

Effect of vermicompost application on the development of plant properties and root architecture analysis with machine learning in *Buxus herlandii*

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ABSTRACT

The effects of liquid vermicompost (commercial product) on nutrient content, root architecture, and plant development were studied at doses of 0, 10, 20, 40, and 80 mL · pot⁻¹. Significant increases in plant height (3.5%), shoot length (25%), leaf width (16.9%), and leaf length (15.8%) were observed at the 40 mL · pot⁻¹ application compared to the control group. The highest number of shoots was observed at 10 mL · pot⁻¹, while the 80 mL · pot⁻¹ application led to a 3.9% reduction in shoot count. Root architecture showed a general decline compared to the control, though root length and tips number increased with 10 mL · pot⁻¹, and root volume was highest at 40 mL · pot⁻¹. However, high doses (40 and 80 mL · pot⁻¹) caused a decrease in root surface area, forks number, and root crossings number. The highest nitrogen (31%) and manganese (57%) values were found at 10 mL · pot⁻¹. Phosphorus (–41%) and magnesium (40%) were lowest at 80 mL · pot⁻¹, while zinc (–46%) was lowest at 10 mL · pot⁻¹. The highest potassium content was recorded at 40 mL · pot⁻¹ (58%). The highest calcium (1.2%), iron (23%), and copper (77%) levels were obtained at 20 mL · pot⁻¹. Machine learning algorithms used for root growth prediction showed the following performance ranking: PART > J48 > Multilayer Perceptron > Multi-Class Classifier. These findings provide valuable insights for predicting root growth in *Buxus* crops

Keywords: Buxus, growing, machine learning, nutrient content, root analysing, vermicompost

Abbreviations: Ca, calcium; Cu, copper; DT, decision tree; Fe, iron; K, potassium; LR, logistic regression; MCC, multiclassclassifier; Mg, magnesium; ML, machine learning; MLP, multilayer perceptron; MLR, multiple linear regression; Mn, manganese; N, nitrogen; NB, naïve bayes; P, phosphorus; RF, random forest; SVM, support vector machine; Zn, zinc.

INTRODUCTION

Boxwoods are evergreen shrubs or trees that can be used alone, in hedges, in mass plantings, as potted plants, as cut greenery, and in shrub forms. In addition, their hardy and showy green foliage is used in celebrations (Köhler, 2014; Sari and Çelikel, 2019). The annual trade volume of boxwoods in the United States exceeds \$141 million (Niemiera, 2018; USDA-NASS, 2020).

Various studies have shown that nutrient deficient conditions hinder plant growth and nutrient accumulation (Xu et al., 2017). Therefore, it is necessary to fertilise plants to help obtain better quality products (Verma et al., 2021). In addition, the nutrient requirements of different plants vary depending on their growth periods and physiological and biochemical

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conditions (Li et al., 2019). Therefore, scientifically determined fertiliser rates are necessary to improve fertiliser use efficiency (Yuan et al., 2013). It is well known that chemical fertilisers play a vital role in higher agricultural production (Bellitürk, 2018). Chemical fertilisers are widely used in ornamental plants to meet the excess demand and increase yield. However, in the current scenario, excessive use of fertilisers leads to environmental problems that are often difficult to overcome in developing countries (Sun et al., 2012; Bellitürk et al., 2017). On the other hand, long-term use of chemical fertilisers leads to an increase in harmful microorganisms in the soil, leading to an unbalanced distribution of nutrients (Younis et al., 2014; Verma et al., 2020). It is well known that chemical fertilisers play a vital role in higher agricultural production (Bellitürk et al., 2017; Bellitürk, 2018). However, in the current scenario, excessive use of fertilisers leads to environmental problems that are often difficult to overcome in developing countries (Sutton et al., 2011; Sun et al., 2012; Bellitürk et al., 2017). Vermicompost is now often presented as an attractive alternative to chemical fertilisers. According to the data obtained, solid and liquid vermicompost have been successfully used to increase the yield and quality of vegetables, fruits, and landscape plants (Bellitürk et al., 2015; Açıkbaş and Bellitürk, 2016; Bidabadi et al., 2016; Barlas and Bellitürk, 2017; Bellitürk et al., 2017; Mengistu et al., 2017; Zahmacıoğlu et al., 2017; Bellitürk, 2018). Vermicompost can be called the 'Second Green Revolution' as it has completely replaced destructive agricultural chemicals (Sinha et al., 2010). Vermicompost improves soil structure by increasing aeration, water retention, and nutrient availability. Its application results in more porous soil, which facilitates better root development and nutrient uptake by plants (Chattopadhyay, 2014).

However, root growth in potted plants is a central element in plant performance (Ramireddy et al., 2018). In general, and particularly for elements with low solubility, root length and root density are positively linked with mineral element uptake (Marschner, 2012). On the other hand, as Bayındır and Kandemir (2023) reported, the increase in total root length is an important indicator of the increase in plant upper part development. Therefore, it is clear that plants with good root development will show better growth. Since the root structure is underground by nature, it is not very easy to study. For this reason, there are only a few studies that use the phenotypic traits of the root as a basis. In recent years, much progress has been made in the measurement of roots. There are now methods for analysing plant images that are simpler, faster, repeatable, and more descriptive of root growth (Judd et al., 2015; Paez-Garcia et al., 2015). In addition, modelling techniques for root trait structure and activity based on multivariate and machine learning (ML) techniques have been investigated. However, further

studies are needed to determine the importance of root traits in influencing aboveground biomass (Moon et al., 2018; Awika et al., 2021). The use of ML in plant science is of growing interest. ML is used to predict the impact of many applications in agriculture, especially crop yield (Suganya et al., 2021). ML algorithms such as support vector machines (SVM), random forest (RF), and multilayer perceptron (MLP) are used to analyse large datasets in plant breeding programs to improve efficiency and develop model-based breeding methods (Yoosefzadeh-Najafabadi et al., 2021). Weka (Machine Learning Group, University of Waikato, Hamilton, New Zealand), a ML workbench, provides a collection of state-of-the-art ML algorithms and data preprocessing tools that can be used in data mining applications (Frank et al., 2010; Harsányi et al., 2023).

This study has examined the effect of vermicompost application on plant and root architectural development. Furthermore, it aims to explain the changes in root nutritional content. The effects of vermicompost applications on root architectural features were evaluated using image analysis. In addition, the study employed methods such as artificial neural network analysis and ML based on data mining to model and predict the impact of applications on the root architecture. Another aim of the study is to suggest an optimum application method to ensure the best root development and nutrient mobilisation in boxwood.

MATERIALS AND METHODS

The research was carried out at the Black Sea Agricultural Research Institute (Samsun, Türkiye).

Plant material and experimental design

B. herlandii was used in the study. Plant materials were obtained from the Forest Nursery Directorate (Gökçebey, Zonguldak).

In the study, cuttings were taken from 4-year-old *B. herlandii*, rooted, and then transferred to 2 L pots, where they were grown for 1 year. Boxwoods were planted in 2 L pots in a mixture of peat and perlite (3:1, v/v) and placed in a polyethylene greenhouse (chemical properties of peat; dry matter [weight ratio] 1–6; N content $[\text{NH}_4/\text{NO}_3\text{-N}] < 50 \text{ mg} \cdot \text{dm}^{-3}$ substrate; P content $[\text{P}_2\text{O}_5] < 30 \text{ mg} \cdot \text{dm}^{-3}$ substrate; K content $[\text{K}_2\text{O}] < 30 \text{ mg} \cdot \text{dm}^{-3}$ substrate; Mg content $[\text{MgO}] < 80 \text{ mg} \cdot \text{dm}^{-3}$ substrate; and pH value 5.5). The chemical properties of perlite are provided in Table 1.

The research was established according to a randomised plot design with 20 replications. A single sapling was used in each replication. Commercial [ORPEX] (İstanbul, Türkiye) liquid vermicompost fertiliser was used in the study. (Fertiliser content: total organic matter 6%, total nitrogen 0.5%, organic nitrogen 0.2%, water-soluble potassium oxide $[\text{K}_2\text{O}]$ 0.2%, phosphorus pentoxide $[\text{P}_2\text{O}_5]$ 0.05%, pH 5.76 and EC 2 $\text{dS} \cdot \text{cm}^{-1}$). For the applications, a control group and 10,

Table 1. Chemical properties of perlite.

Ingredients	%	Ingredients	%
SiO ₂	71.0–75.0	Cr	0.0–0.1
AlO ₃	12.5–18.0	Ba	0.0–0.05
Na ₂ O ₃	2.9–4.0	PbO	0.0–0.03/0.3
K ₂ O	0.5–5.0	NiO	Trace amount
CaO	0.5–0.2	Cu	Trace amount
Fe ₂ O ₃	0.1–1.5	B	Trace amount
MgO	0.02–0.5	Be	Trace amount
TiO ₂	0.03–0.2	free silica	0.0–0.2
MnO ₂	0.0–0.1	Total chlorides	Trace amount – 0.2
SO ₃	0.0–0.2	Total sulphates	None
FeO	0.0–0.1		

20, 40 and 80 mL of vermicompost per pot were used. Applications were made on March 15 before the plants woke up. In the application, 200 mL of vermicompost was mixed into 20 L of water (EC 0.3 dS · cm⁻¹) for soil application. The EC value of the mixture was measured as 0.32 dS · cm⁻¹. Then, 10 mL was added to each pot for the first group, 20 mL for the second group, 40 mL for the third group, and 80 mL for the fourth group were poured onto the soil surface (the ion density and EC value of the mixture from each dose are the same). In 2023, the average temperature inside the greenhouse was 26.6°C, while the average humidity was 67%. After the application, plant height (cm), number of shoots, shoot length (mm), leaf width (cm) and leaf length (cm) measurements were made on 30 August 2023.

Chlorophyll content

The chlorophyll content was measured separately in the plants of each application. Measurements were made on 10 leaves from each plant (30 August). The relative chlorophyll contents in the leaf were measured using the SPAD-502 Chlorophyll Meter (Minolta Camera Co., Ltd., Osaka, Japan). The top four rows of leaves were used to measure the SPAD index.

Rooting potential and phenotypic root development examinations

The WinRhizo root analysis program (Regent Instruments, Québec City, Quebec, Canada) was used to examine the root architecture. Plants with roots were removed from the pots on 30 August. They were washed and dried with paper towels. After drying, the roots were placed on the scanner of the device (Epson Expression 10000XL, Epson America Inc., Long Beach, CA, USA) and computerised in three dimensions. The following parameters of root structure and rooting levels were examined using the WinRhizo program. WinRhizo software (Regent Instruments Inc., Québec City, Quebec, Canada) allowed us to determine total root length (cm), root surface area (cm²), root volume (cm³), average root diameter (mm), number of tips, number of forks, and number of crossings.

Nutrient content analysis of roots

Rooted plants were removed from the pots at the end of the experimental period. They were washed and dried with paper towels. Then, the roots were cut from the healthy tips and side parts. The roots were dried at 65°C for 48 hr, and then three plants were randomly selected from each repetition of each application. Root samples taken from the plants were washed for chemical analysis, dried, and ground at 65°C until a constant weight was reached. Total N in the ground samples was determined according to the modified Kjeldahl method (Kacar and Inal, 2008); for the analysis of P, K, Ca, Mg, Fe, Mn, Zn, and Cu, the samples were wet burned (4:1, HNO₃:HClO₄) and read in the ICP-OES device (Soltanpour and Workman, 1981).

Modeling procedures and classification techniques

To model and predict the root properties of *B. herlandii* after vermicompost application, the results obtained by applying different data mining algorithms available in the WEKA 3.9.6 application (Machine Learning Group, University of Waikato) (Bouckaert et al., 2016) to the dataset were compared. A model was created by selecting the algorithm with the highest success rate among these algorithms. Four ML methods – PART, J48, Multilayer Perceptron, and Multi-Class Classifier – were used in the study. The input variables consisted of one species and seven different root characteristics measured (root length, root surface area, root volume, average root diameter, number of tips, number of forks, and number of crossings). The target variables (output) included control, 10, 20, 40, and 80 mL (Figure 1).

Evaluation indicators

This study aimed to compare the prediction performance of different algorithms. The evaluation metrics were determined based on the confusion matrix, primarily focusing on kappa statistics. Kappa statistics were used to assess the degree of agreement between the classifier's predictions and random classification results. The results of kappa statistical metrics were correlated with the area under the receiver operating characteristic curve (AUC) metrics of the classifier. Kappa ≥ 0.70 was used as an indicator that the consistency of the classifier was acceptable. The WEKA evaluation result showed mean absolute error (MAE), root mean square error (RMSE), root absolute error (RAE), root relative square error (RRSE), true positive rate (TPR) (formula 1), false positive rate (FPR) (formula 2), precision (formula 3), F-measure (formula 4), and accuracy (formula 5) (Table 2).

Data evaluation

The research was established according to a completely randomised design, with each plot containing a single seedling, and 20 replications were evaluated for each treatment. Variance analysis was performed using

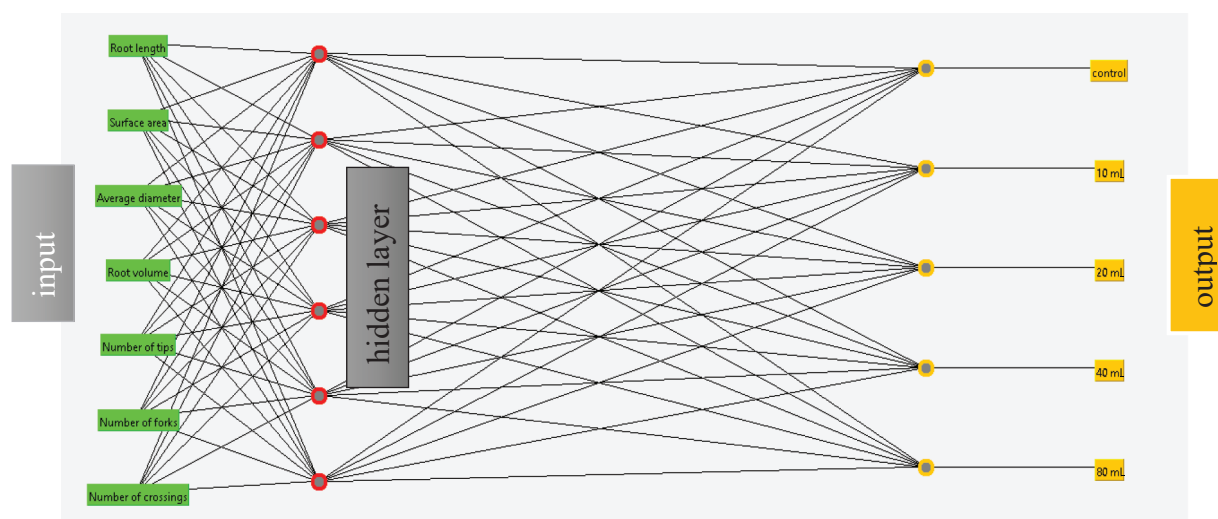


Figure 1. The MLP structure with seven inputs, five outputs, and five hidden neurons. MLP, multilayer perceptron.

Table 2. Formulas used in evaluation.

Formula	Definition
1 $TRP = \frac{TP_i}{TP_i + FN_i} \times 100\%$	The TPR is the proportion of positive instances that are correctly classified by the model. Where TP is the number of true positive instances, and FN is the number of false negative instances. The larger the value the better
2 $FPR = \frac{FP_i}{FP_i + TN_i} \times 100\%$	FPR indicates the probability that a positive decision is wrong. The smaller the value, the better the performance of the model
3 $Precision = \frac{TP_i}{TP_i + FP_i} \times 100$	Precision is the ratio of the samples correctly predicted by the model to all the samples positively predicted
4 $F - Measure = \frac{2 \times Precision \times Recall}{Precision + Recall}$	The F-measure is defined as the weighted harmonic mean of precision and recall
5 $Accuracy = \frac{TP_i + TN_i}{TP_i + TN_i + FP_i + FN_i} \times 100$	The accuracy of correct classification ranges between 0.5 and 1, where higher values indicate a better classifier. Accuracy values between 0.7 and 1 are generally considered acceptable

FPR, false positive rate; TPR, true positive rate.

Table 3. Effect of vermicompost application on plant upper part characteristics.

Applications	Plant height (cm)	Number of shoots	Shoot length (mm)	Leaf width (cm)	Leaf length (cm)
Control	11.5 ab	7.7 c	5.6 c	7.7 c	23.4 c
10 mL	10.9 b	11.2 a	6.0 ab	8.4 b	26.4 ab
20 mL	10.2 c	8.7 b	5.6 c	9.6 a	25.8 b
40 mL	11.4 ab	8.5 b	7.0 a	9.0 ab	27.1 a
80 mL	11.8 a	7.4 c	5.8 bc	8.6 b	25.8 b

There is a significant difference between the means with different letters (Duncan) within the error limits of $p < 0.05$.

SPSS statistical software version (IBM SPSS Statistics Version 20.0, IBM Corporation, Armonk, New York, United States) 20.0, and differences between treatments were compared with the Duncan multiple comparison test (within $p < 0.05$). In addition, linear regression analysis was performed to understand the relationship between percentage increases and independent variables. Percentage increases were obtained by dividing the difference between the previous and current values for

each observation by the previous value and calculating the percentage.

RESULTS

Effect of vermicompost on plant growth properties

Vermicompost applications affected measured plant growth parameters statistically significantly ($p < 0.05$).

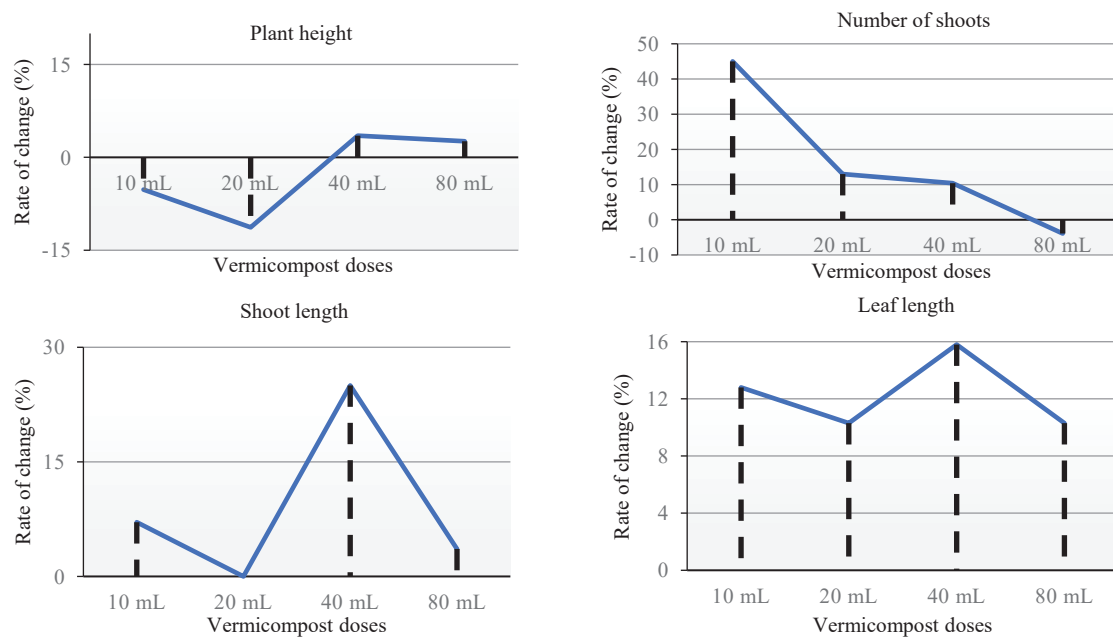


Figure 2. Change rates of plant upper part characteristics compared to the control values of the analysis results after vermicompost applications.

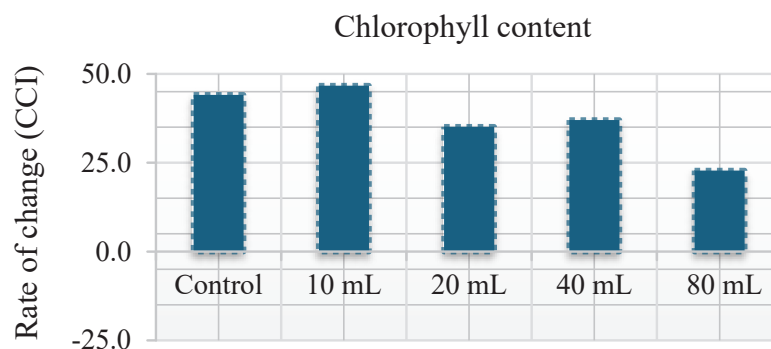


Figure 3. Effect of vermicompost applications on leaf chlorophyll content.

Plant height (3.5%), shoot length (25%), leaf width (16.9%), and leaf length (15.8%) were found to be higher in the 40 mL application than in the control. The highest number of shoots was observed in the 10 mL treatment, showing a 45% increase compared to the control, while the lowest number of shoots was recorded in the 80 mL treatment, being 3.9% lower than the control group (Table 3; Figure 2).

Chlorophyll content

The effect of the applications on chlorophyll content was found to be statistically significant ($p < 0.05$). While the chlorophyll content was 44.1 CCI in the control, it was found to increase by 5.9% and reach 46.7 CCI in the 10 mL application. The results obtained in other applications were found to be lower than the control. The application with the lowest chlorophyll amount compared to the control was found to be 80 mL (-43.3%) (Figure 3).

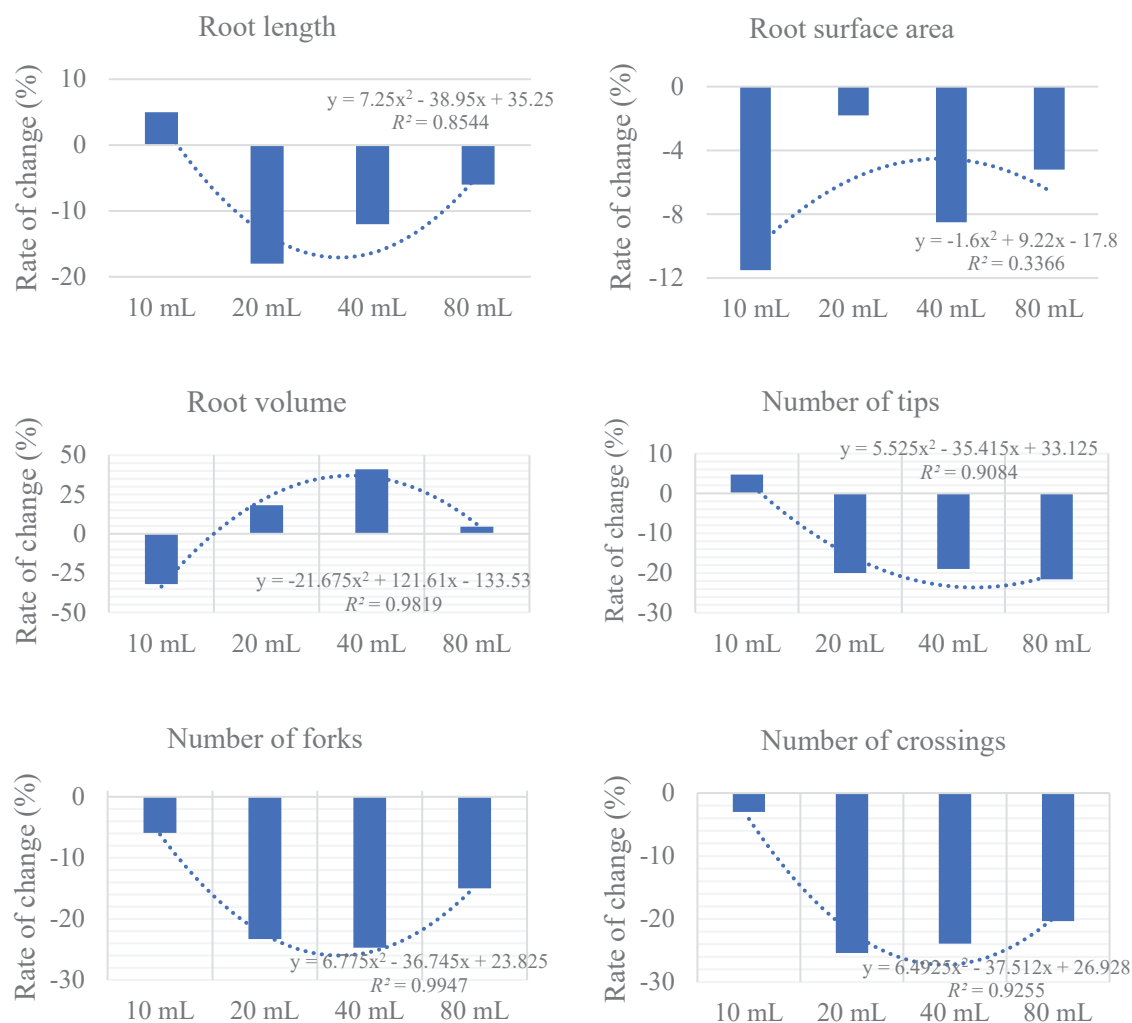
Root morphological and architectural traits

Vermicompost applications affected all measured root properties statistically significantly ($p < 0.05$). Root length was found to be the only application that increased 10 mL (5%) compared to control, while the lowest result was found in the 40 mL (18%) application. In other applications, root length was found to be lower than control. The effect of all applications on root surface area was found to be lower than control. While 40 mL (41%) was found to be the most effective application in root volume, the result obtained in 10 mL was found to be 32% lower than control. While the effects of 20, 40, and 80 mL applications were not different from the control in root diameter, root diameter in the 10 mL application was found to be 33% lower than control. While the most effective application in the number of tips was determined to be 10 mL (4.7%), the effects of other applications were

Table 4. Effect of vermicompost application on root architectural properties.

Applications	Root length (cm)	Root surface area (cm ²)	Root volume (cm ³)	Root diameter (mm)	Number of tips	Number of forks	Number of crossings
Control	35.60 ab	2.90 a	22 bc	3 a	17.99 ab	6.77 a	590 a
10 mL	37.34 a	2.57 b	15 c	2 b	18.84 a	6.37 ab	572 ab
20 mL	29.28 c	2.85 a	26 b	3 a	14.38 b	5.19 c	440 b
40 mL	31.20 bc	2.65 b	31 a	3 a	14.62 b	5.09 c	449 b
80 mL	33.46 b	2.75 ab	23 bc	3 a	14.10 b	5.76 b	470 b

There is a significant difference between the means with different letters (Duncan) within the error limits of $p < 0.05$.

**Figure 4.** The rate of change of root architectural features compared to the control values of the analysis results after vermicompost applications.

found to be lower than the control and not different from each other. It was determined that the effects of all applications were lower than the control in the number of forks and number of crossings. The lowest results (−24.7% and −25.4%) were found at 40 mL (Table 4; Figure 4).

Root nutrient content changes

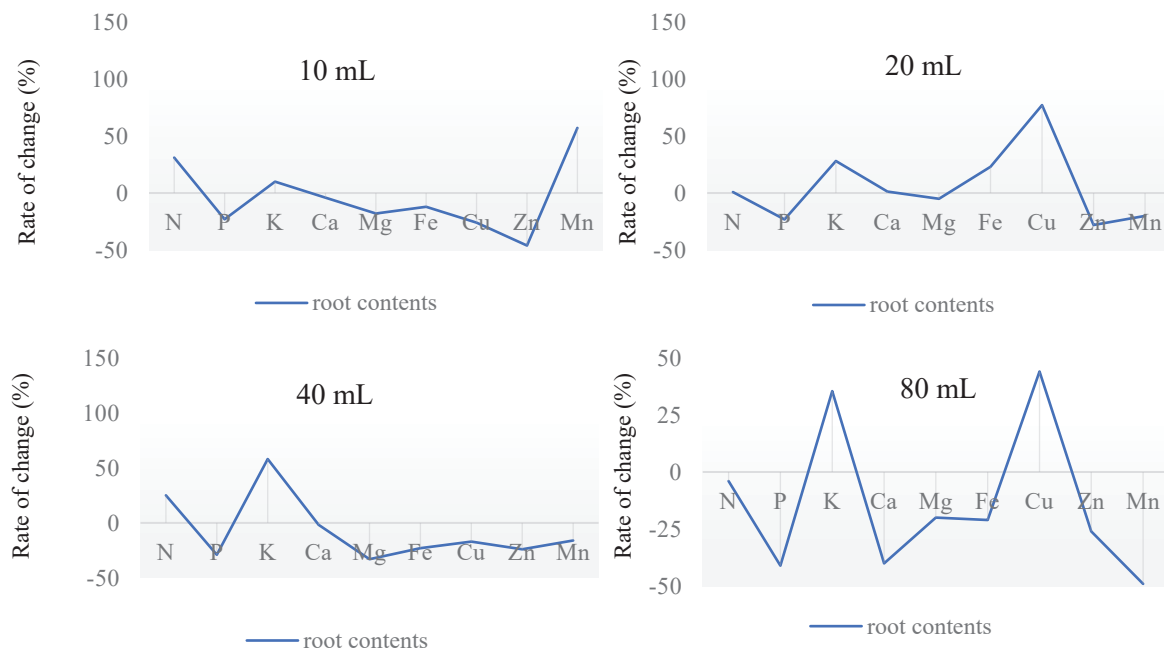
It was determined that the applications significantly affected ($p < 0.05$) the amounts of plant nutrients in the

roots. The highest results were obtained in N (31%) and Mn (57%) contents in the 10 mL application compared to the control. While P, Mg, and Zn contents were found lower than the control in all applications, the lowest results were detected in P (−41%) and Mg (40%) at 80 mL and in Zn (−46%) at 10 mL. Higher potassium (K) content was observed in all treatments compared to the control, with the highest increase (58%) recorded in the 40 mL application. While Ca content was found to be higher than the control only in the 20 mL

Table 5. Effect of vermicompost applications on root nutrient content.

Application	N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
	%				mg · kg ⁻¹				
Control	2.99 b	2075 a	18991 c	6309 a	2876 a	181 ab	10.4 b	58.4 a	146 b
10 mL	3.93 a	1605 b	20914 b	6052 b	2369 b	160 b	7.7 c	31.3 c	229 a
20 mL	3.02 b	1594 b	24264 ab	6386 a	2744 ab	224 a	18.4 a	41.8 bc	118 c
40 mL	3.73 ab	1473 bc	29988 a	6200 ab	1919 bc	140 c	8.6 c	44.1 b	123 bc
80 mL	2.87 c	1230 c	25720 ab	5068 c	1739 c	143 c	15.0 ab	43.5 b	75.0 d

There is a significant difference between the means with different letters (Duncan) within the error limits of $p < 0.05$.

**Figure 5.** The rate of change of nutrient content in roots.

(1.2%) application, lower results were found in other applications. While the highest increases in Fe (23%) and Cu (77%) compared to the control were observed in the 20 mL application, the lowest values were recorded for Fe (−23%) at 40 mL and for Cu (−26%) at 10 mL (Table 5; Figure 5).

ML modelling analysis

The values classified by canopy clustering are divided into five groups. The effects of the applications according to the values classified in five groups are listed as follows; 20 mL (23%) > 40 mL (21%) = 80 mL (21%) > 10 mL (19%) > control (17%). According to this classification, the most effective application on root architecture was shown by artificial intelligence at 20 mL. It made it possible to verify the effect of the 20 mL application on root length with artificial intelligence (Figures 4 and 6). In addition, root length was determined as the most important result using the select attribute result in the CfsSubsetEval algorithm and the BestFirst search method.

Artificial neural networks

The study considered control, 10, 20, 40, and 80 mL. After defining the total root length (cm), root surface

area (cm²), root volume (cm³), average root diameter (mm), number of tips, number of forks, and number of crossings as output variables, the output variable is predicted using the input variables. The decision tree (DT) for the decision is shown in Figure 6.

As can be seen in Figure 6, to classify the applications of vermicompost in terms of their impact on root architecture, it can be seen in the DT that the most important impact in the context of the study is on the number of forks. In particular, it reveals a decision mechanism regarding how the highest or lowest results can emerge as a result of the applications.

Choosing the most suitable model

Algorithms frequently mentioned in the literature (PART, J48, Multilayer Perceptron, Multi-Class Classifier) were used to select the most appropriate model. In this context, the most successful algorithm was selected based on the correct prediction rate. The selected algorithms were used to create models one after the other. As a result, it was decided to apply the logistic regression algorithm, which has the highest accuracy of 77%, to the data set. In selecting this algorithm, the accuracy value, duration, and average absolute error

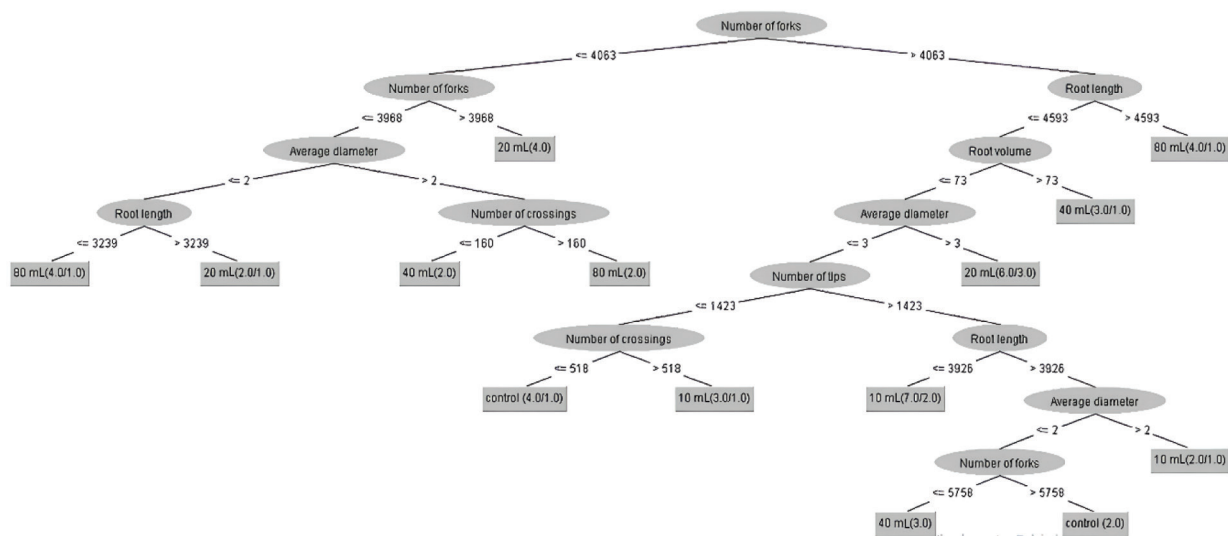


Figure 6. DT obtained by J.48 method. DT, decision tree.

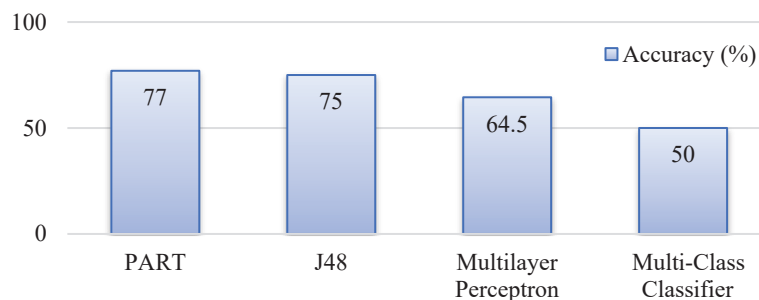


Figure 7. Comparison of performance levels of models created using PART, J48, Multilayer Perceptron, and Multi Class Classifier algorithms.

were considered. Accordingly, the performance levels of the models created using the PART, J48, Multilayer Perceptron, and Multi-Class Classifier algorithms were compared, and the resulting performance levels were noted in the following order: PART > J48 > Multilayer Perceptron > Multi-Class Classifier (Figures 7 and 8).

DISCUSSION

Change of plant characteristics

The study found that vermicompost applications had a statistically significant effect on all measured plant growth parameters. Compared to the control, the 40 mL application resulted in 3.5% increase in plant height, 25% shoot length, 16.9% leaf width, and 15.8% leaf length. The highest shoot number (45%) was observed in the 10 mL application, while the 80 mL application had 3.9% fewer shoots than the control. These results indicate the beneficial effects of vermicompost on various aspects of plant growth, including height, shoot development, and leaf size. The increases seen at medium doses (10–40 mL) are consistent with findings from other studies, showing that vermicompost can

increase plant growth and yield compared to control treatments without organic additives (Blouin et al., 2019; Yüca and Pırlak, 2022). The dose-dependent response, with lower doses being more effective than higher doses, suggests that there may be an optimum level of vermicompost application to maximise plant growth. Applying too much vermicompost can lead to nutrient imbalances or other negative effects that inhibit growth. A meta-analysis found that the positive effect of vermicompost on plant growth is maximal when it represents 30%–50% of the soil volume (Blouin et al., 2019).

Literature also supports the idea that vermicompost can improve various plant growth parameters through its effects on soil properties and nutrient availability. Vermicompost increases soil organic matter, porosity, and water holding capacity while also providing readily available forms of nitrogen, phosphorus, and micronutrients that promote root growth, shoot development, and leaf expansion (Karademir and Kibar, 2022; Rehman et al., 2023). The presence of plant growth regulators, such as auxins and cytokinins, in vermicompost may also contribute to enhanced

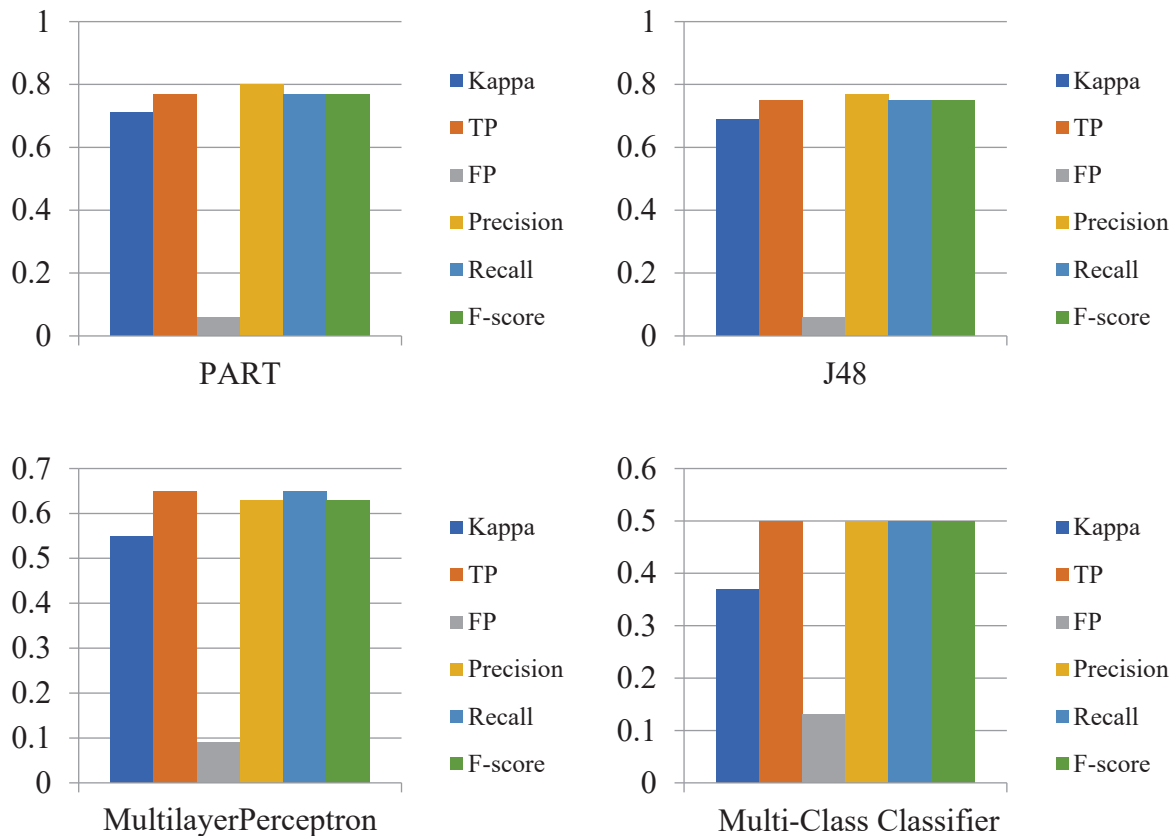


Figure 8. The predictive power of ML models. ML, machine learning.

growth (Elissen et al., 2023). In conclusion, the findings suggest the potential of vermicompost as a sustainable organic amendment to enhance plant growth and productivity. However, care should be taken to optimise the application rate to avoid any adverse effects. Further research is needed to fully elucidate the dose-response relationship and underlying mechanisms for different plant species and growth conditions.

Effect of applications on chlorophyll content

In the study, it was found that the effect of the applications on chlorophyll content was statistically significant ($p < 0.05$). The chlorophyll content in the control group was 44.1 CCI, and it increased by 5.9% to 46.7 CCI with the 10 mL application. The results obtained from other applications were found to be lower than the control group. The application with the lowest chlorophyll amount compared to the control was determined to be 80 mL (−43.3%). These results show that low doses can increase chlorophyll content, while higher doses have a negative effect and reduce chlorophyll levels. This is consistent with findings obtained from other studies, showing that nitrogen fertilisation can increase chlorophyll content in plants to the optimum level and that further increases in nitrogen thereafter lead to decreases in chlorophyll (Uysal, 2018; Linders et al., 2024).

The 5.9% increase in chlorophyll with the 10 mL application suggests that this dose is beneficial for

chlorophyll synthesis. However, the 43.3% decrease with the 80 mL application suggests toxicity or other adverse effects at this high dose, which inhibits chlorophyll production. The literature on the subject supports the idea that optimising application rates is key to maximising chlorophyll levels. A study on maize found significant increases in leaf chlorophyll with increasing nitrogen fertiliser rates up to a certain point in the R1 growth stage, after which higher doses provided no additional benefits (Linders et al., 2024). Another study on durum wheat similarly found that higher chlorophyll-producing varieties had higher grain yields, but only up to a certain nitrogen application rate (Melash et al., 2023). In conclusion, the findings demonstrate the importance of carefully selecting the appropriate application rate to achieve the desired effects on chlorophyll content. While low doses may increase chlorophyll, excessive amounts may be detrimental.

Changes root architectural characteristics

According to the results of the study, the applications generally had a negative effect on the development of root architectural features ($p < 0.05$). In the 10 mL application, root length (5%) and number of tips (4.7%) were found to be higher than the control, while other root features were found to be lower than the control. In the 20, 40, and 80 mL applications, only root volume (18.2%, 41%, and 4.5%) were found to be higher than the control, while other root features were found to be lower

than the control. It was determined that applications except 10 mL tended to increase root volume compared to the control, root length caused a slight increase only in the 10 mL application, and 10 mL had a similar effect on the number of tips. In addition, the applications that had the most negative effects were 20 mL on the number of crossings, root length, root surface area, number of forks, and number of crossings, 10 mL on root volume and root diameter, and 80 mL on the number of tips. Flores (2014) reported in a study investigating the effects of barnyard manure compost, vermicompost, and vermicompost tea on grapevine root growth and development that grapevine roots were 15% longer in vermicompost tea application. Aktaş (2018) found the highest root length to be 17.89 cm on average at $2 \text{ t} \cdot \text{da}^{-1}$ compost dose and 17.86 cm on average at $16 \text{ t} \cdot \text{da}^{-1}$ compost dose in *esperia* (*Triticum aestivum* L.). Dorairaj et al. (2020) found that the root lengths of the species ranged from 313 cm to 1664 cm in their study on Indian rhododendron (*Melastoma malabathricum*), Japanese rose (*Hibiscus rosa-sinensis*), and Christina tree (*Syzygium campanulatum*). In this study, it varied between 3120 cm (40 mL) and 3734 cm (10 mL). Hayat et al. (2020) found the root surface area values between 451 cm^2 and 2130 cm^2 in 'Red Fuji' apple variety grafted on 'M.9', 'M.26', 'Chistock-1', and 'Baleng' rootstocks. In this study, the root surface area varied between 2849 cm^2 (20 mL) and 2900 cm^2 (control). One of the important traits that should be considered in root traits is root diameter. Boldrin et al. (2017) found the root diameter values between 0.7 mm and 2.3 mm in their study on *B. sempervirens*. In this study, it was determined that the root diameter values were between 2 mm and 3 mm. In previous studies conducted on different plant species (*Pinus nigra*, *Cedrus libani*, *Quercus cerris*, *Pinus halepensis*, *Quercus coccifera*, *Ceraton silgua*, and *Pistacia lentiscus*), high root diameters are an indicator of the plant's high ability to adhere to the medium in which it grows, while low diameter values indicate a high absorption capacity. It has also been reported that low diameter values are an indicator that the plants are under stress and therefore their root diameters decrease (Toprak et al., 2016). Again, in this study, root diameter decreased only in the 10 mL application, and other applications had no effect on root diameter. This situation in root diameter may be due to the sufficiency of nutrients and water in the medium, or as can be understood from the results, it may be an indicator of the plant's tendency to compensate for nutrient loss due to the increase in root length and number of tips in the 10 mL application.

Dorairaj et al. (2020) conducted a study on Indian rhododendron (*M. malabathricum*), Japanese rose (*Hibiscus rosa-sinensis*), and Christina tree (*S. campanulatum*) and found that the root volume values of the species ranged from 1.3 cm^3 to 25.6 cm^3 . Hayat et al. (2020) determined that the root volume values of the 'Red Fuji' cultivar grafted on 'M.9', 'M.26', 'Chistock-1', and 'Baleng' rootstocks ranged from 7.3 cm^3 to 22.0 cm^3 . In

this study, the root volume ranged from 15 cm^3 (10 mL) to 31 cm^3 (40 mL). The root volume was significantly higher than the control except for the 10 mL application, and this striking increase in root volume revealed that the main effect of high-dose vermicompost application was on increasing root volume.

Wen et al. (2018) reported that the number of root tips in their study on *Malus prunifolia* and *Malus rokitii* varied between 428 and 731. Zou et al. (2017) reported that the number of root tips varied between 295 and 2119 in their study on trifoliate orange. In this study, the number of root tips varied between 1410 (80 mL) and 1884 (10 mL). In the study by Hayat et al. (2020), it was determined that the root branching number values in 'Red Fuji' cultivar grafted on 'M.9', 'M.26', 'Chistock-1', and 'Baleng' rootstocks varied between 17870 and 134317. In the study by Zou et al. (2017) on trifoliate orange (*Poncirus trifoliata*), the number of branching values varied between 1097 and 2562. The number of root branches in this study varied between 5095 (40 mL) and 6767 (control). In the study conducted by Zou et al. (2017) on trifoliate orange, it was determined that the number of root crossings varied between 252 and 765 as a result of different applications. The number of root intersections in this study varied between 440 (20 mL) and 590 (control). It has been reported that as the number of root tips, forks, and crossings increases, the nutrient uptake capacity of the plant significantly improves (Craine, 2006). However, except for the increases in root length and number of tips at 10 mL, and in root volume at 20, 40, and 80 mL, a general decrease in root traits was observed compared to the control. According to these results, it can be concluded that nutrient uptake is facilitated in boxwoods applied with vermicompost, and therefore, the plant does not need to increase its roots further. In fact, it was determined that root diameters, which are an indicator of increased nutrient and water uptake, did not change except for the decrease in the 10 mL application. It was observed that root length, root surface area, number of forks, and number of crossings were the lowest in the application compared to the control at 40 mL. Therefore, it can be assumed that 40 mL may be the limit for these characteristics. It has been reported that doses applied after the optimum dose have negative effects on plant development. In fact, some studies show that the use of up to 60% worm compost, especially for certain species such as petunia and pepper, gives positive results in root growth. Although it is known that vermicompost increases root branching, exceeding this rate may lead to stunted root development or reduced branching due to nutrient toxicity, nutrient imbalance, or nutrient competition between microorganisms (Makkar et al., 2017; Blouin et al., 2019).

Root nutrient content change

Boxwood vermicompost applications significantly affected the nutrient content of plant roots. Studies have shown that vermicompost significantly increases the uptake of essential nutrients such as nitrogen, phosphorus,

and potassium in ornamental plants (Chattopadhyay, 2014; Rehman et al., 2023). Hınıslı (2014) reported that varying amounts of vermicompost gave good results in the uptake of Ca, Cu, and Zn elements into the plant body in curly lettuce growth. Khan and Ishaq (2011) found that vermicompost application in pea plants was richer in terms of K, Na, Ca, Mg, nitrate, and chloride compared to pit compost and control. In this study, N content in roots was higher than the control except for the 80 mL (−4%) application, and the highest value was found in the 10 mL application. Worm compost supports strong growth and development by increasing nitrogen metabolism in plants (Kumar and Madhu, 2016; Rehman et al., 2023). P, Mg, and Zn were lower than the control in all applications. The lowest P (−41%) and Mg (−40%) values were reached in 80 mL, while Zn (−46%) was reached in 10 mL. In addition, K content was found to be higher than the control in all applications, while the highest value was determined in 40 mL (58%). It was determined that the applications had a similar effect on Ca and Fe. Accordingly, while 20 mL increased Ca (1.2%) and Fe (23%), Ca and Fe values were lower than the control in other applications. It is known that permanent damage to the plant may occur as a result of depletion of Fe in the root apoplast pool (Zheng et al., 2003). In *Murraya exotica* L., *Spathiphyllum* 'Sensation' (Yeh et al., 2000), and *Medicago ciliaris* (M'Sehli et al., 2008), root biomass was found to increase under Fe deficiency. On the other hand, Pestana et al. (2005) reported that *Troyer citrange* and *Taiwanica orange* plants were tolerant to Fe deficiency and had less root biomass under Fe deficiency than under Fe sufficient conditions. In this study, it was found that the increase and decrease in K content, Ca, and Mg were related to each other. Indeed, it has been reported that excessive potassium accumulation reduces calcium and magnesium uptake (Behera et al., 2017; Tränkner et al., 2018; Barzegar et al., 2020). In the study of Hefley (1979) on *B. sempervirens* 'Suffruticosa' and *B. sempervirens* 'Angustifolia', it was observed that magnesium accumulation decreased as potassium concentrations increased. This result was consistent with studies suggesting a correlation between cytosolic calcium and potassium uptake in various plant species (Johansen et al., 1968; Rains and Floyd, 1970). In fact, it has been reported that K⁺ deficiency causes a rapid increase in Ca²⁺ in *Arabidopsis* roots (Behera et al., 2017). Cui et al. (2019) reported that copper accumulates in the root rather than the rice shoot, especially on the root surface and epidermis rather than the xylem. In this study, depending on the application, Cu value was found to be lower than the control in 10 mL (−26%) and 40 mL (−17%), while it was found to be higher than the control in 20 mL (77%) and 80 mL (44%). In general, it was found that the application with the lowest N, P, Ca, Mg, and Mn content was 80 mL. It is thought that the result detected in the 80 mL application is due to the negative effect of high-dose application. The results showed that the nutrient content in the root followed a

fluctuating course depending on the applications and the development of aboveground organs during the vegetation period. In fact, Büyükliz (2016) examined the nutritional status of sunflower plants in a field experiment in which vermicompost was applied to the soil at 4 different doses (0, 200, 400, and 800 kg · da^{−1}), and according to the results, the N, P, K, Mg, Ca, Cu, and Mn contents of the plant increased with vermicompost applications, while the Fe, Zn, and B contents decreased with vermicompost applications. Çıtak et al. (2011) reported that the Fe content of the plant increased with the effect of vermicompost on spinach plants. It is generally known that vermicompost applications increase plant nutrient content, but as seen in some previous studies, different results can be obtained in different plant species. This situation may be due to environmental factors or dose differences. As a result of the applications in this study, it was revealed to what extent the nutrient elements can be used by the plant depending on the dose. In particular, a negative effect of high-dose (80 mL) vermicompost application on nutrient content was observed. Indeed, although it is known that vermicompost increases root branching, excessive use may lead to stunted root development or reduced branching due to nutrient toxicity or nutrient competition between microorganisms.

ML model analysis

Combining ML methods with root image processing techniques has enabled researchers to better understand root development, its interaction with different environments, and its classification (Xu et al., 2022; Tütüncü, 2024). One study addressed the application of ML algorithms, including those found in Weka, to improve agricultural practices. The study noted that the Weka classifier achieved 96.36% accuracy in predicting crop outcomes, demonstrating the effectiveness of ML techniques in agriculture (Purnomo, 2024). The total number of forks was identified as an important classification node in the structure of trees based on vermicompost applications. Indeed, it was determined that the most negative effect of vermicompost applications was on the number of forks. This is because the number of forks of vermicompost applications was lower than the control in all applications. Lower results than the control were also obtained in other applications, but it is assumed that these features do not cause the main effect. The main elements in plant development and propagation are root length and root branching. Therefore, if an automatic ranking system based on classifiers is developed, root branching can be used as the main criterion in evaluating the effect of applications such as vermicompost. ML classification accuracy was ranked as PART 77%, J48 75%, Multilayer Perceptron 64.5%, and Multi-Class Classifier 50%. In particular, in agricultural research, the PART algorithm has been used to classify plant species and predict crop yields based on environmental factors. Its effectiveness in

these applications is attributed to its capacity to produce clear and actionable rules that can guide agricultural practices (Cunningham and Holmes, 1999; Nafie Ali and Mohamed Hamed, 2018). It has been shown that the PART algorithm can achieve accuracy rates around 76% to 81% on various datasets, with specific examples of its performance on the MAGR medical dataset (77.6%) and the Pima Indian Diabetes dataset (77%) (Dou and Meng, 2023). Although it does not specifically address how the PART algorithm addresses the cumulative effects of field variables such as water and nutrient deficiencies, its rule-based classification, data integration capabilities, and predictive modeling make it a valuable tool for assessing these effects in agricultural settings. By providing interpretable results, the PART algorithm supports informed decision-making in effectively managing resources to optimise crop yields (Moldoveanu et al., 2023; Talaat, 2023). It is possible that the input variables cannot explain the behaviour of the specified parameter (Duarte et al., 2022). In fact, it is possible that some algorithms perform poorly and cannot explain some features. In this study, the Multi-Class Classifier 50% algorithm showed the lowest performance.

Çetin et al. (2021) used artificial neural networks, DT, RF, SVM, MLR, NB, and MLP classifiers on *Helianthus annuus* L and reported the highest classification accuracy for RF (80.16%), SVM (79.68%), and then MLP (78.89%). It has been reported that the accuracy of six olive oil classifications based on biochemical properties ranged from 81.63% to 85.71% (Gumus et al., 2018). The findings obtained by the researchers tend to vary. The findings obtained in this study also varied depending on the classifiers.

CONCLUSIONS

The results show the potential of liquid vermicompost (commercial product) as a sustainable organic amendment to increase plant growth and productivity. However, care should be taken to optimise the application rate to avoid any adverse effects. Further research is needed to fully elucidate the dose-response relationship and underlying mechanisms for different plant species and growth conditions. While low doses in the study could increase chlorophyll, excessive amounts could be detrimental. The treatments generally had negative effects on root architectural properties. In root properties, 10 mL caused a slight increase in root length compared to the control. Except for the 10 mL application, the 20, 40, and 80 mL applications significantly increased root volume. While the application negatively affected root development, 20, 40, and 80 mL did not cause any change in root diameter. This is thought to be due to the fact that the plant does not need more root development due to the increase in nutrient content of the medium. As a result, the effect of liquid vermicompost can be explained as increasing the nutrient content of the medium and facilitating nutrient uptake by the plant rather than increasing root development.

In this study, the extent to which nutrient elements can be used by the plant depending on the dose was revealed as a result of the applications. In vermicompost applications, some nutrient contents were found to be higher than the control, while others were lower. In particular, a negative effect of high-dose (80 mL) vermicompost application on nutrient content was observed. In addition, one of the ML methods, the PART algorithm, proved to have sufficient potential in predicting the root architecture of boxwood trees. In addition, these algorithms allowed us to evaluate different vermicompost input variables. It can be suggested that the study will contribute more to the prediction process by determining the best model. As a result, it can be concluded that ML models can effectively predict the effects of different application variables of vermicompost on root architecture.

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AUTHOR CONTRIBUTIONS

Ö.S. designed experiments, performed analytical measurements, performed statistical analysis and manuscript writing. E.E. analysed plant nutritional elements. F.G.Ç. – reading and editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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