Tropical Agricultural Research & Extension 28 (1): 2024

RESEARCH ARTICLE

APPLICABILITY OF AGRONOMIC TRAITS IN THE DETERMINATION OF YIELD OF TURMERIC (*Curcuma longa* L.)

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Received: 08 August 2024; Accepted: 26 November 2024; Published: 31 March 2025

ABSTRACT

Turmeric (*Curcuma longa*) has gained significant attention in medicine, nutrition, and biotechnology due to its pharmacological properties and potential therapeutic applications. Since it is vegetatively propagated through underground rhizomes, the genetic improvement of turmeric is very limited. Screening for superior traits is still practiced for turmeric since it has a broad, untapped natural variation. Different agronomic traits, directly and indirectly, determine rhizome yield in turmeric. The present study reveals yield-determining traits of turmeric as described by correlation coefficients and path coefficients. The yield determinants of turmeric would be useful for selecting higher yields. Turmeric rhizomes were planted in the field, and data on eleven traits of two hundred plants were recorded. The research utilized principal component analysis (PCA) and identified three main components (PC1, PC2, and PC3), which had eigenvalues of 4.157, 3.017, and 1.992, respectively, explaining 76.385% of the total cumulative variability. Plant height is a key factor in determining yield, as it indicates a strong positive correlation and has a significant direct effect on yield. The number of secondary fingers per plant was also a considerable factor as it showed a significant positive correlation and considerable direct influence on yield. The number of mother rhizomes per plant and the length of leaf petiole could still be a viable positive trait for high-yield as they show a lower direct influence on yield. Leaf blade length is not a good criterion for yield determinants. These parameters can be utilized in future breeding programs to select high-yielding genotypes.

Keywords: Direct effect, Indirect effect, PCA, Turmeric, Yield components

INTRODUCTION

Turmeric (*Curcuma longa* L.) is a rhizomatous plant that reproduces vegetatively and is a member of the Zingiberaceae family (Verma *et al.*, 2018). Turmeric originated in Southeast Asia, with some species becoming acclimatized in northeastern India and Java. At the same time, it is grown in various other tropical and subtropical regions, including Sri Lanka, Jamaica, India, and China. Turmeric cultivation in India is predominantly cultivated primarily on Orissa, Maharashtra, Tamil Nadu, Gujarat, Assam Karnataka, and Andhra Pradesh states (Prajapati *et al.*, 2014). However, the highest diversity exists in Thailand and India, where at least 40 species can be found per area (Leong-Skorniekova *et al.* 2007). Turmeric is a triploid (2n = 3x = 63) that exhibits many species (Roy *et al.*, 2011).

Turmeric is a staple ingredient in Sri Lankan cuisine and traditional medicine. It is used in various industries beyond food and medicine, including cosmetics, dyeing, and textile industries (Yadav & Tharun, 2017). Turmeric cultivation provides livelihoods for numerous smallholder farmers in Sri Lanka, particularly in regions like Matara, Gampaha, Kandy, Matale, Kurunegala, Ampara, and Kalutara districts, where the climate and soil conditions favor its cultivation (Heenkende, 2017; Abeynayaka *et al.*, 2020). As such, turmeric is an economic crop that drives economic

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growth, employment generation, and export diversification in Sri Lanka. The annual turmeric yield per hectare is around 10– 15 Tin Sri Lanka (DEA, 2012). Sri Lanka annually produces approximately 2000 MT of turmeric, primarily cultivated by smallholder farmers (DEA, 2019). In 2018 and 2019, the production of turmeric in Sri Lanka was 9697 and 9415 MT (Ministry of Plantation Industries and Export Agriculture, 2020), respectively. Turmeric holds significant economic importance for Sri Lanka's domestic market, with an annual demand of approximately 7,000 MT as of 2020. However, the country's domestic production of turmeric was only 1,500 MT in 2020. Furthermore, since the government implemented import restrictions on export crops such as turmeric, ginger, and pepper in December 2019, farmers have demonstrated significant interest in growing turmeric. In 2020, the production of raw turmeric experienced a significant surge of 170.9 %, reaching a total of 25,506 MT (Central Bank, 2021). There is a growing demand for turmeric in Sri Lanka, driven by its use in several ways. Due to fluctuations in weather conditions and pest infestations, domestic turmeric production does not always meet the demand (Abeynayaka *et al*., 2020). As a result, Sri Lanka imports an average of 5500 to 6000 MT of turmeric annually to bridge the gap between supply and demand, costing around Rs. 1142 million per year (Perera, 2023). The demand for turmeric continues to increase steadily, influenced by factors such as population growth, changing consumer preferences due to health concerns, and expanding industrial usage in cosmetic and ayurvedic industries.

The yield of turmeric is influenced by biotic, abiotic, genetic and environmental components (Sumathi *et al*., 2008; Singh & Ramakrishna, 2014). Biotic factors such as pest infestations, diseases (Shanmugam *et al*., 2015), and competition from weeds (Hossain, 2005; Sahoo *et al*., 2023) can significantly impact turmeric yield. Additionally, genetic factors are crucial in deciding maximum yield (Aswathi *et al*., 2023; Alam *et al*., 2024; Silaru *et al*., 2023), as most inherent traits of turmeric varieties, including disease resistance, growth habits, and rhizome development, directly influence yield potential. Environmental factors such as temperature, rainfall, soil fertility, and light intensity also determine the turmeric yield, as they affect the physiological processes, nutrient uptake, and vegetative growth of turmeric plants (Chovatia *et al*., 2010; Manggoel *et al*., 2012; Singh *et al*., 2020). Therefore, understanding these complex interactions between agronomic traits and environmental influences is essential for implementing effective management strategies to optimize turmeric yield and ensure sustainable production. Plant architecture in turmeric is important in determining turmeric yield, as it directly influences factors such as light interception, nutrient uptake, and overall productivity (Nair *et al*., 2010; Roy *et al*., 2011; Jan *et al*., 2012; Mishra *et al*., 2015). The architecture of a turmeric plant consists of several elements, including plant height, leaf count, tiller formation, and rhizome development (Prasath *et al*., 2019). The formation of tillers, or lateral shoots, allows for greater rhizome proliferation and ultimately leads to increased yield (Khapediya *et al*., 2021).

The study aimed to evaluate the applicability of agronomic traits in determining the yield of turmeric by assessing the strength and direction of relationships between these traits and yield through correlation analysis and analyzing both direct and indirect effects of these traits on yield using path analysis. The research findings can be implemented by prioritizing agronomic traits with strong direct effects on yield in turmeric breeding and cultivation programs, thereby enhancing yield potential through targeted selection and management practices.

MATERIALS AND METHODS

The present study was carried out during the cropping seasons of 2021 and 2022 in Matara, Sri Lanka (Latitude 6.0833, Longitude 80.5667), situated within the WL2a (Wet zone, Low country) agroecological zone. This region experiences a high mean annual rainfall exceeding 2,500 mm, characterized by minimal dry periods (<75 – 75% expectancy value of annual RF in inches). The soil type was Ultisol.

The land was prepared by ploughing and harrowing before the commencement of planting. Partially burnt paddy husk was mixed with topsoil at the rate of 100 kg/ha (Wickramasinghe & De Silva, 2018). The planting materials were collected from farmer fields. Before planting, the rhizomes were treated with fungicide to eradicate possible fungal contaminants. Rhizomes were planted on elevated beds (20 cm high) with a spacing of 30 cm × 30 cm between rows and plants (DEA, 2012). Frequent irrigation was done according to the necessity using a sprinkler system. The weeding was done manually. Triple Super Phosphate (TSP) was applied at 100 kg/ha, along with 20 MT of organic fertilizer as the basal application. Additionally, Urea was incorporated once at a rate of 65 kg/ha at 45 days after planting (DAP) and again at 90 DAP. Potassium (K) was applied as 100 kg/ha of MOP twice, at 45 DAP and 90 DAP, following the guidelines outlined by the Department of Export Agriculture (DEA, 2012). The recommended agronomic management practices (earthing up, field sanitary) were implemented to optimize crop growth and development (*Supplementary figure 1*).

Data collection and analysis

Data was collected on the following parameters: plant height (PH), number of leaves per plant (LVS), number of tillers per plant (NT), leaf blade length (LBL), leaf width (LW), leaf petiole length (LPL), number of mother rhizomes per plant (NMR), number of primary fingers per plant (NPF), number of secondary fingers per plant (NSF), fresh rhizome yield per plant (FYP), and fresh canopy biomass per plant (CBM). Data collection was done in two stages: growth data (PH, LVS, NT, NL, LBL, LW, LPL, and SP) were recorded when plants commenced yellowing, while yield data (NMR, NPF, NSF, FYP, and CBM) were collected at harvest, when plants dried. The PCA was conducted on the collected data using SPSS for Windows, Version 22 (SPSS Inc., 2011). The PCA facilitates the recognition of patterns that highlight similarities and differences within the data of the studied accessions (Jan *et al*., 2012; Quemel *et al*., 2021). Path coefficient analysis was conducted using AMOS Version 26 software (SPSS Inc., 2011) utilizing the path diagram in Figure 2.

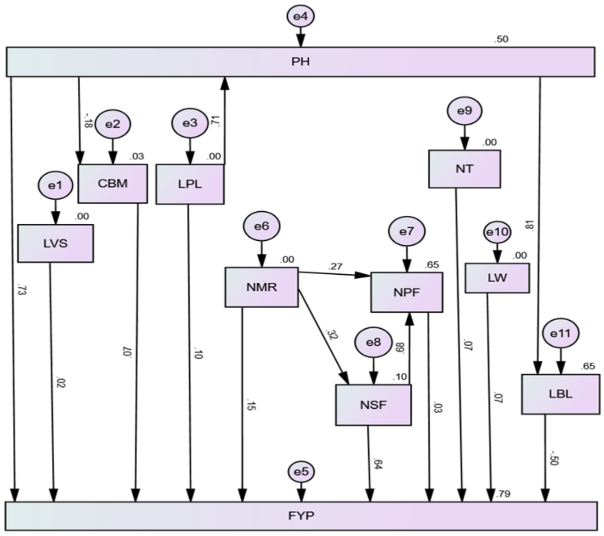

Figure 2: Path diagram representing cause and effect relationships among yield and other traits in turmeric.

PH: Plant height, NT: number of tillers per plant, LVS: number of leaves per plant, LPL: leaf petiole length, LBL: leaf blade length, LW: leaf width, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, CBM: fresh canopy biomass per plant, YPC: fresh rhizome yield per plant

In accordance with the methodology cited in Jagadeeshkanth *et al.,* (2014), both direct effects and indirect effects were then arranged to a rank according to the scales established by Lenka and Misra (1973): Negligible 0.00 to 0.09, Low: 0.10 to 0.19, Moderate: 0.20 to 0.29, High: 0.30 to 0.99, Very high: >1.00 (Jagadeeshkanth *et al.,* 2014)

RESULTS AND DISCUSSION

Turmeric plants exhibited large variation in the number of mother rhizomes per plant and tillers per plant. In contrast, plant height and fresh yield per plant exhibited greater consistency, as shown by their coefficients of variation (Table 1).

Table 1: Descriptive statistics for the studied parameters in turmeric

Trait	Minimum	Maximum	Mean	Std. Error	CV %
PH	84.00	174.00	109.18	0.01	5.02
LVS	6.00	41.00	20.58	0.01	9.42
NT	1.00	10.00	4.27	0.01	22.46
LBL	34.50	72.00	45.14	0.01	5.63
LW	6.50	19.00	11.43	0.01	8.60
LPL	14.00	72.00	27.17	0.02	11.52
SP	22.95	53.20	39.96	0.01	5.39
NMR	1.00	9.00	4.16	0.01	24.98
NPF	7.00	41.00	24.60	0.01	10.35
NSF	17.00	135.00	84.49	0.02	10.10
FYP	314.00	1947.00	715.61	0.01	5.30
CBM	64.00	645.00	247.28	0.02	8.44

PH: Plant height, LVS: number of leaves per plant, NT: number of tillers per plant, LBL: leaf blade length, LW: leaf width, LPL: leaf petiole length, SP: SPAD value, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, FYP: fresh rhizome yield per plant, CBM: fresh canopy biomass per plant.

Correlation analysis was conducted to assess the correlations between agronomic traits and turmeric yield, while path analysis was utilized to examine both the direct and indirect effects among the traits. Additionally, PCA was performed to identify the underlying effects of the traits. According to the results, the strongest correlations with yield were observed with the number of primary fingers per plant (r=0.510), the number of mother rhizomes per plant (r=0.439), and the number of secondary fingers per plant (r=0.367) (Table 2).

When different studies utilized the same agronomic characteristics to determine yield determinants, diverse results were derived (Table 3) in terms of positive and negative relationships. Several factors could contribute to this variability.

However, Mamatha *et al.* (2015) noted a negative correlation between yield and various agronomic parameters, such as the number of tillers, the number of mother rhizomes per plant, and leaf petiole length. Different genotypes within the same crop species may respond differently to the same agronomic characteristics. Variations in genetic makeup can lead to variations in how plants interact with their environment, influencing yield outcomes (Jagadeeshkanth *et al*., 2014; Vimal *et a*l., 2018; Nandakumar *et al*., 2022). Variations in environmental factors such as soil type, climate, temperature, rainfall, and sunlight exposure across different study locations can significantly impact plant growth and development (Nwokocha, *et al.*, 2009; Ali *et al*., 2018; Verma *et al*., 2019; Zonayet & Karim, 2020). These variations may affect the relationship between agronomic characteristics and yield. Variances in cultural practices in the studies may contribute to differences in yield determinants (Kamal & Yousuf, 2012; Shamrao *et al*., 2013; Verma *et al*., 2019). Additionally, variations in experimental designs, including plot sizes, replication levels, sampling techniques, and data

Table 2: Pearson's correlation matrix between morphological characteristics of turmeric

	PH	LVS	NT	LBL	LW	LPL	NMR	NPF	NSF	FYP
LVS	-.342**									
NT	-.271**	.839**								
LBL	.809**	-.463**	-.364**							
LW	.640**	-.360**	-.349**	.537**						
LPL	.708**	-0.08	-0.086	.632**	.322**					
NMR	-.178*	.477**	.562**	-.244**	-.220**	-0.072				
NPF	-.193**	.266**	.270**	-0.004	-0.132	-0.118	.488**			
NSF	-.532**	.219*	0.116	-.494**	-.209*	-.450**	.401**	.745**		
FYP	.232**	.293**	.302**	0.066	.166*	.209**	**.439****	**.510****	**.367****	
CBM	-0.165	.236*	.197*	-0.168	-0.01	-.209*	.439**	.520**	.627**	.487**

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

PH: Plant height, LVS: number of leaves per plant, NT: number of tillers per plant, LBL: leaf blade length, LW: leaf width, LPL: leaf petiole length, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, FYP: fresh rhizome yield per plant, CBM: fresh canopy biomass per plant.

Table 3: Positive and negative correlations of traits with yield in turmeric

Traits	Present study	References for supportive findings
Plant height X Yield	Positive	Mamatha *et al.* (2015), Tomar *et al*. (2005), Singh *et al*. (2018), Vimal *et al*. ((2018), Dev and Sharma (2011), Poonam *et al*. (2022), Singh and Patel (2013), Luiram *et al*. (2018)
Number of leaves per plant X Yield	Positive	Mamatha *et al.* (2015), Vimal *et al*. ((2018), Dev and Sharma (2011), Poonam *et al*. (2022), Jagadeeshkanth *et al*. (2014)
Number of tillers per plant X Yield	Positive	Dev and Sharma (2011), Poonam *et al*. (2022), Jagadeeshkanth *et al*. (2014)
Leaf blade length X Yield	Not significant	Mamatha *et al.* (2015)
Leaf width X Yield	Positive	Mamatha *et al.* (2015)
Leaf petiole length X Yield	Positive	
Number of mother rhizomes/plant X Yield	Positive	Jagadeeshkanth *et al*. (2014), Singh and Patel (2013)
Number of primary fingers/plant X Yield	Positive	Mamatha *et al.* (2015), Singh *et al*., (2018), Prajapati *et al*. (2014), Poonam *et al*. (2022), Luiram *et al*. (2018)
Number of secondary fingers/plant X Yield	Positive	Mamatha *et al.* (2015), Singh *et al*. (2018), Tomar *et al*. (2005), Vimal *et al*. (2018), Poonam *et al*. (2022), Jagadeeshkanth *et al*. (2014)
Fresh canopy biomass/plant X Yield	Positive	No evidence

collection methods, can introduce bias and affect the accuracy of yield determinants identified in different studies (Prabhakaran & Nair, 1984; Anderson *et al*., 2017). However, comparing the results of the present study with the published findings indicates that the factors determining turmeric yield are likely specific to genotype and may be influenced by environmental factors, including management practices.

Principal component analysis on morphological traits

PCA was performed to transform correlated agronomic traits into uncorrelated variables and to separate underlying trait effects on turmeric yield by ordering principal components according to the variance they explain in the dataset.

The first three components have large eigenvalues, indicating that they explain a significant portion of the variance in this study's data (Figure 1).

PC1, PC2, and PC3, with Eigenvalues of 4.157, 3.017, and 1.992 collectively account for 76.385% of the total cumulative variability. The first two principal components, PC1 and PC2, exhibited

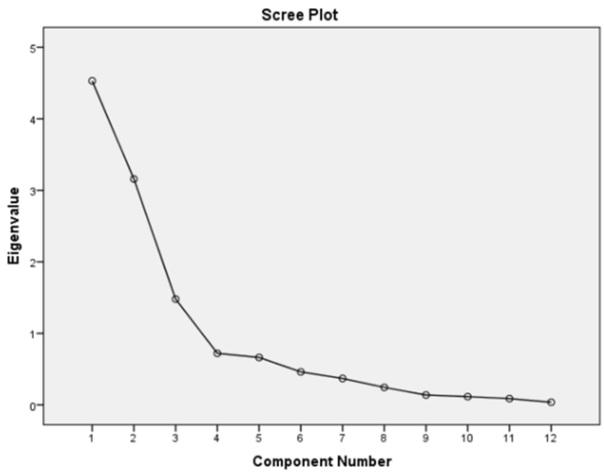

Figure 1: Scree plot of principal component analysis among morphological traits of turmeric

Eigenvalues exceeding two and contributed to 59.788% of the cumulative variability (Table 4). According to the PCA outcomes reported by Dudekula and Kandasamy (2022), approximately 78.88% of the total variation has been elucidated by the first six principal components. In the present study, PC1 significantly contributes 34.64% to the overall variance, with traits such as plant height and leaf blade length displaying the highest contributions. Khumaida *et al.* (2019)

discovered that the first five principal components collectively elucidate 90.041% of the cumulative contribution, with PC1 alone contributing 6.963 variance, representing 34.813% of the total explained variation. These findings emphasize the differences explained by PCA in various studies and the substantial contributions of diverse traits to the overall variance within the traits.

Table 4: Eigenvalues, total variance, and principal components.

Trait	Component		
	PC1	PC2	PC3
PH	0.961	-0.163	0.066
LVS	-0.018	0.167	0.903
NT	0.050	0.126	0.938
LBL	0.940	-0.105	0.046
LW	0.631	0.065	-0.187
LPL	0.849	-0.140	0.013
SP	-0.737	0.214	-0.150
NMR	0.052	0.667	0.446
NPF	-0.391	0.785	0.095
NSF	-0.424	0.805	0.028
FYP	0.587	0.716	0.136
CBM	-0.067	0.803	0.080
Eigenvalues	4.157	3.017	1.992
Percentage of the total variance	34.644	25.144	16.597
Cumulative %	34.644	59.788	76.385

PH: Plant height, LVS: number of leaves per plant, NT: number of tillers per plant, LBL: leaf blade length, LW: leaf width, LPL: leaf petiole length, SP: SPAD value, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, FYP: fresh rhizome yield per plant, CBM: fresh canopy biomass per plant

PC1, accounting for the highest variance (34.64%), was influenced by numerous traits, including plant height (0.961), leaf blade length (0.94), leaf width (0.63), leaf petiole length (0.849), number of mother rhizomes per plant (0.052), and fresh rhizome yield per plant (0.58). Meanwhile, PC2, explaining 25.14% of the total variance, displayed substantial loadings for the number of secondary fingers per plant (0.80), fresh canopy biomass per plant (0.80), number of primary fingers per plant (0.78), fresh rhizome yield per plant (0.716), and number of mother rhizomes per plant (0.66) (Table 4). Traits contributing significantly to PC3 included the number of tillers per plant (0.93), number of leaves per plant (0.90), and number of mother rhizomes per plant (0.446), with PC3 accounting for 16.597% of the total variance (Table 4). Anindita *et al.* (2020) reported that the first three principal components (PCs) highlighted traits such as plant height, number of shoots, number of leaves on the main shoot, petiole length, lamina length, lamina width, number of mother rhizomes, total rhizome weight, weight per shoot, pseudostem habit, leaf margin, and rhizome habit as key differentiators among accessions due to their significant variation. Contrastingly, Khumaida *et al.* (2019) divided the studied traits into five PCs.

Path coefficient analysis

Plant height

The study revealed a positive direct effect on the fresh rhizome yield per plant, with the plant height showing the highest coefficient (0.73) (Table 5). Moreover, a significant positive correlation was observed between plant height and fresh rhizome yield ($r=0.232$, $\alpha=0.01$) (Tables 2 & 5). This finding contrasts with previous research findings by Mamatha *et al.* (2015), which reported a minimal direct effect of plant height on rhizome yield but with a significant positive correlation, aligning with the present study's results. Vimal *et al.* (2018) and Rajyalakshmi *et al.* (2013) also highlighted a substantial direct effect of leaves on fresh rhizome yield. Singh and Patel (2013) and Vimal *et al.* (2018) found a significant positive correlation between plant height and fresh yield. Additionally, Singh *et al.* (2018) reported a significant positive correlation of plant height with fresh yield. In contrast, Bahadur *et al.* (2016) emphasized a high positive direct and indirect effect of plant height with a significant positive association. Consistent with these findings, Roy *et al.* (2011) noted a significant positive correlation between plant height and yield, while Tomar *et al.* (2005) and Vinodhini *et al.* (2022) demonstrated a significant positive correlation between plant height and fresh yield, accompanied by a high positive direct effect. However, Jagadeeshkanth *et al.* (2014) found a significant positive correlation between plant height but a negligible positive direct effect. Similarly, Prajapati *et al.* (2014) reported a

Table 5: Direct, indirect, and total effect traits as determined by path analysis.

	FYP				
Trait	**Direct effect**	**Indirect effect**	**Total effect**	**Significance level of direct effect**	**Correlation coefficient**
NMR	0.153	0.220	0.373	Low	0.439**
NT	0.073	0	0.073	Negligible	0.302**
LPL	0.100	0.223	0.323	Low	0.209**
NSF	**0.641**	0.020	**0.661**	High	0.367**
NPF	0.030	0	0.03	Negligible	0.510**
CBM	0.066	0	0.066	Negligible	0.487**
PH	**0.735**	-0.419	0.316	High	0.232**
LVS	0.023	0	0.023	Negligible	0.293**
LW	0.072	0	0.072	Negligible	0.166*
LBL	-0.503	0	-0.503	High	0.066

PH: Plant height, NT: number of tillers per plant, LVS: number of leaves per plant, LPL: leaf petiole length, LBL: leaf blade length, LW: leaf width, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, CBM: fresh canopy biomass per plant, FYP: fresh rhizome yield per plant

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

high positive direct effect of plant height on yield, while Rao *et al*. (2006) observed a low positive direct effect of plant height with a significantly high positive correlation on yield. Singh *et al*. (2021) indicated a negligible positive direct effect of plant height on yield, contrasting with Mamatha *et al*. (2015), who reported a significant positive correlation but a negligible positive direct effect of plant height on yield.

Further, Luiram *et al*. (2018) demonstrated a significant positive correlation with plant height, and Patel *et al*. (2021) highlighted a highly significant and positive correlation between plant height and green rhizome yield, along with a positive direct effect. The current findings reveal a positive association between plant height and fresh rhizome yield, diverging from some previous research outcomes. This suggests that the influence of plant height on yield is not consistent in all genotypes but varies based on the genetic makeup of the plants. Such variability highlights the importance of considering genotype-specific traits and characteristics when assessing the relationship between plant height and yield.

Plant height (0.735) and number of secondary fingers (0.641) significantly affected on fresh yield, with leaf blade length (-0.503) exerting a considerable negative impact. The number of mother rhizomes (0.373) and leaf petiole length (0.323) showed low total effects due to their substantial indirect contributions, emphasizing their interconnected influence on fresh yield. However, traits like the number of tillers, the number of primary fingers, and canopy biomass showed negligible direct effects but significant correlations, indicating indirect pathways or associations with other traits impacting fresh yield (Table 5).

Number of secondary fingers

The analysis revealed that the number of secondary fingers per plant exhibited the second-highest positive direct effect on fresh rhizome yield per plant (0.641), accompanied by a significant positive correlation (r=0.367, α=0.01). This finding is supported by Patel *et al*. (2021), who similarly observed that the number of secondary fingers per plant had a positive direct effect on yield per plant, with a significant positive correlation. Consistent results have been reported in many studies (Pathania *et al*., 1981, Lal *et al*., 1986, Mukhopadhyay and Roy, 1986, Jalgaonkar and Jamdagni, 1989, Jalgaonkar *et al*., 1990, Nandi *et al*., Tiwari, 1995, Shashidhar and Sulikeri , 1997, Chandra *et al*., 1999, Patel *et al*., 2021, Aarthi *et al*., 2022; Rajyalakshmi *et al*., 2013, Jagadeeshkanth *et al*., 2014). The results of the present study indicates a moderate positive direct effect of the number of secondary rhizomes on yield and a significant positive correlation. Contrarily, Prajapati *et al*. (2014) reported a positive but non-significant association of the number of secondary rhizomes on yield. However, in contrast to the present study, Tomar *et al*. (2005) and Vimal et al. (2018) reported a high negative direct effect of secondary rhizomes on yield but with a high positive correlation. Therefore, considering the consistent positive findings in many studies, the number of secondary rhizomes is a valuable characteristic to be considered for yield prediction.

Number of mother rhizomes per plant

The number of mother rhizomes per plant exhibited a positive direct effect (0.153) on fresh rhizome yield per plant, accompanied by a significant correlation (r=0.439, α=0.01). Jagadeeshkanth *et al*., (2014) conducted a path analysis involving seventeen characters, highlighting a strong positive direct effect of the number of mother rhizomes on rhizome yield, supported by a positive significant correlation. Similarly, Aarthi *et al*., (2022) identified the number of mother rhizomes as the second-highest positive direct effect on rhizome yield, with a significant positive correlation among the variables, consistent with the findings of Singh and Patel (2013). However, Prajapati *et al*. (2014) reported a negative direct effect of the number of mother rhizomes on fresh rhizome yield per plant, despite revealing a highly significant and positive correlation. Mamatha *et al*. (2015) have found a negligible direct negative effect of the number of mother rhizomes on yield but with a positive correlation. Moreover, Patel *et al*. (2021) and Chandra *et al*. (1999) found a negative direct effect of the number of mother rhizomes per plant on fresh rhizome yield in turmeric, with positive and significant correlations. Thus, the number of mother rhizomes per plant demonstrates a significant positive correlation with yield while predominantly exerting a positive direct effect on it. Though on a few occasions, negative direct effects were reported.

Number of tillers per plant

The direct effect of the number of tillers per plant on rhizome yield was found to be high (0.073), with a positive significant correlation (r=0.302, α=0.01). This observation is consistent with the findings of Patel *et al*. (2021), who noted a high and positive direct effect of the number of tillers per plant on fresh rhizome yield per plant, in line with previous studies by Pathania *et al*. (1981), Lal *et al*. (1986), Mukhopadhyay and Roy (1986), Jalgaonkar and Jamdagni (1989), Jalgaonkar *et al*., (1990), Nandi *et al*. (1994), Singh and Tiwari (1995), Shashidhar and Sulikeri (1997), Chandra *et al*. (1999) in turmeric. However, contrasting results were reported by Vimal *et al*. (2018), Aravind *et al*. (2011), and Jagadeeshkanth *et al*. (2014), who found a high negative direct effect of the number of tillers per plant on rhizome yield, despite a significant positive correlation with yield. Suresh *et al*. (2019) explored a negligible negative direct effect of the same trait with a negative but non-significant correlation. Mamatha *et al.* (2015) reported a negligible negative direct effect of the number of tillers per plant on rhizome yield with a significant negative correlation. This variation may be attributed to differences in genotype in different studies.

Number of primary fingers

The number of primary fingers per plant (0.030) exhibited a positive direct effect on fresh rhizome yield per plant, with a significant positive correlation value of (r=0.510, α=0.01) (Table 5). However, contrary to the present study's findings, Prajapati *et al.* (2014) observed that the number of primary fingers per plant negatively influenced rhizome yield, despite having a positive significant correlation. Similarly, Patel *et al.* (2021) documented a negative non-significant correlation and a negative direct effect of primary fingers per rhizome on green rhizome yield. These discrepancies highlight the complexity of the relationship between the number of primary fingers per plant and rhizome yield, suggesting further investigation to elucidate the underlying factors influencing this association.

The number of leaves per plant

The number of leaves per plant exhibited positive direct effects (0.023) on fresh rhizome yield per plant, with a positive significant correlation (r=0.293, α=0.01) (Table 5). Rao *et al*. (2006) also reported a low negative direct effect of the number of leaves per plant on rhizome yield, despite a significant positive correlation. Conversely, Vimal *et al*. (2018), and Mamatha *et al*. (2015) found a positive and significant correlation with a low positive direct effect of the number of leaves on rhizome yield. A negligible direct effect with a non-significant positive correlation was observed by Aarthi *et al*., (2022). Aravind *et al*. (2011), Bahadur *et al*. (2016), and Jagadeeshkanth et al. (2014) reported a highly positive direct effect with a significant positive correlation between the number of leaves on yield, a finding echoed by Prajapati *et al*. (2014). Additionally, Singh *et al*. (2018) reported a non-significant but positive correlation, while Roy *et al*. (2011) found a significantly positive correlation. Shoba *et al*. (2011) highlighted a high positive and direct effect on rhizome yield attributed to the number of leaves. These diverse findings explore the varied impacts of the number of leaves on rhizome yield across different studies, suggesting the need for further investigation to dissect the underlying factors influencing this relationship.

Leaf petiole length

Leaf petiole length exhibited a direct effect (0.100) on yield with a significant positive correlation coefficient of (r=0.209, α=0.01). However, Mamatha *et al*. (2015) reported a negligible positive direct effect of leaf petiole length on rhizome yield with a significant negative correlation. In contrast, Rao *et al*. (2006) and Mamatha *et al*. (2015) found a low negative direct effect of leaf blade length on rhizome yield with a significant positive correlation. Similarly, Prajapati *et al*. (2014) and Aravind *et al*. (2011) revealed a negative direct effect of leaf blade length on the fresh yield of rhizome per plant, despite significant positive correlation in their respective studies. These findings illustrate the varied impacts of leaf petiole length and leaf blade length on rhizome yield, emphasizing the complexity of their relationships in different research contexts.

Leaf blade length

Leaf blade length demonstrated a high negative direct effect (-0.503) on fresh rhizome yield per plant, despite exhibiting a non-significant positive correlation (r=0.066). Gupta *et al*. (2016) and Tomar *et al*., (2005) reported similar findings, highlighting leaf blade length as having the highest direct effect on yield with a significant positive correlation. Singh and Ramakrishna (2014) supported these results, suggesting that leaf length could serve as an effective and reliable selection index based on correlation and path coefficient analysis. However, Patel *et al*. (2021), Lal *et al*. (1986), Jalgaonkar *et al*. (1990), and Singh and Tiwari (1995) found a positive and non-significant correlation between leaf length and green rhizome yield, accompanied by a negative direct effect on green rhizome yield. Singh and Patel (2013), and Mamatha *et al*. (2015) reported a high and positive direct effect of leaf width on rhizome yield with a significant positive correlation. Singh and Ramakrishna (2014) reiterated the importance of leaf length, emphasizing its high positive direct effects on rhizome yield, the same was reported by Shoba *et al*. (2011), a maximum positive and direct effects on rhizome yield for leaf length. These varied findings emphasize the complex relationship between leaf characteristics and rhizome yield, necessitating further investigation to understand their impacts.

Indirect effect

Leaf petiole length exhibited the highest positive indirect effect (0.223) on the fresh yield of rhizome per plant via plant height, characterized as moderate according to the scale (Table 5). Its direct effect on plant height was positive and high (0.708). The leaf petiole length demonstrated a high positive indirect effect with leaf blade length (0.573) and a low negative indirect effect with canopy biomass (-0.125). The second highest indirect effect (0.220) was observed from the number of mother rhizomes per plant, mediated through the number of secondary fingers (0.321) and number of primary fingers

(0.270). These effects on the number of secondary fingers per plant and the number of primary fingers per plant were high and moderate positive values, respectively. Conversely, the number of secondary fingers per plant exhibited the lowest positive indirect effect (0.020) via the number of primary fingers per plant (0.270) and the number of mother rhizomes per plant (0.680). The number of secondary fingers per plant demonstrated a high direct effect (0.680) on the number of primary fingers per plant with a significant positive correlation (r=0.745, α=0.01) (Table 6).

programmes aimed at yield optimization. Meanwhile, leaf petiole length and number of mother rhizomes contribute indirectly, significantly increasing the overall impact on fresh yield. Leaf petiole length exhibited the highest positive indirect effect via plant height, and the number of mother rhizomes contributed via the number of secondary fingers and primary fingers, indicating intercorrelate effects of traits. The leaf blade length showed a high negative direct effect on the turmeric yield, though its correlation with the yield was non-significant and positive. It is better to avoid such characters when selecting for high-yielding traits in turmeric.

Table 6: Indirect effects separation as determined by path analysis

Trait X Trait		D	I	T	Level of direct effect	Correlation coefficient
NSF						
	NMR	0.321	0	0.321	High	0.401**
PH						
	LPL	0.708	0	0.708	High	0.708**
LBL						
	PH	0.809	0	0.809	High	0.809**
	LPL	0	0.573	0.573	Negligible	0.632**
NPF						
	NMR	0.270	0.218	0.488	Moderate	0.488**
	NSF	0.680	0	0.680	High	0.745**
CBM						
	PH	-0.177	0	-0.177	Low	-0.165
	LPL	0	-0.125	-0.125	Negligible	-0.209*

PH: Plant height, LPL: leaf petiole length, LBL: leaf blade length, NMR: number of mother rhizomes per plant, NPF: number of primary fingers per plant, NSF: number of secondary fingers per plant, CBM: fresh canopy biomass per plant, D: Direct effect, I: Indirect effect, T: Total effect

Accordingly, the number of mother rhizomes per plant had a high positive direct effect on the number of secondary fingers per plant (0.321) and a moderate direct effect on the number of primary fingers per plant (0.270). The Number of mother rhizomes positively affected the number of primary fingers per plant (0.218).

CONCLUSIONS

Plant height and number of secondary fingers of turmeric appeared as the most influential traits for directly improving fresh yield per plant of this turmeric geno type owing to their high direct effects and significant correlations with fresh yield. These traits directly contribute to enhancing the productivity of plants and should be prioritized in breeding

This understanding underscores the need for a holistic approach in breeding strategies, where both direct and indirect contributors are considered. Therefore, integrating these key traits into selection criteria can significantly enhance breeding efficiency and yield improvement efforts in turmeric cultivation.

AUTHOR CONTRIBUTION

ALR, SRA, and JWMCS conceptualized and designed the study. JWMCS performed the and analyzed the data. JWMCS drafted the manuscript, and ALR and SRA critically revised the manuscript.

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Supplementary Figure 1: **Turmeric field plantation at two growth stages**