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Correlation Between Morphological Traits and Vigor in Plum Seedlings

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ABSTRACT

Indicators for predicting the quality and vigor of fruit tree seedlings can be worthwhile if they are conveniently and visually assessable in various climatic regions. Since allometric relationships exist between plum seedling vigor index and morphological traits, this study evaluated morphological features in plum seedlings while determining their quality and vigor. The samples were of major commercial varieties from several regions of Iran, and the assessments followed path analysis and multiple linear regression. Plum seedlings of 8 commercial cultivars were harvested in three replicates from 11 nurseries in four provinces. Morphological indicators included seedling height, diameter above the graft line (DAGL) and at root-collar (RCD), root length, number of roots and branches, seedling vigor, dry weights of aerial parts and roots (ADW and RDW, respectively), and ratio of height to DAGL and seedling height to ADW. Simple correlations among these variables appeared diverse, and the correlation coefficients broke down into direct and indirect effects through path analysis, with vigor as the dependent variable. This variable increased with some of its components, including DAGL and dry weight. However, the ratio of height to DAGL decreased when the accumulated growing degree-days (AGDD) increased from 2700 to about 4500 °C per day in the various regions. Average vigor values of certified and uncertified seedlings were 11.7 and 19.2, respectively. Among the visually assessable traits in the nursery, DAGL showed a higher correlation with the vigor variable and other morphological features, thus making it the most important index for plum seedling evaluation.

Abbreviations: Accumulated growing degree-days (AGDD), Aerial dry weight (ADW), Aerial to root dry weight (ARDW), Diameter above graft line (DAGL), Diameter at root-collar (RCD), Height to diameter ratio (HD), Root dry weight (RDW), Root length (RL), Total dry weight (TDW)

Introduction

Plums, including European and Japanese plums, are a prominent fruit tree species in temperate zones. Plum production ranks behind peaches among fruit trees in the stone fruit group, with about 11.7 million tons and more than 2.5 million hectares under cultivation (FAO, 2023). With a production of 389,000 tons, Iran ranks fifth in the world after China, Romania, Chile, and Serbia (Ruiz et al., 2018).

One of the challenges nurseries face in selling seedlings, including plums, is identifying morphological characteristics of seedlings that allow grading and predicting seedling performance in the orchard. These characteristics must be related to the seedling ability to establish,

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grow, and effectively tolerate environmental stresses, and they must also be convenient to evaluate (Nyoka et al., 2018; Gallegos-Cedillo et al., 2021). The morphological characteristics that seedlings acquire in the nursery have as much influence on their performance as their genetic authenticity (Binotto et al., 2010).

Compliance with technical standards for seedling production is an essential prerequisite for morphological traits to develop appropriately, even in seedlings derived from superior genetic resources (Nyoka et al., 2018). On the other hand, unlike physiological features, the morphological traits of seedlings do not fade after they are introduced into the orchard and remain unchanged for years after planting (Thompson, 1985). Some morphological features such as height, diameter, number and length of laterals, and the ratio of diameter to height correlate more or less with other quality indicators such as vigor (a function of seedling dry weight content and distribution, height, and diameter) and other physical traits such as root system size. The latter are more time-consuming, destructive, and complicated to measure. Seedling vigor and other growth parameters reportedly correlated with seedling height in black walnut (*Juglans nigra* L.), seedling diameter in cherry (*Prunus avium* L.), hazelnut (*Corylus colurna* L.), and Persian walnut (*Juglans regia* L.). Seedling vigor significantly correlated with root length (RL) in papaya (*Carica papaya*) (Cirkovic-Mitrovic et al., 2015; Matias et al., 2019). Correlations among morphological traits of three pistachio species, *Pistacia vera*, *P. khinjuk*, and *P. mutica*, showed that only leaf count had a significant correlation with its other morphological traits, thus making it practical for seedling diameter evaluation (Baninasab and Mobli, 2008).

The seedling vigor index is a promising integrated measure of morphological traits. It is a good indicator of seedling quality, as it calculates robustness and biomass distribution, considering several essential parameters (Binotto et al., 2010). With this background, the current research aimed to determine the relationship between morphological growth variables and the vigor index to predict the quality of plum seedlings in a nursery and to classify such variables according to their precision in predicting the quality of plum seedlings.

Materials and Methods

Experiment preparation

Bare-rooted seedlings of 8 major commercial plum cultivars were collected from 10 nurseries located in various climate regions in Iran. The study period was from 2020 to 2021 in the seedling transfer season (Table 1). For each cultivar from each nursery, three plots were randomly selected, each with an area of one square meter and three seedlings per plot (Dickson et al., 1960). Seedlings with healthy and adequate roots and dormant buds were taken from two classes of uncertified (white-labelled) and certified (blue-labelled) seedlings grafted onto Myrobalan seedlings and clonal Myrobalan 29C rootstocks, respectively. The cultivars ‘Stanely’, ‘President’, ‘Shablon’, ‘Baraghan’, ‘Golden drop’, and ‘Bukhara’ were considered from the uncertified class. Cultivars ‘Shiro’ and ‘Santa Rosa’ were from both classes. The characteristics of the cultivars and rootstocks were described in Tables 2 and 3. They were ready-to-sell as one-year-old grafted plants, the scions having been grafted onto two-year-old rootstocks. For each cultivar from each nursery, three plots were randomly selected, each with an area of one square meter and three seedlings per plot.

The nurseries licensed by the Seed and Plant Certification and Registration Institute (SPCRI) were located in four provinces, i.e., Alborz, West Azerbaijan, Isfahan, and Khorasan Razavi. Their locations represent climatically diverse regions, from semi-humid and cold to arid and cold regions (Table 2). The cumulative growth degree day of each region was calculated based on the minimum and maximum daily temperatures of that region, and the base and critical temperatures of stone fruit trees (4.5 °C and 36 °C, respectively) (Fadon et al., 2020; Ruiz et al., 2018; Cosmulescu, 2010). The soil texture in all nurseries was loamy-sand. Phosphorus and nitrogen fertilizers were used during the rooting process and as top dressing application, respectively.

Depending on the climate, the seeds were sown in October and November to produce seedling rootstocks. Rooted cuttings were placed in the field from April to May, and commercial cultivars were grafted onto the desired rootstocks in the March and April of the following year. Seedling aftercare in August and September involved cutting shoot tips off the rootstock above the grafted bud and pinching off unwanted shoots.

Table 1. Latitude (Lat), longitude (Long), elevation (Elev), and annual average values of weather statistics for the locations of the nurseries where the seedlings were taken for the evaluation of their morphological characteristics in Iran in 2020-2021.

City	Lat (N)	Long (E)	Elev (m a.s.l)	Average minimum temperature (°C)	Average maximum temperature (°C)	Average relative humidity (%)	Total precipitation (mm)
Damaneh	32°96'	50°36'	1105	5.3	18.6	43.0	316.4
Golmakan	36°48'	59°28'	1176	7.0	20.5	48.6	190.2
Karaj	35°80'	50°95'	1312	9.8	22.5	48.6	317.6
Khoy	38°55'	44°99'	1103	7.5	20.8	53.5	215.6
Mashhad	36°29'	59°60'	992	9.9	23.1	49.1	215.0
Mobarakeh	32°35'	51°45'	1745	7.9	24.9	31.2	101.3
Nazarabad	35°93'	50°55'	1195	7.8	23.5	53.5	157.4
Oshnavieh	37°05'	45°13'	1470	4.7	19.2	54.8	543.4
Shahreza	31°98'	51°81'	1825	7.5	23.4	32.2	143.8
Tiran	32°70'	51°15'	2932	4.2	19.6	41.5	262.2

Measurements

Plant height from ground level to the apical bud was measured with a ruler. The diameter was measured with a vernier caliper at the root collar (RCD) and above the graft line (DAGL) at 15 cm from the collar. Seedlings height to DAGL ratio (HD) was recorded. Then, the seedlings were uprooted. RL, the number of lateral roots (roots longer than 5 cm), and axillary shoots were recorded. Roots and shoots were separated, weighted, oven-dried for 3 days at 70 °C, and reweighed. The vigor indicator was calculated as below (Dickson et al., 1960):

$$\text{Vigor} = \frac{TDW\ (g)}{\frac{Height\ (cm)}{DAGL\ (mm)} + \frac{ADW\ (g)}{RDW\ (g)}} \qquad (1)$$

Where TDW, ADW and RDW are total, aerial, and root dry weight, respectively.

Data analysis

Pearson's linear correlation analysis was applied to all measured variables and the correlation coefficients were deconstructed into direct and indirect effects by path analysis, with the vigor index as the dependent variable. A multiple linear regression analysis of the vigor index was performed as a function of the independent variables plant height, DAGL, RCD and the ratio of plant height to DAGL. These analyses made it possible to identify, among the non-destructive test variables, those that correlated more strongly with the vigor index, allowing a precise assessment of seedling quality in the nursery.

The criteria of higher adjusted coefficient of determination (R^2aj), lower coefficient of variation (CV%), and lower mean standard error (Sy.x) criteria (Equation 2) were used for selecting the best regression models (Rahmati et al., 2022). All statistical analyses were performed using R 4.1.3 software (R development Core team, 2010) based on a probability level of 5%.

$$Sy.x = \sqrt{\sum_{j=1}^{N} \frac{\left(y_j - y_j^s\right)}{n-k}} \qquad (2)$$

Where Sy.x, yi, yjs and n-k were standard errors of the estimate, actual values, predicted values and regression degrees of freedom, respectively. All statistical analyses were performed using R 4.1.3 software (R development Core team, 2010).

Table 2. Names and characteristics of the plum seedling cultivars examined for their morphological characteristics.

Name	Species	Positive Traits	Negative Traits	References
Shiro	*P. salicina*	early-ripening, dual-purposed	small-sized fruits	Karp, 2015
Santa Rosa	*P. salicina*	self-fertility, high productivity, vigorous, good for fresh eating	*sensitivity to* frost	Karp, 2015; Zeinanloo et al., 2017
Shablon	*P. salicina*	precocious, high fruit quality	*sensitivity to* frost	Barzamini and Fotouhi Ghazvini, 2017; Zeinanloo et al., 2017
Stanley	*P. domestica*	self-fertility, late summer harvest, late blooming, extremely cold hardy. late-ripening, suitable for preserve	low quality for fresh eating	Foundation Plant services, 2024
President	*P. domestica*	late-blooming, late-ripening, cold hardy, big size and high quality fruit	cross-pollinated	Carrasco et al., 2012; Zeinanloo et al., 2017
Bukhara	*P. domestica*	late-blooming and ripening, good for drying, marketability	cross-pollinated, low productivity, *sensitivity to* frost	Zeinanloo et al., 2017; Falati et al., 2019
Baraghan	*P. domestica*	late-ripening, good for drying, marketability	cross-pollinated, low productivity, *sensitivity to* frost	Zeinanloo et al., 2017
Golden drop	*P. ceracifera*	early-harvesting, high and marketable productivity, good for fresh eating	cross-pollinated, not suitable for transfer and storage	Zeinanloo et al., 2017; Falati et al., 2019

Table 3. Names and characteristics of the plum seedling rootstocks examined for their morphological characteristics.

Rootstock	Species	Positive Traits	Negative Traits	References
Clonal Myrobalan 29C	*P. ceracifera*	standard rootstock, tolerant to root-knot nematode, waterlogging, compact soils, and iron-chlorosis deficiency, compatibility with plum and apricot	Susceptible to lesion and ring nematodes and bacterial canker, tendency to lean	Foundation Plant services, 2024
Myrobalan seedling	*P. ceracifera*	Vigorous or semi vigorous rootstock, tolerant to crown gall, low suckering, well suited for a wide range of soil types	Susceptible to root-knot nematode and bacterial canker, late-bearing	Foundation Plant services, 2024

Results

Quality indicators for nondestructive evaluation

The RCD of uncertified seedlings of the main commercial plum cultivars from different nurseries ranged from 9 to 35 mm, whereas it ranged from 15 to 29 mm in the certified seedlings (Table 4). Compared to RCD, DAGL decreased by 36% in uncertified seedlings and up to 28% in certified seedlings, reaching an average of 13 and 15 mm in uncertified and certified plum seedlings, respectively (Table 4). Seedling height and HD of uncertified plum seedlings varied from 100 to 325 cm and from 7.4 to 45.4 cm mm-1, respectively (Table 3). In contrast, those of the certified seedlings ranged from 92.0 to 240 cm and from 7.5 to 14.6 cm, respectively (Table 4). More than 63% of the variance in HD was described by DAGL and only 36% by seedling height (Fig. 1). The number of shoots of uncertified seedlings averaged 11 and that of certified seedlings averaged 17 (Table 4).

Table 4. Descriptive statistics of morphological traits of uncertified and certified plum seedlings collected from various nurseries in Iran (2020-2021).

Seedling type	Morphological traits	Minimum	Maximum	Mean ± standard deviation
Uncertified	DAGL (mm)	3.40	23.00	12.82 ± 3.54
	RCD (mm)	9.00	35.00	19.92 ± 5.01
	Height (cm)	100.00	325.00	187.28 ± 42.68
	HD (cm mm^{-1})	7.39	27.45	15.68 ± 5.99
	ADW (g)	24.00	390.00	119.87 ± 62.43
	RDW (g)	15.00	185.00	62.69 ± 31.08
	TDW (g)	55.00	545.00	182.55 ± 98.00
	ARDW	0.47	6.17	1.94 ± 0.78
	Height to ADW (cm g^{-1})	0.50	2.40	1.97 ± 0.70
	Number of roots	1.00	18.00	7.82 ± 4.19
	Number of shoots	0.00	57.00	10.55 ± 9.24
	RL (cm)	30.00	75.00	58.19 ± 9.13
	Vigor	1.91	39.26	11.68 ± 7.54
Certified	DAGL (mm)	10.80	22.20	14.95 ± 9.16
	RCD (mm)	15.00	29.00	20.67 ± 5.24
	Height (cm)	92.00	240.00	162.17 ± 59.33
	HD (cm mm^{-1})	7.48	14.63	10.78 ± 2.36
	ADW (g)	50.00	416.00	162.00 ± 100.54
	RDW (g)	41.00	168.00	80.67 ± 47.24
	TDW (g)	97.00	584.00	242.67 ± 89.50
	ARDW	0.98	2.48	1.76 ± 0.68
	Height to ADW (cm g^{-1})	0.64	5.50	1.47 ± 0.98
	Number of roots	14.00	29.00	18.67 ± 5.50
	Number of shoots	7.00	27.00	17.17 ± 7.73
	RL (cm)	40.00	46.00	42.83 ± 2.04
	Vigor	7.97	48.56	19.16 ± 15.14

[1]Trait details: DAGL (diameter above grafting line), RCD (root-collar diameter), HD (height to diameter ratio), ADW (aerial dry weight), RDW (root dry weight), TDW (total dry weight), ARDW (aerial to root dry weight), and RL (root length).

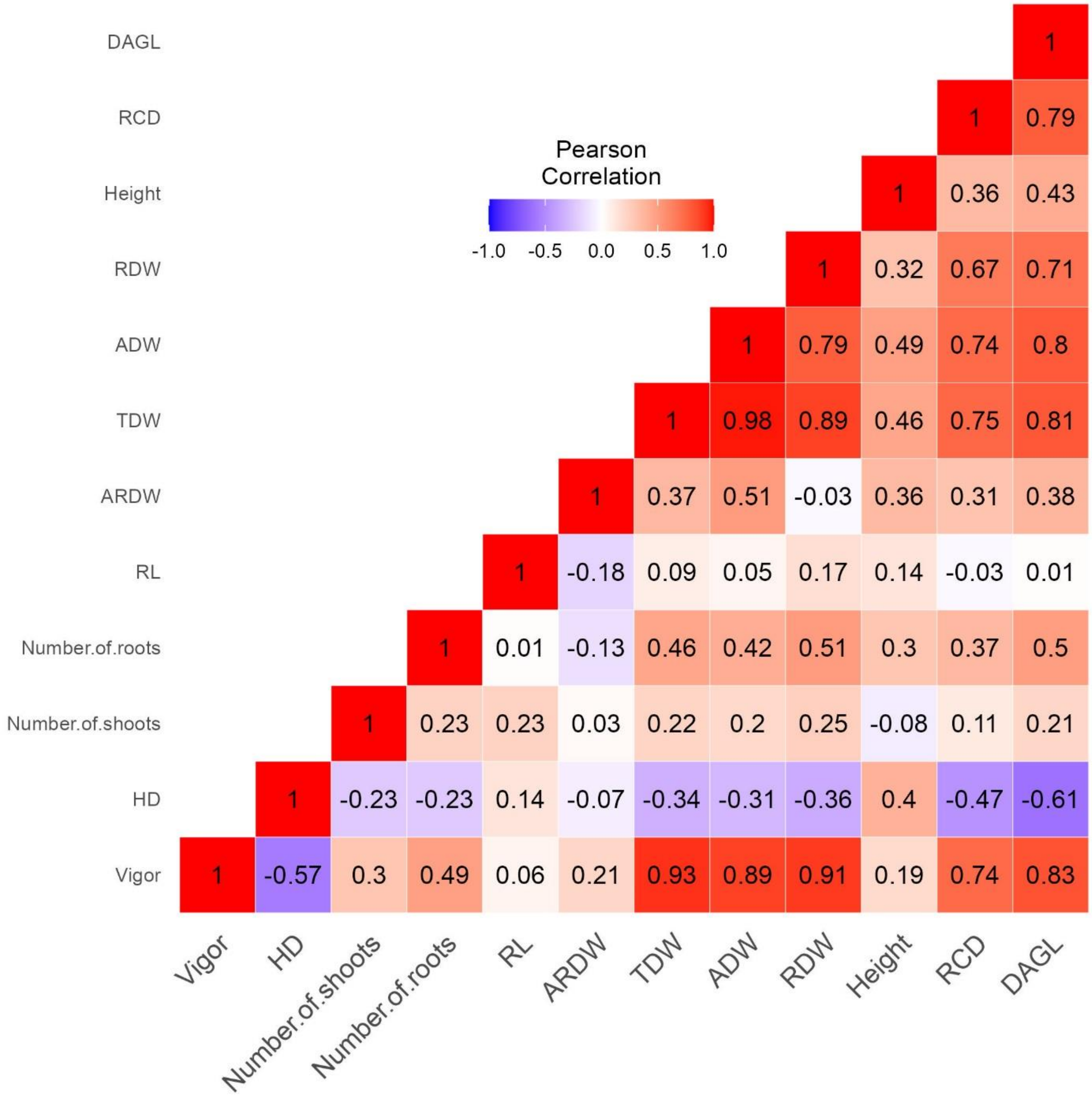

Fig. 1. Correlation matrix and heat map of the various morphological traits of eight major commercial plum cultivars from various nurseries in the seedling transfer season. The positive and negative correlations are indicated by blue and red colors. A greater coefficient is reflected by a color of higher intensity. Trait details include HD (height to diameter ratio (cm mm^{-1})), RL (root length (cm)), ARDW (aerial to root dry weight ratio), TDW (total dry weight (g)), RDW (root dry weight (g)), RCD (root collar diameter (mm)), and DAGL (diameter above grafting line (mm)).

Among the morphological traits that could be evaluated by nondestructive methods in the nursery, the number of shoots had the lowest correlation coefficients with vigor and other measured parameters, indicating that it is not significant as a quality index for sorting out seedlings (Fig. 1). DAGL significantly correlated ($r2 > 0.6$) with most morphological traits (Fig. 1). Its highest correlation coefficients were observed with vigor, TDW, SDW, RCD, RDW, and HD, respectively (Fig. 1).

Seedlings RCD, TDW, ADW, RDW, HD, and vigor were plotted as a function of DAGL (Figs. 2A-D). The RCD increased linearly with increasing DAGL of plum seedlings (Fig. 2A). Accordingly, for each millimeter increase in DAGL, there was a 1.08 mm increase in seedling RCD. There was a quadratic, nonlinear relationship between plum seedling DAGL and seedling TDW and vigor (Figs. 2C and D). Plum seedling vigor increased up to 98% when DAGL was increased from 4 to 11 mm. However, further increasing DAGL (seedlings thicker than 11 mm) resulted in a more rapid increase in vigor (Fig. 2D). The increasing trend in TDW, ADW, and RDW was evident as the DAGL of the seedlings increased (Fig. 2C).

The number of shoots and height of plum seedlings showed lower correlation coefficients with vigor and other morphological traits (Fig. 1). The correlation between HD was negative and significant only in describing DAGL (Fig. 1).

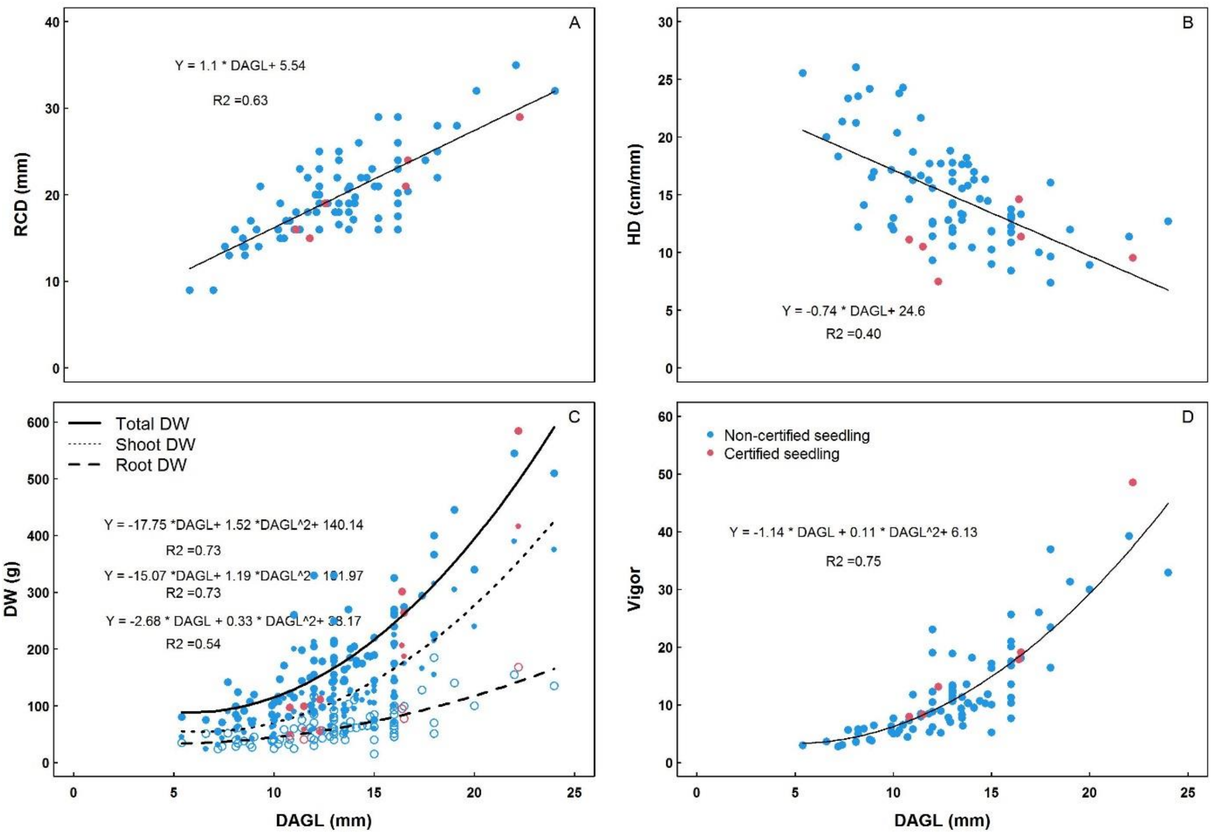

Fig. 2. Relationships between diameter above the grafting line (DAGL) and A) root-collar diameter (RCD), B) height to diameter ratio (HD), C) dry weight (DW) and D) vigor of the grafted plum seedlings of the certified and uncertified types.

Quality indicators for destructive evaluations

The vigor of uncertified plum seedlings from the various nurseries averaged 11.7, while it averaged 19.2 for certified seedlings (Table 4). Seedling vigor and its components (DAGL, TDW, and HD) were plotted as a function of accumulated growing degree days (AGDD) in different regions (Figs. 3A-D). The vigor increased linearly with increasing AGDD in nurseries in the various climate regions (Fig. 2A). Where AGDD exceeded 3400, the vigor was higher than average (Fig. 2A). Among the components of vigor function, as a function of AGDD in nurseries in different climate regions, DAGL and TDW showed an increasing trend, while HD showed a decreasing trend with increasing AGDD.

Among other indicators that were assessable only after harvesting the seedlings, the number, length, and dry weight of the roots of the uncertified apricot seedlings were prominent, which ranged from 1 to 18 root count, 30 to 75 cm, and 15 to 185 g, respectively (Table 4). In certified seedlings, the values varied from 14 to 29 roots, 40 to 46 cm, and 72 to 150 g (Table 4). The ADW and TDW of the uncertified plum seedlings ranged from 24 to 390 g and 55 to 545 g, respectively, and those of the certified seedlings ranged from 50 to 416 g and 97 to 584 g, respectively (Table 4). The aerial-to-root dry weight (ARDW) of the uncertified and certified plum seedlings varied from 0.47 to 6.17 and 0.98 to 2.48, respectively (Table 4). Compared to the RDW, the root count and length did not correlate significantly with seedling vigor and other morphological traits (Fig. 1).

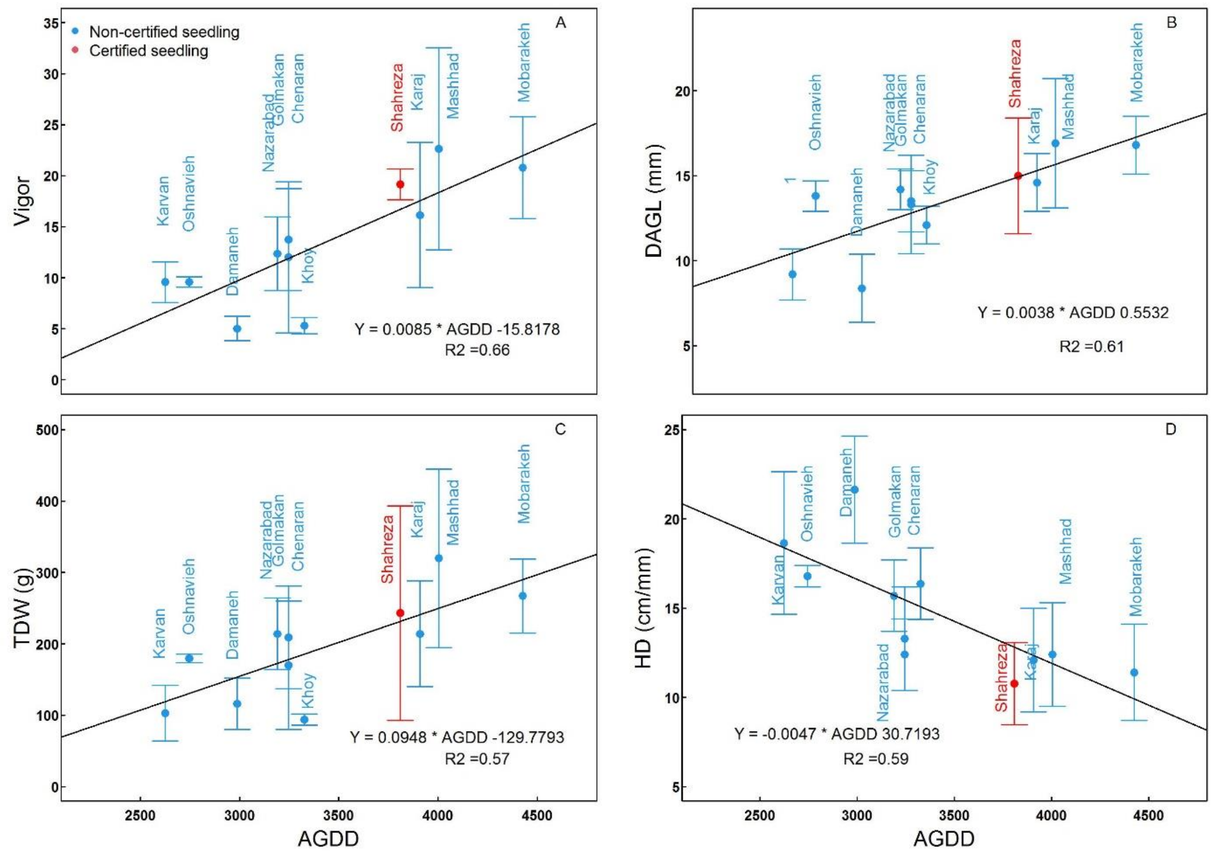

Fig. 3. Relationship between accumulated growth degree day (AGDD) with vigor and other morphological traits for plum seedlings. Each point averages measurements for each nursery and vertical lines indicate the standard error of mean.

Path analysis of seedling vigor

The results of path analysis for seedling vigor showed that the DAGL of plum seedlings had the greatest direct effect (1.46) on vigor and also an indirect effect (0.63) on it through an effect on HD. The DAGL was considered the most important factor in evaluating plum seedling quality (Table 5). Also, a strong positive correlation occurred between seedling vigor and DAGL (0.83) (Fig. 1).

The correlation between plum seedling height and vigor was significant but weak (0.19). The direct effect of seedling height on vigor was also weak (Table 5). However, the indirect effect of height on vigor was significant due to the effect on DAGL (13.31) and HD (10.56) (Table 5). The indirect effect of ADW on vigor was significant, and related to vigor by affecting DAGL.

The best regression model for predicting vigor based on visually measurable morphological traits in nurseries were the models that necessarily included DAGL in the calculations (E1, E3, to E5) (Table 6). The worst models for predicting seedling vigor were equations E2, E6, and E7, which did not account for seedling DAGL (Table 5). The first equation (E1) that accounted for all three traits, i.e., DAGL, height, and HD (Table 6), was the best regression model for predicting seedling vigor.

Table 5. Direct (bold numbers) and indirect effects obtained by using path analysis between vigor and other measured morphological traits in uncertified and certified plum seedlings collected from various nurseries in Iran (2020-2021).

[1]Trait	1	2	3	4	5	6
1- DAGL	**1.46****	0.05**	NS	0.01**	NS	0.63**
2- Height	13.31**	**1.11****	NS	NS	NS	10.56**
3- Root number	NS	NS	**0.05****	NS	0.08**	NS
4- ADW	11.00**	NS	NS	**0.05****	1.13**	NS
5- RDW	NS	NS	1.26**	0.29**	**0.10****	NS
6- HD	1.18**	0.08**	NS	NS	NS	**0.60****
R^2	0.99					

[1]Trait details: DAGL (diameter above grafting line), ADW (aerial dry weight), RDW (root dry weight), and HD (height to diameter ratio). Indirect effects between the traits were significant at $P < 0.05$ (**) or non-significant (NS).

Table 6. Coefficient of variation (CV), coefficient of adjusted determination (R^2aj) and standard error of estimate (Syx) of equations between observed 1traits in uncertified and certified plum seedlings collected from various nurseries in Iran (2020-2021).

Equations	CV%	R^2aj	Syx	Criterion CV%	Criterion R^2aj	Criterion Syx	Sum of scores
E1	0.34	0.78	4.32	7	6	7	20
E2	0.49	0.54	6.22	3	3	3	9
E3	0.39	0.70	4.99	4	4	4	12
E4	0.38	0.72	4.79	6	5	6	11
E5	0.40	0.70	4.97	5	4	5	14
E6	0.70	0.14	8.81	1	1	1	3
E7	0.60	0.31	7.58	2	2	2	6

E1) Vigor = -35.31 + 4.22 × DAGL – 0.17 × height + 1.64 × HD;
E2) Vigor = 9.89 + 0.07 × height - 1.88 × HD;
E3) Vigor = -10.08 + 1.93 × DAGL - 0.17 × HD;
E4) Vigor = -10.07 + 2.26 × DAGL - 0.03 × height;
E5) Vigor = -14.29 + 2.05 × DAGL;
E6) Vigor = 4.18 + 0.04 × height;
E7) Vigor = 29.30 - 1.13 × HD.
[1]Trait details: DAGL (diameter above grafting line), HD (height to diameter ratio).

Discussion

The vigor index reflects the balance of shoot and root biomass and potential growth capacity and determines the potential of the seedling for establishment and future growth (Lin et al., 2019; Liu et al., 2020; Gallegos-Cedillo et al., 2021). The vigor varies depending on plant genetics, growth stage and conditions, and climate (Dardengo et al., 2013; Zuffo et al., 2017; Rahmati et al., 2022 and 2023). Our results showed that the average vigor of certified plum seedlings of the different cultivars was about 19, significantly higher than that of uncertified seedlings (around 11).

This difference seems to be due to the higher biomass and lower HD and ARDW values in the certified seedlings. The certified seedlings were grafted onto the rootstock Myrobalan 29C, which prompted faster graft growth and helped the seedlings reach the physiological flowering stage compared to seedling rootstocks, ultimately improving vigor (Bussi et al., 2002). In addition, the certified nursery producing these seedlings was located in the Shahreza region with temperatures above 3400 AGDD, which can help increase the quality and vigor of the seedlings. One of the characteristics of certified seedlings is their freedom from harmful disease factors, including viruses. The presence of viruses can limit the growth of seedlings and affect their vitality (Rahmati et al., 2022 and 2023).

The value of vigor increased linearly with increasing AGDD in plum nurseries in different climates. Thus, the value is predictable based on AGDD from grafting to harvest. Since temperature directly affects growth and bud break timing, AGDD can simulate seedling growth patterns (Kamata et al., 2020). In addition, higher DAGL and TDW, and lower HD were affected by an increase in AGDD in different regions, consistent with previous findings by Liu et al. (2020).

Since DAGL had the highest correlation with vigor and most morphological traits, it could be the most efficient indicator for plum seedling quality evaluation. The results of the path analysis for vigor also showed that the largest direct effects on the measured morphological traits of bare-root plum seedlings were attributed to the direct effect of DAGL. This variable appeared as a considerable direct effect that underlines its worth in assessment trials of seedling quality. The results obtained are in agreement with those of other researchers. In coffee, RCD and TDW directly affected growth performance (Dardengo et al., 2013). In eucalyptus seedlings, ADW and RDW had a direct effect, and RCD indirectly affected seedling vigor (Binotto et al., 2010). Zuffo et al. (2017) showed that morphological traits such as RCD, TDW, SDW, RDW, and root volume had a direct influence when evaluating the growth performance of *Delonix regia* seedlings. Aran et al. (2011) found a positive correlation between the stem diameter of plum seedlings and vegetative growth. Different regression models that predict vigor based on visually assessable morphological traits in the nursery show that the best approach is to consider all three indicators, i.e., DAGL, height, and HD.

The regression model obtained by Binotto et al. (2010) also confirmed the effectiveness of non-destructive morphological indices, including diameter, height, and number of days after planting, regarding the evaluation of eucalyptus seedlings. However, considering the weak correlation between seedling height as another visually assessable trait in the nursery and vigor, this indicator does not appear to be very effective for evaluating the quality of plum seedlings at harvest.

Seedling height indicates seedling photosynthetic capacity and transpiration area that correlates significantly with vigor but does not correlate with establishment in dry regions or adverse climatic conditions. Similar observations appeared reliable in black walnut nurseries, where seedling height did not correlate with vigor (Thompson, 1985). In eucalyptus seedlings, it is not the height per se but the ratio of height to ADW that is an effective indicator for quality assessment; the lower this ratio, the higher the lignification of the seedling and consequently its establishment level (Gomes et al., 2002). Our results showed that even when considering the height to ADW ratio, certified plum seedlings were preferred compared to uncertified seedlings.

Among the morphological traits, root count and length correlated neither with other seedling variables nor vigor. This observation may be because the number of lateral roots is not an accurate determinant of seedling quality since more lateral roots may have a smaller length and absorption area than a single taproot (Thompson, 1985). These factors alone may not be adequate to assess plum seedling quality and future growth in the orchard.

However, RDW and SDW, as other destructive analytical indicators, correlated strongly with DAGL and vigor, increasing strongly in seedlings thicker than 11 mm.

Root weight is essential because it correlates with seedling diameter, indicating growth and survival. In forest seedlings, RDW and RCD are better indicators of quality rating (Thompson, 1985). There has been a positive and significant relationship between RDW and growth vigor and establishment of bare-root chestnut seedlings (Rahman et al., 2015). The ARDW is studied in seedling evaluation to determine the balance between transpiration and water uptake capacity (Grossnickle and Ivetic, 2022). Our results showed that this morphological indicator did not significantly correlate with vigor or other measured traits, leading to the understanding that this variable alone was insufficient for evaluating bare-root plum seedling quality in the transplanting process.

Conclusion

The current findings showed that the DAGL variable, followed by the dry matter variables, correlated most strongly with the vigor indicator. These variables may be the most effective screening criteria for identifying high-quality plum seedlings in nurseries. The selection of plum seedlings with a stem diameter of more than 11 mm implies selecting seedlings with larger root and shoot dry mass and biomass, which thrive better in the orchard.

Due to the high values of seedling vigor, diameter, biomass, number of roots, and lower height, certified virus-free plum seedlings grafted on clonal Myrobalan 29C rootstocks are better than uncertified seedlings. The certified seedlings are more likely to grow faster, be of higher quality, and establish better in the orchard.

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Conflict of Interest
The authors indicate no conflict of interest in this work.

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