VEGETATIVE GROWTH AND YIELD DYNAMICS OF THE RASPBERRY CULTIVAR 'OPAL'
/
DINAMICA VEGETATIVĂ ȘI PRODUCTIVĂ A SOIULUI DE ZMEUR ''OPAL''

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ABSTRACT
This study provides an original contribution through an integrated analysis of the vegetative growth and yield dynamics of the raspberry cultivar 'Opal', conducted over two consecutive years (2023–2024) under the specific pedoclimatic conditions of the Băneasa area in Bucharest. During the planting year (2023), early vegetative growth was evaluated, while in the productive year (2024), vegetative, yield-related, and pedoclimatic parameters were analyzed. A comprehensive analytical approach was applied, combining polynomial regression models (R^2 > 0.95) with multiple regression and Pearson correlation analyses to investigate multifactorial relationships. The results revealed a pronounced seasonal asynchrony: yield reached a clear maximum in June (391.6 g per plant) and subsequently declined, whereas vegetative growth continued, indicating a marked reallocation of resources following fruiting. Yield showed a strong negative correlation with vegetative development ($r \le -0.93$) and positive correlations with solar radiation and soil moisture ($r \ge 0.78$). The final multiple regression model, integrating plant height, stem diameter, solar radiation, and soil moisture, explained 99.8% of yield variability (R^2 = 0.998), demonstrating strong predictive capability. The findings provide a solid scientific basis for optimizing raspberry cultivation practices and support the development of more efficient yield systems adapted to local climatic variability.

REZUMAT
Acest studiu aduce o contribuție originală prin analiza integrată, pe o perioadă de doi ani consecutivi (2023-2024), a dinamicii vegetative și productive a soiului de zmeură ''Opal'' în condițiile pedoclimatice specifice zonei Băneasa din București. În anul de plantare (2023), s-a analizat creșterea vegetativă timpurie, iar în anul productiv (2024), s-au analizat parametrii vegetativi, productivi si pedoclimatici. Studiul a aplicat o abordare analitică complexă, utilizând modele de regresie polinomială (R^2 > 0,95) și analizând relațiile multifactoriale prin regresie multiplă și corelații Pearson. Rezultatele au arătat, o asincronie sezonieră puternică: producția atinge un maxim pronunțat în iunie (391,6 g/plantă), după care scade în timp ce creșterea vegetativă continuă, indicând o redirecționare clară a resurselor după fructificare. Analiza demonstrează că producția este puternic corelată negativ cu dezvoltarea vegetativă ($r \le -0,93$) și pozitiv cu radiația solară și umiditatea solului ($r \ge 0,78$). Modelul final de regresie multiplă, care integrează înălțimea, diametrul, radiația și umiditatea, explică 99,8% din variația producției (R^2=0,998), oferind un instrument cantitativ robust pentru predicție. Concluziile studiului oferă o bază științifică esențială pentru optimizarea tehnologiilor de cultură a zmeurului, contribuind la o agricultură mai eficientă și adaptată la variațiile climatice locale.

INTRODUCTION
Raspberry (*Rubus idaeus* L.) is one of the most valuable fruit species of temperate zones, being cultivated both in traditional systems and in urban or technological environments. Due to its complex biochemical composition, raspberry is intensively used in the food industry, and its consumption is associated with relevant nutritional and functional benefits (*Kotuła M. et al., 2022; Gavrilă V., 2024*). Therefore, raspberry cultivation confers value both through fruit yield and through secondary biomaterial flows, which increases its attractiveness in integrated and sustainable agricultural systems (*Hărțăgan R. et al., 2018*; Ispiryan A. et al., 2023; *Maj G. et al., 2024;*).

The performance of the crop is largely determined by the genetic characteristics of the cultivar, which influence fruit size, flavor, consistency, handling resistance, shelf life, as well as adaptability to local soil and climatic conditions (*Sawicka B. et al., 2023; Titirică I. et al., 2023*).

Cultivars such as ‘‘Opal’’, ‘‘Gustar” or ‘‘Polka” have proven promising in both conventional and organic systems, due to their ability to maintain stable yield, even in areas with high climatic variability (*Bălan V. et al., 2015; Vanghele N.-A. et al., 2024; Popa R.-G. et al., 2024*).

In recent years, climate change, especially episodes of heatwaves, droughts and intense solar radiation, have necessitated a reassessment of protective technologies. Recent research from Hungary (*Szalay K. et al., 2020*) demonstrated that shade nets can reduce photothermal stress, contributing to yield increases.

Raspberry growth and productivity are regulated by a complex of agroecological factors: light and photoperiod, which control floral initiation (*Sønsteby & Heide, 2012; Amăriuței D.-A. et al., 2023; Cichi M. et al., 2023*); air temperature, critical for shoot development and fruit ripening (*Woznicki, T.L. et al., 2016*); soil temperature and moisture, identified as dominant factors in determining yield variability (*Prive J.P. et al., 1993; Leposavić A. et al. 2013*); the water regime, particularly influential in semi-arid contexts or sandy soils (*Sava P., 2013*); fertilization with macro elements, especially N, P and K, which support vegetative growth and the accumulation of fruiting biomass (*Dogaru M. et al., 2021; Lu Q. et al., 2022; Bolohan D.E. et al., 2025*).

Under heat stress conditions, even moderate temperature variations can alter fruit quality parameters (*Aguilar F. et al., 2025*). Vegetative and reproductive characteristics proved unstable from one year to another in the work (*Atanasova S. et al., 2022*), showing that the plant's response to density is strongly dependent on seasonal climatic conditions.

In the last two decades, world raspberry yield has almost doubled, increasing from 465,447 t (2003) to 940,972 t (2023). Europe dominates the sector, with approximately 69% of total yield, while Romania shows an upward trend, albeit modest, with the area increasing from 98 ha (2003) to 190 ha (2023) and the national yield doubling (*FAOSTAT; Ispiryan A. et al., 2023; Kljajic N. et al., 2025*).

This development suggests a growing agricultural and economic interest, with opportunities for expanding the crop to areas with poorer soils or in protected systems (tunnels, solariums), where harvest seasons can be extended by 20–30 days (*Svensson B., 2016; Hanson E. et al., 2019; Asănică A. et al., 2020*).

The annual growth cycle of raspberries, whether floricane-bearing (biennial) or primocane-bearing types, is governed by complex interactions among photoperiod, temperature, and endogenous carbohydrate accumulation *(Carew et al., 2000; Dai et al., 2024)*. The distinction between these two types is not strictly genetic, but rather reflects differences in photothermal requirements for flower initiation.

Long-term analyses (*Sava P., 2013*) indicates that annual climatic variations can shift phenophases by up to a month, which affects the synchronization between growth and fruiting. Raspberry cultivars show specific adaptations: frost tolerance, drought tolerance, disease resistance. These results support the idea that cultivar selection should be made based on a precise climatic and pedological diagnosis, not only according to theoretical yield potential.

‘‘Opal” cultivar is present in plantations in Romania and recognized for its high productivity, but there are no integrated studies in which the vegetative growth and yield dynamics are analyzed simultaneously, in correlation with local pedoclimatic parameters, during the first two years after planting. In the specialized literature, there are no evaluations that investigate in a unitary manner: the vegetative evolution in the year of plant formation (2023), the yield dynamics in the first year of fruiting (2024), and the way in which climatic and pedological factors influence the vegetative-productive asynchrony. This lack of data limits the ability of farmers and researchers to adapt the cultivation technology to the specific conditions of the Băneasa area of Bucharest, characterized by a temperate-continental climate with frequent episodes of heat and drought. The present study makes an original contribution through: integrated analysis of two simultaneous components, vegetative growth dynamics (2023) and yield dynamics (2024); multifactorial correlation of vegetative, yield-related and pedoclimatic parameters, including the use of: polynomial regression, multiple regression, Pearson correlations; identification of a marked seasonal asynchrony: maximum yield in June vs. continued vegetative growth after the fruiting period; robust predictive model, which explains 99.8% of the yield variation; the first documented data set for the ‘‘Opal’’ cultivar in the pedoclimatic conditions of Băneasa (Bucharest), in a young plantation.

The aim of this study is to analyze and model the vegetative growth and yield dynamics of the raspberry cultivar ‘‘Opal’’ during the first two years after establishment, in relation to key pedoclimatic parameters, with the objective of developing a predictive tool to optimize cultivation practices under the specific climatic conditions of the Bucharest-Băneasa area.

MATERIALS AND METHODS

The study was conducted at the National Institute for Research and Development of Agricultural Machinery and the Food Industry (INMA), located in the Băneasa area of Bucharest, characterized by a temperate-continental climate with pronounced seasonal variations. The experimental plot was established in the spring of 2023, using rhizomes of the raspberry cultivar ‘‘Opal’’. The seedlings were planted at a plant spacing of 0.5 m and a row spacing of 3.3 m. The bushes were trained using a trellis system, with 5–6 vigorous shoots per plant maintained in accordance with standard horticultural practices for *Rubus* species.

Pedoclimatic characteristics

During the entire vegetation period (March–October), essential climatic parameters, namely air temperature, solar radiation and precipitation, were monitored, subsequently used in the analysis of the relationship between the abiotic environment and crop performance. The measurements of climatic parameters were recorded monthly using a meteorological station located in the vicinity of the crop to ensure data accuracy. Climatic data from 2023 were used exclusively to characterize vegetative growth, whereas yield analysis was conducted only for 2024, corresponding to the first physiological fruiting year of the raspberry cultivar ‘‘Opal’’. Table 1 presents data on the evolution of climatic factors during the growing seasons of the raspberry cultivar "Opal" in 2023 and 2024.

Table 1

Values of climatic factors recorded monthly/annually during the vegetation period

Month / Year	Air temperature (°C)		Solar radiation (W/m²)		Rainfall (mm)	
	2023	2024	2023	2024	2023	2024
March	8.24	8.62	127.00	128.00	16.40	57.60
April	10.79	15.15	156.00	184.00	63.00	49.20
May	16.69	16.31	211,00	190.00	28.60	31.00
June	21.95	15.24	245.00	265.00	14.40	87.60
July	25.96	26.86	264.00	262.00	13.20	61.60
August	26.35	26.16	222.00	216.00	0.60	18.20
September	22.13	19.87	152.00	135,00	0.20	68.40
October	15.71	12.43	103.00	101,00	0.80	7.60
Mean	18.48	17.58	185.00	185.13	17.15	47.65
Standard Deviation	6.74	6.38	58.44	61.09	21.00	26.92

The soil in which the raspberry crop was grown had a moderately weakly acidic pH (6.6), sandy-loamy soil type, high porosity (53%) and a good organic matter content (3.08%), which ensured favorable conditions for root development and nutrient absorption.

The physicochemical analyses of the soil were carried out on samples taken from a depth of 30 cm and included the determination of pH, bulk density, porosity, organic matter content and soil texture. The concentrations of some heavy metals and mineral elements (Pb, Cd, Mn and Zn) were also analyzed. The values determined for lead (15.00 mg/kg), cadmium (0.29 mg/kg), manganese (473.3 mg/kg) and zinc (75.3 mg/kg) were below the maximum permitted limits, indicating no toxic risks for plants or for human consumption, which confirms the suitability of the soil for the analysed crops.

Regarding macro- and micronutrients, the soil had a very good supply of calcium (4110 mg/kg – exchangeable calcium), potassium (301.6 mg/kg), magnesium (386.6 mg/kg), sodium (10.1 mg/kg soluble and 158.2 mg/kg exchangeable), sulphates (70 mg/kg), chlorides (84.2 mg/kg), nitrates (48.2 mg/kg), ammonium (5.7 mg/kg), all of which were within safe limits and directly support the development of the raspberry crop.

The data on the soil parameters presented in table 2 were provided by the meteorological station located in the field, near the crop.

Table 2

Soil parameter values recorded monthly/annually during the growing season

Month / Year	Soil moisture (%)		Volumetric ion content		Soil temperature (°C)	
	2023	**2024**	**2023**	**2024**	**2023**	**2024**
March	44.00	37.50	1571	1468	7.30	7.90
April	44.60	37.70	1614	1469	10.20	12.70
May	39.90	32.00	1539	1402	14.50	14.70
June	27.70	27.7	1375	1329	19.50	20.60
July	15.00	9.30	1235	1320	23.20	23.70
August	10.30	7.40	1246	1369	24.10	24.70
September	8.90	6.90	1273	1362	21.90	20.70
October	8.40	6.90	1283	1408	16.70	14.60
Mean	24.85	20.68	1392.00	1390.88	17.18	17.45
Standard Deviation	16.15	14.32	158.22	56.86	6.16	5.87

Relationship between climate and soil properties

The analysis of climatic and pedological data collected during the period March - October highlights a strong and direct relationship between air temperature, solar radiation, precipitation, and the dynamics of soil parameters. Air temperature exhibited a gradual increase from March through the summer months, followed by a decline in September - October, a pattern that was also reflected in soil temperature dynamics. Due to soil thermal inertia, soil temperatures were consistently slightly lower than air temperatures; however, seasonal variations showed a clear and strong correlation between the two.

Solar radiation reaches its maximum during June - July, intensifying evapotranspiration processes and contributing to an increase in soil temperature. This enhanced energy input, combined with reduced precipitation during the summer months, leads to a pronounced decline in soil moisture. Consequently, soil moisture decreases from relatively high values in March - April (approximately 38–45%) to minimal levels in July - August (below 10%), reflecting a strongly negative soil water balance.

The behavior of volumetric ion content also reflects the influence of climatic conditions. In spring, elevated soil moisture promotes ion mobilization, resulting in higher volumetric ion content. As the soil dries during summer, ion concentrations in the soil solution may either decrease due to plant uptake or increase as a result of evapoconcentration, depending on the annual hydrological regime. Overall, variations in volumetric ion content are closely linked to soil moisture dynamics, particularly the processes of dilution and evaporation.

In conclusion, the analyzed data confirm that climatic variables directly regulate the soil water and thermal regimes and influence ion mobility and concentration within the soil solution. Interactions among air temperature, solar radiation, and precipitation drive predictable seasonal variations in soil moisture and temperature, underscoring the central role of climate in pedological ecosystem functioning.

Vegetative and productive parameters

Vegetative growth was monitored monthly in 2023 by measuring shoot height and diameter using standard instruments (a measuring tape and a caliper, respectively). In 2024, yield was determined by weighing the fruit mass per plant using an analytical balance. Vegetative data collected during the planting year (2023) were used exclusively for vegetative growth analysis and were not incorporated into the yield assessment.

Crop maintenance followed standard agrotechnical practices for raspberry cultivation, including spring pruning, trellis training, periodic shallow soil tillage (plowing and harrowing), and drip irrigation, with emitters positioned approximately 40 cm above the soil surface. The applied techniques represent common horticultural practices and did not require specific adaptation for the experimental conditions.

Applied statistical methods

To describe and analyze the relationships among vegetative, yield-related, and pedoclimatic parameters, several regression-based statistical methods were employed, as outlined below:

- *Polynomial regression model for vegetative analysis*

To describe the nonlinear evolution of biological parameters (plant height and stem diameter) during the growing season, a second-degree polynomial regression model was applied, reflecting the inherently nonlinear nature of plant growth dynamics.

The model is expressed by the general equation (1):

$$y = ax^2 + bx + c \tag{1}$$

where: x is the month; y is the plant height (cm) or stem diameter (mm); a is the quadratic coefficient (curvature of evolution); b is the linear coefficient (growth rate); *c* is the estimated initial value; R^2 is the coefficient of determination.

Model fitting was performed using the least squares method, and the statistical significance of regression coefficients was evaluated at a threshold of $p < 0.05$.

- *Linear, polynomial and multiple regression models for yield analysis*

To evaluate the relationship between fruit yield (*P)* in (g/plant) and vegetative parameters, three types of regression models were tested:

- *Simple linear regression* was used to assess the relationship (2) between yield and each vegetative parameter individually, according to Eq. (2):

$$P = \beta_0 + \beta_1 \cdot X \tag{2}$$

where: P is fruit yield (g/plant); X is the predictive biological variable, alternatively represented by stem diameter (*D*) in (mm) or plant height (*H*) in (cm); β_0 is the intercept; β_1 is the slope, expressing the change in yield per unit increase in variable X.

- *Second-degree polynomial regression* was applied to capture potential nonlinear relationships (3) between yield and vegetative parameters, as expressed in Eq. (3):

$$P = \beta_0 + \beta_1 \cdot X + \beta_2 \cdot X^2 \tag{3}$$

where: *X* used alternatively as: stem diameter (D) in (mm) or plant height (H) in (cm).

This model allows the identification of biological thresholds (optimum or limits) of vegetative variables on yield.

- *Multiple regression with two predictors* was used to analyze the combined effects of stem diameter and plant height on yield, as expressed by Eq. (4):

$$P = \beta_0 + \beta_1 \cdot \mathrm{X} + \beta_2 \cdot Y \tag{4}$$

where: X is stem diameter (*D*) in (mm); Y is plant height (*H*) in (cm); β_1, β_2 are regression coefficients quantifying the independent contribution of each predictor to yield.

This model enables assessment of the relative importance of each vegetative parameter while controlling for the effect of the other variable.

- *Multiple regression and integrated correlation analysis*

To quantify the simultaneous influence of vegetative and pedoclimatic factors on yield, a multiple regression model with four independent variables was developed, which allows the evaluation of the individual and combined contribution of biological and environmental parameters.

The general multiple regression model is expressed by Eq. (5):

$$P = \beta_0 + \beta_1 \cdot H + \beta_2 \cdot D + \beta_3 \cdot R + \beta_4 \cdot U \tag{5}$$

where: H is plant height in (cm); D is stem diameter in (mm); R is solar radiation (W/m²); U is the soil moisture (%); β_1–β_4 are regression coefficients representing the independent contribution of each predictor to yield; β_0 is the intercept of the model.

This model enabled the assessment of the direct influence of each factor on yield while accounting for potential collinearity between biological and environmental variables.

In parallel with the multiple regression model, linear relationships between all parameters included in the study were evaluated by calculating the Pearson correlation coefficient *(*r). This integrated correlation analysis aimed to: identify significant associations between vegetative parameters (height, diameter) and yield; examine the relationships between selected pedoclimatic parameters (solar radiation, soil moisture) and plant development; detect possible collinearity that could influence the stability of the regression models. The statistical significance of the correlations was tested standardly, using the p value associated with the coefficient r, with a significance threshold of $\alpha = 0.05$.

In the multiple regression model, only solar radiation and soil moisture were included, as these variables exhibited the highest explanatory power for yield variability and minimal collinearity with other climatic and pedological parameters. Their selection was further justified by their physiological relevance in regulating photosynthetic activity and water availability, as well as by the robustness of the statistical relationships identified with yield.

RESULTS

1. Analysis of vegetative growth in raspberry cultivar ”Opal”

Figure 1 illustrates the dynamics of vegetative growth during the planting year (2023) and the first productive year (2024). The analyzed parameters include shoot height and stem diameter.

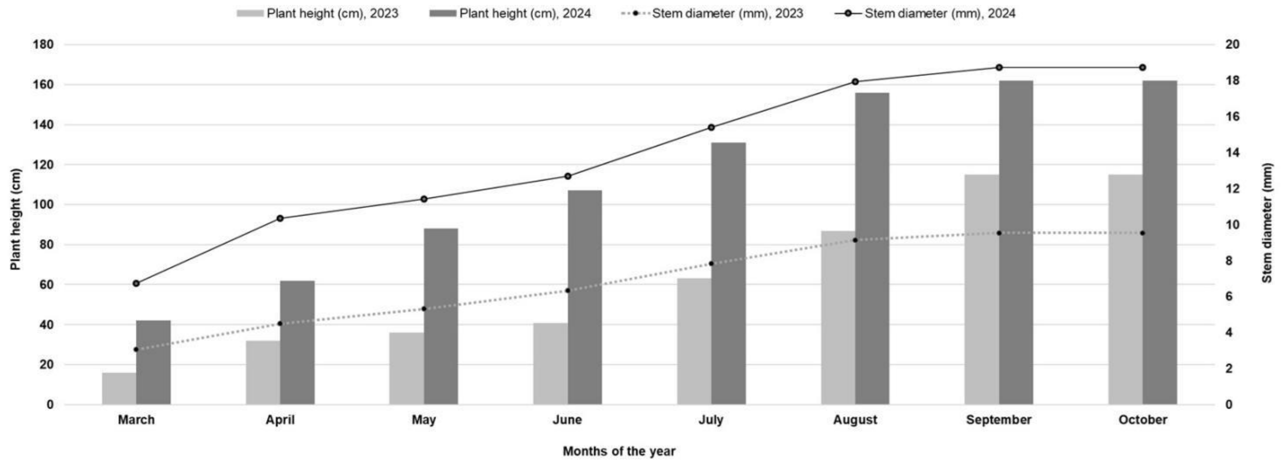

Fig. 1 – Vegetative parameters as a function of month and year for the raspberry cultivar "Opal"

The coefficients of the second-degree polynomial regression models describing vegetative growth are presented in Table 3.

Table 3

Coefficients of second-degree polynomial regression models for vegetative growth parameters

Parameter	Year	Coefficient *a*	Coefficient *b*	Coefficient *c*	R^2
Plant height	**2023**	10.393	59.155	100.04	0.963
	2024	-16.071	331.31	56.429	0.987
Stem diameter	**2023**	-0.071	1.636	1.364	0.982
	2024	-0.055	1.266	2.803	0.950

The regression model for plant height in the planting year (2023) shows that plant height had a progressively accelerated growth during the planting year. The second-order coefficient in the positive polynomial model indicates that the growth rate gradually increased as the plants adapted to the new environment and began to develop the root system. The high linear coefficient confirms a constant evolution, and the high value of R^2 shows that the model describes the real growth dynamics very well.

The stem diameter in the planting year (2023) recorded a constant increase, and the slightly negative quadratic coefficient suggests a slowing trend towards the end of the season, a normal phenomenon in the planting year, when plants prioritize the development of height and the root system. The high R^2 indicates an excellent fit between the model and the observed values.

Regarding plant height in the first productive year (2024), the model indicates rapid vegetative growth during the early part of the season, as evidenced by the high linear coefficient. The negative quadratic coefficient suggests that, following this intensive growth phase, the growth rate gradually stabilized toward the end of the season as the plants entered the fruiting stage. The coefficient of determination R^2, close to 1, confirms that the model accurately captures the observed height dynamics.

The stem diameter in 2024 shows a moderate and constant increase throughout the productive season. The negative quadratic term indicates a slight reduction in the thickening rate in the second part of the season, which is normal when the plant resources are directed towards the formation and maturation of the fruits. The value of R^2 indicates that the model describes the data variation well.

2. Statistical analysis of raspberry yield in the second year of vegetation

This analysis evaluated the relationships between vegetative development, selected pedoclimatic factors and monthly yield in raspberry cultivar ‘‘Opal’’ in the second year of vegetation (2024). Experimental data, collected from May to October based on 5 repetitions, included: plant height (H, cm), stem diameter (D, mm), monthly yield (g/plant), solar radiation (W/m²) and soil moisture (%). Importantly, the data covered the May - October interval, the period in which the plants entered the active fruiting phase.

Table 4 presents the monthly mean values, standard deviations (SD) and coefficients of variation (CV) for the parameters analyzed in raspberry cultivar ‘‘Opal’’.

Table 4

Average values, standard deviation and coefficient of variation between vegetative and productive parameters

Parameter	Height, *H*			Diameter, *D*			Yield, *P*		
Month	Average, (cm)	SD	CV, (%)	Average, (mm)	SD	CV, (%)	Average, (g/plant)	SD	CV, (%)
May	90.0	3.16	3.51	6.24	0.114	1.83	360.4	4.04	1.12
June	108.2	1.92	1.77	6.48	0.249	3.84	391.6	4.16	1.06
July	132.0	1.58	1.20	7.68	0.158	2.06	247.4	2.30	0.93
August	157.6	2.55	1.62	8.92	0.233	2.61	183.0	3.00	1.64
September	163.0	1.58	0.97	9.34	0.206	2.21	103.8	3.56	3.43
October	162.8	1.92	1.18	9.36	0.216	2.31	46.2	1.92	4.15

Taking into account the values in table 5, three statistical models were analyzed, the linear model, the polynomial of degree 2 and the multiple regression. The table below will provide a comparative analysis of the models and coefficients of the analyzed statistical models.

Based on the values presented in Table 5, three statistical models were evaluated: simple linear regression, second-degree polynomial regression, and multiple regression. The table provides a comparative analysis of the models and coefficients of the analyzed statistical models.

Table 5

Comparative analysis of regression models applied to monthly mean vegetative and productive parameters

Pattern applied to	Model type	Coefficients	R²	p-value	Observations
Height	Linear	β_0 = 1150.92, β_1 = -6.67	0.920	<0.05	Significant downward trend
	Polynomial (degree II)	β_0 = 4031.3, β_1 = -65.51, β_2 = 0.194	0.993	<0.01	Optimal model, captures the parabolic curve
Diameter	Linear	β_0 = 1318.5, β_1 = -135.9	0.910	<0.05	Strong negative linear relationship
	Polynomial (degree II)	β_0 = 6516.2, β_1 = -1558.5, β_2 = 84.28	0.992	<0.01	Excellent fit
Height and Diameter	Multiple	β_0 = 2181.7, β_1(Height) = -12.9*, β_2(Diameter) = -63.8	0.940	<0.05	* significant (p<0.05)

The coefficients are estimated by the least squares method.

The results of the models applied to vegetative parameters were:

- Linear regression indicates a negative relationship between yield and height/diameter, but R^2 is smaller compared to the polynomial model.
- The polynomial regression of degree II provides the best fit ($R^2 > 0.99$), capturing the parabolic evolution of yield throughout the season.
- Multiple regression (Height and Diameter) slightly improves the explanation of yield variation (R^2 = 0.94), only height being statistically significant ($p < 0.05$).

3. Analysis of correlations between vegetative, yield-related and pedoclimatic parameters

Next, two more pedoclimatic variables were introduced, namely solar radiation and soil moisture. The set of predictors were restricted to solar radiation and soil moisture, which were highlighted by significant contributions in explaining the variability of yield, while avoiding information overlaps generated by other climatic and pedological factors. Thus, a multiple regression analysis was performed to see how height (*H*), diameter (*D*), solar radiation (*R*) and soil moisture (*U*) influence yield (*P*). From this analysis, the correlations between all five variables presented in figure 2 resulted.

Subsequently, two additional pedoclimatic variables, solar radiation and soil moisture, were incorporated into the analysis. The set of predictors was restricted to these variables because they exhibited the strongest contributions to explaining yield variability, while minimizing redundancy and collinearity associated with other climatic and pedological factors. Accordingly, a multiple regression analysis was performed to assess the combined influence of plant height (*H*), stem diameter *(D*), solar radiation (*R*), and soil moisture (*U*) on yield (*P*). The resulting correlations among all five variables are presented in Fig. 2.

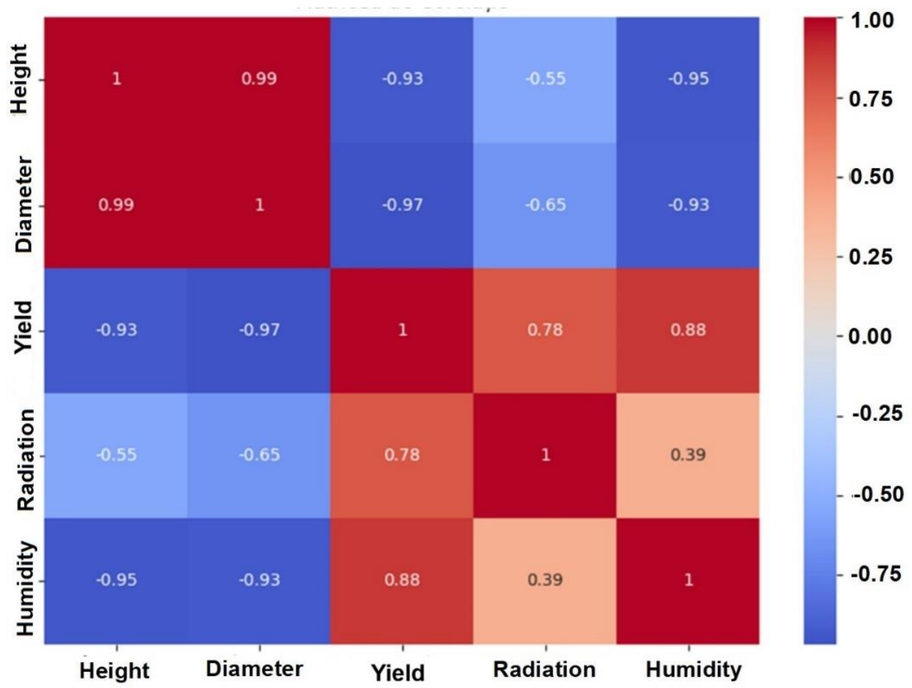

Fig. 2 – Correlation matrix between the analyzed vegetative, yield-related and pedoclimatic parameters

The correlation matrix illustrates the strength and direction of linear relationships among vegetative parameters, yield, and the analyzed pedoclimatic factors. Pearson correlation coefficients (*r*) range from −1 to 1, with values close to ±1 indicating strong linear relationships and values near 0 indicating weak or no linear correlation.

- **Relationships between yield and vegetative parameters (Height, Diameter)**

Yield shows very strong negative correlations with the two vegetative parameters. Height has a correlation of $r = -0.93$, and diameter of $r = -0.97$, indicating that as plants continue to grow in height and thickness, yield decreases significantly.

This relationship is determined by seasonal dynamics: yield reaches its maximum in June, while vegetative growth persists until autumn. Basically, after the fruiting peak, plants redirect metabolic resources to vegetative development, which explains the inversion of the relationship between yield and growth.

- **Relationships between yield and pedoclimatic factors (Solar radiation, Soil moisture)**

Yield is positively correlated with solar radiation ($r = 0.78$) and, more pronouncedly, with soil moisture ($r = 0.88$). These relationships indicate that higher levels of radiation and moisture favor the physiological processes involved in fruit formation, which leads to increased yield. The reduction of these factors in the autumn months is associated with a sharp decrease in yield, a typical formula for raspberries in the annual vegetation cycle.

- **Relationships between vegetative parameters and pedoclimatic factors**

There is a very strong positive correlation between height and diameter ($r = 0.99$), which reflects the natural synchronization of vegetative growth processes: plants that grow taller tend to thicken proportionally.

The relationships between vegetative parameters and pedoclimatic factors are generally negative, indicating that height and diameter increase as solar radiation and soil moisture decrease. This effect does not represent a direct physiological relationship, but reflects seasonal evolution: radiation and humidity are higher in the spring–early summer period, when vegetation is just beginning, and their values decrease towards autumn, a period in which plants are already large.

Overall, the correlation matrix shows that yield is strongly negatively influenced by vegetative development, but positively by solar radiation and soil moisture. Vegetative parameters have close relationships with each other and evolve inversely with pedoclimatic factors, as an effect of the seasonal transition from the fruiting period to the vegetative accumulation period.

4. The final multiple regression model

To simultaneously integrate all predictors (Height, Diameter, Radiation, Humidity), a multiple regression analysis was performed, yielding the model expressed in Eq. (6):

$$Yield = -337.59 - 2.42 \times Height + 63.5674 \times Diameter + 1.28 \times Radiation + 8.66 \times Humidity \qquad (6)$$

The performance indicators of the model were: R^2=0.998, adjusted R^2 0.991, F-statistic 0.0619. The predicted yield values obtained from this model are graphically illustrated in Fig. 3.

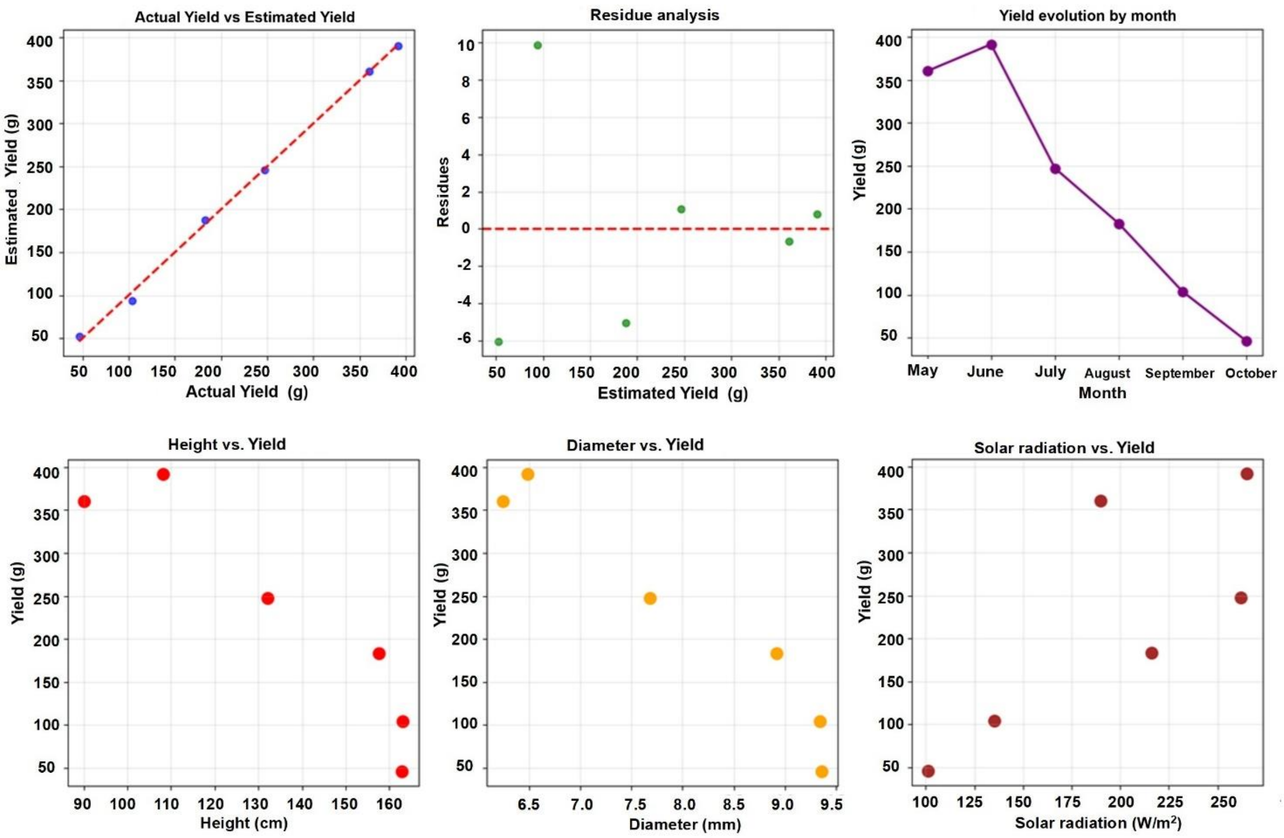

Fig. 3 - Comparison between observed and predicted yield obtained from the multiple regression model

Therefore, as shown in Fig. 3, the multiple regression model explains 99.8% of the variation in yield (R^2 = 0.9983). The estimated effects of the individual predictors are as follows:

• An increase in plant height by 1 cm is associated with a decrease in yield of 2.42 g;
• An increase in stem diameter by 1 mm is associated with an increase in yield of 63.57 g;
• An increase in solar radiation by 1 W/m² leads to an increase in yield of 1.28 g;
• An increase in soil moisture by 1% results in an increase in yield of 8.66 g.

The negative relationships with height and diameter are explained by the seasonal asynchrony between vegetative growth and fruiting.

The observations from the data show that yield is maximum in June (391.6 g); height and diameter increase constantly; radiation and humidity decrease after June and yield decreases dramatically after June.

In conclusion, the statistical analysis of yield dynamics in the cultivar "Opal" revealed that:

- Yield follows a parabolic seasonal pattern, reaching a maximum in June (391.6 g/plant).
- A second-degree polynomial model most effectively describes the relationship between vegetative parameters and yield (R^2 > 0.99).
- Solar radiation and soil moisture exert positive and statistically significant effects on yield.

- Multiple regression incorporating four predictors provides the most accurate yield estimation (R^2 = 0.998).
- Seasonal dynamics indicate that, following peak yield, plants preferentially allocate resources to vegetative growth rather than fruit yield.

CONCLUSIONS

The vegetative growth of the raspberry cultivar ‘‘Opal’’ during the planting year (2023) followed a second-degree polynomial model with a positive quadratic coefficient, indicating rapid adaptation and accelerated early development. In the first productive year (2024), the negative quadratic coefficient for plant height reflected growth stabilization associated with the reallocation of resources toward fruiting (R^2 > 0.95).

Yield dynamics in 2024 exhibited a parabolic pattern, with a pronounced maximum in June (391.6 g/plant), emphasizing the critical role of pedoclimatic conditions and crop management during this peak yield period.

Strong negative correlations between yield and vegetative parameters (plant height: r = –0.93; stem diameter: r = –0.97) highlighted a clear seasonal asynchrony between vegetative growth and fruiting processes.

Among the pedoclimatic factors, solar radiation and soil moisture showed strong positive correlations with yield (r = 0.78 and 0.88, respectively), confirming their essential influence on raspberry performance under the studied conditions.

The multiple regression model integrating vegetative and pedoclimatic parameters explained 99.8% of yield variability (R^2 = 0.998), demonstrating excellent predictive capacity and robustness for yield estimation.

Overall, the results support the development of seasonally differentiated management strategies, focusing on optimizing environmental conditions during peak fruiting and enhancing nutritional management during subsequent vegetative growth phases. The proposed model provides a valuable foundation for decision-support systems in precision raspberry cultivation.

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