



## Feasibility of Raspberry (*Rubus idaeus* L.) Cultivar Cultivation under Greenhouse Conditions

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### Original Article

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### ABSTRACT

This study was conducted to evaluate the performance of four red raspberry cultivars, namely 'Encore', 'Rosana', 'Polana', and 'Saanich', under hydroponic cultivation in a greenhouse. Two-year-old plants were grown in 12-L pots containing a raspberry-specific substrate, using an open drip hydroponic system. The substrate consisted of 40–45% processed wood fiber, 20–25% processed pine bark fiber, 25–30% processed pumice, 1–2% hardening agent, and 0.5–1% wetting agent. Plants were fertigated with a standard nutrient solution formulated for raspberry production. 'Encore' exhibited superior vegetative growth, recording the highest plant height (142 cm), stem diameter (7.24 mm), internode length (3.25 cm), and number of suckers per plant (3.5), while 'Rosana' had the highest leaf number (38). 'Encore' significantly outperformed the other cultivars, with the highest number of fruits per plant (31), fruits per inflorescence (6), inflorescences per plant (5.25), fruit weight (1.4 g), and receptacle diameter (15.35 mm). 'Polana' flowered and fruited earlier than the other cultivars, whereas 'Encore' required a longer period to flowering and harvest. The highest TSS was recorded in 'Polana' (8.87). The highest total phenolic content among the evaluated cultivars was found in 'Saanich' (55.45) and 'Polana' (53.85), while the highest anthocyanin content was observed in 'Rosana' (30.83). The highest vitamin C content was recorded in 'Encore' and 'Polana' (11.66). 'Polana' showed earlier flowering and favorable biochemical characteristics, 'Encore' demonstrated the best vegetative growth and yield performance. Therefore, 'Encore' can be recommended as the most suitable cultivar for hydroponic greenhouse raspberry production.

### ARTICLE

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## 1. Introduction

Raspberry (*Rubus idaeus* L.), a high-value member of the Rosaceae family, has gained significant global attention due to its exceptional organoleptic properties and high concentration of health-promoting bioactive compounds (Szajdek and Borowska, 2008). Raspberries are very attractive, colorful and delicious fruits that are consumed both raw and processed (frozen, dried and in juices) (Calvano *et al.*, 2019). They are also used in a variety of desserts, sweets, smoothies and jams. This fruit is a rich natural source of substances such as anthocyanins, phenolic acids, flavonols, vitamins C and E, folic acid and ellagic acid (Boivin *et al.*, 2007). In addition, raspberries contain a small amount of carbohydrates and a high amount of fiber per unit weight (Calvano *et al.*, 2019). Economically, the global raspberry market has seen a consistent upward trend over the last two decades, driven by the increasing consumer demand for “superfoods” and the fruit’s versatility in both fresh and processed industries (Samofalov, 2025). Raspberry is one of the most popular and valuable berries, and due to the increasing demand, interest in its production and investment in its cultivation has increased significantly worldwide (Kempfer *et al.*, 2011). Currently, major producers such as Russia, Mexico, and Serbia dominate the international market, highlighting the crop’s high profitability and its strategic importance in modern horticulture (FAOSTAT, 2023). The production of this type of raspberry is an important and valuable horticultural industry in most countries of Northern and Central Europe, as its income is generated both directly from the production and sale of fresh fruit and indirectly from fruit processing (Krstić *et al.*, 2019). In Iran, while commercial cultivation is relatively nascent compared to traditional fruit crops, raspberry production has emerged as a lucrative opportunity for diversifying agricultural systems and increasing income for small-scale farmers (Koraqi *et al.*, 2019). However, the expansion of its cultivation is often limited by specific climatic requirements, which has led to a growing interest in utilizing greenhouse technologies to ensure off-season production and superior fruit quality in diverse Iranian provinces (Shayanmehr *et al.*, 2022).

Cultivar type is one of the important factors affecting the morphological, functional, chemical, and sensory characteristics of fruit among different cultivars (Leposavić *et al.*, 2013). Cultivar selection is a key determinant of productivity and fruit quality in protected horticultural systems because genotypic differences can influence adaptation to environmental conditions and overall yield performance under managed production systems (Gülçin *et al.*, 2011). The environmental conditions in which plants grow also affect phenological, morphological, and plant performance traits, mainly flowering, fruiting, maturity, and fruit harvest (Birgi *et al.*, 2019). In controlled-environment berry production, maintaining suitable temperature and humidity is especially important, as excessive moisture can increase the risk of *Botrytis* gray mold and other diseases that reduce marketable yield and fruit quality (Pritt *et al.*, 1999). More broadly, greenhouse and protected horticulture systems provide opportunities for improved environmental control and production stability, but their effectiveness depends on matching crop management and plant material to the specific conditions of the production environment (Huang *et al.*, 2026). Therefore, evaluating berry cultivars under protected conditions is an important step in identifying genotypes with stable agronomic performance and commercial potential in environments where climatic and disease pressures may constrain open-field production (Gülçin *et al.*, 2011).

The four raspberry cultivars evaluated in this study (‘Encore’, ‘Rosana’, ‘Polana’, and ‘Saanich’) were selected because they represent commercially relevant genotypes with distinct agronomic and phenological characteristics that may influence their performance under protected cultivation. ‘Polana’ is a widely cultivated primocane-fruiting cultivar characterized by early ripening, high productivity, and good adaptability to different production systems, making it popular in European berry production (Danek, 2006; Jennings, 1988). In contrast, ‘Encore’ and ‘Saanich’ are generally classified as floricanes-fruiting cultivars valued for their relatively large fruit size, good fruit quality, and high yield potential under temperate growing conditions (Finn and Clark, 2012; Moore, 2004). ‘Rosana’ has also been reported as a productive cultivar with desirable fruit quality traits in several European production regions (Leposavić *et al.*, 2013). Because these cultivars differ in fruiting habit, phenological behavior, and yield potential, they provide a useful genetic and agronomic contrast for evaluating cultivar adaptability and productivity under greenhouse hydroponic conditions.

Despite the increasing interest in protected berry production systems, there is still a lack of comprehensive studies comparing the morphological, yield-related, phenological, and biochemical performance of raspberry cultivars under greenhouse hydroponic conditions. This knowledge gap is particularly evident in Iran, where raspberry cultivation is still emerging and cultivar suitability for controlled-environment production has not been systematically evaluated. Addressing this gap is essential for selecting cultivars that can achieve stable yield and fruit quality under greenhouse hydroponic systems.

## 2. Materials and Methods

This study was conducted to compare four raspberry cultivars (Encore, Rosana, Polana, and Saanich) under hydroponic cultivation and greenhouse conditions in Guilan Province. The experiment was carried out in a glass

greenhouse located at the Faculty of Agricultural Sciences, University of Guilan. The greenhouse was oriented in an east–west direction to optimize light interception. During the experimental period, environmental conditions were monitored using digital sensors installed at canopy height. The average daytime temperature inside the greenhouse was maintained at  $24 \pm 2$  °C, while nighttime temperature averaged  $18 \pm 2$  °C. Relative humidity ranged between 60 and 75%. The average photoperiod during the experiment was approximately 14 h, and natural solar radiation provided a mean photosynthetically active radiation (PAR) of approximately  $350\text{--}500 \mu\text{mol m}^{-2} \text{s}^{-1}$  at canopy level. Environmental data were recorded continuously using an automated greenhouse monitoring system.

Two-year-old raspberry plants (floricane canes) were ordered and obtained as potted plants from Forouzani Nursery in Mazandaran Province. All cultivars used in this experiment belonged to red raspberry (*Rubus idaeus*) and differed only at the cultivar level. The experiment started with transplanting the plants into 12-L pots on 25 March. Therefore, a total of 48 plants (4 cultivars  $\times$  4 replications  $\times$  3 plants per replication) were used in the experiment. The experimental unit was defined as the average of three plants within each replication. Measurements related to vegetative growth, phenology, yield, and fruit quality were recorded from all plants within each replicate and averaged prior to statistical analysis. The flowering period of the cultivars occurred approximately between May–June, and fruit harvesting was carried out from July to August based on physiological fruit maturity. The total duration of the experiment was approximately 9 months, from transplanting to the end of the final harvest.

The hydroponic system operated as an open drip irrigation system, in which nutrient solution was supplied through drip emitters and excess solution drained from the bottom of the pots. Drainage was not recirculated and was discharged outside the system. Irrigation was applied through a fertigation program using a nutrient solution formulated for raspberry production. Irrigation scheduling was based on plant growth stage and substrate moisture conditions. Plants were irrigated 2–4 times per day depending on environmental demand. Each irrigation event was adjusted to maintain a leaching fraction of approximately 15–20% to prevent salt accumulation in the substrate. A hydroponic growing medium specifically formulated for raspberry was procured from Itoq Blupit Green Technology Development Company. The substrate contained 40–45% processed wood fiber, 20–25% processed pine bark fiber, 25–30% processed pumice, 1–2% hardening agent (substrate weight enhancer), and 0.5–1% wetting agent (water-retaining materials). The pH of the growing medium was approximately neutral (7.5), and its electrical conductivity (EC) was 0.6 dS/m. Plants were grown in 12-L pots. The experiment was conducted in a completely randomized design (CRD) with four treatments, corresponding to the four cultivars, and four replications per treatment. A calculated nutrient solution specifically formulated for hydroponic raspberry production was applied. The macronutrient composition included potassium ( $280 \text{ mg}\cdot\text{L}^{-1}$ ), nitrogen ( $240 \text{ mg}\cdot\text{L}^{-1}$ ), calcium ( $170 \text{ mg}\cdot\text{L}^{-1}$ ), sulfur ( $103 \text{ mg}\cdot\text{L}^{-1}$ ), phosphorus ( $65 \text{ mg}\cdot\text{L}^{-1}$ ), and magnesium ( $50 \text{ mg}\cdot\text{L}^{-1}$ ). The micronutrient composition included iron ( $1.7 \text{ mg}\cdot\text{L}^{-1}$ ), manganese ( $1 \text{ mg}\cdot\text{L}^{-1}$ ), boron ( $0.5 \text{ mg}\cdot\text{L}^{-1}$ ), zinc ( $0.25 \text{ mg}\cdot\text{L}^{-1}$ ), molybdenum ( $0.05 \text{ mg}\cdot\text{L}^{-1}$ ), and copper ( $0.02 \text{ mg}\cdot\text{L}^{-1}$ ) (Neocleous et al., 2005). Each time, the nutrient solution was prepared as 1-L stock solutions at 160-fold concentration (160 $\times$ ) for the preparation of 160 L of irrigation water. The nutrient solution was prepared as 1-L aliquots of a 160 $\times$  stock (160-fold) to make 160 L of irrigation water. To ensure complete dissolution and prevent salt precipitation, the formulation was separated into five stock solutions: Stock A contained potassium nitrate ( $\text{KNO}_3$ ) and calcium chloride ( $\text{CaCl}_2$ ); Stock B1 contained manganese sulfate ( $\text{MnSO}_4$ ), ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ), magnesium sulfate ( $\text{MgSO}_4$ ), sodium chloride ( $\text{NaCl}$ ), potassium sulfate ( $\text{K}_2\text{SO}_4$ ), potassium chloride ( $\text{KCl}$ ), and potassium nitrate ( $\text{KNO}_3$ ); Stock B2 contained boric acid ( $\text{H}_3\text{BO}_3$ ), ammonium molybdate ( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$ ), and copper sulfate ( $\text{CuSO}_4$ ); Stock B3 contained zinc sulfate ( $\text{ZnSO}_4$ ), monopotassium phosphate ( $\text{KH}_2\text{PO}_4$ ), and dipotassium phosphate ( $\text{K}_2\text{HPO}_4$ ); and Stock C contained an iron chelate (6% Fe-EDDHA). During each irrigation, 500 mL of the diluted nutrient solution (1 $\times$  concentration) was applied per plant. This protocol ensured optimal nutrient availability while minimizing chemical interactions that could lead to precipitation. In addition to the nutrient solution applied daily, the first irrigation after transplanting the raspberry plants into new pots was carried out using an amino acid solution at a concentration of 1% (1:1000) to enhance root adaptation to the new growing medium and to reduce transplant stress. During the growing season, foliar applications of seaweed extract at a concentration of 1.5% and 100% pure potassium phosphite at a concentration of 2.5% were performed to improve plant performance and minimize potential stress.

Thiophanate-methyl fungicide was applied through irrigation at a concentration of 0.5% to prevent root rot and systemic diseases. Since aphids and mites are among the major pests causing serious damage to raspberry, and symptoms of spider mite infestation were repeatedly observed on the leaves, pest control was carried out at 10-day intervals using malathion and abamectin at a concentration of 2%.

These compounds were applied uniformly to all plants regardless of cultivar in order to maintain optimal plant health and minimize abiotic stress under greenhouse conditions. Therefore, these applications were not considered experimental treatments and were not expected to introduce bias in cultivar comparisons.

Vegetative traits were recorded as follows. Plant height was measured at the end of the growing season from the soil surface (crown/collar region) to the tip of the main cane, and reported in centimeters. The number of

remaining leaves per plant at the end of the growing season was counted and recorded. Stem diameter was measured at the crown (collar) on the front side of each plant using a Stainless Hardened caliper and expressed in millimeters. Internode length was measured for each plant using a measuring tape and reported in centimeters. The number of suckers per plant (excluding current-season primocanes) was recorded separately for each plant.

Regarding reproductive traits and fruit yield components, fruits were harvested in the morning at physiological maturity, when they could be easily detached, and the number of fruits per plant was recorded. Inflorescences of each plant were evaluated separately, and the number of fruits per inflorescence was counted and recorded. The number of inflorescences per plant was also counted and reported. Fruit weight was recorded in grams using a balance (Foster et al., 2019). Receptacle diameter was measured at the widest part of the fruit (Robbins and Sjulín, 1989) using a digital caliper and expressed in millimeters (Foster et al., 2019). Receptacle length was measured at the longest part of the fruit (Robbins and Sjulín, 1989) using a digital caliper and expressed in millimeters (Foster et al., 2019). The onset of flowering for each cultivar was determined as the date when approximately 10% of buds had opened (Schmid et al., 2001).

Fruit biochemical traits were determined in the laboratory, including total soluble solids (TSS; fruit sugars) using a refractometer, antioxidant capacity (Sariburun et al., 2010), total phenolic content (Singleton and Rossi, 1965), anthocyanin content (Nadernejad et al., 2013), and vitamin C content (Adebayo, 2015).

Data collected from vegetative growth, phenological traits, yield components, and fruit biochemical characteristics were subjected to statistical analysis using analysis of variance (ANOVA). The statistical model included cultivar as the main fixed factor. Prior to performing ANOVA, the assumptions of normality and homogeneity of variance were evaluated. Normality of residuals was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene’s test. When necessary, data transformations were applied to meet ANOVA assumptions; however, most traits satisfied these assumptions without transformation. Mean comparisons among cultivars were performed using Honesty significant differences at a significance level of  $\alpha = 0.05$  or  $\alpha = 0.01$ . All statistical analyses were conducted using statistical software SAS version 9.2.

### 3. Results

According to the analysis of variance results (Table 1), significant differences at the 1% level were observed among the genotypes evaluated in this study for morphological traits, including plant height, stem diameter, internode length, and number of suckers. The ANOVA table also indicated significant differences at the 5% level among the studied genotypes for leaf number. Mean comparison results (Table 2) indicated that the highest mean plant height was observed in the cultivar ‘Encore’ (142 cm), whereas the lowest mean plant height was recorded in ‘Saanich’ (57.75 cm) and ‘Rosana’ (47.75 cm). The cultivar ‘Polana’ showed an intermediate mean plant height of 100.75 cm. The highest number of leaves was observed in the cultivar ‘Rosana’, with a mean of 38 leaves, while the lowest number of leaves was recorded in ‘Saanich’, with a mean of 27 leaves. The cultivars ‘Encore’ and ‘Polana’ showed intermediate values, with mean leaf numbers of 33 and 29.75, respectively. The greatest stem diameter was observed in the cultivar ‘Encore’ (7.24 mm). No significant differences were found among ‘Polana’ (4.19 mm), ‘Saanich’ (3.64 mm), and ‘Rosana’ (3.20 mm). The cultivar ‘Encore’ showed the greatest internode length (3.25 cm), whereas ‘Rosana’ had the shortest internode length (1.87 cm). ‘Saanich’ exhibited an intermediate internode length (2.57 cm), and no significant difference was observed between ‘Rosana’ and ‘Polana’. ‘Encore’, with a mean of 3.5 suckers per plant, produced the highest number of suckers. In contrast, ‘Rosana’ and ‘Polana’, each with a mean of 1.5 suckers per plant, showed the lowest number of suckers, with no significant difference between them. ‘Saanich’, with a mean of 2.5 suckers per plant, was intermediate.

**Table 1. Analysis of variance (ANOVA) of morphological traits in raspberry cultivars.**

Source of variation	of d.f.	Mean of squares				
		Plant height	Number of leaves	Stem diameter	Internode length	Number of suckers
Cultivar	3	7480.22**	89.39*	13.33**	1.34**	3.66**
Error	12	157.85	21.72	0.32	0.08	0.33
C.V. (%)		14.43	14.59	12.38	11.98	25.66

Values marked with \* and \*\* are significant at the 5% and 1% probability levels respectively.

According to the analysis of variance for phenological and yield-related traits (Table 3), significant differences were observed among the genotypes evaluated in this study at the 1% probability level for number of fruits per plant, number of fruits per inflorescence, number of inflorescences per plant, fruit weight, receptacle diameter, and days to flowering. In addition, significant differences among the studied genotypes were detected at the 5% probability level for the phenological trait days to harvest and for receptacle length. The highest mean number of fruits per plant was recorded in ‘Encore’ (31 fruits), whereas the lowest values were observed in ‘Rosana’ (25.7 fruits) and ‘Saanich’ (8.75 fruits). ‘Polana’ showed an intermediate number of fruits per plant (25.17) (Table 4).

The number of fruits per inflorescence was higher in 'Encore' (6) and 'Polana' (5) than in 'Rosana' (3) and 'Saanich' (3).

**Table 2. Mean comparison of morphological traits in raspberry cultivars.**

Cultivar	Plant height (cm)	Number of leaves	of Stem diameter (mm)	Internode length (cm)	Number of suckers
Encore	142a	33ab	7.24a	3.25a	3.5a
Rosana	47.75c	38a	3.2b	1.87b	1.5b
Polana	100.75b	29.75ab	4.19b	2.27b	1.5b
Saanich	57.75c	27b	3.64b	2.57ab	2.5ab

Values followed by the same letter within each column are not significantly different according to Tukey test.

Regarding the number of inflorescences per plant, 'Encore' produced the greatest number (5.25 inflorescences per plant). 'Rosana' (2.5), 'Saanich' (3), and 'Polana' (3.5) had the lowest numbers of inflorescences per plant; however, differences among these three cultivars were not significant at the 5% level. 'Encore' also had the highest mean fruit weight (1.4 g). No significant differences were found among 'Saanich' (1.01 g), 'Rosana' (0.94 g), and 'Polana' (0.90 g) in fruit weight. The largest mean receptacle diameter was observed in 'Encore' (15.35 mm), while the smallest was found in 'Rosana' (11.36 mm). 'Polana' (13.38 mm) and 'Saanich' (13.16 mm) showed intermediate receptacle diameters. Receptacle length was greatest in 'Saanich' (13.12 mm) and lowest in 'Rosana' (10.61 mm), whereas 'Encore' (11.39 mm) and 'Polana' (10.76 mm) had intermediate values. In terms of phenology, 'Encore' required more days to reach flowering after transplanting to the greenhouse (19.75 days), indicating a later flowering time compared with the other cultivars. In contrast, 'Polana' (9.25), 'Rosana' (12.5), and 'Saanich' (13.75) required fewer days to flowering and therefore reached this stage earlier. For days to harvest, 'Encore' had the longest growth period after greenhouse transfer (56.5 days) and thus required the greatest number of days to harvest, whereas 'Polana' showed the shortest period (35.75 days). 'Rosana' (45.5 days) and 'Saanich' (50.75 days) were intermediate in the number of days required to reach harvest.

**Table 3. Analysis of variance (ANOVA) of phenological and yield traits in raspberry cultivars.**

Source of variation	d.f.	Mean of squares							
		Number of fruits per plant	Number of fruits per cluster	Number of clusters per plant	Fruit weight	Receptacle diameter	Receptacle length	Days to flowering	Days to harvest
Cultivar	3	474.22**	9**	5.72**	0.21**	10.65**	5.30*	77.06**	254.08*
Error	12	6.35	0.66	0.56	0.02	1.24	1.34	4.77	44.95
C.V. (%)		15.69	19.21	21.05	13.33	8.36	10.08	15.81	14.07

Values marked with \* and \*\* are significant at the 5% and 1% probability levels respectively.

**Table 4. Mean comparison of phenological and yield traits in raspberry cultivars.**

Cultivar	Number of fruits per plant	Number of fruits per inflorescence	of Number of inflorescences per plant	of Fruit weight (g)	Calyx diameter (mm)	Calyx length (mm)	Days to flowering	Days to harvest
Encore	31a	6a	5.25a	1.4a	15.35a	11.39ab	19.75a	65.5a
Rosana	7.25c	3b	2.5b	0.94b	11.36b	10.61b	12.5b	45.5ab
Polana	17.25b	5ab	3.5ab	0.9b	13.38ab	10.76ab	9.25b	37.75b
Saanich	8.75c	3b	3b	1.01b	13.16ab	13.12a	13.75ab	5.75ab

Values followed by the same letter within each column are not significantly different according to Tukey test.

The analysis of variance for biochemical traits (Table 5) revealed significant differences among the raspberry cultivars at the 5% probability level for fruit soluble solids content (TSS). Significant differences were also detected at the 1% probability level for total phenolics, anthocyanin content, and vitamin C. However, no significant differences were observed among the raspberry genotypes for antioxidant capacity. The highest TSS was recorded in 'Polana' (8.87), whereas the lowest value was observed in 'Rosana' (8.02). 'Encore' (8.20) and 'Saanich' (8.12) showed intermediate TSS values compared with the other cultivars (Table 6). The highest total phenolic content among the evaluated cultivars was found in 'Saanich' (55.45) and 'Polana' (53.85), while the lowest phenolic content was recorded in 'Encore' (29.78) and 'Rosana' (37.84). The highest anthocyanin content

was observed in 'Rosana' (30.83), and the lowest in 'Saanich' (23.15); 'Encore' (23.69) and 'Polana' (27.54) had intermediate anthocyanin contents. The highest vitamin C content was recorded in 'Encore' and 'Polana' (11.66), whereas 'Saanich' had the lowest vitamin C content (8.28). Among the tested cultivars, 'Rosana' (10.44) showed an intermediate value. Growing location and contrasting climatic conditions can markedly affect the measured biochemical traits and confirm the existence of variability among cultivars (Maro et al., 2013). In the present experiment, the results likewise indicated that except for antioxidant capacity, for which no significant differences were detected among the four raspberry genotypes significant cultivar differences existed for other biochemical attributes, including fruit total soluble solid (TSS), total phenolics, anthocyanins, and vitamin C.

**Table 5. Analysis of variance (ANOVA) of biochemical traits in raspberry cultivars.**

Source of variation	d.f.	Mean of squares				
		TSS	Antioxidant	Total phenol	Anthocyanin	Vit. C
Cultivar	3	0.59*	1.86ns	624.16**	51.69**	10.14**
Error	12	0.16	1.71	20.18	7.72	0.79
C.V. (%)		4.86	1.53	10.15	10.56	8.48

Values marked with ns, \* and \*\* are non-significant, significant at the 5% and 1% probability levels respectively

**Table 6. Mean comparison of biochemical traits in raspberry cultivars.**

Cultivar	TSS (° brix)	Antioxidant (% inhibition)	Total phenol (mg GA/100 g FW)	Anthocyanin (mg C3G/100 g FW)	Vit. C (mg AA/100 g FW)
Encore	8.2ab	84.72a	29.78b	23.69ab	11.66a
Rosana	8.02b	85.86a	37.84b	30.83a	10.44ab
Polana	8.87a	84.96a	53.85a	27.54ab	11.66a
Saanich	8.12ab	86.13a	55.45a	23.15b	8.28b

Values followed by the same letter within each column are not significantly different according to Tukey test.

#### 4. Discussion

The results of this study reflect the comparative performance of raspberry cultivars under greenhouse hydroponic conditions. Since the experiment did not include an open-field control treatment, the findings should not be interpreted as evidence that greenhouse cultivation inherently improves productivity or fruit quality. Rather, the study highlights how different cultivars respond to controlled-environment production systems. Studying different raspberry cultivars, evaluating their yield, and comparing their morphological, phenological, and biochemical traits can provide valuable information for growers to better meet consumer demands (Titirică et al., 2023). Previous research has reported substantial differences among raspberry genotypes in all morphological characteristics, across measurement dates, across years of florican and primocane growth, and across harvests (Robbins and Sjulín, 1989), which is consistent with the results obtained in the present study. Similarly, studies on raspberry in Pakistan have shown significant variation among collected accessions in plant height, leaf length and width, number of canes and suckers per plant, and fruit length, width, and weight (Ahmed et al., 2014), supporting our findings. Because strong genotype-dependent interactions exist among fruit production, cane length, node number, and leaf area per plant, morphological variables help explain how plants grow and how they influence other traits such as yield and the quality of harvested fruits (Birgi et al., 2019). Raspberry fruit morphological traits also vary among cultivars (Skrovankova et al., 2015). These traits are influenced by multiple factors, including environmental conditions (temperature, rainfall, and soil type), irrigation regime, yield efficiency, harvest maturity, and the agricultural practices employed (Canan et al., 2016). Raspberry flowering and growth exhibit pronounced responses to temperature; under higher temperatures, both node number and shoot length tend to increase (Sønsteby and Heide, 2008). Conversely, when plants experience leaf loss, leaf breakage, or reductions in leaf area due to factors such as temperature stress or wind, the leaf area index and consequently plant productivity declines (Fischer, 2000). In general, longer and more vigorous canes produce higher yields; however, excessive cane length may reduce bud formation and increase the risk of winter injury, a challenge that can be more effectively managed under greenhouse conditions (Martin et al., 1980). Therefore, morphological traits, which are strongly affected by temperature and wind, directly influence fruit production, node number, and leaf area, and their management is more feasible in greenhouse systems (Birgi et al., 2019). The observed differences in vegetative growth among the raspberry cultivars may be associated with cultivar-specific vigor and differences in carbon assimilation and assimilate allocation. The superior plant height, stem diameter, and sucker production observed in 'Encore' suggest a stronger vegetative growth capacity, which may enhance photosynthetic surface area and increase the availability of assimilates for both vegetative and reproductive development. In raspberry, cane vigor and node formation play a crucial role in determining the potential number of fruiting sites, which directly influences yield performance.

Therefore, cultivars with greater cane elongation and thicker stems generally exhibit higher productivity due to improved resource transport and structural support for fruit-bearing laterals. In contrast, cultivars with shorter canes or reduced vegetative growth, such as 'Rosana' and 'Saanich', may allocate fewer resources to canopy expansion, potentially limiting the number of productive nodes and inflorescences. These differences are often genetically controlled but can be further influenced by environmental factors such as temperature, light availability, and nutrient supply under greenhouse conditions. In hydroponic systems, where nutrient availability is optimized, genotypic differences in growth potential may become more evident because environmental limitations are reduced. Consequently, cultivars with inherently stronger vegetative vigor may exhibit greater yield potential under controlled greenhouse cultivation. Therefore, based on the findings of the present study and previous research conducted in other countries, selecting a cultivar that performs best in growth and morphological traits under greenhouse conditions can lead to the highest yield and best fruit quality. Among the cultivars evaluated in this study, 'Rosana' produced a higher mean number of leaves; however, under greenhouse and hydroponic growing conditions, 'Encore' showed superior vegetative growth and morphological performance compared with the other cultivars, including plant height, stem diameter, internode length, sucker production, and even the number of lateral leaves.

Nevertheless, these traits should be considered alongside the available greenhouse space for vegetative growth and the production of new shoots and leaves. In greenhouse production, plant height and the extent of lateral branching and foliage are important factors in determining the required growing space. In addition, receptacle length and diameter, which contribute to fruit appearance and marketability, may also influence the grower's choice of cultivar. Since 'Encore' exhibited more favorable vegetative characteristics, it appears to have suitable growth potential for raspberry production under hydroponic and greenhouse conditions in Guilan Province. Studies on raspberry have shown considerable differences among raspberry genotypes in fruit length, width, and weight across collected samples (Ahmed et al., 2014), which is consistent with the findings of the present study. The effect of the growth environment on raspberry developmental stages and flowering, red raspberry fruit production under greenhouse conditions was reported to be 42% higher than in open-field cultivation (Sønsteby et al., 2009). Similarly, another greenhouse study found that the average productivity of raspberry plants in the greenhouse was 65% higher than that of plants grown outdoors, and that open-field cultivation resulted in an approximately 90% reduction in yield (Birgi et al., 2019). One major reason for this difference is that, under open-field conditions, wind movement stimulates the shoots and can inhibit fruit growth, mainly through inhibitory signals that reduce leaf size (Fischer, 2000). Among different raspberry cultivars, substantial variation exists in growth and yield habits, flowering time, fruit set, fruit ripening time, and even fruit shape and color. Significant differences have also been reported for phenological traits, including days to flowering and days to harvest, among collected raspberry samples (Ahmed et al., 2014). Accordingly, cultivar type is considered one of the key factors affecting morphological and yield-related traits as well as the chemical and sensory characteristics of the fruit among different cultivars (Leposavić et al., 2013). The environmental conditions under which plants grow also influence phenological and morphological traits and overall performance, particularly flowering, fruiting, fruit maturation, and harvest timing. Moreover, greenhouse-grown raspberries tend to have a longer bud development period, and phenological phases such as flowering, fruiting, fruit maturation, and harvesting are generally extended (Birgi et al., 2019). Given that fresh raspberry fruit has a very short shelf life and that demand for off-season fresh raspberry production has recently increased, obtaining information on the physical, chemical, and morphological properties of raspberry during crop management and harvest operations is essential (Augšpole et al., 2021). This is particularly important because greenhouse-grown raspberry plants can continue fruit production over a prolonged period (Birgi et al., 2019). Among the cultivars evaluated in this study, all of which were grown under the same nutritional and environmental conditions, 'Polana' reached flowering and fruiting earlier than the other three cultivars, while 'Rosana' and 'Saanich' showed the longest harvesting period compared with the other two cultivars. However, considering the economic importance of raspberry production for growers, the results indicated that cultivation of 'Encore' would be more advantageous than the other cultivars under hydroponic greenhouse conditions in Guilan Province, due to its higher fruit production, superior yield performance, and greater mean fruit weight. In fact, an inverse relationship was observed between the time required to reach fruit production and the overall crop load. Since comparing cultivars and selecting the superior one based on yield-related and phenological traits can help identify cultivars with earlier flowering and, consequently, earlier harvest, the cultivation of 'Encore' is recommended among the four raspberry cultivars evaluated in this study for greenhouse hydroponic production in Guilan Province.

The lack of a significant difference in antioxidant capacity can be explained by compensatory changes among the indices contributing to antioxidant potential; in other words, a decrease in one parameter in a given cultivar may be offset by an increase in another, resulting in similar overall antioxidant capacity across cultivars (Gündeşli et al., 2019). Previous reports have also shown a direct relationship between antioxidant activity and both total phenolic content and anthocyanin concentration in raspberry (Sariburun et al., 2010; Chen et al., 2013). Information on the chemical properties of raspberry fruit is essential during postharvest operations such as harvesting, transportation, sorting, grading, packaging, and storage, and is therefore of high practical importance (Augšpole et al., 2021). Based on experiments conducted in the Horticultural Science Laboratory of the University

of Guilan, since all plants were grown under uniform conditions greenhouse cultivation in a hydroponic substrate using a raspberry specific nutrient solution the measured biochemical values across cultivars were relatively close. Nevertheless, in terms of bioactive compounds, 'Polana' and 'Rosana' can be considered superior to 'Encore' and 'Saanich', noting that these traits are influenced by multiple environmental and genetic factors as well as postharvest conditions, and may also vary between growing seasons and cane types (primocanes vs. floricanes). Other studies have similarly reported significant differences among cultivars in polyphenol content and antioxidant-related traits, which may be affected by ecological factors, fruit maturity stage, and soil conditions (Günderli et al., 2019), supporting the present findings. Genetic factors have been shown to significantly influence fruit quality (Milivojevic et al., 2011). Moreover, studies on raspberry plants collected from 17 different regions of Lithuania and subsequently cultivated in a research field demonstrated that environmental conditions and genetic background play key roles in the accumulation of bioactive compounds in raspberry fruits (Dvaranauskaitė et al., 2006).

## Conclusion

The results of the present study clearly demonstrate that hydroponic greenhouse cultivation of red raspberry is technically feasible under the environmental conditions of Guilan Province, Iran. Significant differences among cultivars were observed for most morphological, phenological, yield-related, and biochemical traits, confirming the strong influence of genotype on plant performance under controlled conditions. Among the four evaluated cultivars, 'Encore' exhibited superior vegetative vigor and yield performance. It produced the tallest plants, the greatest stem diameter, the highest number of suckers, and the longest internodes, which were accompanied by significantly higher fruit number per plant, more inflorescences, greater fruit weight, and larger receptacle diameter. Although 'Encore' required a longer period to flowering and harvest, its higher crop load and superior yield components make it the most economically promising cultivar for greenhouse hydroponic production in the region. In contrast, 'Polana' demonstrated earlier flowering and harvesting, along with higher total soluble solids and elevated phenolic content, indicating its potential suitability for early-season production and markets emphasizing fruit quality and sweetness. 'Rosana' showed the highest anthocyanin content, while 'Saanich' and 'Polana' were superior in total phenolics. However, these biochemical advantages were not accompanied by superior yield components under the tested conditions. Overall, the findings suggest that cultivar selection is a decisive factor for successful raspberry production in protected hydroponic systems. Considering the combined evaluation of vegetative growth, yield components, and fruit quality, 'Encore' can be recommended as the most suitable cultivar for commercial hydroponic greenhouse production in Guilan Province. Nevertheless, multi-season trials and economic analyses are recommended to further validate long-term productivity, stability, and market profitability of the tested cultivars under controlled-environment agriculture systems.

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