



Article

Efficiency of Phosphorus Use in Sunflower

Anna Kézia Soares de Oliveira ¹, Enielson Bezerra Soares ¹, Manoel Galdino dos Santos ¹ , Hamurábi Anizio Lins ^{1,*} , Matheus de Freitas Souza ² , Ester dos Santos Coêlho ¹, Lindomar Maria Silveira ¹, Vander Mendonça ¹, Aurélio Paes Barros Júnior ¹ and Welder de Araújo Rangel Lopes ¹

- ¹ Department of Agronomic and Forest Sciences, Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró 59625-900, Brazil; annakezia@outlook.com (A.K.S.d.O.); enielsonufs@gmail.com (E.B.S.); manoel.galdino5@gmail.com (M.G.d.S.); estersantos12@hotmail.com (E.d.S.C.); lindomarmaria@ufersa.edu.br (L.M.S.); vander@ufersa.edu.br (V.M.); aurelio.barros@ufersa.edu.br (A.P.B.J.); welder.lopes@hotmail.com (W.d.A.R.L.)
- ² Department of Agronomy, Universidade de Rio Verde, Rio Verde 75901-970, Brazil; matheusfreitas@unirv.edu.br
- * Correspondence: hamurabi_a@hotmail.com

Abstract: Sunflower is an oleaginous plant of great importance worldwide that stands out in the production of edible oil and human food. The identification of differences between cultivars regarding the use of phosphorus and the production of achenes at different levels of phosphate fertilization is a viable strategy to allow its cultivation in soils with different concentrations of phosphorus, without compromising yield and reducing environmental damage associated with excessive applications of phosphate fertilizers. Thus, the objective of this study was to evaluate different levels of phosphorus fertilization and sunflower cultivars regarding the efficiency of phosphorus use in two agricultural crops. The experimental design was in randomized blocks with four replications in split-plots, where four doses of phosphorus (50, 100, 150, and 200 kg ha⁻¹ of P₂O₅) were allocated in the plots, and in the subplots three sunflower cultivars (Aguará 06, Altis 99, and BRS 122). The phosphorus use efficiency of sunflower cultivars was estimated through agronomic efficiency, vegetative efficiency, agrophysiological efficiency, apparent recovery efficiency, and utilization efficiency. The dose of 50 kg ha⁻¹ of P₂O₅ provided the best phosphorus efficiency indices for the different sunflower cultivars in the two studied crops. Cultivar Aguará 06 was more efficient in conditions with P₂O₅ supply below 150 kg ha⁻¹, regardless of the crop. Sunflower cultivars had the best efficiency indices of phosphorus applied in the 2016 harvest.

Keywords: *Helianthus annuus* L.; efficiency indices; phosphate fertilization; genetic variability



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1. Introduction

Sunflower (*Helianthus annuus* L.) is an oleaginous species cultivated in many regions of the world, such as Russia, Ukraine, United States, Argentina, and China [1], due to its wide phenotypic plasticity. This crop has high nutritional value and medicinal properties through compounds extracted from seeds fixed in achene (dried fruit) of this oilseed [2]. In addition to the production of edible oil, sunflower has also been used as a raw material in the production of cosmetics, paints, lubricants, and biodiesel [3]. After the process of extracting oil from the seeds, sunflower bran is also a byproduct used as a protein source for human consumption or as a food supplement for ruminant and non-ruminant feed [2].

The sunflower crop has tolerance to drought and high temperatures. Consequently, sunflower is an alternative for rural producers located in semiarid regions. This oilseed is the main source of edible oil (40%) for African countries located in regions with food risk due to arid and semiarid conditions [4]. In addition to adapting to semiarid regions, sunflower has desirable agronomic characteristics, such as a short cycle, good productivity, and high oil quality and yield, allowing the producer to obtain a human and animal food

source and economic returns in the short term [5]. However, these advantages are only achieved by agricultural properties when all the technology involved in the production of this crop is adjusted to the adverse conditions of the semiarid region.

Highly productive crops are achieved through the careful adjustment of agricultural practices such as tillage, fertilization, weed management, and phytosanitary control [6–9]. For sunflower, balanced nutrition directly affects the production of achenes, oil, and fatty acid content [10–15]. reported that the supply of nitrogen (N) is crucial for the production of unsaturated fatty acids (oleic and linoleic acids), compounds directly correlated with the high quality of sunflower oil [16]. However, high doses of N can decrease the oil concentration and increase the risk of lodging due to excessive vegetative growth of the plant, resulting in reduced yields. Another important nutrient for sunflower is potassium (K). Studies have shown that the proper application of this nutrient increased the levels of oleic acid, linoleic acid, and proteins in sunflower seeds, important characteristics for the food and energy industries.

The benefits of phosphorus (P) fertilization for sunflower have also been described in the literature. Studies have shown that the application of P accelerates growth and increases sunflower yield [17,18]. This nutrient is required until seed filling, with a rate of remobilization of leaves and stems for maturing achenes between 30 to 60% [19]. The lack of P in plants, especially at the beginning of the vegetative cycle, results in lower growth, delay in flowering, less filling of the achenes, and lower oil content [20,21]. Although previous studies have already demonstrated the productive behavior of sunflower and P application rates [22–25], few studies have been published conducted in semiarid regions, especially for the Brazilian semiarid region. Nutrient supply based on recommendations for humid or semi-humid regions should not be extrapolated to dry conditions because, in addition to environmental conditions, the cultivation system in the semiarid region is extremely peculiar [26]. This extrapolation can lead to lower yields or inefficiency in the use of the nutrient. Ref. [27] observed that even reaching the maximum yield of achenes for sunflower hybrids with 180 kg ha^{-1} of N, the maximum yield was lower in dry compared to wet conditions, resulting in lower efficiency in the use of this nutrient.

The application of nutrients, especially for those minerals and non-renewables such as P, should focus on the efficiency of their use, not just on the final yield obtained [28]. This is a good strategy to extend the shelf life of reserves, sustain agricultural productivity, and reduce the environmental impacts associated with the excessive use of this fertilizer [29,30]. The concept of nutritional efficiency characterizes the ability of a given genotype to achieve high growth and productivity rates with low application of the input [31]. This concept is important because varieties of the same crop can absorb and accumulate similar amounts of the nutrient; however, differences in growth and productivity can occur due to the nutritional efficiency of each variety [32]. Researchers observed that the evaluation of nutritional efficiency can differentiate varieties in terms of their adaptation to different soil fertility conditions [33,34].

The nutritional efficiency of cultivars is obtained through constructed indices that extract the relationship between the amount of applied nutrient and the production of biomass from shoots, roots, seeds, grains, fruits, and forage [31,35]. Some examples are agronomic efficiency (AE), physiological efficiency (PE), agrophysiological efficiency (APE), recovery efficiency (RE), and utilization efficiency (UE) [36]. Tests can be conducted in the field or under controlled conditions; however, the first has the advantage of encompassing other environmental factors that can affect the efficiency of nutrient use [22,37–39]. In this way, it is possible to select cultivars for a more efficient use of nutrients [40,41].

The availability of P to plants represents a key factor for global food security and sustainable agriculture [29,30]. Agriculture is highly dependent on phosphorus derived from phosphate rock, which is a non-renewable resource whose global reserves could be depleted within 40 to 150 years [42]. Thus, the supply of this nutrient via mineral fertilization should aim at maximum efficiency (amount applied versus productivity) rather than just gains in production. For sunflower, studies on the nutritional efficiency

of varieties under field conditions are needed for the Brazilian semiarid region. Thus, we hypothesized that sunflower cultivars differ in relation to P use efficiency under semiarid conditions. In this article, different combinations of phosphorus doses and sunflower cultivars were tested in field experiments (1) to investigate the interactions between P doses and the use efficiency indices of this nutrient; and (2) to determine adequate amounts of phosphate fertilizers to achieve maximum P use efficiency. It is hoped that the results of this field study will provide insight to help optimize the application of P-fertilizer in the sunflower crop, benefiting both the producer and the environment.

2. Materials and Methods

2.1. Location and Characterization of the Experimental Area

The experiments were conducted in the field at the Rafael Fernandes Experimental Farm, belonging to the Universidade Federal Rural do Semi-Árido (UFERSA), from September to December (1st agricultural harvest) of 2016, and March to July (2nd agricultural harvest) of 2017. The farm is located at the following coordinates: latitude 5°03'37" S and longitude 37°23'50" W Gr, with an approximate altitude of 72 m.

The region's climate, according to the Köppen climate classification, is of the BSw_h' type, with an average temperature of 27.2 °C, average annual rainfall of 766 mm [43]. The average meteorological data for the period in which the experiments were carried out for the two agricultural seasons are presented in Figure 1.

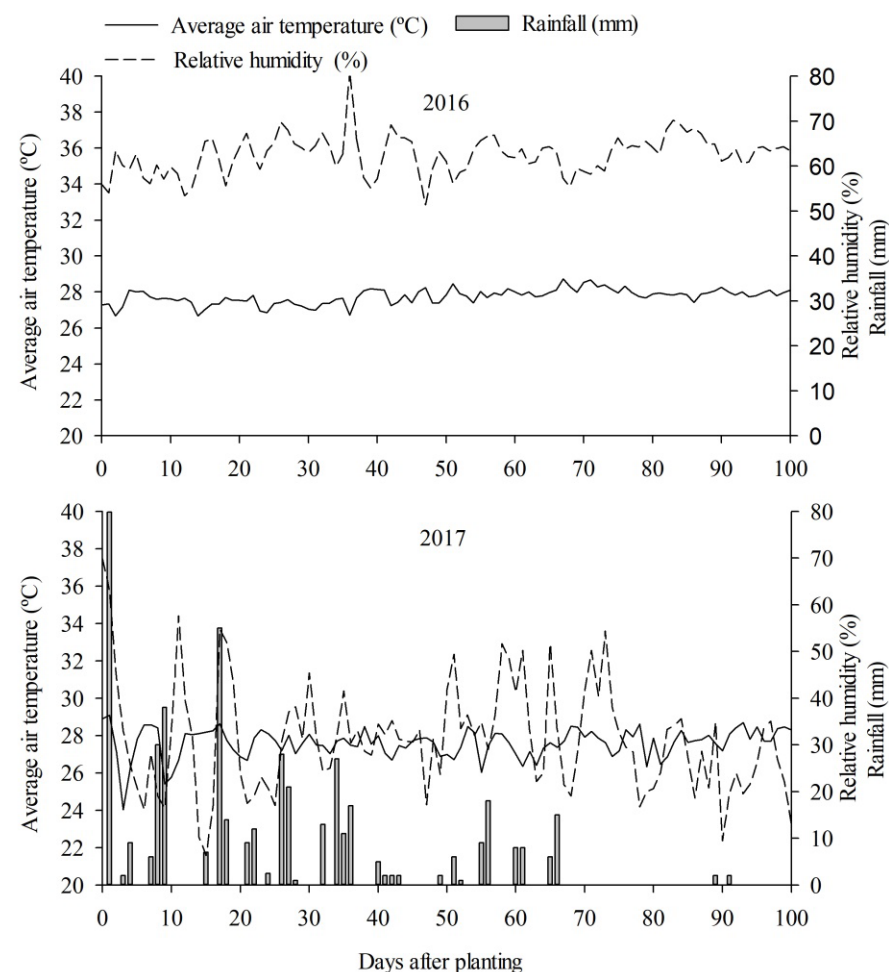


Figure 1. Average values of temperatures (°C), relative humidity (%), and precipitation (mm) in the two agricultural crops of sunflower. Source: INMET Automatic Meteorological Station and Rain Gauge from the Rafael Fernandes Experimental Farm (UFERSA).

The soil type of the experimental area is classified as Abrupt Eutrophic Red-Yellow Latosol, with a free sand texture [44]. Plowing and harrowing were carried out to prepare the soil. Soil samples were collected at a depth of 0–20 cm for chemical analysis. The chemical characteristics of the soil at a depth of 0–20 cm at 1st and 2nd agricultural harvest, respectively, were: pH = 6.50 and 5.63; electrical conductivity = 0.68 and 0.75 dS m⁻¹; organic matter = 9.28 and 12.78 g kg⁻¹; K = 51.08 and 58.8 mg dm⁻³; P = 4.21 and 3.0 mg dm⁻³; Na = 4.4 and 4.8 mg dm⁻³; Ca = 1.55 and 1.00 cmolc dm⁻³; and Mg = 0.85 and 1.80 cmolc dm⁻³. Fertilization was carried out in accordance with the recommendations of the State of Minas Gerais, Brazil, for the use of correctives and fertilizers [45]. The nitrogen source used was urea, of which 60 kg ha⁻¹ was between two applications as follows: 20 kg ha⁻¹ at the plantation and 40 kg ha⁻¹ 50 days after emergence. For the potassium source, potassium chloride was used, 50 kg ha⁻¹. For the phosphate fertilization, simple superphosphate was used, P doses were applied manually in the planting hole, according to each treatment established in the study.

2.2. Experimental Design

The experimental design used in each experiment was completely randomized blocks, with four replications. The treatments were arranged in split plots, with four phosphorus rates (50, 100, 150, and 200 kg of ha⁻¹ P₂O₅) being allocated in the plots and the three sunflower cultivars (Aguará 06, Altis 99, and BRS 122 in the subplots). In the study site, there are many Latosols, which in their surface layers have low pH values, in addition to clay and iron oxides. The soils also present P sorption which reduces the efficiency of phosphate fertilization. The available P content for plants is generally less than the available P content required for satisfactory agricultural production, therefore, the application of simple superphosphate (Ca(H₂PO₄)₂CaSO₄2H₂O) was determined at doses of 50, 100, 150, and 200 kg ha⁻¹ of P₂O₅, which are equivalent to 21.85, 43.70, 65.55, and 87.40 kg ha⁻¹ of P, respectively.

The total area of the experiment was 756 m², with each experimental plot consisting of four rows of plants with 0.30 m between plants and 0.70 m between rows, totaling an area of 12.6 m² (4.5 m × 2.8 m), in which the two central lines were considered, disregarding the plants at the ends, totaling a population of 47,619 plants ha⁻¹.

2.3. Implementation and Conduct of the Experiment

The irrigation system used was drip irrigation with spacing between the ribbons of 0.70 m and emitters of 0.30 m with an average flow of 1.5 L h⁻¹. Irrigation was performed daily based on the estimated crop ET_c (ET_c = ET_o × K_c), where the K_c values corresponded to the development of the sunflower crop [46,47].

The nitrogen source used was urea, with 60 kg ha⁻¹ between two applications: 20 kg ha⁻¹ at planting and 40 kg ha⁻¹ 50 days after emergence. Potassium chloride was used as a source of potassium, in which 50 kg ha⁻¹ was applied in planting as recommended by [45]. Fertilizers (N and K) were injected into the irrigation water with the aid of a diversion tank (“lung”). For phosphate fertilization, simple superphosphate was used, with the amounts applied according to the studied treatments. The doses of P₂O₅ were applied directly to the pit manually according to each treatment.

Sunflower was planted on 20 September 2016 for the first crop, and for the second crop, on 23 March 2017. Direct sowing was carried out at a depth of 2 cm, with 3 to 4 seeds being sown per hole. After 15 days of emergence, thinning was carried out, leaving only one plant per hole. Plant management and phytosanitary control were carried out in accordance with technical recommendations and crop needs.

Sunflower was harvested in 2016 and 2017, when the plants were at the R9 stage, which indicates the maturity of the achenes (physiological maturation), when the moisture content is between 30 and 32%, the bracts changed color from yellow to brown, and a large part of the back of the head turned brown [48], which occurred 88 days after sowing (DAS) for Embrapa 122 and 90 DAS for cultivars Aguará 06 and Altis 90 in the 2016 season. In the

2017 harvest, the cultivar Embrapa 122 was harvested at 91 DAS, Aguará 06 and Altis 99, 97 DAS.

2.4. Response Variables

The heads of all plants in the experimental area were collected and then dried. After drying, the achenes were threshed and cleaned. The productivity of achenes was calculated by the mass of achenes in an experimental plot, which was corrected to 13% moisture and transformed into kg ha^{-1} .

At the time of harvest, four plants from the useful area were collected, divided into stem, leaf, and capitulum; then, the washing process was carried out and, subsequently, the plant material was dried in an oven at $65\text{ }^{\circ}\text{C}$ for approximately 48 h or until constant mass was obtained. After drying, they were weighed to obtain the dry mass in grams. The total dry mass of the plant was considered the sum of the dry mass of the leaf, stem, and capitulum. Afterwards, the results were converted to g ha^{-1} , multiplying the result by the plant population and then to kg ha^{-1} .

The dry mass of each vegetable component was ground in a Wiley electric mill, equipped with a stainless-steel sieve, until the material became homogeneous. Then, the material was packed in plastic bags for subsequent chemical analysis of the nutrient content. Subsequently, sulfuric digestion was carried out to determine the phosphorus content in a spectrophotometer [49]. To determine the amount accumulated in each fraction of the plant, the concentration was multiplied by the dry mass of that fraction. To estimate the amount of total nutrients accumulated by the crop (kg ha^{-1}) at the end of the cycle, the concentration of the accumulated nutrient in the plant was multiplied by the population density.

The nutrient use efficiency (NUE) by sunflower crop was estimated through agronomic efficiency (AE), physiological efficiency (PE), agrophysiological efficiency (APE), apparent recovery efficiency (ARE), and utilization efficiency (UE), adapted from the methodology of [50–52].

The agronomic efficiency (AE) in the use of applied P was estimated by the relationship between the productivity of achenes with and without the application of P and the amount of P applied, in kg kg^{-1} (Equation (1)):

$$\text{AE} = (\text{PACp} - \text{PAsP})/\text{QP}_a \quad (1)$$

where PACp (kg) is the yield of sunflower achenes with P application; PAsP (kg) is the yield of sunflower achenes without P application; and QPa is the amount of P applied (kg).

The physiological efficiency (PE) of sunflower was estimated by the relationship between shoot biomass with and without P application and P accumulation in shoot biomass with and without P application, in kg kg^{-1} (Equation (2)):

$$\text{PE} = (\text{PBcP} - \text{PBsP})/(\text{APBcP} - \text{APBsP}) \quad (2)$$

where PBcP (kg) is the total biological productivity (stem, leaves, and capitulum) with P application; PBsP (kg) is the total biological productivity (stem, leaves, and capitulum) without the application of P; and APBcP (kg) is the accumulation of P in the aboveground biomass (stem, leaves, and capitulum) with application of P and APBsP (kg) is the accumulation of P in the aboveground biomass (stem, leaves, and capitulum) without the application of P.

Agrophysiological efficiency (APE) was estimated by the relationship between sunflower achene yield with and without P application and P accumulation in shoot biomass with and without P application, in kg kg^{-1} (Equation (3)):

$$\text{APE} = (\text{PACp} - \text{PAsP})/(\text{APBcP} - \text{APBsP}) \quad (3)$$

where PACp is the yield of sunflower achenes with P application; PAsP is the yield of sunflower achenes without P application; APBcP is the accumulation of P in the aboveground

biomass (stem, leaves, and capitulum) with application of P and APBsP is the accumulation of P in the aboveground biomass (stem, leaves, and capitulum) without the application of P.

The apparent recovery efficiency (ARE) was estimated by the relationship between the accumulation of P in the aboveground biomass with and without P application and the amount of P applied, in % (Equation (4)):

$$\text{ARE} = (\text{APBcP} - \text{APBsP}/\text{QP}_a) \times 100 \quad (4)$$

where APBcP is the accumulation of P in the aboveground biomass (stem, leaves, and capitulum) with application of P and APBsP is the accumulation of P in the aboveground biomass (stem, leaves, and capitulum) without the application of P; and QP_a is the amount of P applied.

The utilization efficiency (UE) is the relationship between the physiological efficiency (PE) and the apparent recovery efficiency (ARE), in kg kg^{−1} (Equation (5)):

$$\text{UE} = \text{PE} \times \text{ARE} \quad (5)$$

2.5. Statistical Analysis

Analyses of variance of agricultural crops were carried out separately for all characteristics evaluated, using the SISVAR 5.6 application [53]. After observing the homogeneity of variances between agricultural crops, a joint analysis of these same characteristics was applied. The response curve fitting procedure was performed using the Table Curve 2D program [54], with graphs created in SigmaPlot 12.0 [55]. Tukey's test ($p < 0.05$) was used to compare the means for sunflower cultivars and each agricultural season.

3. Results

3.1. Productivity of Achenes

The productivity of achenes in the 2016 crop had a responsive effect depending on the doses of P₂O₅ applied. The maximum yields obtained were 3273.21 kg ha^{−1} at the rate of 115.18 kg ha^{−1} of P₂O₅ for Aguará 06, 2790.85 kg ha^{−1} at the rate of 146.87 kg ha^{−1} of P₂O₅ for Altis 99, and 1697.29 kg ha^{−1} at the dose 122.40 kg ha^{−1} for BRS 122. In the 2017 crop, the maximum yields obtained were 1766.37 kg ha^{−1} for Aguará 06, at the dose 133.25 kg ha^{−1} of P₂O₅ and 1430.50 kg ha^{−1} for BRS 122 at the dose 187.13 kg ha^{−1} of P₂O₅. There was no curve adjustment for the cultivar Altis 99, obtaining an average of 1183.27 kg ha^{−1} of achenes. The dose that provided the best sunflower performance varied for the different cultivars. Among the harvests, the 2016 agricultural harvest provided higher productivity of achenes. The cultivar Aguará 06 produced more achenes than the other cultivars analyzed in the agricultural seasons.

3.2. Agronomic Efficiency (AE)

The interaction between P doses × sunflower cultivars × crops was significant for agronomic efficiency (AE). In 2016, all cultivars obtained greater agronomic efficiency at the dose of 50 kg ha^{−1} P₂O₅, with values of 29.03 kg kg^{−1}, 23.63 kg kg^{−1}, and 16.65 kg kg^{−1} for Aguará 06, Altis 99, and BRS 122, respectively. This efficiency was reduced by 58.5% (Aguará 06), 43.5% (Altis 99), and 66.1% (BRS 122) when applying the dose equivalent to 200 kg kg^{−1} (Table 1). At the doses of 50 and 100 kg ha^{−1} of P₂O₅, the cultivar Aguará 06 (29.03 and 26.46 kg kg^{−1}) showed greater agronomic efficiency compared to the cultivar Altis 99 (23.63 and 22.87 kg kg^{−1}), followed by BRS 122 (16.65 and 10.44 kg kg^{−1}) (Table 1). There were no differences between cultivars Aguará 06 and Altis 99 at doses of 150 and 200 kg ha^{−1} of P₂O₅, but these cultivars showed greater agronomic efficiency compared to BRS 122 (Table 1).

Table 1. Average values for agronomic efficiency as a function of sunflower cultivars within phosphorus doses in the 2016 and 2017 agricultural season.

Agronomic Efficiency in the 2016 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	29.03 a	26.46 a	12.66 a	12.06 a
Altis 99	23.63 b	22.87 b	14.55 a	13.34 a
BRS 122	16.65 c	10.44 c	4.67 b	5.64 b

Agronomic Efficiency in the 2017 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	12.28 a	10.52 a	7.42 a	4.24 a
Altis 99	3.09 b	1.97 b	3.47 c	2.38 b
BRS 122	0.02 c	2.83 b	5.21 b	4.59 a

Means followed by the same lowercase letter in the column do not differ from each other by Tukey's test at 5% probability.

3.3. Physiological Efficiency (PE)

There was an interaction between the doses of P × cultivar × crop for physiological efficiency (PE). In the 2016 harvest, there was only an isolated effect of cultivars and doses. The increase in P₂O₅ doses reduced the PE from 109.75 kg kg⁻¹ (50 kg ha⁻¹) to 65.22 kg kg⁻¹ (200 kg ha⁻¹), representing an average difference of 40.57% (Figure 2A). This behavior was not observed in 2017, there was a significant difference between cultivars only at the dose of 50 kg ha⁻¹ of P₂O₅, where the cultivar Altis 99 had the highest PE at the dose of 50 kg ha⁻¹ of P₂O₅ (315.02 kg kg⁻¹) (Figure 2B). Cultivars Aguará 06 and BRS 122 had no change in PE due to increased doses of P₂O₅ (Figure 2B, Table 2).

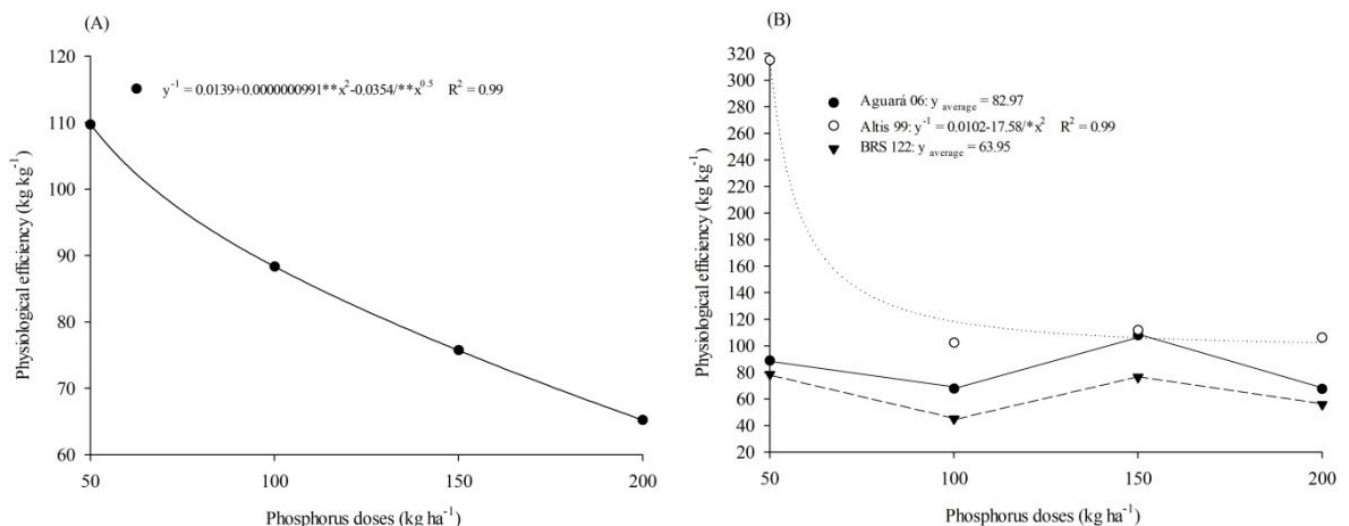
**Figure 2.** Physiological efficiency of sunflower as a function of phosphorus doses in the 2016 agricultural harvest (A) and 2017 agricultural harvest (B).

Table 2. Mean values for physiological efficiency as a function of sunflower cultivars within phosphorus doses in the 1st agricultural harvest.

Physiological Efficiency in the 2016 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	105.29 ab	84.58 a	68.38 b	47.81 b
Altis 99	128.69 a	99.85 a	97.94 a	91.22 a
BRS 122	95.27 b	80.51 a	60.87 b	56.62 b

Physiological Efficiency in the 2017 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	88.81 b	67.77 a	107.81 a	67.48 a
Altis 99	315.02 a	102.27 a	111.80 a	106.12 a
BRS 122	78.51 b	45.12 a	76.32 a	55.82 a

Means followed by the same lowercase letter in the column do not differ from each other by Tukey's test at 5% probability.

3.4. Agrophysiological Efficiency (APE)

The interaction between P doses × sunflower cultivars × crops was significant for agrophysiological efficiency (APE). In 2016, the highest agrophysiological efficiencies were obtained at the highest doses. The cultivar Aguará 06 obtained APE of 72.07 kg kg⁻¹ (150 kg ha⁻¹), Altis 99 of 54.76 kg kg⁻¹ (200 kg ha⁻¹), and BRS122 of 40.51 kg kg⁻¹ (200 kg ha⁻¹), respectively, and there were no APE differences between cultivars at the dose of 200 kg ha⁻¹ of P₂O₅ (Table 3). In the 2017 crop, the cultivar Aguará 06 showed a similar behavior to the 2016 crop. Among the crops, the main difference was observed between cultivars Altis 99 and BRS 122. In 2016, Altis 99 increased its APE with increasing P₂O₅ doses, achieving greater efficiency than BRS 122 at doses of 100, 150, and 200 kg ha⁻¹ (Table 3). This scenario was inverted in 2017, with higher APE for cultivar BRS 122 due to increased P₂O₅ doses, surpassing cultivar Altis 99 (Table 3, Figure 3B).

Table 3. Average values for agrophysiological efficiency as a function of sunflower cultivars within phosphorus doses in agricultural crops.

Dose of P ₂ O ₅	Grow Crops	1st Agricultural Crop	2nd Agricultural Crop
50 kg ha ⁻¹	Aguará 06	58.44 aA	29.59 aB
	Altis 99	26.82 bA	33.40 aA
	BRS 122	40.47 bA	0.00 bB
100 kg ha ⁻¹	Aguará 06	51.08 aA	37.35 aA
	Altis 99	43.75 aA	7.76 bB
	BRS 122	25.09 bA	27.58 aA
150 kg ha ⁻¹	Aguará 06	72.07 aA	65.07 aA
	Altis 99	43.93 bA	23.63 cB
	BRS 122	14.80 cB	46.12 bA
200 kg ha ⁻¹	Aguará 06	50.59 aA	21.05 bB
	Altis 99	54.76 aA	30.71 bB
	BRS 122	40.51 aA	49.17 aA

Means followed by the same lowercase letter in the column and uppercase in the row do not differ by Tukey's test at 5% probability.

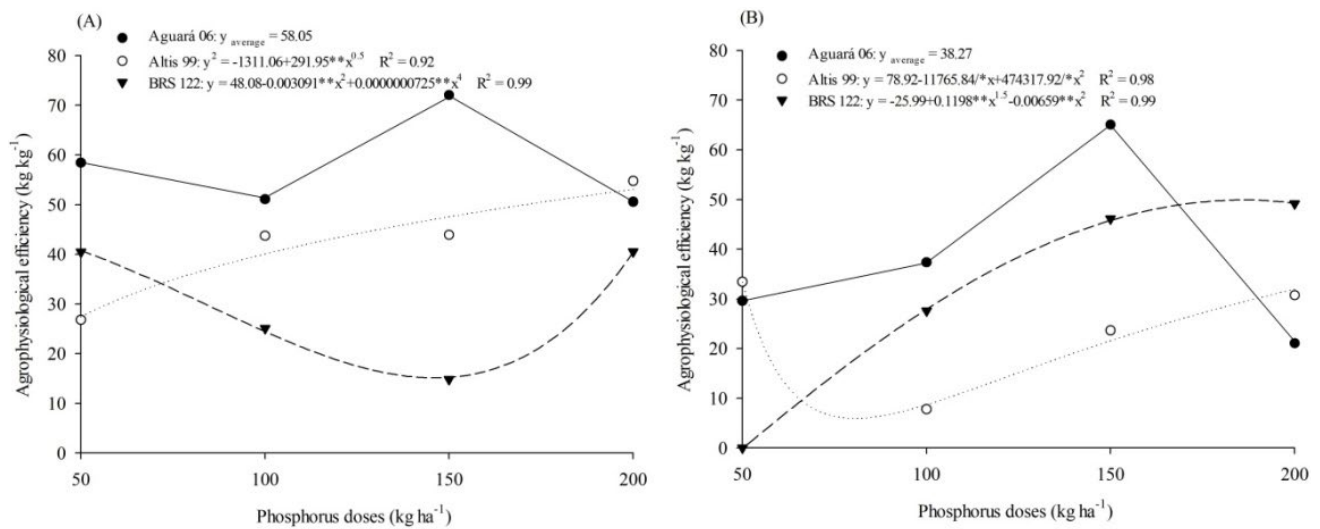


Figure 3. Agrophysiological efficiency of sunflower as a function of phosphorus doses in the 2016 agricultural harvest (A) and 2017 agricultural harvest (B).

3.5. Apparent Recovery Efficiency (ARE)

There was a significant triple interaction between phosphorus doses, sunflower cultivars, and crop for the apparent recovery efficiency index (ARE). In 2016, all cultivars had the highest average apparent recovery efficiency at the dose of 50 kg ha⁻¹ P₂O₅, with values of 54.22 kg kg⁻¹, 91.21 kg kg⁻¹, and 45.01 kg kg⁻¹ for Aguará 06, Altis 99, and BRS 122, respectively. This efficiency was reduced by 55.5% (Aguará 06), 27.1% (Altis 99), and 31.4% (BRS 122) when applying the dose equivalent to 200 kg kg⁻¹ (Figure 4A). At the doses of 100 and 200 kg ha⁻¹ of P₂O₅, the cultivars showed no significant difference for ARE (Table 4). In the 2017 harvest, only cultivar Altis 99 did not obtain the highest ARE at the dose of 50 kg ha⁻¹ of P₂O₅, the highest ARE by the cultivar was reached at the dose of 100 kg ha⁻¹ of P₂O₅ (28.11 kg kg⁻¹) (Figure 4B). Cultivars Aguará 06 and BRS 122 had higher averages of ARE of 42.38 and 42.45 kg kg⁻¹, respectively (50 kg ha⁻¹ of P₂O₅) (Table 4).

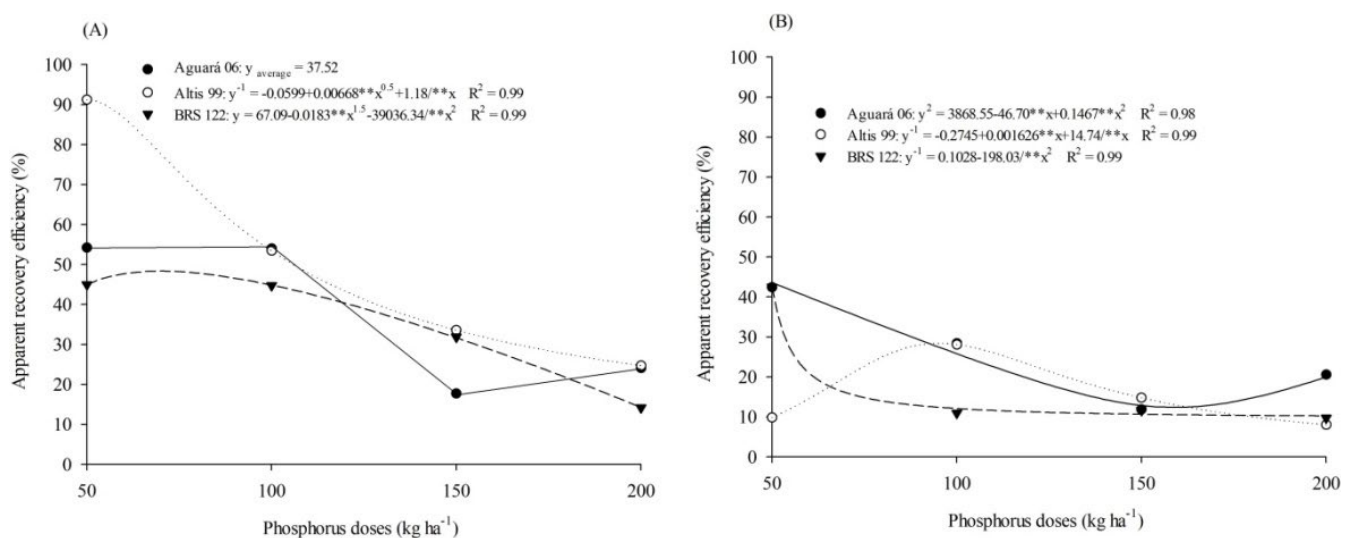


Figure 4. Apparent recovery efficiency of sunflower as a function of phosphorus doses in the 2016 agricultural season (A) and 2017 agricultural season (B).

Table 4. Average values for apparent recovery efficiency as a function of sunflower cultivars within phosphorus doses in agricultural crops.

Dose of P ₂ O ₅	Grow Crops	1st Agricultural Crop	2nd Agricultural Crop
50 kg ha ⁻¹	Altis 99	54.22 bA	42.38 aB
	BRS 122	91.21 aA	9.83 bB
	Aguará 06	45.01 bA	42.45 aA
100 kg ha ⁻¹	Altis 99	54.00 aA	28.39 aB
	BRS 122	53.43 aA	28.11 aB
	Aguará 06	44.72 aA	10.97 bB
150 kg ha ⁻¹	Altis 99	17.71 bA	11.88 aA
	BRS 122	33.57 aA	14.76 aB
	Aguará 06	31.85 aA	11.63 aB
200 kg ha ⁻¹	Altis 99	24.12 aA	20.57 aA
	BRS 122	24.70 aA	8.03 bB
	Aguará 06	14.15 aA	9.74 abA

Means followed by the same lowercase letter in the column and uppercase in the row do not differ from each other by Tukey's test at 5% probability.

3.6. Utilization Efficiency (UE)

The interaction between P doses x sunflower cultivars x crops was significant for P utilization efficiency. In 2016, all cultivars obtained greater efficiency of utilization at the dose of 50 kg ha⁻¹ P₂O₅, with values of 53.46 kg kg⁻¹, 115.67 kg kg⁻¹, and 41.99 kg kg⁻¹ for Aguará 06, Altis 99, and BRS 122, respectively. This efficiency was reduced by 78.54% (Aguará 06), 80.66% (Altis 99), and 81.33% (BRS 122) when applying the dose equivalent to 200 kg kg⁻¹ (Table 5). There were no differences between the cultivars Aguará 06 and BRS 122 in the doses studied, with Altis being more efficient in using P (Table 5).

Table 5. Average values for utilization efficiency as a function of sunflower cultivars within phosphorus doses in the 2016 and 2017 agricultural season.

Utilization Efficiency in the 2016 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	53.46 b	45.40 ab	11.90 b	11.47 ab
Altis 99	115.67 a	52.75 a	32.54 a	22.37 a
BRS 122	41.99 b	36.34 b	19.31 b	7.84 b
Utilization Efficiency in the 2017 Agricultural Harvest				
Grow Crops	Phosphorus Dose (kg ha ⁻¹)			
	50	100	150	200
Aguará 06	36.90 a	19.16 b	12.46 b	13.66 a
Altis 99	24.16 c	28.09 a	16.50 a	8.39 b
BRS 122	30.59 b	5.00 c	8.73 b	5.35 b

Means followed by the same lowercase letter in the column do not differ from each other by Tukey's test at 5% probability.

4. Discussion

4.1. Agronomic Efficiency (AE)

In the first crop, the increase in P₂O₅ doses reduced the agronomic efficiency of sunflower cultivars. Two factors may be involved; first, possibly because the higher doses are approaching the maximum yield or exceeding the need required by the culture for the production parameters, such as achene size, seed numbers, seed weight, among others. This behavior is known as the "law of decreasing increments", in which the yield response is gradually smaller with increasing doses of the nutrient [56]. Despite the higher efficiency

of Aguará 06 at lower doses, this cultivar presents a lower rate of increase in productivity due to the increase in the dose of P, resulting in higher angular coefficients (102.86) than the other cultivars (60.88 and 6.25 for Altis 99 and BRS 122, respectively). This fact equaled the productive efficiency between the cultivars Aguará 06 and Altis 99.

In the 2017 harvest, the cultivar Aguará 06 showed similar behavior to 2016, with greater agronomic efficiency (12.28 kg kg^{-1}) at a dose of 50 kg ha^{-1} of P_2O_5 and linear reduction up to 200 kg ha^{-1} of P_2O_5 (Figure 5B). This scenario was not observed for cultivars Altis 99 and BRS 122. The behavior of these cultivars was different between 2016 and 2017 for agronomic efficiency. Altis 99 has not changed its efficiency. On the other hand, BRS 122 increased its agronomic efficiency due to the increase in P_2O_5 doses (Figure 5B). Cultivar Aguará 06 had greater agronomic efficiency compared to other cultivars at doses of 50, 100, and 150 kg ha^{-1} of P_2O_5 , with values of 12.28, 10.52, and 7.42 kg kg^{-1} , respectively (Table 1). At a dose of 200 kg ha^{-1} of P_2O_5 , the cultivars Aguará 06 and BRS 122 had similar agronomic efficiency and superior to Altis 99 (Table 1).

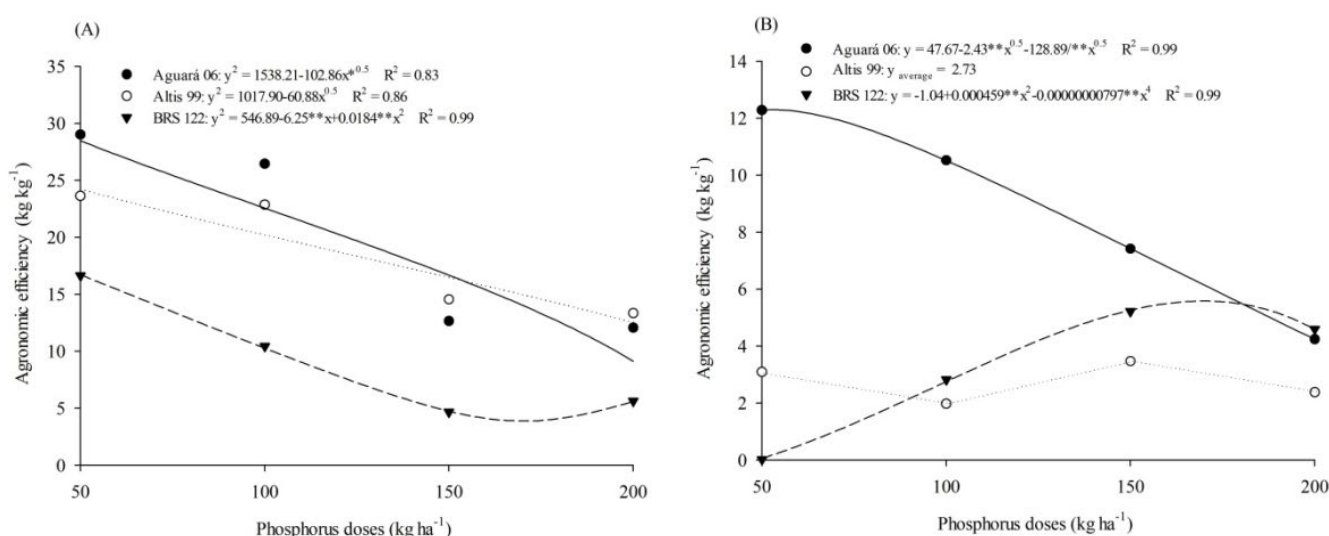


Figure 5. Agronomic efficiency of sunflower as a function of phosphorus doses in the 2016 agricultural harvest (A) and 2017 agricultural harvest (B).

For conditions with P_2O_5 supply below 150 kg ha^{-1} , Aguará 06 is more efficient in converting the P applied to achene production, regardless of the crop. Differences between cultivars in response to phosphorus have been reported in other crops [57–60]. Efficient cultivars, such as Aguará 06, can reduce fertilizer costs [61] and increase the marginal gains of the harvested product, important characteristics for producers with less investment power.

The greater agronomic efficiency of cultivars at doses lower than 150 kg ha^{-1} of P_2O_5 in the 2016 crop compared to the 2017 crop, possibly occurred due to climatic conditions. In the 2017 harvest, a large volume of rain was observed during planting and during the initial phase of sunflower development, and the high P content in the soil surface layer from fertilization may have resulted in a reduction in phosphorus concentration and consequently in availability for the plants. Phosphate fertilizers have high concentrations of soluble phosphorus and the occurrence of a rain event after application of the nutrient can result in runoff and a reduction in the concentration of phosphorus in the soil [62]. P losses can also occur from soil erosion, when runoff water gains enough energy, and the amount of phosphorus lost from the field increases dramatically, as in addition to solubilization in water, soil particles have the ability to fix phosphorus. Studies have already addressed the removal of P from the soil by water runoff and erosion [63–67]. Soil P accumulation is easily eroded with soil by rain [68].

The variation in the response of cultivars Altis 99 and BRS122 between crops may be related to the differential characteristics of P uptake and the response of cultivars to changes in the environment. Plants can develop a diverse set of strategies to obtain adequate P for their growth under P-limiting conditions. These strategies include modification of root architecture, development of long root system and thinner roots, exudation of organic acids, enzymes such as phosphatases and phytases, association with mycorrhiza, production of cluster roots, and expression of high affinity P transporters, all contributing to the increase in the efficiency of P uptake by the plant [69].

4.2. Physiological Efficiency (PE)

The lowest dose provided the highest biomass yield (stem and leaves) per unit of P accumulated in the biomass. This result indicates that cultivars invested in plant vegetative organs under lower P availability, different studies reported biomass partitioning and investment in plant active organs, such as young leaves and roots, under lower P availability [70,71].

Cultivars were more efficient at lower doses. Studies demonstrated that plants, in general, use phosphorus more efficiently when it is less available, thus expressing the greatest potential in the use of the absorbed nutrient [72,73]. In the 2017 harvest, the cultivars Aguará 06 and BRS 122 were the most efficient in the absorption and conversion of phosphorus for biomass production compared to the 2016 harvest, which indicates that the cultivars responded to phosphate application by developing adaptive mechanisms and translocating the P more easily for the plant and using it more efficiently. response to phosphate application, plants can develop adaptive mechanisms such as absorption, translocation and internal use, presence of hair on the root and lateral root growth, presence of mycorrhizae, and increase in root number among other resources for the formation of grains [74–76].

The PE of Altis 99 was higher compared to cultivars Aguará 06 and BRS 122 for doses of 150 and 200 kg ha⁻¹ P₂O₅ during 2016. In 2017, Altis 99 showed higher PE only for the 50 kg ha⁻¹ dose, equaling the PE values for cultivars Altis 99 and BRS 122 in the other doses (Table 2).

Cultivar Aguará 06 has greater reproductive efficiency and low vegetative growth, which indicates a better ability to allocate resources to reproductive organs, resulting in greater productivity of achenes. The greater vegetative efficiency of the cultivar was due to the greater accumulation of plant biomass, especially at low levels of P, the greater concentration of resources in the biomass is due to remobilization to growing tissues and vegetative organs.

4.3. Agrophysiological Efficiency (APE)

Differences between crops for these cultivars is related to the response to environmental change. According to [77], crop management and environmental factors, including sowing time, crop choice, soil properties and abiotic stresses, interact to influence crop demands for nutrients and nutrient uptake by plants. Compared to the 2017 crop, the 2016 agricultural crop (average temperature of 28 °C, average relative humidity of 65%, and no rainfall) cultivar Altis 99 had higher APE. Changes in environmental factors may have increased the requirement of the crop, resulting in lower APE in the 2017 harvest. As for cultivar BRS 122, the climatic conditions of the 2017 crop were more favorable for the uptake of P by the plants.

As can be seen in Figure 3A,B, the dose of 150 kg ha⁻¹ P₂O₅ and 200 kg ha⁻¹ P₂O₅ provided higher achene yields per unit of P accumulated in biomass (stem, leaf, and capitulum), possibly due to greater P absorption, increasing biomass, and translocation of photoassimilates for achene production.

The cultivar Aguará 06 obtained the highest APE for most doses tested in the two agricultural crops. Only at the dose 200 kg ha⁻¹, Aguará 06 did not provide higher APE compared to the other cultivars (Table 3).

The cultivar Aguará 06 has greater response capacity to added P, this cultivar produced more achenes with lower P fixed in tissues, indicating greater production capacity of achenes per unit of phosphorus absorbed when compared to other cultivars. This difference may be related to differences in nutrient intake and nutrient use. Cultivars with more biomass and/or efficient yield such as Aguará 06 are desired because they can adapt to a wider range of P environments without compromising yield. This ability of Aguará 06 can reduce the amount of P applied, environmental damage, as well as allow cultivation in regions with soils with low concentrations of P.

4.4. Apparent Recovery Efficiency (ARE)

Sunflower cultivars showed greater accumulation of P in biomass at lower doses of P, indicating no increase in phosphorus uptake at high doses of P_2O_5 . This fact raises the hypothesis that cultivars recover more phosphorus from the soil when the nutrient is less available on the ground. Some scholars have reported that P-efficient plants showed a significant increase in biomass under conditions of low P availability [68,78].

The highest apparent recovery efficiency averages were observed in the 2016 crop, especially in the lower doses of P_2O_5 , demonstrating a better response to the supply of P under the conditions of this crop. In the 2017 harvest, the average EAR between cultivars showed less variation with increasing doses.

In the apparent efficiency of recovery, the amount of nutrient accumulated in the aboveground biomass per unit of applied nutrient, the cultivars showed different results among the crops. The differences observed in phosphorus accumulation may have been influenced by environmental factors and genotypic differences between cultivars. The greater accumulation of P in the 2016 crop by cultivars Aguará 06, Altis 99, and BRS 122 contributes to greater recovery efficiency in this crop. In 2017, the fact that there is similarity in phosphorus uptake between cultivars at the different doses studied may have occurred due to greater phosphorus loss and immobilization, making the plants unavailable.

4.5. Utilization Efficiency (UE)

The greater efficiency of phosphorus use in the lowest doses of P_2O_5 indicates that the cultivars have greater adaptation to conditions of low P concentration. The sunflower response to phosphate fertilization is mainly related to its availability in the soil. When a dose of P is applied to the soil, most of the P is sorption to the soil. The sorption of P in the soil is the main cause of the decrease in the efficiency of phosphate fertilizers, since a small part of the P applied to the soil as fertilizer is sorbed and available to the plants.

In both crops, the cultivars Aguará 06 and BRS 122 had greater efficiency of use at the dose of $50 \text{ kg ha}^{-1} P_2O_5$, while cultivar Altis 99 had greater efficiency of use at the doses of 50 and $100 \text{ kg ha}^{-1} P_2O_5$ in the first and second crop, respectively (Figure 6B). Lower utilization efficiency averages were also observed in the 2017 harvest.

For the efficiency of use, it was observed that the lowest dose provided greater efficiency of P applied in both crops. The use of sunflower cultivars with high nutrient absorption and utilization efficiency can reduce the amount of P applied, as well as allow cultivation in regions with soils with low levels of this nutrient. The lowest utilization efficiency values in the 2017 harvest are associated with the occurrence of rain during sunflower cultivation. When soil is subject to erosion, P is also lost, reducing the efficiency of phosphorus use [79]. Water and wind erosion are significant factors that contribute to the low efficiency of phosphorus use worldwide and represent an economic and environmental risk [80].

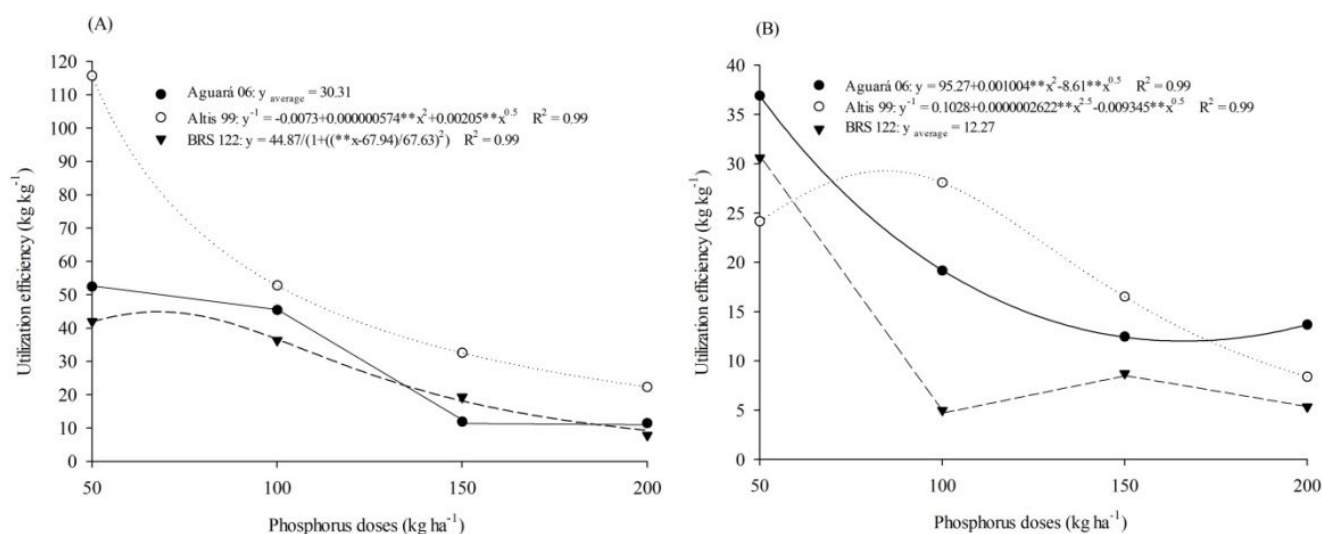


Figure 6. Utilization efficiency of sunflower as a function of phosphorus doses in the 2016 agricultural harvest (A) and 2017 agricultural harvest (B).

5. Conclusions

The dose of 50 kg ha⁻¹ of P₂O₅ provided the best phosphorus efficiency indices for the different sunflower cultivars in the two studied crops. Cultivar Aguará 06 was more efficient under conditions with P₂O₅ supply below 150 kg ha⁻¹ regardless of the crop. This ability demonstrates that the cultivar can adapt to a wider range of P environments without compromising yield, reducing fertilizer costs and increasing economic returns for producers, reducing environmental damage, and allowing cultivation in regions with low soils concentrations of P. The 2016 harvest had the best efficiency indices for P applied to sunflower.

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