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Agronomic Performance of European Pear Cultivars in Different Training Systems in the Highland Region of Southern Brazil

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Abstract: This study aimed to evaluate the vegetative, productive, and fruit quality parameters of the European pear cultivars 'Rocha' and 'Santa Maria' under the training systems of Tall Spindle, with branches bent at an angle of 45° (Tall Spindle—45°) and 90° (Tall Spindle—90°) to the leader, and Bi-axis. The evaluation was conducted over the 2016/2017 to 2022/2023 growing seasons in the highland region of southern Brazil. Both Tall Spindle systems significantly improved the yield and productive efficiency compared to the Bi-axis system, with 'Santa Maria' showing superior performance under Tall Spindle—90°. While 'Rocha' exhibited no significant differences between Tall Spindle systems, it benefited from better vigor control and reduced biennial bearing when trained under the Bi-axis system. Fruit quality parameters were consistent across training systems, indicating Tall Spindle—90° as an optimal choice for productivity and stability in 'Santa Maria'. These results emphasize the adaptability and efficiency of training systems for pear orchard management.

Keywords: tall spindle; bi-axis; productive efficiency; alternate bearing; fruit quality

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1. Introduction

Pear production in Brazil is expanding rapidly as an agricultural activity. In 2022 and 2023, Brazil produced approximately 15.8 and 17.5 thousand tons of pears, respectively [1]. However, this increase in production is still insufficient to meet the country's domestic demand, estimated at around 150 thousand tons annually [2].

Increasing production depends on several factors, including the selection of scion cultivars, rootstocks, and training systems, all of which are critical for improving production efficiency [3,4]. In pears, as in other deciduous fruit species, selecting an appropriate training system is essential, because it determines the choice of rootstock, inter-row spacing, and tree spacing [5]. Training systems represent a foundational principle of orchard management, playing a critical role in optimizing light interception and distribution within the canopy to enhance productivity and fruit quality [6,7]. Moreover, the proper choice of training systems, combined with the selection of appropriate scion cultivars and rootstocks, enhances mechanization and optimizes labor efficiency [5,8].

In Brazil, the central leader is the predominant training system, characterized by lateral branches that are not permanently fixed and originate from a central axis, creating a conical or pyramidal canopy structure [9]. However, this system has been gradually replaced with the use of dwarfing rootstocks that allow the implementation of high-density systems [10,11]. Among the various training systems, notable examples include the Vertical Axis, Spindle, Multi-Leader, Palmette, V-System, and Bi-axis [5].

Within the Spindle group, the Tall Spindle system has emerged, incorporating elements from Slender Spindle, Vertical Axis, Solaxe, and Super Spindle systems; it is considered a high-density system [10]. Tall Spindle is based on the Slender Spindle tree developed by Wertheim [12], which was designed to improve early yields and management efficiency by planting higher tree densities and reducing tree height to allow all management to be handled from the ground. Its key characteristic is the continuous renewal of lateral branches, without retaining permanent branches along the central leader [10]. Designed to achieve early production, the Tall Spindle system is typically used in high-density plantings of 3500 to 4500 trees per hectare and is recommended for orchards using dwarfing rootstocks [10,13]. This system simplifies orchard management by reducing tree size, thereby minimizing the need for ladders during pruning and harvesting [6,10].

Another medium-density system gaining worldwide adoption is the Bi-axis system [13]. The Bi-axis concept involves splitting the tree's vigor between two main leaders, which can be achieved through pre-formed double-grafted plants (Bibaum®, Ferrara, Italy) or field-grown trees with reduced height to promote the development of two leaders [5]. The Bi-axis system aims to simplify and expedite cultural practices, especially winter pruning, summer branch bending, and harvesting [14]. It serves as an alternative for vigor control and increased planting density without significantly raising the cost of tree acquisition [15]. Effective vigor management in the Bi-axis system is crucial because it enhances leaf area distribution, light penetration, and nutrient allocation, ultimately enhancing carbohydrate production and fruit quality [5].

Branch bending is a management technique employed in certain training systems, such as Tall Spindle, to balance vegetative and reproductive growth by regulating acrotony and suppressing apical dominance [16,17]. Adjusting branch angles affects the flow of water, metabolites, and hormones, enabling their efficient distribution along branches and the main leader [17,18]. This technique enhances light penetration into the canopy, promotes flower bud formation, and increases fruit set and quality [19].

Several authors have emphasized the importance of these practices for efficient resource use in current and future fruit production systems [7,17]. Considering planar canopy systems, various two-dimensional tree architectures have been developed or are under development in many countries [13,18].

This research addresses global agricultural challenges, including the need for sustainable orchard management practices that enhance productivity and resource efficiency. By focusing on high-density training systems in high-altitude regions, it contributes to broader scientific efforts to understand how training systems influence tree architecture and productivity under diverse environmental conditions. Furthermore, the findings offer practical implications for growers aiming to balance economic viability with environmental stewardship, aligning with the global push toward sustainable horticulture.

This study focused on the 'Rocha' and 'Santa Maria' pear cultivars, which are commercially significant due to their high productivity, fruit quality, and adaptability to diverse growing conditions. However, their performance in high-density orchards using modern training systems remains underexplored, particularly in high-altitude regions like southern

Brazil [9,11]. The Tall Spindle and Bi-axis systems were selected as innovative alternatives to traditional training methods. This research addresses the need for optimized orchard management practices tailored to the unique edaphoclimatic conditions of the region, aiming to provide growers with evidence-based recommendations

Thus, this study aimed to analyze the vegetative and productive parameters as well as the fruit quality of the European pear cultivars 'Rocha' and 'Santa Maria', under three training systems of Tall Spindle—45°, —90°, and Bi-axis, during the 2016/2017 to 2022/2023 growing seasons in the highland region of southern Brazil.

2. Materials and Methods

2.1. Meteorological Observations

The experiments were conducted in a commercial orchard of European pear cultivars located in the São Joaquim municipality, Santa Catarina State, southern Brazil (28°14′ S, 50°00′ W), at an altitude of 1360 m above sea level. The trials were carried out over six years, from the 2016/2017 to 2022/2023 crop seasons. The climate in this region is classified as humid mesothermal with mild summers (Cfb in the Köppen classification) [20]. Annual precipitation averages between 1200 and 1900 mm, with evenly distributed rainfall throughout the year. The annual mean temperature ranges from 15 °C to 16 °C, with occasional snow and frost during colder periods [2]. The soil is a Humic Cambisol [2] characterized by high clay content (498 $g \cdot kg^{-1}$) and organic matter (69 $g \cdot kg^{-1}$).

2.2. Plant Materials

The four-hectares orchard consisted of three-year-old European pear trees (*Pyrus communis* L. 'Rocha' and 'Santa Maria') grafted onto BA-29 (*Cydonia oblonga* L.) rootstocks. The training system was the main plot factor with each main plot consisting of 4 rows 40 m long. The trees were trained using three different systems: Tall Spindle with branch bending at 45° (Tall Spindle—45°), Tall Spindle with branch bending at 90° (Tall Spindle—90°), and Bi-axis. The planting density was 2857 trees per hectare, with a spacing of 3.5 m × 1.0 m. Trees reached an average height of 2.5 m. Experimental plots were isolated using buffer rows, and standard management practices, such as fertilization, irrigation, and pest control, were applied uniformly across all plots to ensure consistency.

2.3. Training and Pruning Systems

For the Tall Spindle and Bi-axis systems, branch bending began during the winter of 2014 (July) and the angles were measured and adjusted to 45° and 90° relative to the central leader using a digital angle finder. Measurements were taken at the midpoint of each branch to ensure consistency across all replicates. A two-year pre-treatment period was implemented before initiating the experimental treatments to ensure uniformity and minimize residual effects from prior orchard management practices. In the Bi-axis system, trees were headed back after planting to encourage the formation of two main leaders from new shoots. Branch bending was repeated during the 2015 and 2016 seasons during formative-phase years. By 2016, the trees had likely reached a stable architectural structure under the respective training systems. Throughout the experiment, pruning involved the removal of branches with a diameter exceeding two-thirds of the central leader to prevent competition with the leader [10].

2.4. Data Collection

Data on vegetative growth, productivity, and fruit quality were collected from the 2016/2017 to 2022/2023 crop seasons. Evaluations of vegetative parameters were conducted during winter (June and July), while productive and fruit quality parameter assessments occurred in summer (January and February).

2.5. Vegetative and Productive Parameters

(a) Vegetative parameters: plant height (m); trunk cross-sectional area (TCSA) (cm^2);
(b) Productive parameters: productivity ($ton \cdot ha^{-1}$); yield efficiency (YE) ($kg \cdot cm^{-2}$);
(c) Fruit quality parameters: fruit weight (g), diameter (mm), and height (mm); pulp firmness (N); and soluble solid content (SSC) (°Brix).

2.6. Measurement Methods

- The plant height (m) was measured with a flexible tape graduated in millimeters, from the grafting point to the apex of the plant;
- The TCSA was measured by the average of the longitudinal and transversal measurements of the central leader diameter at 10 cm above the grafting point. To transform the diameter values into TCSA, the equation A = (πd 2)/4 was used, where d = trunk diameter;
- The productivity ($ton \cdot ha^{-1}$) was calculated, by using the fruit mass per plant and the number of plants per hectare multiplied as a function of the spacing used. Only the five central plants of each plot were harvested;
- The accumulated productivity was obtained by the sum of the productivity of each year;
- The Biennial Bearing Indices (BBIs) were calculated using yield data from the harvests 2017–2023. The BBI was calculated by the following equation, adapted from Hoblyn [21]:

$$\sum_{i=2}^{n}\left[\frac{|y_i - y_{i-1}|/(y_i + y_{i-1})}{(n-1)}\right]$$

where

- ys is the yield observed in the plot, in the sth crop, in the ordered series of size n, where n is the number of harvests;
- -($y_i + y_{i-1}$) is the absolute difference between the yields of two successive crops. This BBI corresponds to the average of the absolute differences between two successive crops expressed as a proportion of the total produced in the two years and varies from zero to one; the closer its value is to one (1), the more pronounced the alternation or oscillation of production;
- The yield efficiency (YE) ($kg \cdot cm^{-2}$) was calculated by the ratio of the average weight of fruits per plant ($kg \cdot plant^{-1}$) by the TCSA of the scion (cm^{-2}), expressed in kg of fruits produced per centimeter square (cm^{-2}) of TCSA. The accumulated yield efficiency was obtained by the sum of the productivity of each year.

2.7. Fruit Quality Parameters

A sample of 30 fruits per plot was randomly collected from the upper, middle, and lower parts of the canopy, and was evaluated for the following:

- Fruit diameter: measured using a graduated wooden ruler;
- Pulp firmness: measured with a TA.XTexpress digital texture analyzer, with readings taken from two equatorial zones of the fruit after removing epidermal discs;
- Soluble solid content (SSC): measured using juice extracted from slices of 10 fruits with a digital refractometer—ITREFD-45, Dortmund, Germany.

2.8. Statistical Analysis

The experiments were arranged in a randomized complete block design with four replicates and ten trees per plot and conducted within the same orchard area, ensuring that all plots were exposed to similar conditions. Univariate data were subjected to the Shapiro–Wilk test for normality and Bartlett's test for homoscedasticity, followed by ANOVA and Tukey's test at a 5% significance level. For multivariate analysis, normality was assessed using Kurtosis, and homogeneity was verified using Box's M test. Treatments were grouped using non-hierarchical cluster analysis (K-Means), followed by principal component analysis (PCA), to examine variable inter-relationships.

PCA was performed in RStudio (version 4.3.1) using R programming [22]. PCA reduces complex multivariate data into principal components (PCs), which represent linear combinations of original variables, simplifying data interpretation. Correlation analyses and ANOVA were used as supplementary tools to support PCA findings.

3. Results

Significant differences ($p \leq 0.05$) were observed in the effects of the Tall Spindle—45°, —90°, and Bi-axis systems on vegetative and productive parameters. However, no significant differences ($p \leq 0.05$) were found in the fruit quality parameters for the cultivars 'Rocha' and 'Santa Maria' across the 2016/2017 to 2022/2023 growing seasons (Tables 1 and 2).

The cultivar 'Rocha' exhibited greater plant height compared to 'Santa Maria' (Table 1). In the 'Rocha' cultivar, the Tall Spindle systems (45° and 90°) produced higher average plant heights than the Bi-axis system (Table 1). In contrast, for the 'Santa Maria' cultivar, which displayed shorter plants, the TCSA did not significantly differ ($p \leq 0.05$) among the training systems (Table 1).

Tall Spindle—90° exhibited the highest cumulative productivity for both 'Rocha' and 'Santa Maria' cultivars. The 'Santa Maria' cultivar trained under Tall Spindle—90° achieved the highest productivity. In contrast, the Bi-axis system, although less productive overall, exhibited greater productive stability over the 2016/2017 to 2022/2023 growing seasons (Table 1). Productive efficiency was significantly ($p \leq 0.05$) higher in the Tall Spindle system for both cultivars, with Tall Spindle—45° yielding higher values for the 'Santa Maria' cultivar compared to the Bi-axis system (Table 1).

Table 1. Mean values of vegetative and productive parameters for the European cultivars 'Rocha' and 'Santa Maria' trained under different systems during the 2016/2017 to 2022/2023 growing seasons in a highland region of southern Brazil.

Cultivars	Training System	Productivity Mean	Cumulative Productivity	Productivity Efficiency Mean	Total Plant Height	TCSA	BBI
		$t \cdot ha^{-1}$	$t \cdot ha^{-1}$	$kg \cdot cm^{-2}$	m	cm^2	(unit)
Rocha	Tall Spindle—45°	30.22 a	211.55 a	0.27 a	3.42 a	64.77 a	0.49 ab
	Tall Spindle—90°	28.24 a	197.69 a	0.27 a	3.31 a	59.53 ab	0.51 a
	Biaxis	22.31 b	156.14 b	0.24 b	3.02 b	51.47 b	0.45 b
	CV (%)	7.24	9.11	3.21	4.03	11.09	6.87
Santa Maria	Tall Spindle—45°	38.70 b	270.91 b	0.61 a	3.18 a	43.95 ^{ns}	0.37 a
	Tall Spindle—90°	49.10 a	343.69 a	0.56 b	3.23 a	40.63	0.30 b
	Biaxis	30.85 c	215.92 c	0.37 c	2.34 b	43.95	0.26 b
	CV (%)	8.02	8.03	2.58	3.98	13.14	7.32

TCSA: trunk cross-sectional area; BBI: biennial bearing indices. Means followed by the same lowercase letters comparing training systems for each cultivar do not differ by Tukey ($p \leq 0.05$); ns: not significant; CV: coefficient of variance.

Table 2. Mean values of fruit quality parameters for the European cultivars 'Rocha' and 'Santa Maria', trained under different training systems during the 2016/2017 to 2022/2023 seasons in a high-altitude region of southern Brazil.

Cultivars	Training System	Fruit Weight	Fruit Diameter	Fruit Height	Pulp Firmness	Soluble Solids
		g	cm	cm	N	°Brix
Rocha	Tall Spindle—45°	143.87 ns	7.19 ns	7.65 ns	54.04 ns	10.91 ns
	Tall Spindle—90°	149.81	7.25	7.64	56.05	10.90
	Bi-axis	148.42	7.23	7.70	53.42	10.93
	CV (%)	3.12	2.85	4.01	3.78	2.23
Santa Maria	Tall Spindle—45°	175.41 ns	6.59 ns	8.82 ns	43.55 ns	10.25 ns
	Tall Spindle—90°	184.04	6.66	9.04	44.25	10.15
	Bi-axis	184.14	6.51	8.87	44.00	10.15
	CV (%)	3.76	3.18	4.76	3.55	2.54

ns = not significant; CV = coefficient of variance.

Plants trained under the Bi-axis system exhibited lower BBI values, particularly in the 'Santa Maria' cultivar. Tall Spindle—90° also reduced the BBI for 'Santa Maria'. Conversely, for the 'Rocha' cultivar, the BBI was more pronounced under this system (Table 1), primarily due to the observed reduction in flowering.

No significant differences ($p \leq 0.05$) were observed in the effects of the Tall Spindle—45°, Tall Spindle—90°, and Bi-axis systems on fruit quality parameters, including weight, diameter, height, pulp firmness, and soluble solid content, regardless of the cultivar (Table 2). Despite the lack of statistical significance ($p \leq 0.05$), the 'Santa Maria' cultivar demonstrated higher fruit weight and height, whereas the 'Rocha' cultivar exhibited greater fruit diameter, pulp firmness, and soluble solid content (Table 2).

The productivity of the cultivars 'Rocha' and 'Santa Maria' over time (Figures 1 and 2) revealed that, starting from the third season (2018/2019), the Tall Spindle—45° and—90° systems for 'Rocha' exhibited significant differences ($p \leq 0.05$) compared to the Bi-axis system. The cumulative productivity of both Tall Spindle systems (45° and 90°) was consistently higher than that of the Bi-axis system across the evaluated seasons (Figures 1 and 2).

The annual productivity fluctuation of the 'Rocha' cultivar was more pronounced in most seasons compared to 'Santa Maria', and this trend was consistent across the three training systems. This pattern highlights a similar biennial bearing index (BBI) for 'Rocha' across the Tall Spindle—45°, Tall Spindle—90°, and Bi-axis systems (Figure 1).

As observed for 'Rocha', the Tall Spindle—45° and Tall Spindle—90° systems also exhibited higher productivity for the 'Santa Maria' cultivar starting from the third season (2018/2019) (Figure 2). However, the Tall Spindle—90° system demonstrated higher cumulative productivity and lower annual productivity fluctuation compared to the Tall Spindle—45° system, indicating a reduced biennial bearing index (BBI) for 'Santa Maria' (Figure 2).

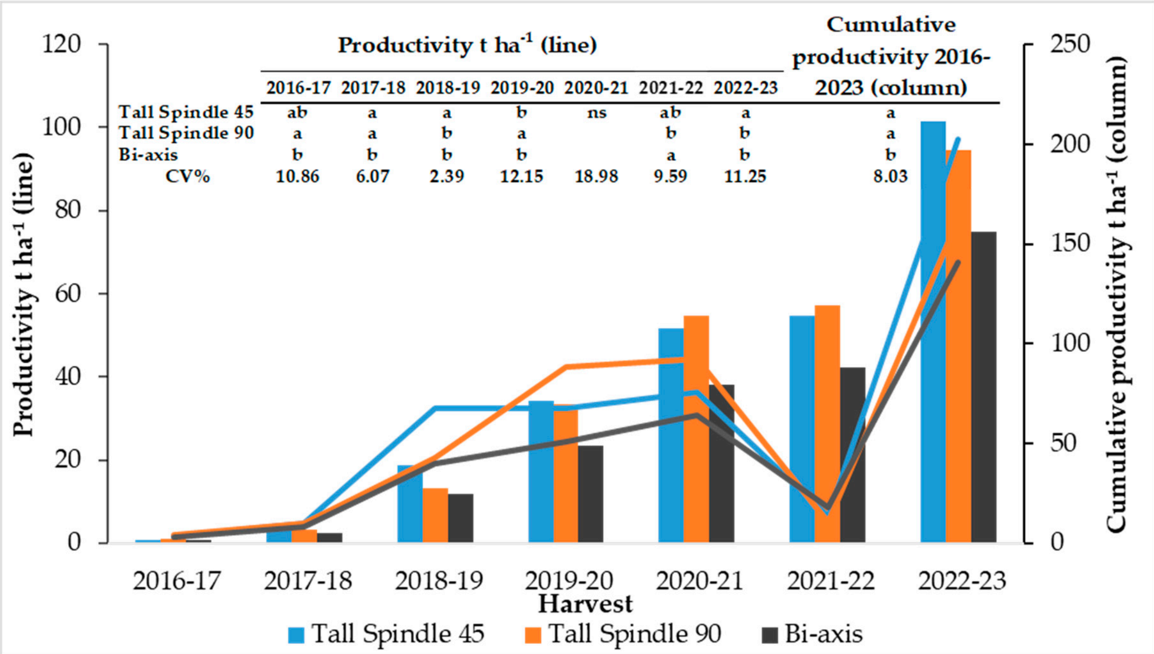

Figure 1. Productivity and cumulative productivity in the Tall Spindle—45°, Tall Spindle—90°, and Bi-axis systems for the 'Rocha' cultivar during the 2016/2017 to 2022/2023 growing seasons in a highland region of southern Brazil. Means followed by the same lowercase letter did not differ significantly among treatments according to Tukey's test ($p \leq 0.05$). ns—not significant.

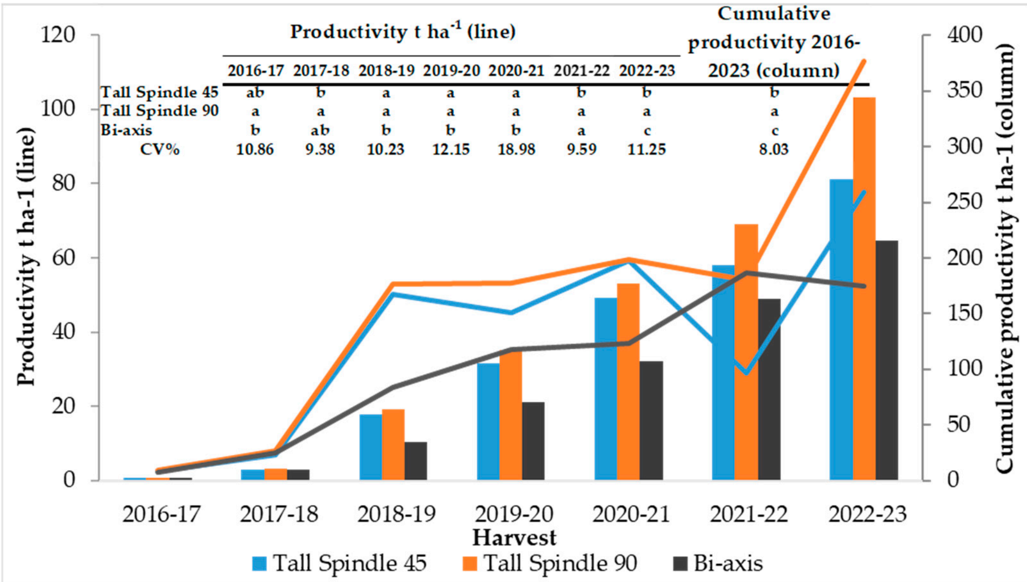

Figure 2. Productivity and cumulative productivity in the Tall Spindle—45°, Tall Spindle—90°, and Bi-axis systems for the 'Santa Maria' cultivar during the 2016/2017 to 2022/2023 growing seasons in a highland region of southern Brazil. Means followed by the same lowercase letter did not differ significantly among treatments according to Tukey's test ($p \leq 0.05$).

The analysis of variance and PCA of vegetative–productive parameters and fruit quality over the 2016/2017 to 2022/2023 growing seasons (Table 1 and Figure 3) revealed that the 'Santa Maria' cultivar exhibited higher productivity, reduced vigor, lower BBI, and greater fruit weight. These parameters indicated higher productive efficiency for the 'Santa Maria' cultivar compared to 'Rocha', regardless of the training system.

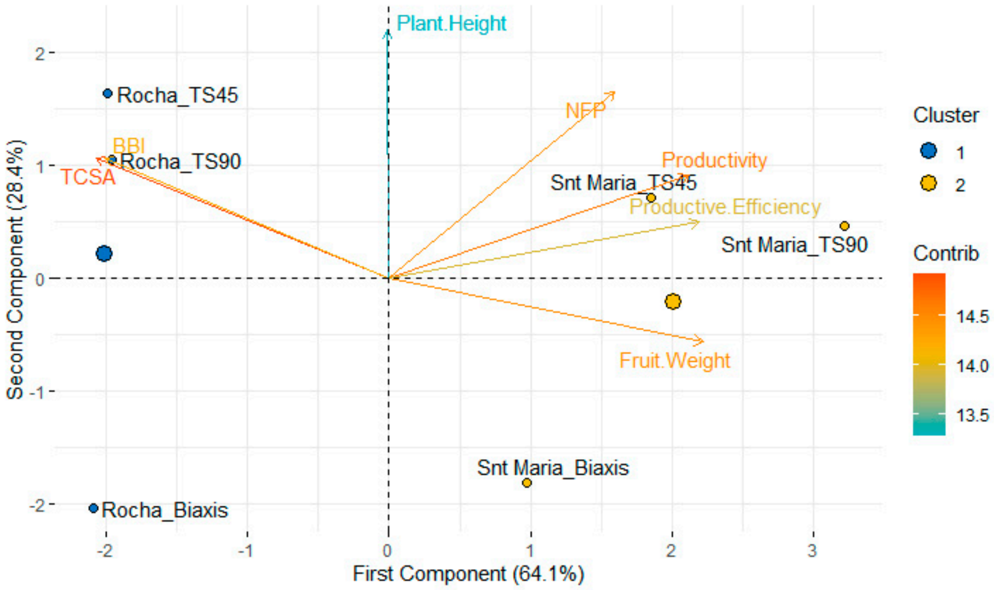

Figure 3. Principal component analysis (PCA) of vegetative–productive parameters including plant height, trunk cross-sectional area (TCSA), number of fruits per plant (NFP), fruit weight, productivity, productive efficiency, and biennial bearing index (BBI) for the European cultivars 'Rocha' and 'Santa Maria'. The cultivars were trained under the Tall Spindle (TS) systems with 45° (TS45) and 90° (TS90) bending angles, and the Bi-axis system during the 2016/2017 to 2022/2023 seasons in a highland region of southern Brazil. The largest blue and yellow circles represent the average of each training system.

The Bi-axis system resulted in lower plant height and reduced fruit quantity, leading to lower productivity and productive efficiency compared to the Tall Spindle—45° and Tall Spindle—90° systems. Tall Spindle—90° demonstrated more productive plants with a lower BBI compared to Tall Spindle—45°. However, no significant differences in vegetative–productive parameters were observed between the Tall Spindle—45° and Tall Spindle—90° systems for the 'Rocha' cultivar.

The effects of training systems and research years on fruit quality of the 'Rocha' and 'Santa Maria' cultivar are given in Table 2 and Figure 4. Fruit weight, diameter and height, as well as pulp firmness and soluble solids, showed that all fruit characteristics were not found to be statistically significant.

The PCA analysis of fruit quality parameters demonstrated that each cultivar exhibits a well-defined pattern in terms of fruit size, shape, and texture (Table 2 and Figure 4). Regardless of the training system, the 'Santa Maria' cultivar produced fruits with greater weight and height, lower pulp firmness, and higher soluble solid content compared to the 'Rocha' cultivar (Table 2 and Figure 4).

The PCA analysis revealed that the differences between training systems for each cultivar, as evidenced by the second principal component, accounted for only 1.1% of the data variation. Consequently, no significant differences in fruit quality parameters were observed among the Tall Spindle—45°, Tall Spindle—90°, and Bi-axis systems for either 'Rocha' or 'Santa Maria' cultivars.

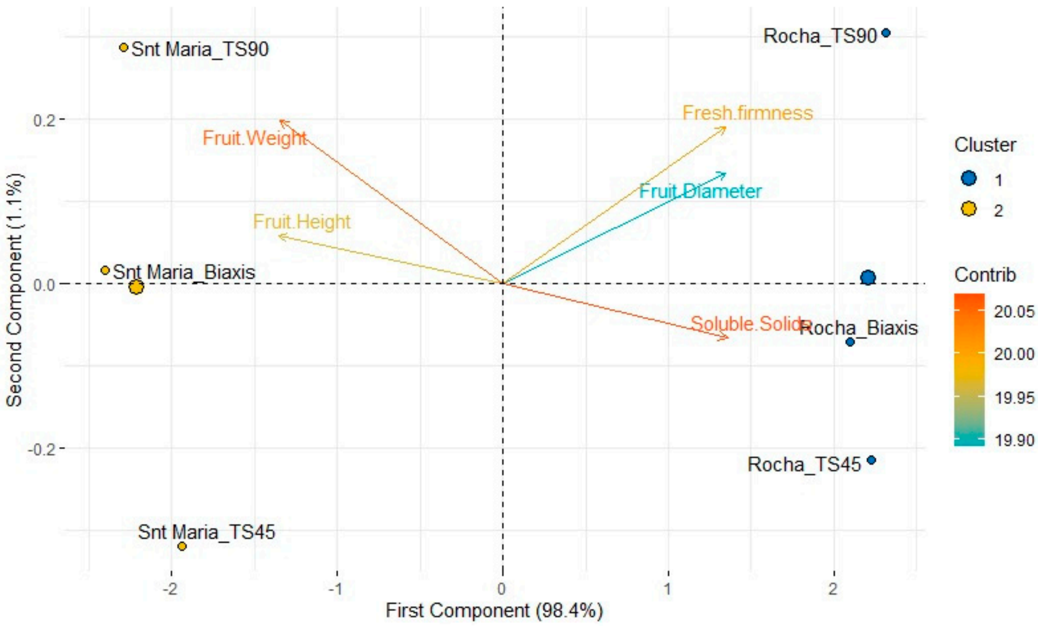

Figure 4. Principal component analysis (PCA) of fruit quality parameters including weight, height, diameter, pulp firmness, and soluble solid content for the European cultivars 'Rocha' and 'Santa Maria'. The cultivars were trained under the Tall Spindle (TS) systems with 45° (TS45) and 90° (TS90) bending angles, and the Bi-axis system during the 2016/2017 to 2022/2023 growing seasons in a highland region of southern Brazil. The largest blue and yellow circles represent the average of each training system.

4. Discussion

The 45° and 90° branch angles in the Tall Spindle system were selected based on their known impact on balancing vegetative and reproductive growth. The 45° angle is often associated with moderate vigor control and increased light interception, while the 90° angle encourages greater fruiting spur formation by suppressing apical dominance. These angles represent both regional practices and experimental adaptations aimed at optimizing productivity and canopy management under high-density planting conditions. The Bi-axis system was selected as it is increasingly recognized for its potential to control vigor by distributing growth across two leaders, particularly in high-density systems. This system simplifies pruning and harvesting, making it a viable alternative to traditional training methods in regions aiming for mechanization and labor efficiency.

While the Tall Spindle and Bi-axis systems are gaining traction globally, their application in high-altitude regions with distinct edaphoclimatic conditions is still underexplored. This study aims to bridge this gap by evaluating their performance in a novel context, offering insights that may guide future innovations in sustainable orchard management.

The data highlight the significant effects of the three training systems on the vegetative–productive parameters of the 'Rocha' and 'Santa Maria' cultivars, particularly the Tall Spindle—45° and Tall Spindle—90° systems. For the 'Rocha' cultivar, the Tall Spindle—45° and Tall Spindle—90° systems exhibited greater average plant height and trunk cross-sectional area (TCSA) compared to the Bi-axis system, with no significant effects on the 'Santa Maria' cultivar.

The Tall Spindle system's benefits, including increased productivity, early yield potential, compatibility with high-density plantings, and ease of mechanization, make it an attractive option for modern orchards. Additionally, its sustainability features, such as improved light interception, water-use efficiency, and reduced pesticide requirements, align with environmentally responsible farming practices.

Mitre et al. [23] demonstrated that the Tall Spindle system produced higher plant height and TCSA for apple cultivars such as 'Gala', 'Pinova', 'Topaz', and 'Florina' compared to the Slender Spindle, Vertical Axis, and 'Solaxe' systems. Regarding vigor, the 'Rocha' cultivar exhibited higher values for plant height and TCSA, traits that are consistently observed even when grown on dwarfing rootstocks [24]. Conversely, the 'Santa Maria' cultivar was characterized by less vigorous canopies compared to other cultivars, such as 'Rocha', which facilitated orchard management due to reduced pruning requirements [24]. Musacchi et al. [5] noted that the Bi-axis system reduced TCSA in the 'Abate Fetel' cultivar, suggesting that distributing plant vigor across two leaders positively impacts vegetative growth control.

The specific effects of the Tall Spindle—45° and Tall Spindle—90° systems on the 'Rocha' cultivar are likely linked to the greater vigor of this cultivar and its relationship with production. The Bi-axis system proved advantageous for controlling vigor and ensuring production stability, with a lower impact on BBI. However, its lower efficiency highlights the need for system adaptations for cultivars with reduced vigor. Jovanović [25] demonstrated that the central leader system in the 'Rocha' and 'Santa Maria' cultivars grafted on Belgian quince 'Adams' rootstocks showed intermediate vigor under similar edaphoclimatic conditions of highland regions in southern Brazil.

The choice of training system should account for the cultivar and production goals. The Tall Spindle—45° and Tall Spindle—90° systems were more suitable for achieving high productivity, while the Bi-axis system offered stability and ease of management for moderately vigorous plants. Both Tall Spindle bending angles exhibited higher average productivity and cumulative production than the Bi-axis system for both 'Rocha' and 'Santa Maria' over the 2016/2017 to 2022/2023 seasons. Despite lower values compared to Tall Spindle—45° and Tall Spindle—90°, the Bi-axis system achieved average productivity values of 22.30 $t \cdot ha^{-1}$ for 'Rocha' and 30.85 $t \cdot ha^{-1}$ for 'Santa Maria', exceeding both the national average of 16.7 $t \cdot ha^{-1}$ [26] and the global average of 18.6 $t \cdot ha^{-1}$ [1]. Similarly, Robinson [10] observed greater productivity with the Tall Spindle system compared to other training systems for the apple cultivars 'McIntosh' and 'Honeycrisp'.

The Tall Spindle—90° system induced a better productive performance in the 'Santa Maria' cultivar than in 'Rocha'. Regardless of the bending angle, the Tall Spindle system did not significantly ($p \leq 0.05$) affect the cumulative productivity of 'Rocha', showing only a minor difference of 7% in production. According to Musacchi et al. [5], Colaric et al. [18], Sherif [19], and Khandaker et al. [27], branch bending can improve flowering, fruit development, and yield by controlling vigor. However, cultivars respond differently to vigor control. In this study, the vigor of the 'Rocha' cultivar positively correlated with production, while in 'Santa Maria', vigor control resulted in increased productivity.

The degree of branch bending influences sap translocation speed, directly affecting floral induction and inversely impacting vegetative growth [28]. Branches bent at a 90° angle were stimulated to form short shoots, a characteristic more associated with the 'Rocha' cultivar. In contrast, branch bending in the 'Santa Maria' cultivar promoted the formation of spurs and fruiting clusters [5,7,14], positively impacting production.

The average plant height was lower in the Bi-axis system, likely due to the presence of two central leaders, which positively affect the control of vegetative growth [5,14]. However, the enhanced vigor control in the Bi-axis system did not ensure higher productivity or productive efficiency, suggesting this system may be better suited to more vigorous rootstocks [5]. Studies with the 'Fuji' apple cultivar conducted under the Bi-axis system reported better control of plant height and reduced production alternation [9].

The Tall Spindle—45° and Tall Spindle—90° systems resulted in greater vigor to plants, as evidenced by higher TCSA values and the excellent productivity and productive efficiency. Compared to the ‘Rocha’ cultivar, ‘Santa Maria’ achieved higher productive efficiency, surpassing ‘Rocha’ by 0.37 $kg \cdot cm^{-2}$. Despite this increase not being too high, the ‘Santa Maria’ cultivar still shows untapped potential. For instance, Ozturk and Faizi [29] reported a productive efficiency of 2.24 $kg \cdot cm^{-2}$ for ‘Santa Maria’ under a modified leader system, while Rufato [9] observed an efficiency of 2.97 $kg \cdot cm^{-2}$ for the same cultivar in a central leader system adapted to climatic conditions similar to those in this study.

The production decline observed during the 2021–2022 growing season indicated a production alternation pattern for each cultivar and training system combination. Vigorous plants tend to exhibit greater production alternation [30], likely due to reduced floral return and effective fruit set rates [3,28]. In this study, lower floral return rates were observed in more vigorous plants, such as ‘Rocha’, regardless of the training systems. For ‘Santa Maria’, these lower rates were seen with the Tall Spindle—45° system. Moreover, production alternation has been studied in these cultivars by Carra [3] and Campbell and Kalcsits [4]. The Bi-axis system showed the lowest BBI (0.26) for ‘Santa Maria’, which may be related to the lower fruit load per plant in this system. The reduced fruit load allowed for a better balance between vegetative growth and fruiting, resulting in more consistent productivity [31]. BBI can serve as a metric for determining the optimal fruit load that a plant can sustain without compromising future yields [27]. The bending angle in the Tall Spindle system had a greater influence on BBI, underscoring the importance of cultivar-specific adjustments to maintain productive stability. Additionally, strategies such as using plant growth regulators [3] and proper fruit load management [4,31] may effectively reduce the BBI.

Training systems can influence fruit quality parameters through changes in the canopy microclimate. In the Bi-axis system, where two central leaders control vigor and production, light interception may be compromised compared to the Tall Spindle system, potentially affecting fruit quality parameters positively or negatively. The ‘Santa Maria’ cultivar produced larger and heavier fruits than ‘Rocha’ regardless of the training system, corroborating findings by Jovanović et al. [25]. The average fresh weight of ‘Rocha’ fruits was 150 g, which, while relatively low, was higher than results reported by Rufato et al. [9]. Pulp firmness and soluble solid content, although not significantly affected by training systems for each cultivar, were higher in the ‘Rocha’ cultivar compared with ‘Santa Maria’. In contrast, the ‘Santa Maria’ cultivar pulp was characterized by a softer, butter-like flesh [24].

These results highlight that the higher productivity and efficiency achieved with the Tall Spindle—90° system, particularly in the ’Santa Maria’ cultivar, translate into greater economic viability by optimizing resource use, increasing early returns, and reducing the labor costs associated with pruning and harvesting.

The findings of this study offer valuable insights into the potential adaptability of the Tall Spindle and Bi-axis systems for other pear cultivars. For instance, cultivars with varying vigor levels or canopy architectures may require adjustments in training angles or planting densities to optimize productivity. Additionally, regions with different climatic conditions, such as lower altitudes or drier environments, may benefit from modifications to irrigation or canopy management practices to maximize the efficiency of these training systems.

5. Conclusions

- The Bi-axis system produces less vigorous plants for both cultivars, making it a suitable alternative for high-density plantings.
- The bending angle in the Tall Spindle system modifies the productive characteristics of plants depending on the cultivar.
- Bending at 45° or 90° in the Tall Spindle training system does not differentiate productive performance in the Rocha cultivar.

- The Tall Spindle—90° system produces more productive plants with a lower BBI in the 'Santa Maria' cultivar. Thus, bending at 90° in the Tall Spindle training system may be an alternative to addressing one of the challenges in pear cultivation: production instability.
- Different training systems did not affect fruit quality parameters, which were more dependent on cultivar characteristics.
- The results indicate that the 'Santa Maria' cultivar, particularly when trained under the Tall Spindle—90° system, demonstrates higher productivity and efficiency, making it a promising candidate for cultivation under the edaphoclimatic conditions of high-altitude regions in southern Brazil. However, further studies on long-term sustainability and adaptability across different environmental conditions are recommended.

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