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Phosphate Fertilizer Doses in Carrot Production in an Organic System

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HIGHLIGHTS

- Max yield of 103 and 115 t ha^{-1} at 974 and 1602 kg P_2O_5 ha^{-1} for Yoorin® thermophosphate and bone meal.
- The physicochemical characteristics did not present significant differences between fertilizers.
- Excess P_2O_5 above optimal rates reduced yield, stressing precise management.

Abstract: The growing consumer demand for organically grown vegetables highlights the need for research into organic fertilization strategies. Phosphorus, a key nutrient required in large quantities, warrants further investigation into its application doses and sources, particularly for short-cycle crops like carrots. This study evaluated the efficacy of bone meal and Yoorin® thermophosphate as organic phosphorus sources in carrot production. The experiment was conducted using the 'Fernanda' hybrid (Feltrin®) at 'Sítio Alvorada' in Botucatu-SP, Brazil. A randomized block design with four replications in a 2 x 6 factorial arrangement was employed, testing two organic fertilizers (bone meal and Yoorin® thermophosphate) at six phosphorus doses (0, 360, 720, 1080, 1440, and 1800 kg P_2O_5 ha^{-1}). Parameters assessed included fresh weight of shoots, roots, total biomass, plant and root length, diameter, yield, and root physicochemical properties (pH, soluble solids, titratable acidity, and the 'ratio'). Bone meal's slower nutrient release required higher doses (1586 kg P_2O_5 ha^{-1}) for optimal performance, while Yoorin® thermophosphate achieved peak effectiveness at lower doses (974 kg P_2O_5 ha^{-1}). Excessive phosphorus application beyond optimal doses led to yield reductions. No significant variations were observed in physicochemical attributes. Bone meal produced higher root yields compared to Yoorin® thermophosphate, but this difference was significant only at application doses above 1440 kg P_2O_5 ha^{-1}.

Keywords: *Daucus carota* L.; bone meal; thermophosphate; organic fertilization.

INTRODUCTION

The growing consumer demand for organically cultivated vegetables has significantly expanded organic production systems. Carrots, a popular tuberous vegetable, are highly valued for their nutritional profile, particularly their rich content of β-carotene, a precursor to vitamin A [1,2].Organic carrot production necessitates effective management practices, with fertilization being a cornerstone. Organic fertilization not only supplies essential nutrients for plant growth but also enhances soil quality and promotes sustainable agricultural systems [3,4].

Phosphorus, a nutrient frequently limiting crop yields, especially in tropical soils rich in iron and aluminum oxides, plays a pivotal role in carrot nutrition [5,6]. The efficient utilization of phosphorus is crucial for sustainable agriculture given its finite nature [7].

Organic phosphorus sources, such as bone meal and thermophosphate, provide environmentally friendly alternatives to conventional mineral fertilizers [8, 9,10]. Bone meal, derived from animal processing, offers both calcium and phosphorus while reducing agricultural waste [11]. Thermophosphate, a mineral phosphorus source, exhibits slow release properties, minimizing environmental impacts [12].

While organic phosphorus sources are increasingly used in organic farming, optimal application doses for carrots remain inadequately studied. The slower release of phosphorus from organic sources compared to mineral fertilizers necessitates tailored application strategies, particularly for short-cycle crops like carrots. Phosphorus is the fourth most absorbed nutrient by carrots and the third most exported [13,14]. It plays a critical role in plant metabolism, being essential for plant establishment and development, as it promotes root growth, enhancing water and nutrient uptake, which directly impacts root yield [15,16]. However, phosphorus deficiency negatively affects yield by reducing the absorption of other nutrients [17], while its excess can decrease the availability of metallic micronutrients, such as Zn [18, 19].

Organic carrot production requires efficient and sustainable fertilization practices. We hypothesized that bone meal and Yoorin® thermophosphate, as organic phosphorus sources, would positively influence carrot yield and quality due to their slow-release properties and ability to enhance nutrient uptake, particularly in short-cycle crops like carrots. This study aimed to evaluate the efficacy of bone meal and Yoorin® thermophosphate as sources of organic phosphorus in carrot production, assessing their impact on crop yield, root quality, and physicochemical properties.

MATERIAL AND METHODS

The experiment was conducted from June to October 2022 at Sítio Alvorada (22° 56'S, 48° 23'W, 810 m), a certified organic vegetable production area located in Botucatu, Brazil. According to the updated Köppen climate classification, the region has a tropical savanna climate (Aw), characterized by hot, rainy summers and cold, dry winters [20].The climatological normals for the period from 1991 to 2020 indicate average minimum, mean, and maximum temperatures of 17.24°C, 21.34°C, and 26.51°C, respectively, with an annual precipitation of approximately 1.500 mm distributed over 107 rainy days per year. During the experiment, the average monthly rainfall was 52.1 mm, with maximum and minimum temperatures of 25°C and 12.1°C, respectively. Figure 1 illustrates the distribution of precipitation and temperature throughout the study period, highlighting the climatic conditions during the crop cycle.

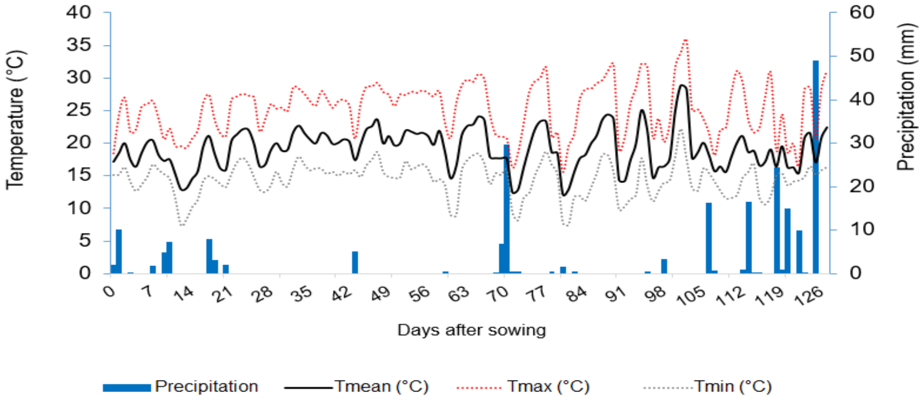

Figure 1. Precipitation, mean temperature (Tmean), maximum temperature (Tmax) and minimum temperature (Tmin) during the carrot crop cycle. FCA/UNESP, Botucatu-SP, 2022.

The soil at the experimental site was classified as a sandy-textured typic distrophic Red Latosol. A soil analysis of the 0-20 cm depth layer revealed the following characteristics: pH ($CaCl_2$) 6.3; organic matter content 19 g dm^{-3}; phosphorus 25 mg dm^{-3}; potassium 2.6 $mmol_c$ dm^{-3}; calcium 27 $mmol_c$ dm^{-3}; magnesium 11 $mmol_c$ dm^{-3}; sum of bases 41 $mmol_c$ dm^{-3}; cation exchange capacity (CEC) 54 $mmol_c$ dm^{-3}; and base saturation 76%. These findings indicate a soil with moderate organic matter content, adequate doses of essential nutrients, and a slightly acidic pH.

A randomized complete block design with four replications in a 2 x 6 factorial scheme was used to evaluate twelve treatments.These consisted of two organic fertilizers (bone meal and Yoorin® thermophosphate) applied at six P_2O_5 doses (0, 360, 720, 1080, 1440, and 1800 kg ha^{-1}). The dose of 360 kg P_2O_5 ha^{-1} aligned with regional recommendations based on soil analysis and the fertilization guidelines of the Boletim 100 of the Agronomic Institute of Campinas (IAC) [3], which recommends this value for carrot cultivation under similar soil conditions. Higher doses (up to 1800 kg ha^{-1}) were tested to evaluate the response of carrots to excessive phosphorus application.

Prior to sowing, the entire experimental area received 30 t ha^{-1} of organic compost, which was incorporated into the soil using a rototiller. Phosphate fertilizers were applied manually seven days before sowing and integrated into the soil. The organic compost contained 1.15% N, 1.30% P_2O_5, 1.57% K_2O, 1.14% Ca, 0.47% Mg, 0.20% S, and 30.0% moisture (wet matter basis).

Bone meal and Yoorin® thermophosphate contained 9.22% and 17% P_2O_5, respectively. Other nutrient contents of bone meal included 0.85% N, 24.41% Ca, 1.18% Mg, 1.70% S, and 8% organic matter.

The 'Fernanda' hybrid (Feltrin®) was used, seeds were sown manually on May 31, 2022, in four rows spaced 0.20 m apart with 0.05 m between plants. Thinning was conducted 14 days after sowing (DAS). The two central rows of each experimental plot (1.0 m x 1.0 m) were considered the useful area, while the lateral rows and plants at the ends of the plots were discarded. Sprinkler irrigation was used, with water depth determined based on crop evapotranspiration (ETc) and soil water balance. The ETc was calculated using reference evapotranspiration (ETo) data from a local weather station and crop coefficients (Kc) specific to carrot growth stages, following the recommendations for carrot irrigation described by Marouelli and coauthors [21]. Spontaneous weeds were controlled through manual weeding, performed every two weeks until crop establishment, to prevent competition for nutrients, water, and light.

Harvesting occurred 127 days after sowing (DAS). Ten plants were randomly selected from the central two rows of each plot for evaluation. Plant height, number of leaves, fresh weight of leaves and roots, root length, diameter, yield, total soluble solids, titratable acidity, and root pH were assessed.

Plant height was measured from the soil surface to the tallest leaf using a ruler. Root diameter was measured at the widest base of the root with a digital caliper. Fresh weight was determined using a precision scale. Yield per hectare was estimated based on the harvested plants.

To measure total soluble solids, juice extracted from three roots per plot was analyzed using a bench refractometer. Titratable acidity was determined by titrating 5 g of homogenized pulp diluted in 100 mL of distilled water. pH was measured directly using a digital potentiometer. All measurements adhered to the standards of the Adolfo Lutz Institute [22].

Data were analyzed using analysis of variance (ANOVA). The F-test was employed to evaluate the effects of sources, while polynomial regression was applied to the doses factor ($p \leq 0.05$). Statistical analysis was performed using Sisvar software [23].

RESULTS AND DISCUSSION

According to the analysis of variance, there was interaction between factors for root and total fresh matter weight, number of leaves and yield (Table 1).

Table 1. Summary of analysis of variance for fresh matter weight of leaves (FMWL), roots (FRMW), and total (TFW), plant height (PH), number of leaves (NL), root length (RL), root diameter (DR), and yield of carrot plants as a function of phosphorus doses for Yoorin® Thermophosphate and bone meal fertilizers. Botucatu-SP, 2022.

	FMWL	FRMW	TFW	PH	NL	RL	DR	YIELD
Fertilizers (A)	43,60^{ns}	1784,86 **	1270,09*	12,18^{ns}	0,52^{ns}	1,541^{ns}	60,87**	1142,0**
Doses (D)	38,55*	1754,90**	2244,44**	33,55^{ns}	5,23**	7,171^{ns}	212,29**	1123,2**
Interaction (AxD)	24,16^{ns}	1164,55**	1234,47**	47,49^{ns}	2,48**	2,930^{ns}	10,78^{ns}	745,4**
Residual	12,60	235,97	240,80	39,42	0,676	3,292	12,49	151,0
CV (%)	24,7	12,7	11,5	14,5	12,7	9,6	11,5	12,7

MS = Mean square; CV = Coefficient of variation; *, ** = Significant by F-test at 5% and 1%, respectively; ns = Not significant by F-test at 5% probability.

No significant differences were observed between bone meal and Yoorin® thermophosphate in terms of plant height, fresh weight or root length (Table 2). However, bone meal consistently produced thicker roots, with an increase of just over 2 mm (≈7.5%).

Table 2. Averages for plant height (PH), fresh matter weight of leaves (FMWL), root length (RL) and diameter (RD) as a function of Yoorin® thermophosphate and bone meal fertilizers. Botucatu-SP, 2022.

	PH (cm)	FMWL (g plant^{-1})	RL (cm)	RD (mm)
Yoorin® thermophosphate	42.6 a	15.3 a	18.7 a	29.7 b
Bone meal	43.6 a	13.4 a	19.1 a	31.9 a
CV (%)	14.5	25.6	9.5	11.5

CV: Coefficient of variation, *Averages followed by the same lowercase letter in the column do not differ from each other using the t test at 5% probability.

While there were no differences in fresh leaf matter weight between fertilizers, Yoorin® thermophosphate consistently produced higher yields of fresh root and total matter at the dose 720 kg P_2O_5 ha^{-1} (Table 3). However, at higher doses (1440 and 1800 kg P_2O_5 ha^{-1}), bone meal outperformed Yoorin® thermophosphate in terms of root and total fresh matter weight and yield. These findings likely reflect the distinct dynamics of these fertilizers in the soil.

Table 3. Comparative analysis of carrot growth parameters in response to varying phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers. Botucatu-SP, 2022.

	Doses (kg of P_2O_5 ha^{-1})					
	360	720	1080	1440	1800	CV%
Number of leaves per plant						
Yoorin® thermophosphate	6.5 a	7.6 a	6.4 b	6.3 a	6.1 a	12.6
Bone meal	5.9 a	6.1 b	7.6 a	7.3 a	7.3 a	
Weight of root fresh matter (g plant^{-1})						
Yoorin® thermophosphate	106.0 a	144.0 a	123.0 a	111.0 b	110.0 b	12.7
Bone meal	119.0 a	117.0 b	138.0 a	155.0 a	137.0 a	
Total fresh matter weight (g plant^{-1})						
Yoorin® thermophosphate	118.6 a	161.0 a	144.5 a	126.1 b	124.4 b	11.5
Bone meal	132.0 a	130.9 b	152.1 a	169.7 a	150.4 a	
Yield (t ha^{-1})						
Yoorin® thermophosphate	85.2 a	115.7 a	98.1 a	88.6 b	87.6 b	12.7
Bone meal	94.9 a	93.9 b	110.8 a	123.8 a	109.3 a	

CV: coefficient of variation. Means followed by the same lowercase letter in the columns do not differ from each other using the t test at 5% probability.

Yoorin® thermophosphate exhibited a more pronounced response to phosphorus applications, with peak yields achieved at lower doses (974-992 kg P_2O_5 ha^{-1}). In contrast, bone meal demonstrated a more gradual increase in yield, with optimal results at higher doses (1586-1633 kg P_2O_5 ha^{-1}). These findings suggest that Yoorin® thermophosphate may release phosphorus more rapidly than bone meal under these experimental conditions. This aligns with the observations of Cardoso and coauthors [7], who reported that soluble phosphorus sources, such as triple superphosphate, required lower doses to achieve maximum broccoli yields compared to less soluble sources like thermophosphate. The faster phosphorus availability from Yoorin® thermophosphate may explain its superior performance at lower application doses, while bone meal's slower release likely necessitated higher doses to achieve similar results.

While organic phosphorus sources like bone meal are generally more effective in acidic soils [24], excessive application can elevate soil pH, potentially reducing phosphorus availability. Although bone meal may achieve higher yields at elevated phosphorus doses, producers must weigh the economic implications of increased fertilizer costs. However, for direct-to-consumer sales of organic carrots, the premium price may justify the additional expense.

For most characteristics, a quadratic model was fitted (Figures 1 to 6). However, for fresh leaf weight with bone meal, the applied doses did not have a significant effect (Figure 4).

Regarding number of leaves, the highest estimated values were 7 leaves per plant at application doses of 989 and 1592 kg of P_2O_5 ha^{-1} for Yoorin® thermophosphate and bone meal, respectively (Figure 2). The health of the leaves is closely tied to root development, as the assimilates produced in the leaves are redistributed to other plant parts and storage tissues, analogous to the tuberous root development in carrots [25].

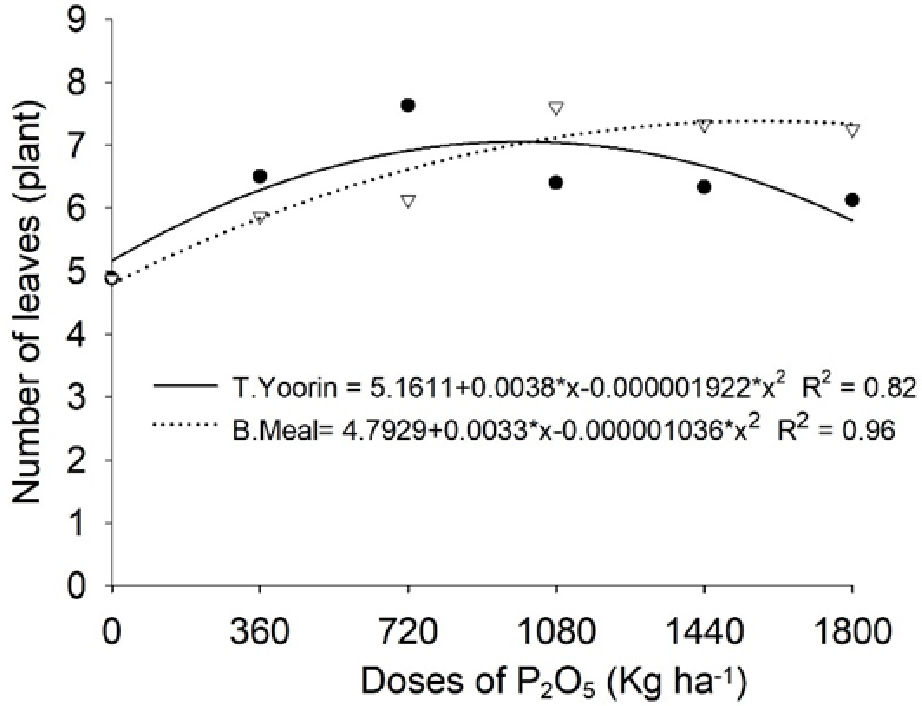

Figure 2. Effect of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers on the number of leaves of carrot plants.

The largest estimated root diameters were 26.1 mm for Yoorin® thermophosphate and 36.6 mm for bone meal at doses of 1167 and 1356 kg P_2O_5 ha^{-1}, respectively (Figure 3). These values are similar to those reported by Colombari and coauthors (2018) [26] (35 mm) and Kushwah and coauthors (2023) [27] (28.8-33.8 mm).Root length showed no significant differences between treatments, averaging 18.9 cm, which aligns with Colombari and coauthors (2018) [26] (17.8 cm) and Kushwah and coauthors (2023) [27] (19.9 cm). Since consumers prefer cylindrical, smooth carrots with a diameter of 30-40 mm, the observed values meet commercial standards, classifying them as class 18 carrots (18-22 cm in length) [28, 29].

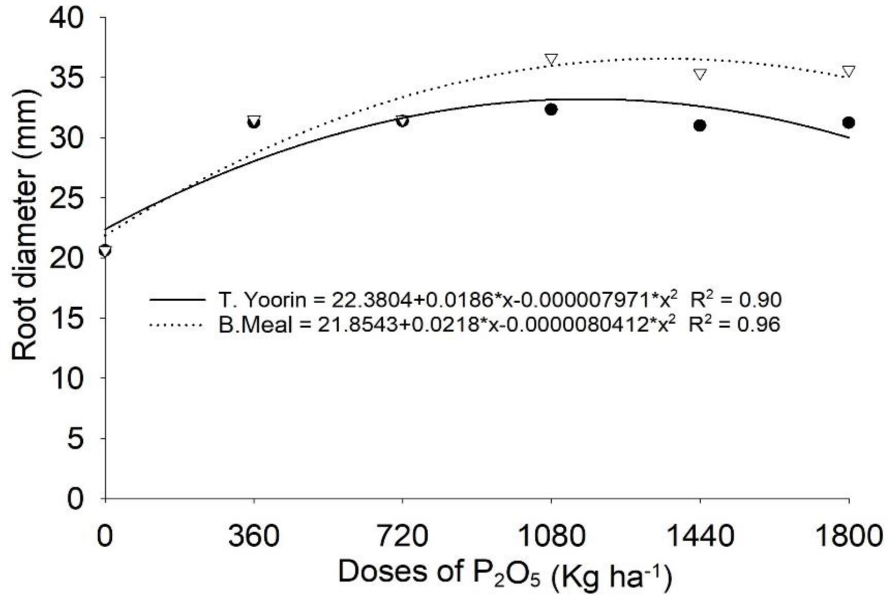

Figure 3. Effect of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers on carrot root diameter.

The highest fresh matter weight of leaves was 18.2 g per plant, achieved with the application of 1092 kg of P_2O_5 ha^{-1} using Yoorin® thermophosphate, representing an 81.8% increase compared to the control treatment without phosphorus application (dose 0). For bone meal, the applied doses did not have a significant effect, resulting in an average weight of 13.28 g per plant (Figure 4). These values are lower than those reported by Colombari and coauthors (2018) [26], who observed a maximum of 37.7 g per plant under conventional cultivation.

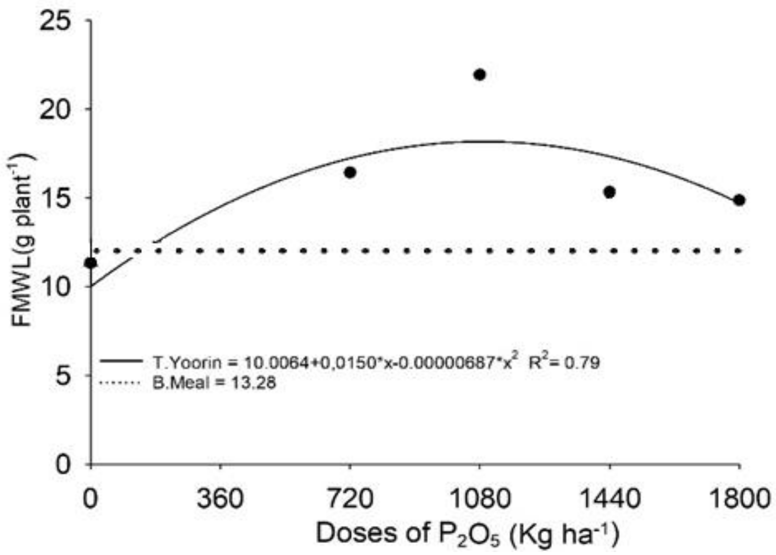

Figure 4. Effect of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers on fresh matter weight of carrot leaves (FMWL).

The maximum estimated fresh root matter weight was 129 and 144 g $plant^{-1}$ for Yoorin® thermophosphate and bone meal, respectively, at the phosphorus application doses of 979 (37.7% increase compared to control: dose 0) and 1634 (51.7% increase) kg P_2O_5 ha^{-1} (Figure 5). These results align with previous research demonstrating the positive impact of phosphorus on carrot root development, were comparable to those reported by Colombari and coauthors [26] (110-145 g) using inorganic fertilizers, but exceeded the values reported by Moniruzzaman and coauthors [30] (68.3 g) and Zanella and Moreira [31] (100 g). This indicates that the organic phosphorus sources evaluated in this study effectively promoted carrot root growth.However, excessive phosphorus application can lead to reduced production due to factors such as nutrient imbalances, soil toxicity, or increased production costs.

It's important to note that the observed variability in root weight within each treatment might be attributed to factors such as soil heterogeneity, microclimate variations, or individual plant differences.

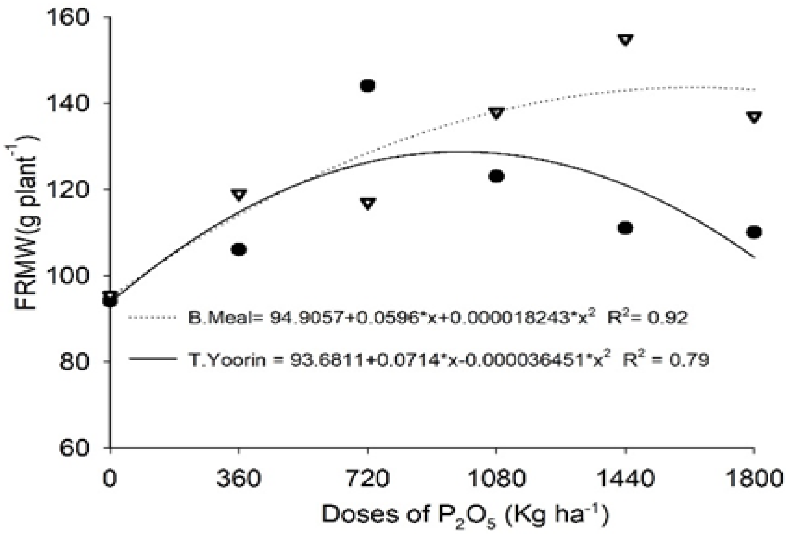

Figure 5. Influence of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers on fresh root matter weight (FRMW) of carrots. Botucatu-SP, 2022.

The maximum estimated total fresh weight was significantly higher for plants treated with bone meal (158 g per plant at 1586 kg P_2O_5 ha^{-1}, representing a 48.7% increase compared to dose 0) compared to Yoorin® thermophosphate (147 g per plant at 992 kg P_2O_5 ha^{-1}, representing a 41.5% increase), as shown in Figure 6. At harvest, approximately 91% of the total fresh weight was attributed to the tuberous root, highlighting its dominant role as the primary nutrient sink in carrot growth. These results indicate that both fertilizers can effectively enhance carrot yield, with bone meal potentially offering superior performance at higher P_2O_5 doses.

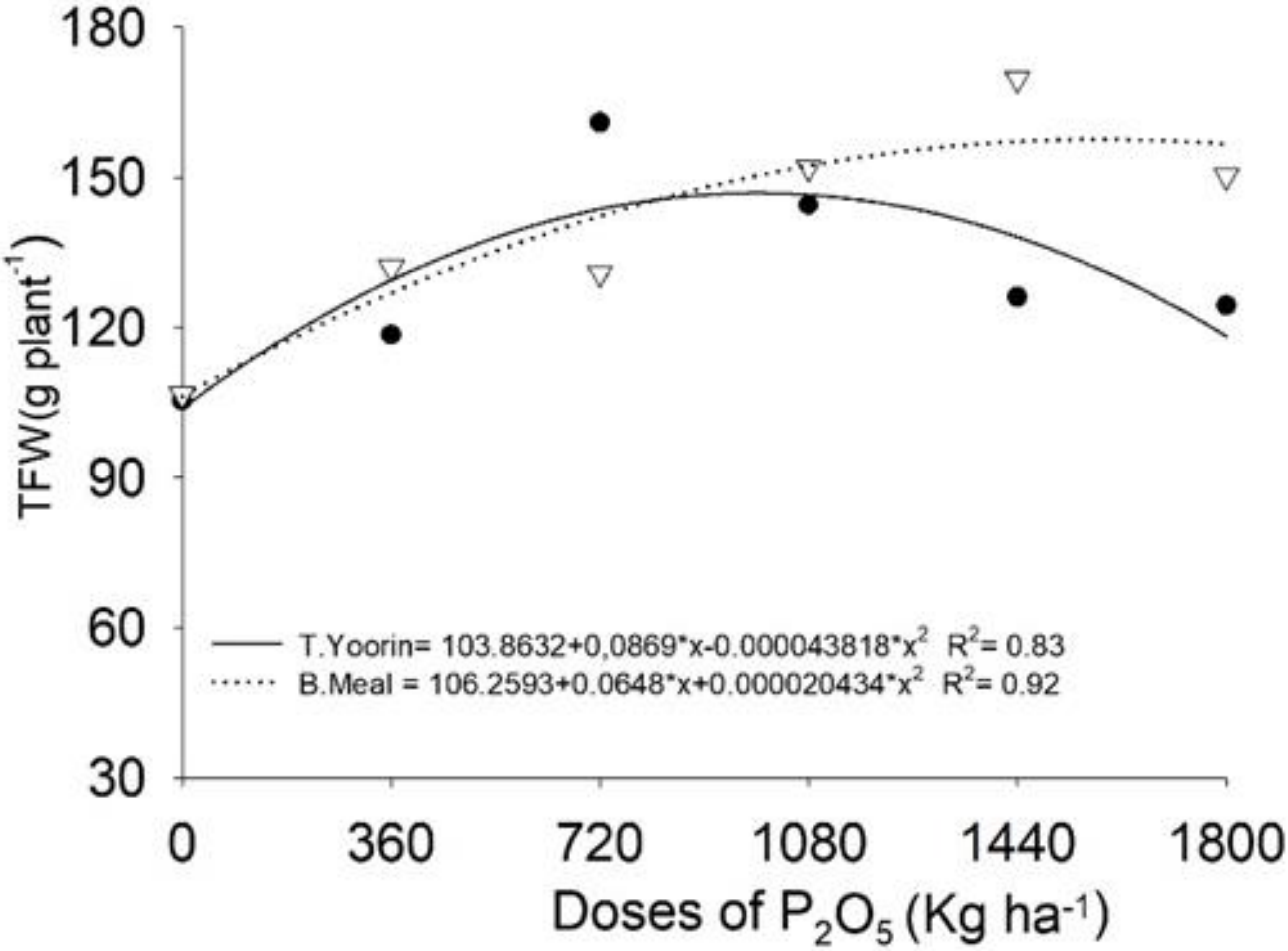

Figure 6. Total fresh weight (TFW) of carrot plants as a function of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers.

For total yield, the maximum estimated values were 103 and 115 t ha^{-1} at doses of 974 and 1602 kg of P_2O_5 ha^{-1} for Yoorin® thermophosphate and bone meal, respectively (Figure 7). Despite the use of high doses of phosphorus and potassium, our maximum yield of 115 t ha^{-1} was lower than the 126 t ha^{-1} reported by Azeredo Neto and coauthors [32], likely due to their use of soluble nutrient sources. Chaves and coauthors [33] also observed a quadratic adjustment, achieving an estimated commercial yield of 25.24 t ha^{-1} with the application of 200 kg of P_2O_5 ha^{-1}. On the other hand, the values obtained in this study were higher than those reported by Ferraz and coauthors [34], who achieved a maximum yield of 39.5 t ha^{-1} with a dose of 255.8 kg of P_2O_5 ha^{-1}. These differences can be attributed to several factors, such as the use of different genotypes, cultivation under varying soil, climate, and management conditions, including differences in plant populations.

In a study conducted by Jesus and coauthors (2021) [35], the total yield in response to P doses followed a quadratic regression model, with the highest yields obtained by the Nativa cultivar in both the first (47.13 t ha^{-1}) and second planting periods (55.42 t ha^{-1}), at estimated maximum doses of 170.2 and 209.6 kg ha^{-1} of P_2O_5, respectively. For the other cultivars in the first period, the doses were 183.8, 251.5, and 195 kg ha^{-1} of P_2O_5 for Suprema (39.64 t ha^{-1}), Brasília (37.40 t ha^{-1}), and Planalto (35.59 t ha^{-1}), respectively. In the second period, the doses for maximum estimated yields were 212.4, 201.6, and 190.4 kg ha^{-1} of P_2O_5 for Suprema (54.90 t ha^{-1}), Planalto (52.93 t ha^{-1}), and Brasília (50.66 t ha^{-1}), respectively. These results reinforce the influence of genetic and environmental factors on crop response to phosphate fertilization, highlighting the importance of adjusting P_2O_5 doses according to specific cultivation conditions.

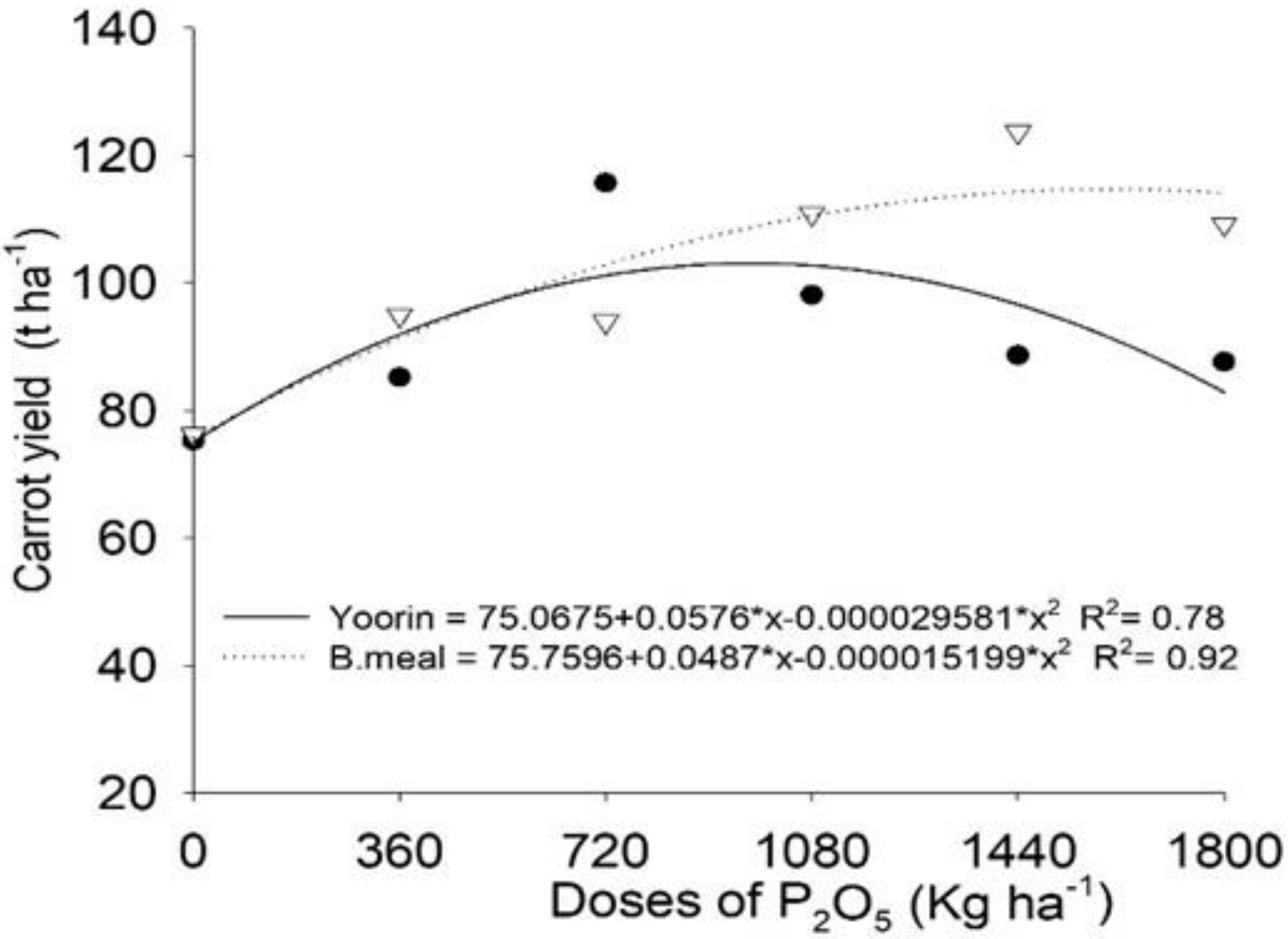

Figure 7. The influence of phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers on carrot yield.

Consistent with previous studies [36, 37], our research demonstrated a positive relationship between phosphorus application dose and carrot yield up to a critical threshold. Beyond this optimum dosage, excessive phosphorus application led to a reduction in yield and increased production costs.

Compared to the control treatment, the best phosphorus application doses resulted in substantial increases in all measured parameters, ranging from 26.7% to 67.0%. Yield enhancements were particularly pronounced, reaching 37.0% to 50.5% with the application of Yoorin® thermophosphate and bone meal, respectively. These gains were on par with or exceeded those reported in previous studies using conventional inorganic fertilizers [36, 37]. However, excessive phosphorus fertilization can negatively impact carrot yield. In this research, applying phosphorus doses beyond the optimal doses resulted in a 14.1% and 14.9% decrease in total fresh matter weight and yield, respectively, for Yoorin® thermophosphate and bone meal.

Phosphorus is a critical macronutrient that frequently limits vegetative development in tropical crops, particularly in phosphorus-deficient soils with complex adsorption dynamics [38]. Although the soil in this study contained a medium dose of phosphorus (25 mg dm^{-3}), excessive phosphorus application can still occur due to frequent fertilization practices in vegetable production [39]. Our findings align with previous research demonstrating the positive impact of phosphorus on carrot growth [40, 41]. Nevertheless, excessive phosphorus can lead to reduced vegetable production [42,43].

Regarding the physicochemical analyses in this study, no significant differences were observed in soluble solids content, pH, titratable acidity, or "ratio" among the treatments (Table 4). These results suggest that neither bone meal nor Yoorin® thermophosphate significantly influenced the physicochemical properties of carrot roots, even under varying phosphorus application doses in a medium-phosphorus soil.

Table 4. Summary of carrot root quality characteristics, including soluble solids content (SSC), pH, titratable acidity (TA), and the SSC/TA ratio, in response to different phosphorus (P_2O_5) doses from Yoorin® thermophosphate and bone meal fertilizers. Botucatu-SP, 2022.

	SSC	pH	TA	SSC/TA
Yoorin® thermophosphate	7.44 a	6.35 a	0.067 a	112.2 a
Bone meal	7.49 a	6.39 a	0.071 a	106.5 a
Means	7.47	6.37	0.069	109.4
CV (%)	5.9	1.4	13.1	15.1

CV: Coefficient of variation, *Averages followed by the same lowercase letter in the column do not differ from each other using the t test at 5% probability.

According to Moraes [44], the higher the total soluble solids content, the greater the sweetness of the vegetable, that is, each 1 ºBrix refers to 1 g of sugar for 100 g of solution. Soluble solids correspond to all substances that are dissolved in a specific solvent, which, in the case of food, is water. They are mainly made up of sugars (constituting 85 to 90% of soluble solids), and vary depending on the species, cultivar, stage of maturation and climate [45]. Titratable acidity indicates the acidic flavor of vegetables, being attributed mainly to organic acids present in plant cells. The higher the acidity, the lower the pH [45]. Carrots are classified as a low acidic food, as they have a pH greater than 4.5 [46]. The acidity in vegetables is mainly attributed to organic acids that are dissolved in the vacuoles of the cells, both in free form and combined with salts, esters, glycosides, etc. In some products, organic acids not only contribute to the acidity, but also to the characteristic aroma [45].

Soluble solids content (SSC) in crops is a complex trait influenced by a multitude of factors [47]. Varietal selection, maturity stage, and physiological processes, such as photosynthesis and respiration, exert the most direct and significant impacts on SSC, often leading to rapid changes in Brix levels. Conversely, soil conditions, including nutrient availability and water status, and environmental factors such as light intensity and temperature, tend to have more indirect and nuanced effects on SSC. These factors can influence SSC by modulating growth rate, metabolic pathways, and solute partitioning within the plant. The SSC observed are similar to those obtained by other authors who reported values of 6.2 to 10.9 ºBrix [46, 48, 49, 50, 51].

The titratable acidity (TA) values found in this study for the 'Fernanda' hybrid were lower than those reported by other authors for the 'Brasília' cultivar, which ranged from 0.11 to 0.69% [26, 46, 48, 49, 51]. This difference can be attributed to several factors, including the cultivar used, which may have different metabolic profiles, and the climatic conditions of the tropical cultivation region, which influence the plant's respiration rate and, consequently, the oxidation of organic acids such as malic and citric acids in the Krebs cycle. Additionally, the maturity stage at harvest and post-harvest practices, including storage temperature and packaging, may have contributed to the reduction in acidity [52]. The 'Fernanda' hybrid may naturally have a lower acid content, which would justify the lower values found in this study. Future studies with different cultivars and cultivation conditions, considering factors such as soil type and fertilization, are needed to confirm this hypothesis and deepen the understanding of the factors that influence titratable acidity.

The relationship between soluble solids content (SSC) and titratable acidity (TA) is a crucial indicator of carrot sensory quality. In the present study, the average SSC/TA ratio was 112.2 for Yoorin® thermophosphate and 106.5 for bone meal, considerably higher than those found by Alves and coauthors [46] in 'Brasília', 'Alvorada', and 'Esplanada' (50.15, 55.70, and 59.85, respectively).

The elevated SSC/TA ratio observed in this study, facilitated by the application of Yoorin® thermophosphate and bone meal, can be attributed to the pivotal role of phosphorus in plant metabolic processes. The macronutrient significantly influences the translocation of photosynthates to the root system, thereby stimulating the accumulation of soluble sugars within the carrot taproot and consequently increasing SSC/TA. Furthermore, phosphorus modulates cellular pH, impacting titratable acidity and indirectly influencing the SSC/TA ratio. The unique properties of the fertilizers employed, including enhanced phosphorus availability and synergistic effects with other nutrients, likely contributed to the observed results.

While Colombari and coauthors [26] reported lower SSC/TA values (82.89 and 98.65) in 'Belgrado' carrots subjected to nitrogen fertilization partitioning, our findings underscore the preeminent role of phosphorus in optimizing carrot quality. Nevertheless, it is imperative to acknowledge the intricate interactions among various nutrients that can influence the SSC/TA ratio. The utilization of organic amendments, as demonstrated by Figueiredo Neto and coauthors [51], can yield diverse outcomes due to the complex dynamics of soil microbial communities and the sustained release of nutrients.

Furthermore, our research unequivocally demonstdoses that the SSC/TA ratio in carrots is profoundly influenced by nutritional management, with phosphate fertilization exerting a particularly pronounced effect. The strategic application of phosphorus sources, such as Yoorin® thermophosphate and bone meal, offers a promising approach to enhance carrot sweetness and overall sensory quality.

Beyond demonstrating the agronomic performance of bone meal and Yoorin® thermophosphate, the results of this study point to their potential use in shaping fertilization guidelines tailored for organic systems, especially under tropical conditions. Such insights can contribute to more sustainable practices and support the development of technologies aligned with organic certification standards.

CONCLUSION

Bone meal and Yoorin® thermophosphate are effective organic phosphorus sources for carrot production, significantly enhancing yield.

Bone meal's slower nutrient release required higher doses (1586 kg P_2O_5 ha^{-1}) for optimal performance, while Yoorin® thermophosphate achieved peak effectiveness at lower doses (974 kg P_2O_5 ha^{-1}), emphasizing the need for tailored phosphorus management.

The doses of bone meal and Yoorin® thermophosphate did not significantly affect the physicochemical characteristics of carrot roots.

The excessive phosphorus application beyond optimal doses can lead to yield reductions, emphasizing the need for precise nutrient management.

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