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Morphological, phenological, curd and yield characterization of different broccoli (*Brassica oleracea* var. italica Plenck) cultivars under temperate agroclimatic conditions

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Abstract

Evaluating different germplasm resources is the basis of selecting excellent broccoli cultivars in a specific climatic condition for the fresh market and the processing industry. Agronomic traits of thirteen broccoli cultivars were studied to determine the suitable cultivars for temperate regions. Cultivars, *viz*. Bonanza, Sun King, Volta, De Cicco, Coronado Crown, Packman, Belstar, Kabuki, Marathon, Green Magic, Parthenon, Blue Wind and Green Sprouting were included in the study. Significant differences ($P \leq 0.05$) were found in morphological, phenological, curd-related, and yield-related variables among 13 broccoli cultivars. Morphological parameters such as plant height, plant spread, and stem diameter were maximum in cultivar Marathon, whereas phenological traits such as minimum days to curd formation and total days to harvest were counted in broccoli cultivars De Cicco, Packman, and Blue Wind. Maximum curd diameter was recorded in cultivars Bonanza, De Cicco, Coronado Crown, Packman, Kabuki, Marathon, and Parthenon, whereas the highest per hectare curd yield was obtained from cultivars De Cicco, Packman, Marathon, and Parthenon. The present finding also demonstrated a significant association between different broccoli cultivars with plant height, curd weight, and yield traits. Similarly, a significant positive correlation was observed among stem diameter, curd diameter, curd weight, and curd yield parameters, and between leaf number per plant, days to curd initiation, days to curd formation, and total days to harvest parameters.

Key words: Broccoli, cultivars, phenotypic traits, growth and development, temperate zone

Introduction

Broccoli (*Brassica oleraceae* var. italica Plenck) is rapidly becoming an important fresh market and processing vegetable crop in many parts of the world. There are two types of broccoli: heading and sprouting. Heading broccoli has a large central head consumed as a vegetable, much like cauliflower, whereas sprouting broccoli has one central sprout and many small florets, making it suitable for multiple harvesting. It is a popular crop in the home garden and small commercial areas. Several promising broccoli cultivars for the fresh market and the processing industry have been introduced, suitable for large-scale commercial cultivation (Ciancaleoni and Negri, 2020). It is cultivated for its edible curd, which has become popular in kitchens due to its excellent organoleptic qualities and high nutritional value (Jeffery *et al.*, 2003). Among Brassicas, broccoli is the second major vegetable crop in the United Kingdom after cauliflower. It is cultivated on 8217 hectares with an annual production of ca. 78 thousand tonnes (DEFRA, 2021). Globally, cauliflower and broccoli are grown on 1.86 million hectares, yielding 35.45 million tonnes annually (FAOSTAT, 2021).

It has enormous health benefits, such as lowering cholesterol levels, reducing cancer risk through anti-cancer agents, and being a rich source of vitamins A, D, K, and flavonoids. Glucoraphanin, gluconasturtiian, and glucobrassicin are three glucosinolate phytonutrients found in a unique combination in this vegetable, which can support all steps in the body's detox process, including activation, neutralization, and elimination of unwanted contaminants. Compared with other brassica vegetables, it has been found to have the highest protein, dietary fibre, and vitamin C content (Li *et al.*, 2022).

Two crucial factors that influence the success of the commercial cultivation of broccoli for processing or the fresh market are yield and quality. Although crop yield is the main factor in determining overall market returns, curd quality can be equally important because it affects the crop's marketability and value. On the other hand, formulating sowing and harvesting schedules would benefit from the knowledge of the crop's rate of development and maturity characteristics. These facilitate the effective use of farm resources and are crucial for marketing purposes (Titley, 1985; Rangavajhyala and Ghorpade, 1998; Sterrett *et al.*, 1990).

The interaction between genotype and environment affects broccoli's growth rate, curd yield, and quality. The selection of suitable broccoli cultivars for a diverse climate is crucial. There has been extensive research on the environment's impact on cauliflower's growth and development, however, only a few studies have been conducted on broccoli. Although the two crops are closely related, research has shown that they respond to their environment very distinctly physiologically (Li *et al.*, 2019; Thapa *et al.*, 2017; Chevilly *et al.*, 2021; Siomos *et al.*, 2022). In the United Kingdom, broccoli production faces many challenges, such as uncertain environmental conditions during the spring and summer months. In previous years, unexpected rainfall during these seasons brought localized flooding, restricting sapling planting due to waterlogged soils and encouraging slugs and

diseases that seriously lower crop yield (DEFRA, 2013). Both very cold and warm weather are disadvantageous for the growth of broccoli. It is susceptible to cold injury in cold conditions, and bud clusters loose quickly in warm weather (Siomos *et al.*, 2022).

Broccoli is becoming more and more popular all over the globe as a result of changes in dietary preferences and a rise in health and nutrition awareness. Farmers in the United Kingdom are gradually switching to grow broccoli as they recognize the enormous potential of this vegetable in both domestic and international markets. The genotypes highly influence the growth, yield, and quality of broccoli. Although not many broccoli cultivars are grown in this country, growers' increasing interest in the crop necessitates genotypic evaluation. Therefore, the present study assessed the morphological, phenological, curd, and yield attributes of thirteen broccoli cultivars under temperate agro-climatic conditions to increase farmer awareness of this high-value crop.

Materials and methods

Two years (2018 and 2019) study was carried out at the research area of Bulmershe Horticultural Society, Wokingham (latitude 51.42° 25' 12" North of the Equator and longitude -0.85° 51' 0" West of the Prime Meridian) United Kingdom. Seeds of broccoli cultivars viz. Parthenon, Green Sprouting (Suttons Seeds, Devon, UK), Green Magic, Kabuki, Marathon, Volta (Marshalls Seeds, Cambs., UK), Bonanza, Sun King, De Cicco (Burpee, Pennsylvania, USA), Coronado Crown, Blue Wind (Gurney's Seed and Nursery Co., Indiana, USA), Packman and Belstar (Swallowtail Garden Seed, California, USA) were sown on 10th April each year into module trays (Erin 60 cell plug trays, Wyevale Garden Centre, Reading, UK) containing peat-based modular compost (Homebase John Innes Seed Germination Compost, UK). Seed trays were watered and held for germination in a shade house under an ambient environment (Table 1). Uniform-sized seedlings with four leaves were transplanted in the experimental plot on 1st May each year, where plant-to-plant and row-to-row distance was maintained at 40 cm and 50 cm, respectively. The soil was ploughed and levelled before the transplantation of seedlings and weeds were controlled manually. Light irrigation was given using a sprinkler after transplanting and whenever required. The experiment was laid out on Randomized Complete Block Design (RCBD) with three replications.

The soil of the experimental plot is categorized as standard mineral with pH 6.5 and organic matter 3.5%. RB209 fertilizer manual (MAFF, 1994) was followed to estimate the standard dose of NPK for broccoli cultivars. For nitrogen requirement, Soil Nitrogen Supply (SNS) index was calculated using annual rainfall (689.9 mm in 2018 and 634.8 mm in 2019), soil type (standard mineral) and previous crop (un-cropped land) variables, which indicated SNS as 80-100 kg N ha^{-1} at index 2. Therefore, an additional 165 kg N ha^{-1} was applied in two splits (100 kg N ha^{-1} after 20 days of transplantation and the remainder dose was applied at curd initiation stage) in the form of urea. Similarly, triple super phosphate and muriate of potash were applied to maintain the phosphorus index at 2 (100 kg P_2O_5 ha^{-1}) and potassium at 2+ (125 kg K_2O ha^{-1}), respectively. Plant measurements were taken by selecting inner plants to avoid border effects. The parameters recorded were: plant height, plant spread, stem diameter, leaf number per plant, days to curd initiation, days to curd formation, days to harvest, curd diameter, curd weight and curd yield (A.O.A.C., 2005). Statistical data of these parameters were analysed using GenStat-16 (VSN International Ltd. UK) and means were separated with Duncan's Multiple Range Test (DMRT) at 5% level of significance (Gomez and Gomez, 1984; Waller and Duncan, 1969). The path coefficient correlation analysis was performed using the R programming scripts (R 4.2.2, R Core Development Team, 2022). The post hoc pairwise tests of independence in conjunction with asymptotic generalized Pearson chi-squared tests were used to assess any association between the frequencies of each parameter and broccoli cultivars. The correlation and chord diagrams were generated using RStudio IDE 2021.09.0 (RStudio Team, 2021), integrated into the R software, visualization of 'corrplot' and 'circlize' packages.

Table 1. Environmental detail of the experiment

Growing Season	Temperature (°C)			Sunshine (hours)	Rainfall (mm)	Days rain >1 mm	Days air frost	Day length (hours)
	Max	Min	Avg					
April 2018	14.5	3.8	9.2	233.8	22.6	4.70	3.0	16.11
May 2018	16.1	5.9	11.0	203.0	30.2	5.80	1.7	17.60
June 2018	21.4	10.1	15.7	262.5	32.9	5.30	0.0	18.19
July 2018	23.1	13.2	18.1	204.5	26.1	6.00	0.0	18.06
April 2019	18.2	6.7	12.4	234.8	3.7	1.40	0.3	16.11
May 2019	17.6	7.9	12.8	232.9	27.0	4.60	0.3	17.60
June 2019	19.3	9.8	14.5	198.5	82.3	12.70	0.0	18.19
July 2019	20.5	10.9	15.7	186.9	49.1	9.00	0.0	18.06

Results and discussion

To systematically analyze the morphological, phenological, curd, and yield characteristics of the thirteen broccoli cultivars, their plant height, plant spread, stem diameter, leaf number per plant, days to curd initiation, days to curd formation, total days to harvest, curd diameter, curd weight, and curd yield agronomic traits were investigated. The results shown in Table 2 indicated a statistically significant difference ($P \leq 0.05$) between the broccoli cultivar in all parameters. The findings of morphological traits showed that broccoli cultivar Marathon had maximum plant height (74.33 cm) followed by Green Magic (72.67 cm), whereas maximum plant spread was measured in cultivar Marathon (60.33 cm) followed by Parthenon (55.33 cm), and Green Magic (53.33 cm). Similarly, stem diameter was maximum in cultivar Marathon (39.33 mm), followed by Parthenon and Packman (37.67 mm), and De Cicco (35.67 mm). The highest leaf number per plant was counted in cultivar Parthenon (15.67) and Volta (15.33) followed by Kabuki (14), Marathon, Green Magic, and Green Sprouting (13.67). Data regarding phenological attributes indicated that the cultivar Parthenon took maximum days to curd initiation (58.33 days), days to curd formation (27 days), and total days to harvest (85.33 days). However, minimum days to curd initiation were recorded in cultivars Blue Wind (34.33 days) and De Cicco (35 days), minimum days to curd formation in cultivars Blue Wind (16.33 days), Packman (16.67 days), and De Cicco (17.67 days), and minimum total days to harvest in cultivars Blue Wind (50.67 days), De Cicco (52.67 days), and Packman (53.33 days). Furthermore, the data related to curd and yield traits showed that maximum curd diameter was measured in cultivar Marathon (17.33 cm) followed by Parthenon (16.33 cm), Packman and De Cicco (16 cm), Kabuki (15.17 cm), Bonanza

Table 2. Performance of different cultivars of broccoli under temperate agroclimatic conditions

Broccoli cultivars	Plant height (cm)	Plant spread (cm)	Stem diameter (mm)	Leaf number	Days to curd Initiation	Days to curd formation	Total days to harvest	Curd diameter (cm)	Curd weight (g)	Curd yield (t ha^{-1})
Bonanza	63.33^{AD}	32.67^{F}	28.00^{DE}	12.33^{CD}	36.00^{GH}	20.67^{D}	56.67^{FG}	15.00^{AB}	452.67^{B}	22.63^{B}
Sun King	40.33^{F}	40.33^{E}	19.67^{F}	15.00^{AB}	49.00^{BC}	24.33^{BC}	73.33^{BC}	12.33^{CD}	200.33^{D}	10.02^{D}
Volta	67.33^{AC}	32.67^{F}	24.67^{E}	15.33^{A}	50.67^{B}	24.67^{B}	75.33^{B}	12.33^{CD}	312.67^{C}	15.63^{C}
De Cicco	62.33^{BD}	40.33^{E}	35.67^{AB}	10.67^{DE}	35.00^{H}	17.67^{E}	52.67^{G}	16.00^{AB}	570.67^{A}	28.53^{A}
Coronado Crown	55.33^{DE}	50.33^{BC}	33.33^{BC}	13.00^{BC}	42.67^{EF}	21.67^{D}	64.33^{DE}	15.00^{AB}	450.33^{B}	22.52^{B}
Packman	47.33^{EF}	41.33^{DE}	37.67^{AB}	10.67^{DE}	36.67^{GH}	16.67^{E}	53.33^{G}	16.00^{AB}	583.67^{A}	29.18^{A}
Belstar	46.67^{EF}	40.33^{E}	24.33^{EF}	12.00^{CE}	39.67^{FG}	20.67^{D}	60.33^{EF}	11.17^{D}	302.33^{C}	15.12^{C}
Kabuki	41.33^{F}	47.67^{CD}	29.00^{CE}	14.00^{AC}	45.00^{CE}	22.67^{BD}	67.67^{CD}	15.17^{AB}	380.33^{BC}	19.02^{BC}
Marathon	74.33^{A}	60.33^{A}	39.33^{A}	13.67^{AC}	49.00^{BC}	21.00^{D}	70.00^{BD}	17.33^{A}	604.00^{A}	30.20^{A}
Green Magic	72.67^{AB}	53.33^{AC}	29.00^{CE}	13.67^{AC}	44.33^{DE}	22.33^{CD}	66.67^{D}	14.67^{BC}	376.67^{BC}	18.83^{BC}
Parthenon	52.67^{DE}	55.33^{AB}	37.67^{AB}	15.67^{A}	58.33^{A}	27.00^{A}	85.33^{A}	16.33^{AB}	583.67^{A}	29.18^{A}
Blue Wind	60.67^{CD}	50.33^{BC}	27.33^{DE}	10.00^{E}	34.33^{H}	16.33^{E}	50.67^{G}	12.33^{CD}	344.67^{C}	17.23^{C}
Green Sprouting	60.33^{CD}	41.67^{DE}	29.67^{CD}	13.67^{AC}	48.00^{BD}	22.33^{CD}	70.33^{BD}	14.33^{BC}	393.33^{BC}	19.67^{BC}
	**	**	**	**	**	**	**	**	**	**
$LSD_{(p\leq 0.05)}$	11.12	7.19	4.73	2.24	4.18	2.14	6.05	2.62	98.17	4.91
$SED_{(p\leq 0.05)}$	5.39	3.49	2.29	1.09	2.02	1.04	2.93	1.27	47.57	2.38
CV%	11.5	9.5	9.2	10.2	5.4	5.9	5.5	10.8	13.6	13.6

Means within column followed by the same letters did not differ significantly at 5% level of probability. Each data point is the average of two growing seasons (2018-2019). ** represents the significant difference between cultivar means, LSD stands for least significant difference between cultivar means, SED stands for standard errors of difference within the sample, and CV stands for coefficients of variation.

and Coronado Crown (15 cm). Four broccoli cultivars had higher curd weight and yield and there was a non-significant difference among them. Maximum curd weight was recorded in cultivars Marathon (604 g), Packman and Parthenon (583.67 g), and De Cicco (570.67 g). A similar trend was observed in the curd yield parameter, *i.e.*, maximum curd yield was recorded in cultivars Marathon (30.20 t ha^{-1}), Packman and Parthenon (29.18 t ha^{-1}), and De Cicco (28.53 t ha^{-1}).

A significant association was found between different broccoli cultivars with plant height ($\chi^2 = 26.01$; $p = 0.0107$), curd weight ($\chi^2 = 456.03$; $p = 0.0001$), and curd yield ($\chi^2 = 22.80$; $p = 0.0295$) attributes (Fig. 1). However, the non-significant association was observed between different broccoli cultivars and plant spread ($\chi^2 = 19.26$; $p = 0.0800$), stem diameter ($\chi^2 = 14.02$; $p = 0.2996$), leaf number per plant ($\chi^2 = 3.08$; $p = 0.9949$), days to curd initiation ($\chi^2 = 14.38$; $p = 0.2773$), days to curd formation ($\chi^2 = 5.49$; $p = 0.9398$), total days to harvest ($\chi^2 = 19.01$; $p = 0.0883$), and curd diameter ($\chi^2 = 2.91$; $p = 0.9962$) parameters.

The hierarchical clustering presented in Fig. 2 categorized the correlation data into two groups. A significant positive correlation was observed among stem diameter, curd diameter, curd weight, and curd yield parameters in group one. In contrast, a significant positive correlation was observed in group two between leaf number per plant, days to curd initiation, days to curd formation, and total days to harvest (Table 3). The correlation coefficient of stem diameter with curd diameter, curd weight, and curd yield were 0.89, 0.97, and 0.97, respectively. Similarly, the correlation coefficient of leaf number per plant with days to curd initiation, days to curd formation, and total days to harvest were 0.93, 0.97, and 0.96, respectively. The positive correlation between different parameters indicated that if one increased, the other also increased. Therefore, the present results can be elaborated that with the increase in stem diameter, the curd diameter, curd weight, and curd yield were also increased. Similarly, with the increase in leaf number per plant, the days to curd initiation, curd formation, and total days to harvest also increased. A negative correlation was found between plant height, stem diameter, curd weight, and curd yield with leaf number per plant, days to curd initiation, days to curd formation, and total days to harvest.

Thirteen broccoli cultivars have been assessed for their morphological, phenological, and curd characteristics. Cultivar Marathon had promising morphological characteristics whereas cultivars De Cicco, Packman, and Blue Wind showed encouraging phenological traits. However, broccoli yield and related parameters were positive in cultivars De Cicco, Packman, Marathon, and Parthenon. It is apparent that the curd weight and size, and yield are important traits linked to broccoli marketing and productivity. Therefore, cultivars De Cicco, Packman, Marathon, and Parthenon appeared superior to cultivating under temperate agroclimatic conditions. Broccoli is widely cultivated in the United Kingdom which is usually harvested from Summer to Autumn. Most of the broccoli cultivars are sold as fresh produce. Recent interest in commercial broccoli production has been motivated by the development and availability of commercial cultivars adapted to temperate and tropical conditions (Edwards-Jones *et al.*, 2009). Selecting suitable broccoli cultivars likely impacts their quality and shelf life in local and supermarkets (Le Strange *et al.*, 2010). Dahal *et al.* (2022) observed significant variation among different broccoli genotypes regarding their morphological, phenological, curd and yield traits grown at different locations in Nepal and recommended BL-16003 and BL-18009 as high-yielding ones. Similarly, Kundu *et al.* (2022) evaluated six broccoli cultivars in India and recommended the cultivar Centauro due to its best yield attributing characters and

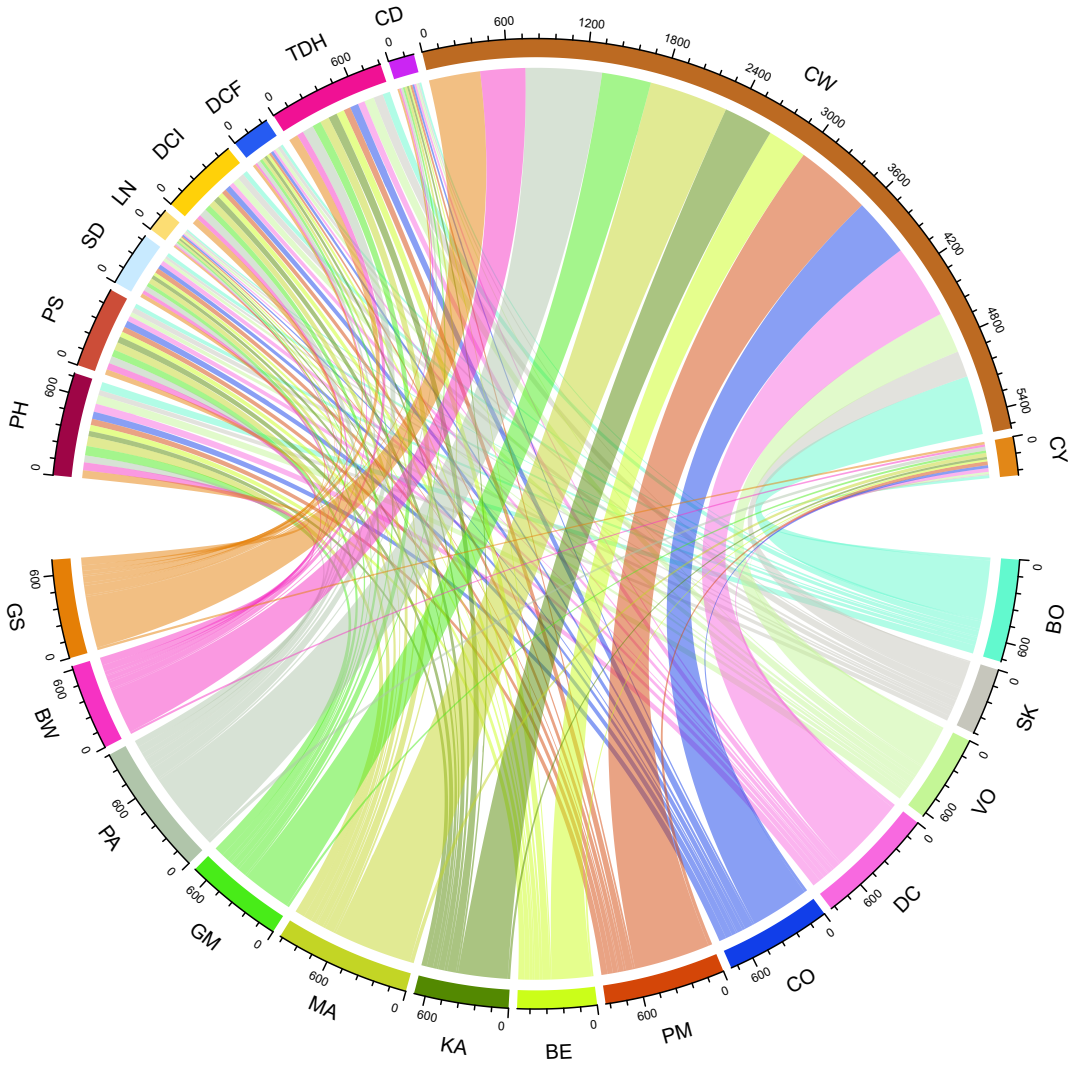

Fig. 1. Chord diagram showing the association between the different agronomic attributes and the thirteen broccoli cultivars. The chords are unidirectional. Chord thickness corresponds to the observed values of different agronomic attributes that is related to a respective broccoli cultivars viz: Bonanza (BO), Sun King (SK), Volta (VO), De Cicco (DC), Coronado Crown (CO), Packman (PM), Belstar (BE), Kabuki (KA), Marathon (MA), Green Magic (GM), Parthenon (PA), Blue Wind (BW), and Green Sprouting (GS). Plant growth variables: plant height (PH), plant spread (PS), stem diameter (SD), leaf number per plant (LN), days to curd initiation (DCI), days to curd formation (DCF), total days to harvest (TDH), curd diameter (CD), curd weight (CW), and curd yield (CY).

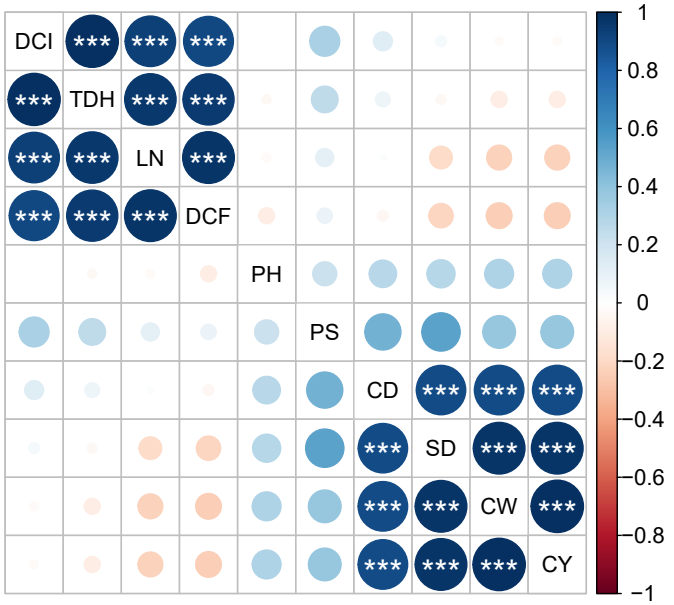

Fig. 2. Correlation chart showing the significance of association of plant growth variables in broccoli cultivars. Plant growth variables: plant height (PH), plant spread (PS), stem diameter (SD), leaf number per plant (LN), days to curd initiation (DCI), days to curd formation (DCF), total days to harvest (TDH), curd diameter (CD), curd weight (CW), and curd yield (CY). *** represented highly significant $P \leq 0.001$.

biochemical properties. The results regarding morphological and yield traits of the present study also coincide with the findings of Thapa and Rai (2012), Sanchez *et al.* (2016), and Tejaswini *et al.* (2018).

The study evaluated thirteen broccoli cultivars in temperate conditions, revealing significant variations in morphological, phenological, and yield attributes. Marathon stood out for plant height and curd features, while Parthenon, Packman, and De Cicco exhibited positive yield traits. Correlations highlighted interconnectedness between certain attributes, aiding cultivar selection. These findings contribute to optimal broccoli production, meet market demands, and align with prior research. Cultivars De Cicco, Packman, Marathon, and Parthenon emerged as strong candidates for successful cultivation. This study underscores the importance of cultivar selection and its impact on broccoli farming and marketing strategies.

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Table 3. Path coefficient correlation computed by Pearson-method for plant growth variables of broccoli cultivars.

Traits	PH	PS	SD	LN	DCI	DCF	TDH	CD	CW
PS	0.211		0.535	0.118	0.326	0.086	0.259	0.476	0.390
SD	0.288	0.535		-0.188	0.044	-0.216	-0.035	0.890***	0.974***
LN	-0.029	0.118	-0.188		0.931***	0.974***	0.963***	0.015	-0.226
DCI	-0.002	0.326	0.044	0.931***		0.905***	0.991***	0.130	-0.028
DCF	-0.093	0.086	-0.216	0.974***	0.905***		0.953***	-0.042	-0.241
TDH	-0.030	0.259	-0.035	0.963***	0.991***	0.953***		0.080	-0.094
CD	0.275	0.476	0.890***	0.015	0.130	-0.042	0.080		0.895***
CW	0.304	0.390	0.974***	-0.226	-0.028	-0.241	-0.094	0.895***	
CY	0.304	0.390	0.974***	-0.226	-0.027	-0.240	-0.094	0.895***	1.000***

Plant growth variables: plant height (PH), plant spread (PS), stem diameter (SD), leaf number per plant (LN), days to curd initiation (DCI), days to curd formation (DCF), total days to harvest (TDH), curd diameter (CD), curd weight (CW), and curd yield (CY). *** represented highly significant correlation between the variables at 1% level of probability ($P \leq 0.001$).

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