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Niacin as a Biostimulant in Carrot Production in a Minimum Soil Tillage System in Brazil

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ABSTRACT

Conservation practices and biostimulants have helped to increase the production and quality of horticultural products in regions with periods of limited water supply. With a focus on the Brazilian Center-West, the objective of this study was to evaluate the potential use of cover crops for establishing direct carrot planting while exploring the effects of applying nicotinamide as a biostimulant on the crop. The treatments consisted of niacin application and different soil cover managements: control (manual weeding); straw from spontaneous plants, millet, sunn hemp, and a combination of millet and sunn hemp (mix). The presence of cover crops from the cultivated species, millet and sunn hemp, alone or together, provided gains in relation to the development, productivity and quality of carrots, as well as resulting in average economic gains of up to 259%. Also, the application of niacin increased growth parameters and productivity by 82%, which increased gross revenue by around 50%. Thus, niacin can be used in carrot cultivation as a biostimulant while aiming to increase root development and obtain greater margins of economic return, regardless of management with cover crops. However, the joint use of niacin and cover crops is recommended, taking into account possible phytosanitary implications due to the presence of spontaneous plants.

Introduction

Carrot (*Daucus carota* L.) is cultivated in many countries and is one of the most economically important vegetable crops in Brazil, largely due to its nutritional benefits (Carvalho et al., 2018). Although vegetable crop production has been increasing, it remains insufficient to meet global demand. Estimates suggest that by 2050, the world population will reach 9 billion (Jiang et al., 2022). Several techniques can be used to boost crop productivity with minimal impact on production costs, such as the use of cover crops and the application of vitamins or biostimulants.

Using dead vegetation as soil cover provides beneficial effects, such as reducing soil temperature and increasing water retention. For instance, Resende et al. (2005) observed lower soil temperatures and higher soil moisture when using vegetable cover in carrot cultivation. In addition, soil cover helps control weeds and is effective in organic farming. A reduction in weed incidence has been reported with plant cover use (Resende et al., 2005; Lang et al., 2023; Pinto et al., 2023). Cover crops also protect the soil against erosion, promote soil microorganism activity, and increase organic matter, which helps improve nutrient availability (Lang et al., 2023; Pinto et al., 2023). These factors can reduce production costs and increase profitability (Pinto et al., 2023).

In addition to these conservation techniques, modern agriculture is exploring compounds that support plants in stressful conditions or help them reach their full productive potential. Vitamins are particularly promising in this regard. Acting as hormone precursors and bioregulators, vitamins play a key role in plant growth and development. Niacin, for example, regulates the cell cycle, stimulates growth and differentiation, and helps plants cope with stress (Mirret & Bosch, 2014).

Nicotinamide application has been shown to increase shoot length, number of fruiting branches, shoot and seed mass, and enhance the carbohydrate, protein, and oil content in quinoa plants (Abdallah et al., 2016). In mustard plants, niacin improved growth and chlorophyll content (Vendruscolo et al., 2017). Specifically, vitamin B3 has been found to raise internal auxin levels in treated plants (Ahmad et al., 2021; Laurell et al., 2022), which positively influences carrot root development, particularly during the first half of the tuberous root development cycle (Kondhare et al., 2021). Additionally, its role as a precursor in NADH production enhances cellular energy transfer, stimulating photosynthesis and sugar production, which can support the development of tuberous roots (El-Lateef et al., 2020). The objective of this study was to evaluate the potential use of cover species for direct carrot planting, as well as to explore the effects of nicotinamide application as a biostimulant on the crop.

Materials and Methods

The study was conducted in an experimental area at the State University of Mato Grosso do Sul, located in the municipality of Cassilândia, MS. The region predominantly experiences an Aw climate, characterized by a tropical climate with a rainy season from October to April, and a dry period from May to September, with monthly rainfall of less than 100 mm. Climatic data on air temperature and humidity during carrot cultivation were collected from an automatic meteorological station installed in the experimental area (Fig. 1).

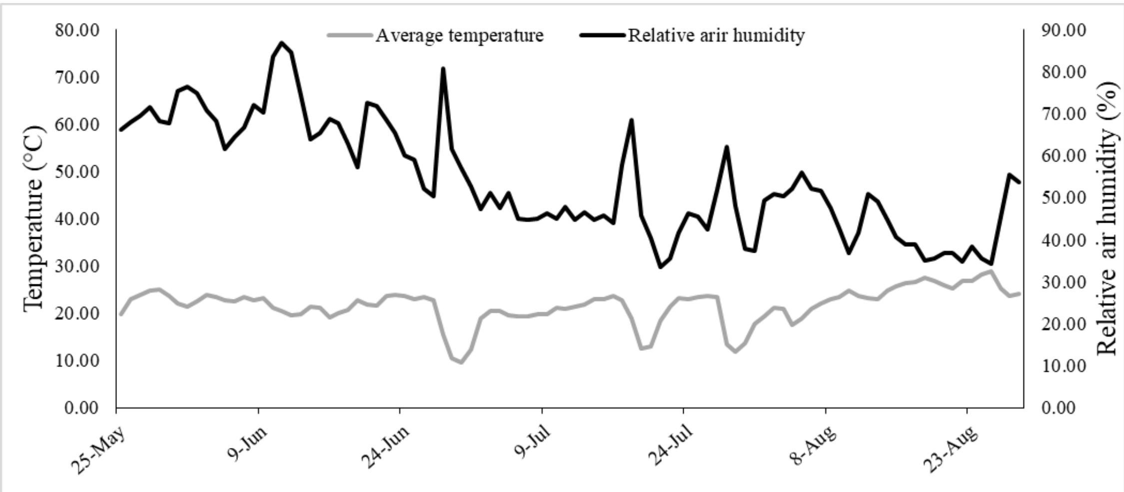

Fig. 1. Climatic conditions of relative air humidity and average temperature during the study period.

The soil was classified as quartzarenic neosol. The chemical analysis of the soil before implementing the direct planting system in 2019 showed the following characteristics: pH ($CaCl_2$): 5.0, Ca^{2+}: 24.0 mmol$_c$ dm^{-3}, Mg^{2+}: 14.0 mmol$_c$ dm^{-3} , K^+: 3.0 mmol$_c$ dm^{-3}, P (resin): 14.0 mg dm^{-3}, organic matter: 13.0 g dm^{-3}, Al^{3+}: 0.0 cmol$_c$ dm^{-3}, H + Al: 17 .0 cmol$_c$ dm^{-3}, cation exchange capacity: 58.0 mmolc dm^{-3}, and base saturation: 71%.

Prior to planting the cover crops (2019), liming was carried out to increase base saturation to 80% while harrowing with a plow to incorporate limestone, and then harrowing with a leveling harrow to construct the beds with a roto-filter. The beds were 1.00 m wide and spaced 0.50 m apart. After implementing the direct planting system, according to the outline below, lettuce was cultivated in 2020, followed by a subsequent replanting of cover crops.

The experimental design was a randomized block, in a 2×5 factorial, with four replications. The treatments consisted of the presence or absence of niacin application and different soil cover management approaches, including manual weeding (as control); straw from spontaneous plants (35 g of straw m^{-2}), millet (75 g of straw m^{-2}), sunn hemp (80 g of straw m^{-2}) and the combination of millet and sunn hemp (mix) (73 g of straw m^{-2}). In the treatment comprising spontaneous plants, the community was formed predominantly by *Cenchrus echinatus*, *Portulaca oleracea*, *Eleusine indica* and *Indigofera hirsuta* and isolated populations of *Commelina benghalensis* and *Conyza bonariensis*.

Each plot had dimensions of 1.0×1.2 m (1.2 m^2) and comprised 80 carrot plants, with a spacing of 0.05 m between plants and 0.25 between rows. To obtain a useful plot, 20 central plants were evaluated, excluding the ends as margins.

The cover crops were sown in the second half of December, a period in which there was adequate rainfall distribution in the region, and were grown for a period of 75 d (flowering stage), being subsequently dried with glyphosate-based herbicide and cut. Then, they were deposited homogeneously on the flowerbeds.

The carrot cultivar was "Tropical," which has a cylindrical root, measuring between 20 and 25 cm in length and between 3 and 4 cm in diameter, with a production cycle of 80-90 d. Sowing was carried out in May 2021, by opening furrows 0.5 cm deep. To enrich the soil, 60 kg ha^{-1} of N and 60 kg ha^{-1} of K_2O were applied, which were divided into three applications at 15, 30, and 45 d after sowing. Also, 30 d after sowing, niacin was applied at a concentration of 100 mg L^{-1} through targeted spray and in a total volume equivalent to 200 L ha^{-1}.

Irrigation was carried out using a microsprinkler. The application intensity was equal to 8.7 mm h^{-1}, equivalent to 0.14 mm min^{-1}, thus dividing the ETc (ETo obtained through the meteorological station installed close to the experimental area, multiplying the crop coefficient) by the intensity of application, the necessary irrigation times for the crop were established, taking into account its daily water requirement, while the harvest was carried out manually 85 d after sowing.

After harvesting, several characteristics were measured, including the number of leaves, shoot length, shoot fresh mass, root diameter, root length, root fresh mass/shoot fresh mass ratio, and productivity. The participation of commercial classes of carrots $treatment^{-1}$ was also established, observing the classification applied by the Company of Warehouses and General Stores of São Paulo (CEAGESP). The roots were classified according to their length: 1A – less than 16 cm; 2A – 16 to 20 cm; 3A – 20 to 24 cm; G – greater than 24 cm.

The treatments were considered as commercial crops to determine the production costs of a carrot production cycle. In this way, the total operating cost (TOC) structure proposed by Martin et al. (1998) was used which can be obtained by summing the expenses with interest costs, other expenses and the effective operating cost (EOC), which, in turn, comprises operational expenses and inputs used.

Obtaining the average prices received by producers took into account the data contained on the CEAGESP website. The average price paid to producers was obtained for calculation purposes, with the following values per commercial class: Class 1A = $ 0.36 kg^{-1}; Class 2A = $ 0.38 kg^{-1}; Class 3A = $ 0.44 kg^{-1}; Class G = $ 0.34 kg^{-1}.

The average prevailing labor rate in the region in the first half of 2023 was $ 20.66 d^{-1}. Thus, labor costs were obtained through an index generated by a need for manual operations per operation, multiplied by the daily rate. For inputs, the cost was calculated based on the average value of the product in the region and the quantity of material used. Five percent of total expenses with the EOC was considered for other expenses, while the funding interest was taken as 6.5% p.a. over 50% of the EOC (Martin et al., 1998).

The profitability of each treatment was obtained through estimates of gross revenue, obtained between the quantity produced (kg) and the average price received by the producer. The operating profit was obtained by the difference between gross revenue and total operating costs. The profitability index was established as the proportion of gross revenue that represents the final amount after covering the total operational cost of production.

Plant growth and productivity data were subjected to preliminary normality tests and submitted to an analysis of variance. Mean values were compared using the t test (LSD) ($P \leq 0.05$). However, no statistical tests were carried out for economic characteristics, given their monetary nature.

Results

It was observed that the application of niacin, when combined with sunn hemp or millet straw treatments, led to an increase in the number of leaves. However, treatments involving spontaneous plant straw and millet showed superior performance compared to the other treatments, except for the control without niacin application (Fig. 2A). On average, niacin reduced leaf production by 24% compared to untreated plants.

For the aerial part length, treatments involving mulch, regardless of niacin application, performed better than the control. However, a significant effect of niacin was only seen when combined with spontaneous plant straw, which resulted in an increase in aerial part length (Fig. 2B). In this case, niacin increased the aerial part length by 8%, while the use of cover crops, compared to the control, reduced it by around 15%.

Similarly, the fresh mass of the aerial parts benefited from the presence of mulches, irrespective of niacin application, except in the mix treatment without niacin, where results were similar to the control. The application of niacin had a positive effect on the aerial part's development when combined with spontaneous plant straw, sunn hemp, or millet (Fig. 2C).

Despite reductions in the number of leaves and aerial part length, the combined use of niacin and vegetation cover led to increases of 45% and 98%, respectively, in the fresh mass of the aerial parts, compared to the control.

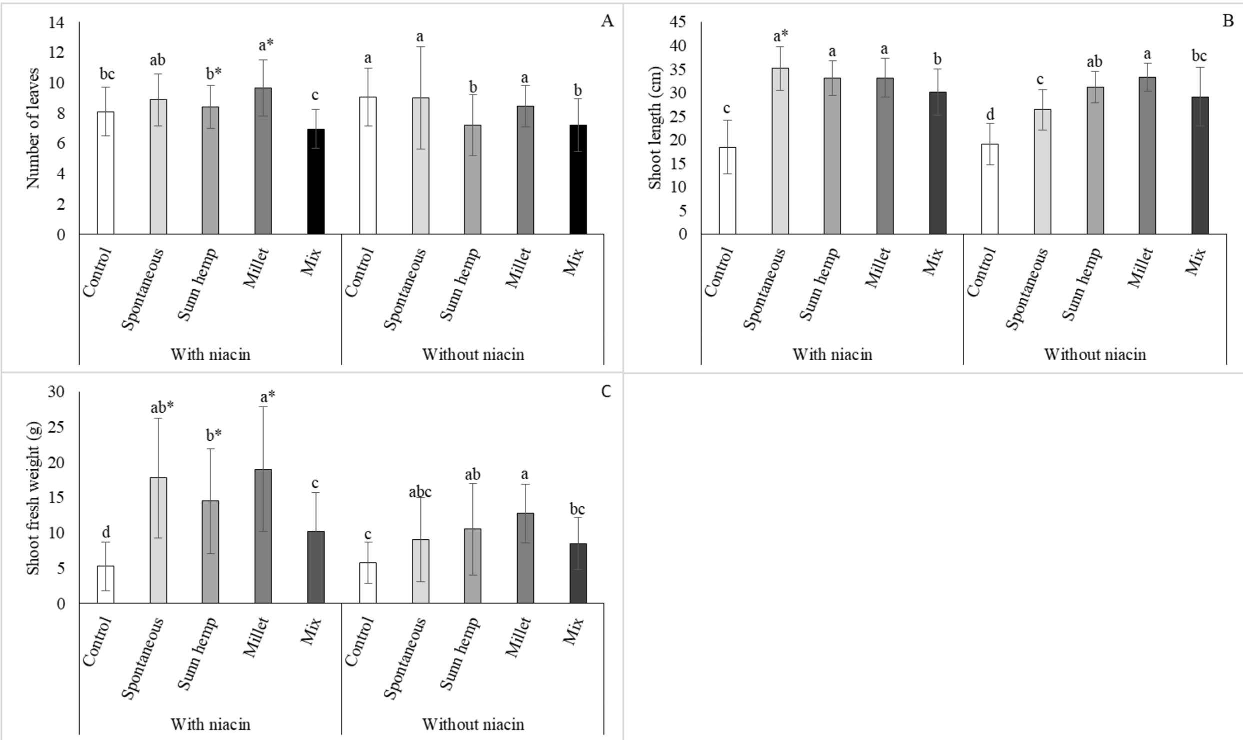

Fig. 2. Number of leaves (A), shoot length (B), shoot fresh mass (C) of carrot plants grown in succession to different species of cover crops and niacin management.

Root diameter (Fig. 3A), root length (Fig. 3B), MFR/MFT ratio (Fig. 3C), and productivity (Fig. 3D) were enhanced by the presence of mulch, regardless of niacin application, with millet showing the greatest impact. Niacin had a positive effect on root development when combined with straw from spontaneous plants, sunn hemp, or millet. On average, the presence of cover crops led to increases of 7%, 14%, and 115% in root diameter, length, and productivity, respectively. Additionally, the exogenous application of niacin resulted in respective increases of approximately 28%, 22%, and 82% in these same characteristics.

The treatments also influenced the distribution of roots among marketing categories. It was observed that niacin application led to a higher concentration of roots in the 2A and 3A categories, which have greater commercial value. Among the cover crops, millet stood out in the treatments without niacin, with 50% of roots falling into the 2A and 3A categories. When combined with niacin, sunn hemp and millet resulted in 80% and 60% of roots, respectively, in these higher-value categories (Fig. 4).

The total operating cost (TOC) of carrot cultivation per hectare was influenced by three main factors (Table 1): mechanized operations, manual labor, and inputs, which accounted for 14%, 46%, and 32% of the TOC, respectively. Additionally, other expenses and interest on costs contributed 5% and 3%, respectively, to the TOC.

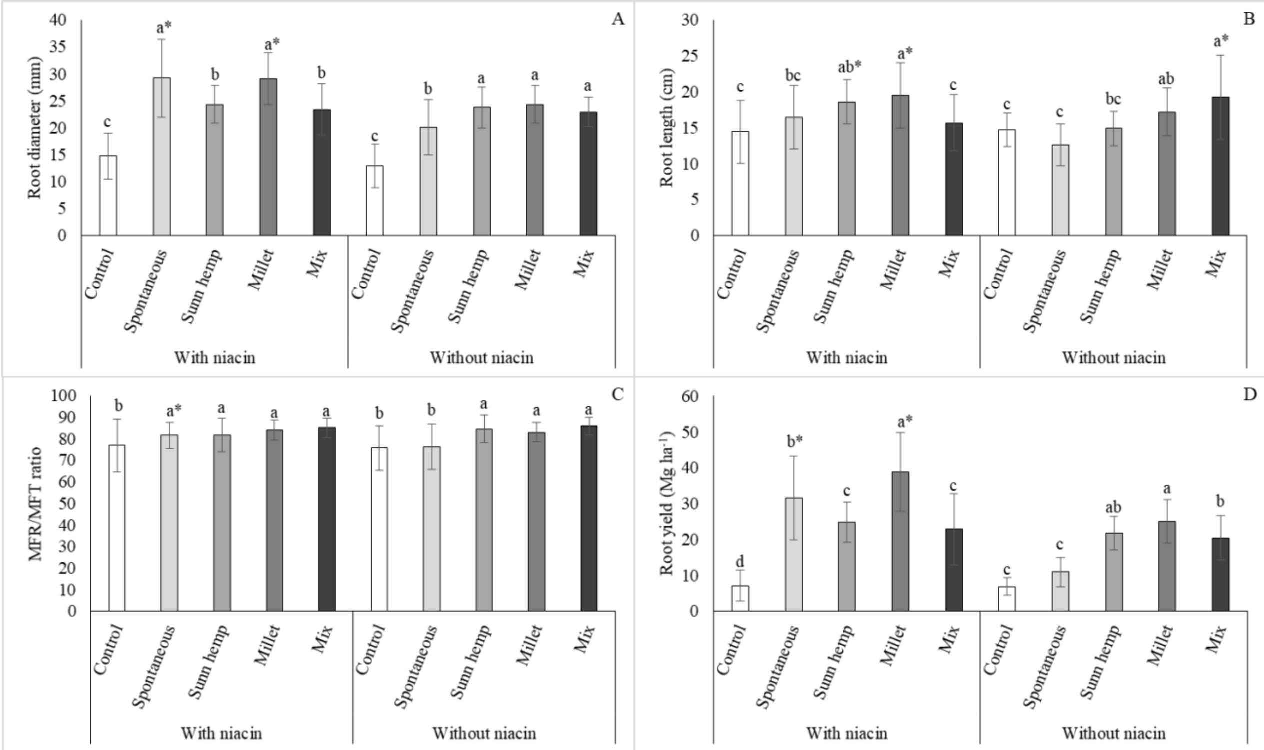

Fig. 3. Root diameter (A), root length (B), relationship between root and total fresh mass (C), and root yield (D) of carrot plants grown in succession to different species of cover crops and niacin management.

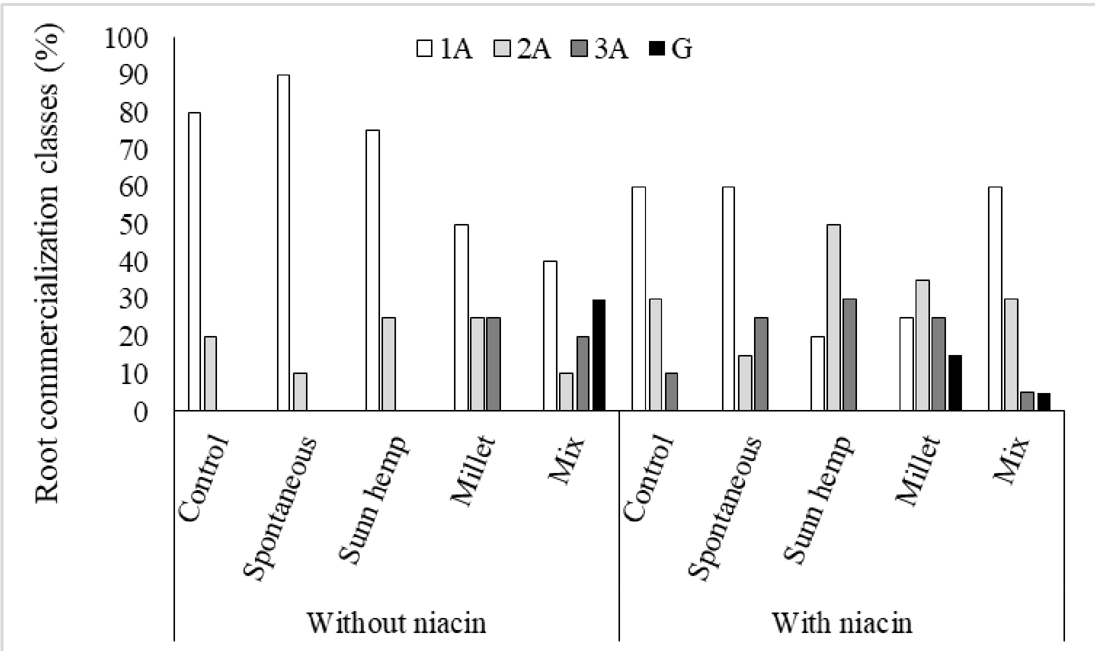

Fig. 4. Distribution of commercialization classes of carrot roots grown in succession to different species of cover crops and niacin management.

In general, labor costs for managing cover crops formed the main factor related to the increase over the base TOC, with the exception of the treatment consisting of the use of sunn hemp, in which the value of the seed exceeded the hand labor. Also, the low participation of niacin in the final amount of TOC was noted, with less than 1% (Table 2).

Table 1. Estimated total operating cost for a carrot crop on 10,000 m².

Descrição	Especificação	Qtde. -	V.U. $	Valor $ ha^{-1}
	A – Mechanized operations			
Tillage	HM Tp 80cv. 4x4 + plow harrow 14 x 26"	2.5	25.26	63.15
Disk harrow	HM Tp 80cv. 4x4 + leveling grid 20 x 20"	2	23.59	47.17
Liming	HM Tp 80cv. 4x4 + limestone distributor	4.6	26.42	121.51
Beds preparation	HM Tp 80cv. 4x4 + rotoencanteirador	3.5	24.42	85.46
Fertilization	HM Tp 80cv. 4x4 + Cultivator-fertilizer	2	24.28	48.56
Irrigation	Electrical energy (kWh)	1300	0.25	322.31
Subtotal A				688.17
	B- Manual operations			
Beds mantainance	Man-d	5	21	103.31
Sowing	Man-d	30	21	619.83
Thinning	Man-d	30	21	619.83
Harvest, classification and packaging	Man-d	40	21	826.45
Subtotal B				2,169.42
	C- Inputs			
C1- Fertilizers				
Limestone	Mg	2	42	84.30
Single superphosphate	Mg	1.0	661	661.16
KCl	Mg	0.15	1,281	192.15
Urea (45% N)	Mg	0.18	1,198	215.70
C2- Seeds				
‘Primavera’ cultivar	Kg	5	54	268.60
C3- Herbicide				
Round Up original	Liter	5	18	90.91
Subtotal B ($ ha^{-1})				1,512.81
Effective Operational Cost (A + B) ($ ha^{-1})				4,370.40
C- Other expenses ($ ha^{-1})				218.52
D- Costing Interest year^{-1}				142.04
Total Operational Cost (A + B + C + D) ($ ha^{-1})				4,730.96

Table 2. Participation of cost variation factors in the total operating cost (TOC) for carrot cultivation in succession to cover crops and application of niacin in a direct planting system for 10,000 m².

Cover crop	Niacin	Seeds ($ ha^{-1})	Niacin ($ ha^{-1})	Labor ($ ha^{-1})	TOC increase	
					$ ha^{-1}	%
Control	Without	0	0	0.00	0.00	0,00
Spontaneous	Without	0	0	123.46	123.46	2,62
Sunn hemp	Without	154.32	0	133.74	288.07	6,11
Millet	Without	36.01	0	133.74	169.75	3,60
Mix	Without	74.07	0	133.74	207.82	4,41
Control	With	0	4.12	0,00	4.12	0,22
Spontaneous	With	0	4.12	123.46	127.57	2,84
Sunn hemp	With	154.32	4.12	133.74	292.18	6,33
Millet	With	36.01	4.12	133.74	173.87	3,82
Mix	With	74.07	4.12	133.74	211.93	4,63

It was observed that the control treatment, with or without niacin, as well as the treatment with spontaneous plants without niacin, did not generate enough gross revenue to cover the TOC, resulting in negative operating profit and profitability index. However, the use of millet as a cover crop significantly improved carrot cultivation, as did the application of niacin across all treatments (Table 3). Specifically, gross revenue increased by an average of 50% with niacin application and 259% with the presence of cover crops.

Table 3. Productivity, gross revenue, total operating cost (TOC), operating profit (OP) and profitability index (PI), obtained for carrot cultivation in succession to cover crops and application of niacin in a direct planting system for 10000 m^2.

Cover crop	Niacin	Yiel (Mg ha^{-1})	Gross revenue ($ ha^{-1})	TOC ($ ha^{-1})	OP ($ ha^{-1})	PI (%)
Control	Without	6,90	2,495.93	4,711.49	-2,215.56	-88,77
Spontaneous	Without	10,90	3,922.65	4,834.94	-912.29	-23,26
Sunn hemp	Without	21,80	7,905.86	4,999.55	2,906.31	36,76
Millet	Without	25,10	9,606.17	4,881.24	4,724.93	49,19
Mix	Without	20,40	7,555.56	4,919.31	2,636.25	34,89
Control	With	7,10	2,638.40	4,721.78	-2,083.38	-78,96
Spontaneous	With	31,40	11,959.14	4,845.23	7,113.90	59,49
Sunn hemp	With	24,80	9,705.68	5,009.84	4,695.84	48,38
Millet	With	38,80	14,813.46	4,891.53	9,921.93	66,98
Mix	With	22,80	8,360.00	4,929.59	3,430.41	41,03

Discussion

The treatment without soil cover resulted in reduced shoot length, fresh mass, root diameter, root length, and productivity (Figs. 2 and 3). Similar results were observed by Resende et al. (2005), where carrots grown without soil cover exhibited lower leaf length, average root weight, and productivity. Lang et al. (2023) also reported reduced biomass accumulation in carrots grown without soil cover, whereas soil cover led to greater biomass and nutrient accumulation. In addition to providing higher soil moisture and lower temperatures, soil cover can supply nutrients, reduce soil erosion, and increase microbial activity, among other benefits (Carvalho et al., 2018; Lang et al., 2023; Pinto et al., 2023). These effects contribute to increased biomass and productivity.

Carrot productivity improved with the use of soil cover, particularly when irrigation did not meet 100% of the crop's water requirements. The soil cover also enhanced water-use efficiency and overall productivity (Carvalho et al., 2018). When niacin was applied in combination with soil cover, there were further increases in shoot length, fresh mass of shoots and roots, root diameter, and productivity (Figs. 2 and 3).

In onions, niacin application increased the net assimilation rate and plant height (Paterlini et al., 2022). Similarly, in mustard plants, niacin promoted increases in fresh and dry shoot mass, leaf number, and leaf area (Vendruscolo et al., 2017). The application of vitamins like niacin supports plant metabolism, enhancing growth, cell division, and carbohydrate accumulation (Abdallah et al., 2016; Vendruscolo et al., 2017; Li et al., 2020), all of which contribute to higher productivity and quality, as observed in the present study (Fig. 3, Tables 1 and 2).

The positive effects of niacin on plants are closely linked to its role in plant development, particularly through its involvement in the structures of NADH and NADPH (Maria, 2011; Moreira, 2011). Consequently, the exogenous application of niacin likely influences various metabolic activities, including nitrate assimilation by roots, sulfate uptake by leaves, and overall photosynthetic processes (Taiz et al., 2017).

Vendruscolo et al. (2017) reported that niacin application in melon trees increased root length and dry mass at doses of up to 43.60 mg L-1 and 29.40 mg L-1, respectively, which aligns with the findings of this study (Fig. 3A, B, C). Additionally, according to Vendruscolo et al. (2023), vitamins can significantly affect the morphophysiology of lettuce. In hydroponic production systems, niacin increased gas exchange and fresh mass by approximately 30% compared to the control when applied in conjunction with thiamine, similar to the results observed in this study (Fig. 3A, B, C).

Soltani et al. (2014) also reported that vitamin application led to greater dry matter accumulation and an increase in the number of productive branches. Abdallah et al. (2016) found that quinoa plants treated with vitamin B3 exhibited enhanced growth in both aerial parts and roots. Furthermore, Vendruscolo et al. (2017, 2018) observed increased vegetative development, measured by the number of leaves, plant height, and accumulation of fresh and dry matter in aerial organs, in curly mustard and common beans treated with niacin.

These improvements can be attributed to enhanced energy and nutritional reserves in the plants, which ultimately boost crop development and production (El-Bassiouny et al., 2014). Additionally, Vendruscolo et al. (2017) noted that the exogenous application of thiamine and niacin positively affected the growth of upland rice plants.

The foliar application of niacin and thiamine induced several morphophysiological changes, including increased photosynthetic capacity under stressful conditions (Ramos et al., 2021; Vendruscolo et al., 2022), improved development of vegetative and reproductive organs (Colla et al., 2021), and higher levels of photosynthetic pigments (Vendruscolo et al., 2021). These responses are associated with enhanced metabolic activity, as vitamin B3 exhibits strong antioxidant properties in plant tissues, increasing plant efficiency even under stress (Ferreira et al., 2023).

B complex vitamins promote the accumulation of foliar carbohydrates, stimulating leaf expansion (Paixão et al., 2014). This accumulation leads to higher sugar levels in vegetables, creating favorable conditions for the development of tuberous roots, as observed in various sugar beet cultivars (El-Lateef et al., 2020). Furthermore, these vitamins enhance chlorophyll and carotenoid levels (El-Bassiouny et al., 2014), thereby increasing plant productivity.

According to Ali and Al-Bayaty (2023), spraying peppermint plants with nano-iron oxide and vitamin B3 significantly boosts the concentration of nutrients in the leaves. Additionally, the interaction between these substances positively impacts plant growth and nutrient content, evidenced by increased concentrations of nitrogen, phosphorus, and potassium in peppermint plants.

Regarding cost analysis, the use of cover crops significantly increased carrot profitability (Tables 2 and 3). Similar results were reported by Pinto et al. (2023), who observed increased profitability with the use of mulch and plastic mulch in carrot cultivation. Cover crops reduce operational costs compared to plastic covers, as the material can be sourced from the cultivation area or brought from another part of the property, eliminating purchasing costs (Pinto et al., 2023). Additionally, soil cover can decrease management expenses related to irrigation and weed control (Carvalho et al., 2018; Pinto et al., 2023).

Notably, the primary factor contributing to economic gains from using cover crops and niacin is the low cost of these technologies relative to the significant improvements in the productive performance of carrot plants. In this study, we found that the application of niacin increased production costs by only 0.22%, which is negligible compared to the approximately 50% return it generates. Similarly, the use of cover crops results in an average increase of only 4% in cultivation expenses, while the average return exceeds 259%.

Despite the growth of areas cultivated under regenerative agriculture systems, which have low environmental and social impacts, there remain gaps in research, particularly regarding the combined use of technologies that enhance crop quality and productivity. Our findings highlight the potential of niacin as a biostimulant in conservation agriculture, demonstrating its ability to increase monetary returns for rural producers.

Conclusions

Cultivated cover crops, such as sunn hemp and millet, whether grown in monoculture or intercropped, can enhance the growth and profitability of carrot cultivation. Niacin can be utilized as a biostimulant in carrot production to promote root development and achieve higher economic returns, regardless of the management practices involving cover crops. However, it is advisable to use the vitamin in conjunction with cultivated species, considering the potential phytosanitary implications associated with the presence of spontaneous plants.

Conflict of Interest

The authors indicate no conflict of interest in this work.

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