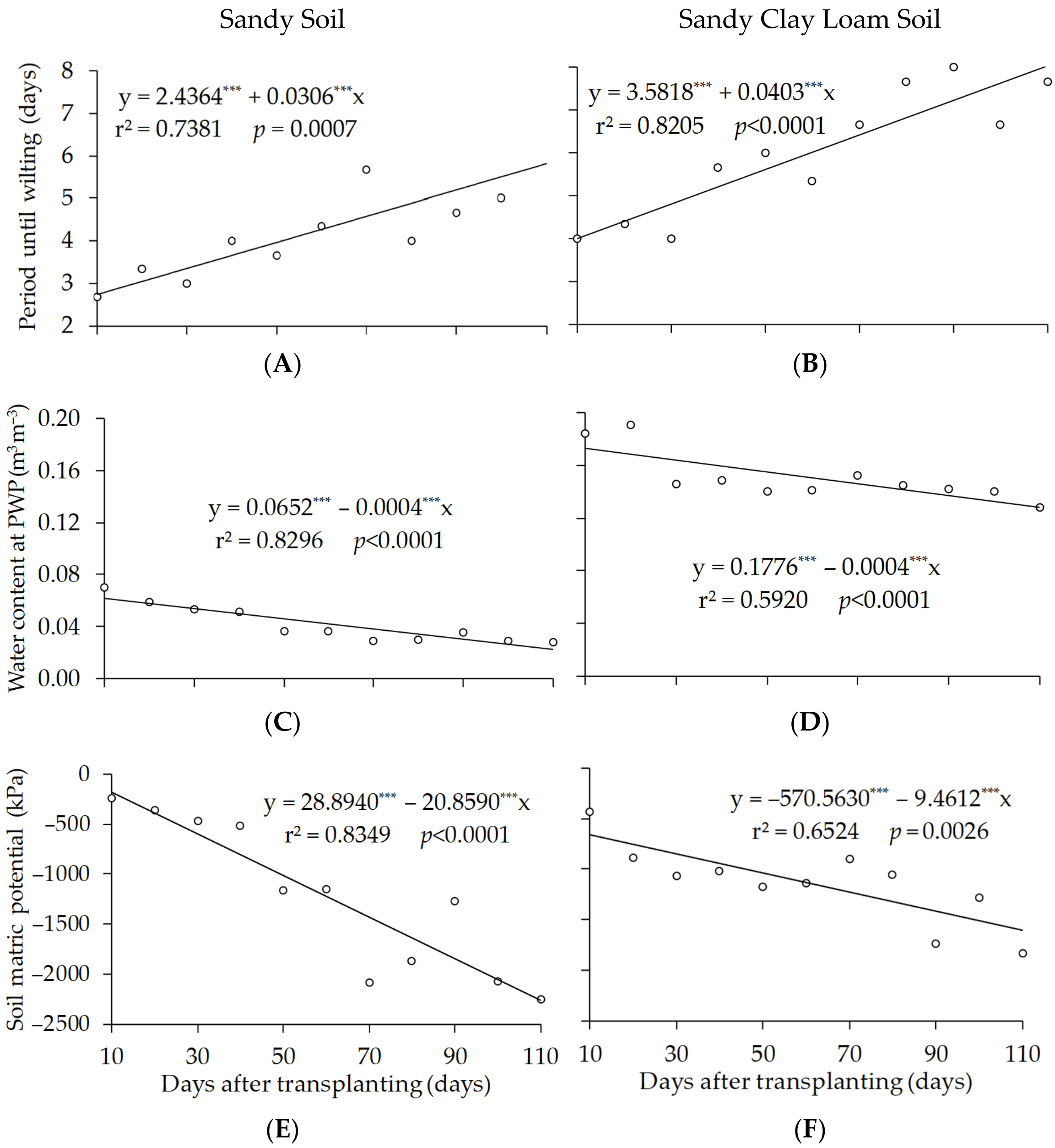


**Figure 4.** (**A**,**B**) Time required for plants to wilt and (**C**,**D**) water contents and (**E**,**F**) matric potentials equivalent to the permanent wilting point (PWP) of *Physalis peruviana* along one cultivation cycle in (**A**,**C**,**E**) sandy soil and (**B**,**D**,**F**) sandy clay loam soil. *** $p < 0.001$ by the *t*-test.

It can be verified that the behavior of soil matric potentials (Figure 4E,F) reflects the behavior of soil moisture (Figure 4C,D). Regardless of the type of soil, *P. peruviana* was able to extract water at lower matric potentials as the cultivation cycle progressed.

Figure 4E,F also shows that the matric potentials equivalent to PWP for *P. peruviana* cultivated in sandy soil ranged from −180 to −2266 kPa along the cultivation cycle. For the soil with sandy clay loam texture, this variation was from −665 to −1611 kPa. It can be noticed that, at the beginning of the cultivation cycle, the matric potentials equivalent to PWP for *P. peruviana* were higher when it was cultivated in sandy soil. In the middle of the cycle, the matric potentials equivalent to PWP became equal and, at the end of the cycle, the values were higher in the sandy clay loam soil.

Figure 5 shows the moisture contents equivalent to PWP along the *P. peruviana* cultivation cycle and the differences with PWP considering the standard soil matric potential of

−1500 kPa. For the sandy soil, it is noticed that the measured PWP of *P. peruviana* presented a value 90% higher than that estimated with the moisture release curve at the beginning of the cultivation cycle. This error is reduced as the cultivation cycle progresses, becoming negative (15% lower) at 70 DAT. For the sandy clay loam soil, the behavior was similar, but PWP measured in relation to that estimated for −1500 kPa matric potential with the moisture release curve was only 40% higher at the beginning of the cycle. At the end of the cultivation cycle, at 110 DAT, it was found that the measured PWP was 5% lower than the estimated value.

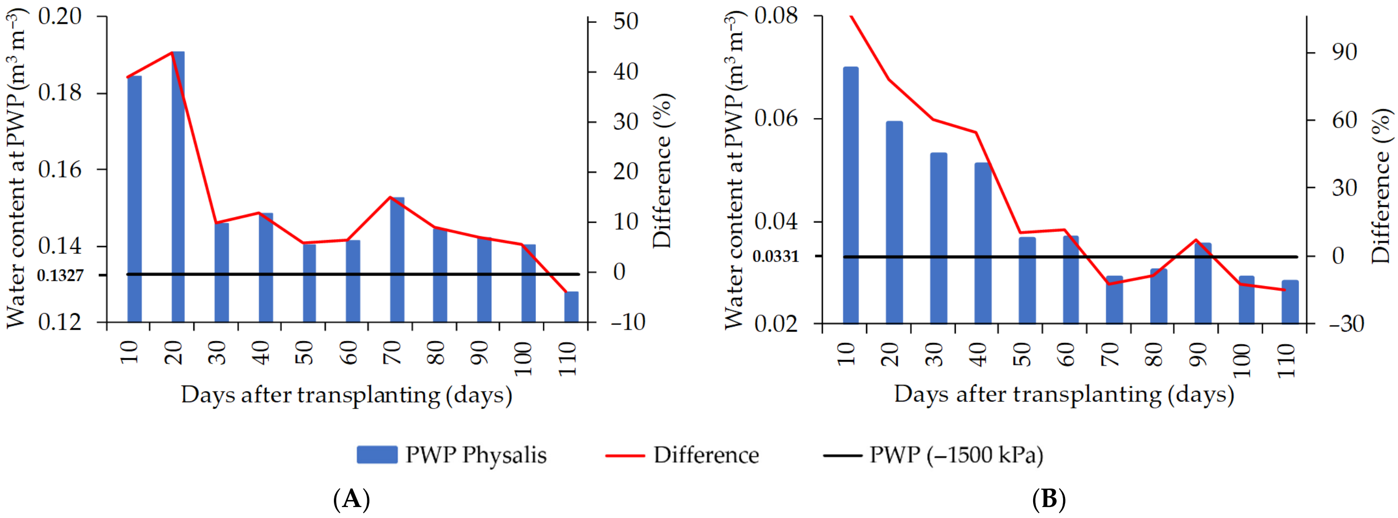


**Figure 5.** Water contents equivalent to the permanent wilting point (PWP) along the *Physalis peruviana* cultivation cycle and the differences with PWP equivalent to the standard matric potential of −1500 kPa for (**A**) sandy and (**B**) sandy clay loam soils.

## 4. Discussion

The time required for the soil to reach moisture equivalent to PWP increased throughout the *P. peruviana* cycle. This behavior is possibly explained by the smaller volume of soil explored by the roots at the beginning of the cycle. Thus, a smaller amount of soil is explored, and low water uptake leads to large variations in soil–water contents and matric potentials. In addition, another factor that contributed to the shorter times for *P. peruviana* to wilt at the beginning of the cycle was the requirement of higher water content in this period.

*P. peruviana* cultivated in sandy soil required a shorter time to wilt compared to the sandy clay loam soil. This occurred because the sandy clay loam soil has higher water retention than the sandy soil. Results similar to those presented here were obtained by Moline et al. [39], in the early development stages of tomato. The authors verified that, when the tomato crop had three pairs of true leaves, wilting occurred four days after water suspension for plants grown in sandy soil and five days after water suspension for plants grown in clay soil.

As the crop cycle progressed, *P. peruviana* was able to extract water at lower soil moisture levels. This means that the crop was able to extract water from the soil at lower matric potentials as it grew older. This behavior has already been clarified for crops with thin roots, which is the case of *P. peruviana*.

Crops with thinner roots and smaller amount of root hairs have limitation in water absorption [40]. In the early stages, due to these characteristics, even if the plant develops high suction, it is not able to absorb water, which reduces its flow from the soil to the roots. During plant development, root density and length increase until the beginning of flowering, allowing the absorption of water that is more strongly retained in the soil [39]. These results reinforce that there is a direct relationship between PWP and the capacity of plants to extract water from the soil, due to aspects related to the roots or to the species itself.

It is also observed that *P. peruviana* was able to extract water at lower moisture content when grown in sandy soil. This is easily understood, as sandy soils have lower water retention compared to soils with sandy clay loam texture [37,41,42]. This can be confirmed by the fitted retention curves (Figure 3).

During the initial phase of the cropping cycle, the matric potentials equivalent to the PWP for *P. peruviana* were lower when cultivated in sandy clay loam soil. As the cycle progressed, the matric potentials equivalent to PWP became equal, and toward the end of the cycle, the values were lower in the sandy soil.

The clay contents in soils are correlated with their water retention capacity [43–45]. The clay fraction affects the formation of micropores, which increase capillary forces and the specific surface area of soils, contributing to a higher water content retained at high matric suctions. According to Wiecheteck et al. [21], the movement of water toward the roots will be more significant for high matric suction in fine-textured soils compared to coarse-textured soils. Soils with finer texture have greater intensity of adsorption forces [46]. Sandy soils, due to their greater macroporosity and smaller specific surface area, lose the retained water more quickly, besides retaining a lower volume of water for the same matric potential [47].

Thus, soils of sandy clay loam texture, due to their composition with higher clay contents, maintain a larger water reservoir at PWP, thus making water available to crops for a longer period [41,48]. This also explains why *P. peruviana* plants take longer to show signs of wilting when grown in these soils.

For most agricultural crops, the matric potential of −1500 kPa is assumed to be that equivalent to PWP [49]. According to the regression equations in Figure 4E,F, *P. peruviana* had this matric potential equivalent to PWP at 71 and 98 DAT for the sandy and sandy clay loam soils, respectively. Before that, the soils showed matric potentials higher than −1500 kPa for PWP and, after these dates, lower values.

Regarding the moisture contents equivalent to PWP along the *P. peruviana* cultivation cycle, the differences with PWP are considered the standard soil matric potential of −1500 kPa. If the standard matric potential is considered for the irrigation management of *P. peruviana*, there may be errors between −15 and 110% in sandy soils. For sandy clay loam soils, the errors would be lower, ranging from −4 to 44%. PWP is an important parameter for irrigation management, as it is necessary for calculating the available water in the soil [49].

Our results differ from those obtained in the pioneering studies of Briggs and Shantz [9], Richards and Weaver [10], and Veihmeyer and Hendrickson [11]. Our findings do not suggest a single matric potential, regardless of soil texture. However, studies should be repeated with different soils and crops to confirm these results. For now, the results found in the present study help in the calculation of available water in the soil and will contribute to the water management of *P. peruviana*.

## 5. Conclusions

The determination of PWP is essential for irrigation management. Its correct measurement contributes to increasing the water use efficiency of agricultural crops. It was observed in the present study that PWP is affected by the phenological stage of *P. peruviana* and by different soil types. This suggests that the use of PWP equivalent to the matric potential of −1500 kPa is incorrect and that this strategy may lead to an increase in water consumption and losses in the yield and quality of *P. peruviana*.

Considering the same soil volume, *P. peruviana* cultivated in sandy soils reaches PWP 1.7 days faster when compared to sandy clay loam soils. Regardless of the soil, matric potential equivalent to PWP decreased throughout the *P. peruviana* crop cycle. For sandy soil, the matric potential equivalent to the PWP of *P. peruviana* ranges from −180 kPa (equivalent to 12% of the estimated value) at the beginning of the cycle to −2266 kPa (151% of the estimated value) at the end of the cropping cycle. In sandy clay loam soil, this matric potential ranges from −665 kPa (44% of the estimated value) at the beginning of the cycle to −1611 kPa (107% of the estimated value) at the end of the cultivation cycle of *P. peruviana*.

In the present study, only two types of soil were used. These different soil textures do not have the same matric potential equivalent to PWP. Therefore, future studies are needed in other types of soil to determine the PWP for *P. peruviana*.

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