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ASSESSMENT OF FERTIGATION REGIMES FOR IMPROVING CURING PERCENTAGE AND YIELD IN GINGER (*ZINGIBER OFFICINALE* ROSC.)

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ABSTRACT

A study was carried out with an objective to evaluate the effect of different fertigation levels integrated with organic amendments on growth attributes, rhizome development, yield and curing characteristics of ginger cultivars. Parallel field experiments with RCBD were conducted during the Kharif season at the Department of Horticulture, Gandhi Krishi Vignana Kendra (GKVK), University of Agricultural Sciences, Bengaluru, Karnataka to evaluate the effect of different fertigation regimes combined with organic amendments on growth, rhizome development, yield, and curing characteristics of ginger (*Zingiber officinale* Rosc.) cultivars Rio-de-Janeiro and Himachal. The experiment comprised eleven treatments involving varying levels of recommended dose of fertilizers (RDF) applied through fertigation along with farmyard manure (FYM) and neem cake. The study revealed that the treatment T_2 [200% RDF (200:100:100 kg N:P_2O_5:K_2O ha^{-1}) applied through fertigation + FYM 30 t ha^{-1} + neem cake 2 t ha^{-1}] was the most effective, significantly improving growth, rhizome development, yield and curing characteristics in both ginger cultivars, Rio de Janeiro and Himachal. In essence, higher levels of fertilizers applied through irrigation water significantly improved all growth and yield parameters, while the integration of organic amendments (FYM and neem cake) further enhanced performance. This combined approach resulted in maximum rhizome girth and node number, highest biomass accumulation, superior fresh and dry rhizome yield and improved curing percentage along with higher cured rhizome yield. Further, the application of 200% RDF through fertigation along with FYM and neem cake significantly enhances growth, yield and curing efficiency in ginger cultivars.

Key words : Integrated Nutrient Management, Spice crop, Rhizome yield, Curing percentage, Nutrient use efficiency, Organic amendments, Farmyard manure, Neem cake, Precision crop nutrition.

Introduction

Ginger (*Zingiber officinale* Rosc.) is one of the most important spice crops cultivated in tropical and subtropical regions due to its extensive culinary, medicinal and industrial uses. It is valued for its bioactive compounds such as gingerols and shogaols, which exhibit antioxidant, anti-inflammatory, and therapeutic properties. Globally, ginger production has shown a steady increase, reaching about 4.8 million tonnes in 2024, with Asia contributing the major share. India remains the largest producer, contributing nearly 45 per cent of global production with an annual output of around 2.2–2.3 million tonnes. Within India, ginger is cultivated across diverse agro-climatic regions with an average productivity of about 11–12 t ha^{-1}, although higher yields are reported under improved management practices.

Efficient nutrient management is a critical factor influencing growth, rhizome development, yield and quality of ginger. However, conventional soil application of fertilizers is often associated with low nutrient use efficiency due to losses through leaching, volatilization, and fixation. In recent years, fertigation has emerged as an efficient nutrient delivery system that ensures precise and timely supply of nutrients directly to the root zone. This method enhances nutrient uptake, improves crop productivity and reduces environmental losses, thereby contributing to sustainable intensification of spice production systems.

Integrated nutrient management (INM), combining organic and inorganic nutrient sources, has gained importance in maintaining soil fertility and sustaining crop productivity. Organic amendments such as farmyard manure (FYM) and neem cake improve soil structure, increase water holding capacity, and stimulate microbial activity, which in turn enhances nutrient mineralization and availability. Recent studies have also emphasized that integrated application of nutrients improves soil health and resilience under changing climatic conditions, which is crucial for ginger cultivation (Kakar *et al*., 2020). Adequate supply of essential nutrients, particularly nitrogen, phosphorus, and potassium, plays a vital role in promoting vegetative growth, photosynthetic efficiency, and translocation of assimilates towards rhizomes, thereby improving rhizome size, biomass accumulation and yield.

In addition to yield, quality parameters such as curing percentage and cured rhizome yield are of significant economic importance, as they determine the recovery and market value of dry ginger. Despite the recognized benefits of fertigation and integrated nutrient management, information on cultivar-specific responses of ginger under different fertigation regimes combined with organic amendments remains limited, particularly under region-specific agro-climatic conditions.

Therefore, the present study was undertaken with an objective to evaluate the effect of different fertigation levels integrated with organic amendments on growth attributes, rhizome development, yield and curing characteristics of ginger cultivars.

Materials and Methods

A field experiment was conducted during the *kharif* season of 2021 at the Department of Horticulture, University of Agricultural Sciences Bangalore, Gandhi Krishi Vignana Kendra (GKVK), Bengaluru, Karnataka with the objective of evaluating fertigation responses within individual ginger cultivars rather than comparing cultivars per se under different fertigation levels and their effect on vegetative growth and biomass accumulation.

The region falls under the southern dry zone of Karnataka with a mean annual rainfall of 800–900 mm, mainly received from May to November. Soil in the experiment was well-drained and red sandy loam with a slightly acidic pH of 6.4, low organic carbon (0.35%), low available nitrogen (201.14 kg ha^{-1}), medium available phosphorus (34.0 kg ha^{-1}) and medium available potassium (152 kg ha^{-1}).

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Two ginger cultivars, Rio-de-Janeiro and Himachal, were included in the study. Each cultivar was treated as an independent experiment, and within each cultivar, eleven fertigation treatments were imposed. Thus, two Parallel Experiments were conducted. Accordingly, treatment effects were evaluated within each cultivar separately, rather than as a combined factorial experiment. The eleven treatments consisted of different levels of recommended dose of fertilizers (RDF) applied through fertigation and soil application methods, in combination with organic amendments such as farmyard manure (FYM) and neem cake. The details of fertigation treatments applied to ginger cultivars are presented in Table 1.

The crop was grown in plots of 10.0 m × 1.0 m with a spacing of 45 cm between rows and 30 cm between plants. The land was prepared to a fine tilth by ploughing followed by harrowing, and ridges and furrows were formed after levelling. Healthy, disease-free seed rhizomes and uniform fingers with well-developed buds were procured from the Zonal Agricultural Research Station Chamarajanagara and used for planting in furrows.

Farmyard manure was applied at 30 t ha^{-1} as a basal dose during land preparation. Fertilizers were applied in the form of urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O) as per the treatment schedule. In fertigation treatments, water-soluble fertilizers were applied through irrigation, while in non-fertigated treatments, fertilizers were applied through conventional soil application methods. Phosphorus and potassium were applied as basal, while nitrogen was applied in split doses. Organic amendments were applied as per treatment schedule. Standard cultural practices like weeding, plant protection measures etc., were followed uniformly for all treatments.

Observations on vegetative growth parameters were recorded from five randomly selected tagged plants per treatment at regular intervals of 30, 60, 90, 120, 150, 180 and 210 days after planting (DAP). Dry weight of plant parts was determined by oven drying the samples at 70°C until constant weight and expressed as dry matter per plant (g). Fresh rhizomes harvested from each plot were weighed and expressed as kg per plot, and the yield was converted to t ha^{-1}. The number and length of primary fingers arising from the mother rhizome and the number and length of secondary fingers arising from primary fingers were recorded using a non-stretchable string and

Table 1 : Details of fertigation treatments applied to ginger cultivars.

Treatments	Details of fertigation Regimes
T_1	RDF (100:50:50 N: P_2O_5: K_2O kg /ha normal fertilizers) + FYM 30 t/ha, Neem cake 2 t/ha
T_2	200 % RDF (200:100:100 N: P_2O_5: K_2O kg/ha) Fertigation + FYM 30t/ha, Neem cake 2 t/ha
T_3	150 % RDF (150:75:75 N: P_2O_5: K_2O kg/ha) Fertigation + FYM 30t/ha, Neem cake 2 t/ha
T_4	100 % RDF (100:50:50 N: P_2O_5: K_2O kg/ha) Fertigation + FYM 30t/ha, Neem cake 2 t/ha
T_5	75 % RDF (75:37.5:37.5 N: P_2O_5: K_2O kg/ha) Fertigation + FYM 30t/ha, Neem cake 2 t/ha
T_6	50 % RDF (50:25:25 N: P_2O_5: K_2O kg/ha) NF soil application + 50% Fertigation (50:25:25 NPK kg/ha) WSP + FYM 30 t/ha, Neem cake 2 t/ha
T_7	100 % RDF (100:50:50 N: P_2O_5: K_2O kg/ha NF) + Azotobacter + PSB + AMF + KMB + FYM 30 t/ha, Neem cake 2 t/ha
T_8	75 % RDF (75:37.5:37.5 N: P_2O_5: K_2O kg/ha WSF) + Azotobacter + PSB + AMF +KMB + FYM 30 t/ha, Neem cake 2 t/ha
T_9	50 % RDF (50:25:25 N: P_2O_5: K_2O kg/ha WSF) + Azotobacter + PSB +AMF + KMB + FYM 30 t/ha, Neem cake 2 t/ha
T_{10}	50 % RDF (50:25:25 N: P_2O_5: K_2O kg/ha WSF) + 25 % N: P2O5: K2O Foliar spray at 60, 90, 120 DAP + Azotobacter + PSB + AMF + KMB + FYM 30 t/ha, Neem cake 2 t/ha
T_{11}	100 % RDF (100:50:50 N: P_2O_5: K_2O kg/ha WSF) + Azotobacter + PSB + AMF + KMB + FYM + Neem cake

Ginger special (5 ml/L) was common for all the treatments but for the treatment T_{10}, 25% N: P_2O_5: K_2O Foliar spray was given in different stages of crop growth (60, 90 and 120 DAP).

expressed in centimetres. The crop was harvested at physiological maturity indicated by drying of leaves and pseudostems and lodging of plants. Light irrigation was provided one day before harvest to facilitate digging of rhizomes. Observations were recorded on girth of mother rhizome, primary and secondary fingers; number of nodes in primary and secondary fingers; fresh and dry weight of plant parts; fresh and dry rhizome yield; curing percentage; and cured rhizome yield.

The experimental data were subjected to analysis of variance (ANOVA) appropriate for RCBD. The significance of treatment effects was tested using the F-test at 5% probability level, and critical difference (CD) values were calculated wherever treatment effects were significant. The two cultivars were analysed separately as independent experiments. Therefore, results are interpreted as treatment responses within individual cultivars.

Results and Discussion

The results obtained from the present investigation on the effect of different fertigation regimes combined with organic amendments on various parameters such as girth of mother rhizome and fingers, number of nodes, fresh and dry weight of plant parts, rhizome yield, curing percentage and cured rhizome yield of ginger cultivars Rio-de-Janeiro and Himachal are presented and discussed hereunder:

Girth of mother rhizome, primary and secondary fingers : The observations on rhizome and finger girth of ginger cultivars revealed significant variation among treatments (Table 2 and Fig. 1). In the cultivar Rio-de-Janeiro, treatment T_2 [200% RDF (200:100:100 kg N: P_2O_5 : K_2O ha^{-1}) applied through fertigation along with FYM @ 30 t ha^{-1} and neem cake @ 2 t ha^{-1}] recorded the highest girth of mother rhizome (7.96 cm) and maximum girth of secondary fingers (6.48 cm). Similarly, in parallel experiment with the cultivar Himachal, the highest girth of mother rhizome (7.81 cm) and maximum girth of secondary fingers (6.33 cm) were recorded under the same treatment T_2. The girth of primary fingers was found to be highest under treatment T_3 (7.24) in cultivar Rio-de-Janeiro and a similar result was observed in cultivar Himachal under T_3 (7.09). Overall, higher levels of RDF through fertigation combined with organic amendments significantly improved rhizome and finger girth, which may be attributed to a continuous and balanced nutrient supply, enhanced nutrient uptake and improved soil physical and biological properties, resulting in better assimilate translocation and rhizome development.

The beneficial effect of integrated nutrient management was highlighted by Gill *et al.* (1999), who reported an increased rhizome yield with higher FYM application. In turmeric, Kumar *et al.* (2015) and Kamal and Yousuf (2012) observed improved growth and yield

Table 2 : Effect of fertigation treatments on girth of mother rhizome, primary and secondary fingers in ginger cultivars.

Treatments	Girth (cm)					
	Rio-de-Janeiro			Himachal		
	Mother Rhizome	Primary fingers	Secondary fingers	Mother Rhizome	Primary fingers	Secondary fingers
T_1	5.80	5.64	4.79	5.67	5.47	4.61
T_2	7.96	6.25	6.48	7.81	6.10	6.33
T_3	7.93	7.24	5.70	7.74	7.09	5.52
T_4	7.66	6.70	5.42	7.25	5.65	4.74
T_5	7.02	6.76	5.28	6.70	6.02	5.28
T_6	6.64	6.49	5.71	6.47	6.36	5.61
T_7	7.40	5.76	4.88	7.51	6.55	5.29
T_8	6.89	6.13	5.41	6.89	6.62	5.16
T_9	6.33	6.05	5.00	6.20	5.87	4.83
T_{10}	6.45	6.26	5.15	6.30	5.96	5.10
T_{11}	7.74	6.37	5.80	7.55	6.23	5.54
F test	*	*	*	*	*	*
SEm ±	0.19	0.13	0.14	0.18	0.14	0.14
CD at 5%	0.55	0.39	0.41	0.53	0.40	0.42

Table 3 : Effect of fertigation treatments on nodes in primary and secondary fingers in ginger cultivars.

Treatments	Nodes in primary and secondary fingers in ginger cultivars (No.)			
	Rio-de-Janeiro		Himachal	
	Primary Fingers	Secondary Fingers	Primary Fingers	Secondary Fingers
T_1	3.73	4.22	3.85	4.45
T_2	4.68	6.48	4.81	5.68
T_3	4.44	5.54	4.70	5.62
T_4	4.25	4.35	4.57	4.81
T_5	4.26	4.43	4.41	4.55
T_6	3.86	4.04	3.97	4.26
T_7	4.39	4.67	4.62	4.96
T_8	4.24	4.57	4.41	4.76
T_9	4.12	4.43	4.28	4.69
T_{10}	4.25	4.47	4.35	4.79
T_{11}	4.39	4.77	4.44	4.64
F test	*	*	*	*
SEm ±	0.06	0.07	0.08	0.08
CD at 5%	0.19	0.20	0.23	0.21

with combined application of FYM, neem cake and fertilizers. Similarly, Bahadur *et al*. (2000) and Sunil *et al*. (2014) reported a significant improvement in plant growth and rhizome yield with higher NPK levels. Similar results have been reported in recent studies on ginger by Patra *et al*. (2022), Behera and Sial (2023) and Shende *et al*. (2025). Shende *et al*. (2024) also observed improved growth, yield and soil properties due to organic amendments and integrated nutrient approaches. Aswani *et al.* (2025) reported further, increased nutrient uptake and yield with combined organic and inorganic nutrient sources.

Therefore, the results of the present study are in close agreement with earlier findings that higher levels of nutrients supplied through efficient fertigation along with organic amendments enhance nutrient availability, improve plant growth and ultimately promote better development and girth of rhizomes and fingers in ginger.

Nodes in primary and secondary fingers : The observations on the number of nodes in primary and secondary fingers of ginger cultivars revealed significant variation among treatments (Table 3, Figs. 2 and 3). In the cultivar Rio de Janeiro, the highest number of nodes in primary fingers (4.68) was recorded in T_2 [200% RDF (200:100:100 kg N:P_2O_5 :K_2O ha^{-1}) through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}], which was followed by other treatments. A similar trend was observed in secondary fingers, where T_2 recorded the highest number of nodes (6.48), which was statistically on par with T_3 (5.54). Similarly, in the parallel experiment with the cultivar Himachal, T_2 recorded the highest number of nodes in primary fingers (4.81), which was on par with T_3 (4.70) and T_7 (4.62). However, in secondary fingers, the maximum number of nodes (5.68) was observed in T_4, which was statistically comparable with T_2 (5.62). Overall, higher levels of nutrients supplied

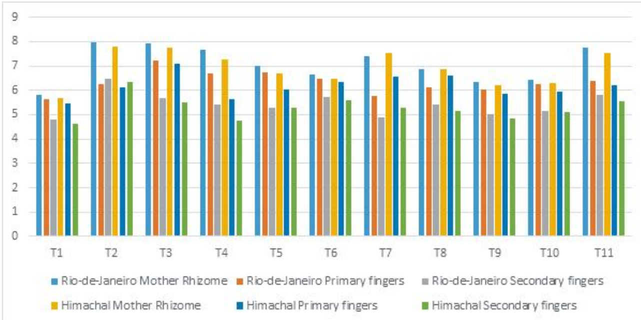

Fig. 1 : Effect of fertigation treatments on girth of mother rhizome in ginger cultivars.

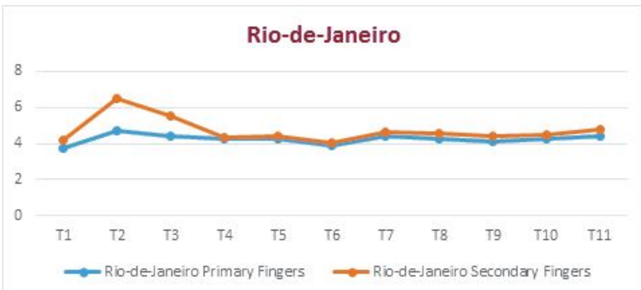

Fig. 2 : Effect of fertigation treatments on number of nodes in primary and secondary fingers in ginger cultivar, Rio-de-Janeiro.

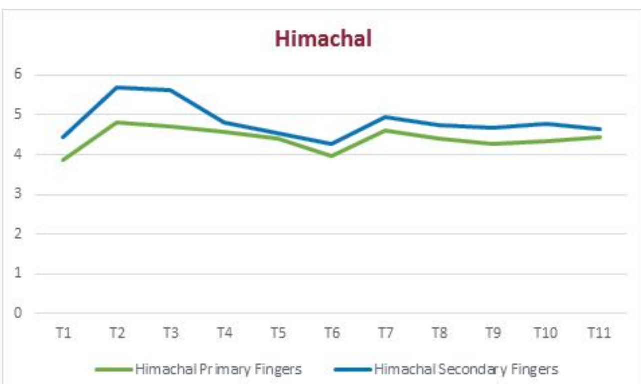

Fig. 3 : Effect of fertigation treatments on number of nodes in primary and secondary fingers in ginger cultivar, Himachal.

through fertigation along with organic amendments resulted in an increased number of nodes in ginger fingers. The increase in number of nodes in primary and secondary fingers under higher fertilizer levels may be due to improved nutrient availability through fertigation combined with organic inputs. Adequate supply of nitrogen, phosphorus and potassium promotes vegetative growth, cell division and elongation, leading to better development of rhizome fingers and more nodes. The application of FYM and neem cake further improves soil fertility and nutrient use efficiency, resulting in improved rhizome and finger characteristics in ginger.

Gill *et al.* (1999) and Kumar *et al.* (2015), who observed improved growth and rhizome yield with application of FYM, neem cake and recommended fertilizers, also reported the beneficial role of organic amendments along with fertilizers. These findings are in agreement with recent studies indicating the positive influence of higher fertilizer levels and integrated nutrient management on growth and rhizome development in ginger by Patra *et al.* (2022), Behera and Sial (2023), Aswani *et al.* (2025), Shende *et al.* (2024) and Shende *et al.* (2025).

Therefore, the results of the present investigation clearly indicate that higher levels of nutrients supplied through fertigation along with organic amendments improve nutrient availability, enhance plant growth and promote better rhizome development, leading to an increased number of nodes in primary and secondary fingers of ginger cultivars.

Fresh weight of plant parts (aerial parts, roots and rhizomes) : Data on fresh weight of different plant components of ginger cultivars revealed significant variation among treatments (Table 4, Figs. 4 and 5). In the cultivar Rio-de-Janeiro, the highest total fresh weight (198.83 g plant^{-1}) was recorded in T_2 [200% RDF (200:100:100 kg N:P_2O_5 :K_2O ha^{-1}) through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}]. The same treatment also resulted in maximum aerial biomass (27.61 g), which was statistically comparable with T_3 (24.90 g) and T_{11} (22.86 g). Root fresh weight was highest in T_2 (17.23 g) and remained on par with T_8 (16.46 g). However, the maximum rhizome fresh weight (155.08 g) was observed in T_7. Similarly, in the parallel experiment with the cultivar Himachal, T_2 recorded the highest total fresh weight (269.35 g plant^{-1}). A similar trend was observed for aerial biomass (29.33 g), which was statistically comparable with T_3 (26.75 g), T_7 (24.83 g) and T_4 (24.78 g). Root fresh weight was also highest in T_2 (19.70 g), which was on par with T_4 (18.85 g) and T_3 (15.71 g). The highest rhizome fresh weight (220.32 g) was recorded in T_2. The increased fresh weight of aerial parts, roots and rhizomes under higher fertilizer levels may be attributed to improved nutrient availability through fertigation combined with organic amendments. Continuous nutrient supply enhances vegetative growth, root development and biomass accumulation. Nitrogen promotes plant growth, phosphorus supports root development and potassium aids photosynthesis and carbohydrate accumulation in rhizomes. The addition of FYM and neem cake further improves soil fertility and nutrient availability, thereby enhancing plant growth and fresh weight of ginger.

Table 4 : Effect of fertigation treatments on fresh weight of plant parts in Ginger cultivars.

Treatments	Fresh weight (g/plant)							
	Rio-de-Janeiro				Himachal			
	Aerial parts	Roots	Rhizomes	Total	Aerial parts	Roots	Rhizomes	Total
T_1	11.21	9.50	100.66	121.37	11.61	9.65	111.33	132.59
T_2	27.61	17.23	153.99	198.83	29.33	19.70	220.32	269.35
T_3	24.90	10.18	128.66	163.74	26.75	15.71	206.32	248.78
T_4	22.46	5.43	104.33	132.22	24.78	18.85	176.33	219.96
T_5	12.20	8.66	161.99	182.85	17.00	10.20	158.66	185.86
T_6	11.80	10.81	173.66	196.27	13.86	10.78	169.66	194.3
T_7	22.61	12.71	143.32	178.64	24.83	9.61	187.99	222.43
T_8	19.55	16.46	117.66	153.67	13.55	11.16	180.99	205.70
T_9	15.91	8.26	119.32	143.49	20.90	11.20	190.66	222.76
T_{10}	16.75	9.12	128.59	154.46	22.15	12.26	203.32	237.73
T_{11}	22.86	8.45	124.88	156.19	23.78	4.85	168.00	196.63
F test	*	*	*	*	*	*	*	*
SEm±	1.65	1.21	8.88	4.89	1.83	1.45	12.69	12.40
CD at 5%	4.87	3.56	26.21	14.42	5.39	4.28	37.45	36.57

Ramchandrappa (2009), who observed higher plant growth and biomass accumulation under drip irrigation with adequate nutrient supply, reported similar results. Gill *et al*. (1999) and Kumar *et al*. (2015) documented the beneficial effect of integrated nutrient management on plant growth and biomass production and Kamal and Yousuf (2012), who reported improved growth and rhizome yield with application of FYM, neem cake and fertilizers. Similarly, Bahadur *et al*. (2000) and Sunil *et al*. (2014) reported enhanced plant growth, biomass and rhizome yield in turmeric with higher NPK levels. Similar findings have been reported in recent studies, highlighting the positive influence of fertigation and integrated nutrient management on plant growth and biomass accumulation in ginger by Behera and Sial (2023), Shende *et al.* (2024) and Shende *et al.* (2025).

Thus, the results of the present investigation are in agreement with earlier findings that efficient fertigation combined with organic amendments improves nutrient availability and uptake, enhances vegetative growth and biomass accumulation, and ultimately results in higher fresh weight of different plant parts in ginger cultivars.

Dry weight of plant parts (aerial parts, roots and rhizomes) : The data on dry weight of different plant parts of ginger cultivars revealed significant variation among treatments. (Table 5, Figs. 6 and 7). In the cultivar Rio-de-Janeiro, the highest total dry weight of the plant (68.25 g) was recorded in T_2 [200% RDF (200:100:100 kg N: P_2O_5 : K_2O ha^{-1}) through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}]. The maximum dry weight of aerial parts (8.51 g) was also recorded in T_2, which was statistically on par with T_3 (7.36 g), T_{11} (7.26 g) and T_7 (6.65 g). The highest dry weight of roots (3.26 g) was observed in T_3 [150% RDF through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}], which was on par with T_{11} (2.75 g) and T_7 (2.08 g). In the case of rhizomes, the highest dry weight (57.73 g) was recorded in T_2, which was statistically comparable with T_3 (43.30 g). Similarly, in the parallel experiment with the cultivar Himachal, the highest total dry weight of the plant (47.99 g) was recorded in T_2. The maximum dry weight of aerial parts (8.13 g) was also observed in T_2, which was on par with T_3 (6.97 g). The highest dry weight of roots (2.81 g) was recorded in T_2, which was statistically comparable with T_3 (2.50 g) and T_{11} (2.26 g). The highest dry weight of rhizomes (37.36 g) was also recorded in T_2. Overall, higher fertilizer levels through fertigation along with organic amendments resulted in greater dry matter accumulation in both cultivars. The higher dry weight of plant parts under increased fertilizer levels through fertigation may be attributed to improved nutrient availability, efficient uptake and better translocation of assimilates. Continuous nutrient supply enhances photosynthesis and dry matter accumulation in aerial parts, roots and rhizomes. Nitrogen supports vegetative growth, phosphorus aids root development and potassium facilitate carbohydrate metabolism and translocation to rhizomes. The addition of FYM and neem cake further improves soil fertility and nutrient use efficiency, resulting in greater biomass production.

Gill *et al*. (1999), Kumar *et al*. (2015) and Kamal

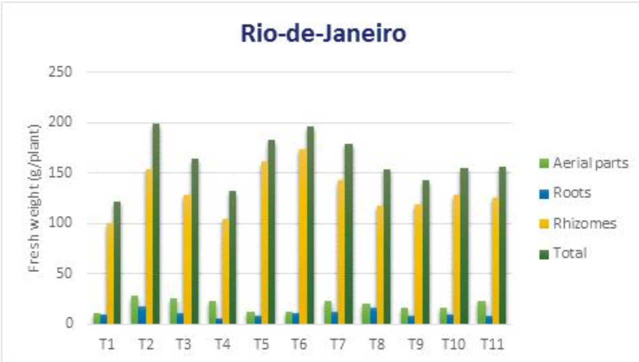

Fig. 4 : Effect of fertigation treatments on fresh weight of plants in ginger (Rio-de-Janeiro).

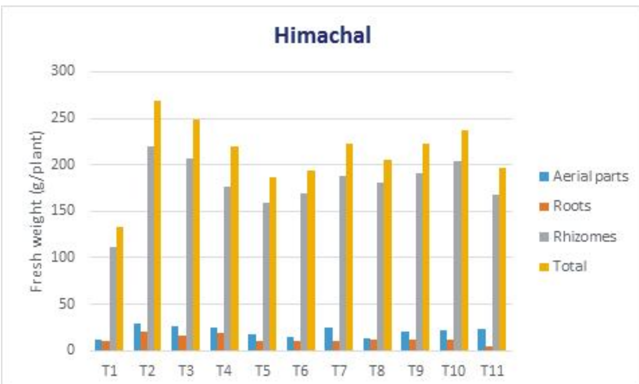

Fig. 5 : Effect of fertigation treatments on fresh weight of plants in ginger (Himachal).

and Yousuf (2012) also reported the beneficial role of organic amendments along with fertilizers resulting from improved growth and rhizome yield with application of FYM, neem cake and fertilizers. Similarly, Bahadur *et al*. (2000) and Sunil *et al*. (2014) reported increased plant growth, biomass and rhizome yield in turmeric with higher NPK levels. These results are in agreement with recent findings indicating that higher and balanced fertilizer application significantly enhances biomass accumulation and rhizome development in ginger by Patra *et al.* (2022) and Shende *et al.* (2025).

Thus, the findings of the present study are in conformity with earlier reports that higher fertilizer levels supplied through efficient fertigation along with organic amendments improve nutrient availability, enhance plant growth and photosynthetic efficiency, and ultimately result in greater dry matter accumulation in different plant parts of ginger cultivars.

Fresh and dry yield of rhizome : The data on fresh and dry rhizome yield of ginger cultivars Rio-de-Janeiro and Himachal as influenced by different treatments are presented in Table 6, Figs. 8 and 9.

Fresh rhizome yield: Fresh rhizome yield differed significantly among treatments under RCBD in both cultivars. In the cultivar Rio-de-Janeiro, the highest fresh rhizome yield (11.46 t ha^{-1}) was recorded in T_2 [200% RDF (200:100:100 kg N:P_2O_5 :K_2O ha^{-1}) through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}], which was followed by T_3 (10.69 t ha^{-1}) and T_5 (10.16 t ha^{-1}). The lowest yield (6.64 t ha^{-1}) was recorded in T_1. Similarly, in parallel experiment with the cultivar Himachal, the highest fresh rhizome yield (14.54 t ha^{-1}) was recorded in T_2, followed by T_3 (13.62 t ha^{-1}) and T_{10} (13.42 t ha^{-1}), while the lowest yield (7.35 t ha^{-1}) was observed in T_1. The differences among treatments were found to be statistically significant based on the F-test. The higher fresh rhizome yield under T_2 may be attributed to the combined effect of higher nutrient supply through fertigation along with FYM and neem cake. Fertigation ensures continuous nutrient availability at the root zone, improving nutrient uptake, plant growth and rhizome development. Nitrogen promotes vegetative growth, phosphorus enhances root and rhizome development and potassium improves photosynthesis and translocation of assimilates, resulting in higher rhizome yield in ginger cultivars.

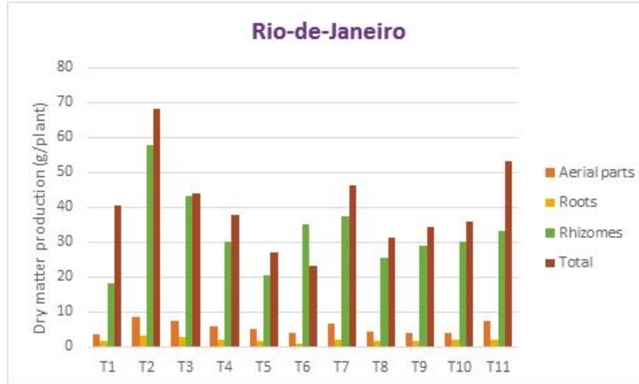

Fig. 6 : Effect of fertigation treatments on dry weight of plants in ginger (Rio-de-Janeiro).

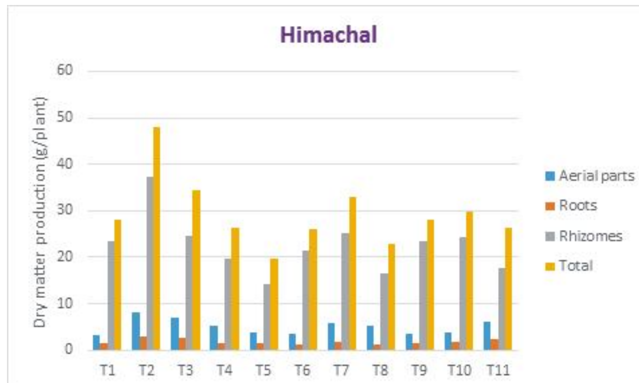

Fig. 7 : Effect of fertigation treatments on dry weight of plants in ginger (Himachal).

Similar beneficial effects of integrated nutrient management were reported by Gill *et al*. (1999), Kumar

Table 5 : Effect of fertigation treatments on dry weight of plant parts in ginger cultivars.

Treatments	Dry matter production (g/plant)							
	Rio-de-Janeiro				Himachal			
	Aerial parts	Roots	Rhizomes	Total	Aerial parts	Roots	Rhizomes	Total
T_1	3.50	1.53	18.25	40.31	3.15	1.51	23.49	28.15
T_2	8.51	3.26	57.73	68.25	8.13	2.81	37.36	47.99
T_3	7.36	2.75	43.30	43.87	6.97	2.50	24.50	34.28
T_4	5.75	1.81	30.15	37.71	5.31	1.35	19.66	26.32
T_5	5.16	1.45	20.58	27.19	3.88	1.53	14.28	19.69
T_6	3.83	0.95	35.28	23.03	3.45	1.26	21.35	26.06
T_7	6.65	2.08	37.35	46.08	5.84	1.75	25.26	32.85
T_8	4.11	1.70	25.61	31.42	5.13	1.12	16.61	22.86
T_9	3.72	1.68	28.91	34.31	3.41	1.41	23.35	28.17
T_{10}	3.93	1.84	29.96	35.73	3.76	1.64	24.36	29.76
T_{11}	7.26	2.01	33.25	53.31	6.16	2.26	17.78	26.20
F test	*	*	*	*	*	*	*	*
SEm±	0.63	0.78	5.56	3.82	0.59	0.24	4.05	2.39
CD at 5%	1.87	1.24	16.39	11.31	1.75	0.72	11.96	7.08

et al. (2015) and Kamal and Yousuf (2012). Studies by Bahadur *et al.* (2000) and Sunil *et al.* (2014) also indicated improved growth and rhizome yield in turmeric with higher NPK levels. The results are in agreement with recent findings indicating that higher fertilizer levels significantly enhance rhizome yield in ginger by Patra *et al.* (2022), Behera and Sial (2023), Aswani *et al*. (2025), Shende *et al.* (2024) and Shende *et al.* (2025).

Thus, the findings of the present study clearly indicate that higher levels of nutrients supplied through fertigation along with organic amendments improve nutrient use efficiency, enhance plant growth and biomass accumulation and ultimately result in increased fresh rhizome yield of ginger cultivars.

Dry rhizome yield: Dry rhizome yield exhibited significant variation among treatments under RCBD in both cultivars. In the cultivar Rio-de-Janeiro, the highest dry rhizome yield (3.81 t ha^{-1}) was recorded in T_2, followed by T_{11} (2.86 t ha^{-1}) and T_7 (2.47 t ha^{-1}), while the lowest yield (1.20 t ha^{-1}) was recorded in T_6. Similarly, in parallel experiment with the cultivar Himachal, the maximum dry rhizome yield (2.47 t ha^{-1}) was recorded in T_2, followed by T_7 (1.67 t ha^{-1}) and T_{10} (1.61 t ha^{-1}), whereas the lowest yield (0.94 t ha^{-1}) was recorded in T_5. The differences among treatments were found to be statistically significant based on the F-test. Dry rhizome yield followed a similar trend as fresh rhizome yield, with T_2 recording the highest yield in both cultivars. Higher dry rhizome yield under this treatment may be due to better accumulation and translocation of carbohydrates in rhizomes as a result of balanced nutrient supply and improved physiological processes. Fertigation combined with organic inputs enhances nutrient use efficiency and supports higher dry matter production, which ultimately results in greater dry rhizome yield.

Table 6 : Effect of fertigation treatments on fresh and dry rhizome yield in ginger cultivars.

Treatments	Fresh rhizome yield (t/ha)		Dry rhizome yield (t/ha)	
	Rio-de -Janeiro	Himachal	Rio-de -Janeiro	Himachal
T_1	6.64	7.35	2.33	1.55
T_2	11.46	14.54	3.81	2.47
T_3	10.69	13.62	2.19	1.62
T_4	6.89	11.64	1.99	1.30
T_5	10.16	10.47	1.36	0.94
T_6	8.49	11.20	1.20	1.41
T_7	9.46	12.41	2.47	1.67
T_8	7.77	11.95	1.69	1.10
T_9	7.88	12.58	1.91	1.54
T_{10}	8.49	13.42	1.98	1.61
T_{11}	8.24	11.09	2.86	1.17
F-test	*	*	*	*
SEm±	0.41	0.62	0.23	0.13
CD at 5%	1.20	1.80	0.65	0.38

The beneficial role of organic amendments was also reported by Gill *et al*. (1999), Kumar *et al*. (2015) and Kamal and Yousuf (2012). Similarly, Bahadur *et al.* (2000) and Sunil *et al.* (2014) reported improved growth and rhizome yield in turmeric with higher NPK levels. The

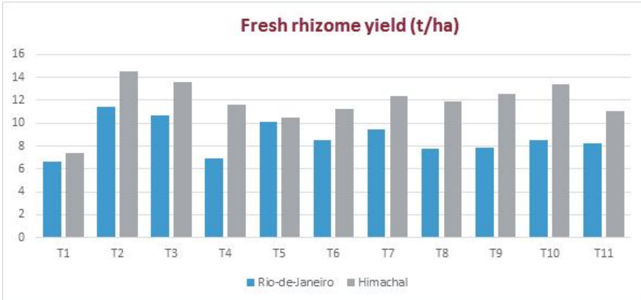

Fig. 8 : Effect of fertigation treatments on fresh weight of rhizomes (t/ha) in ginger.

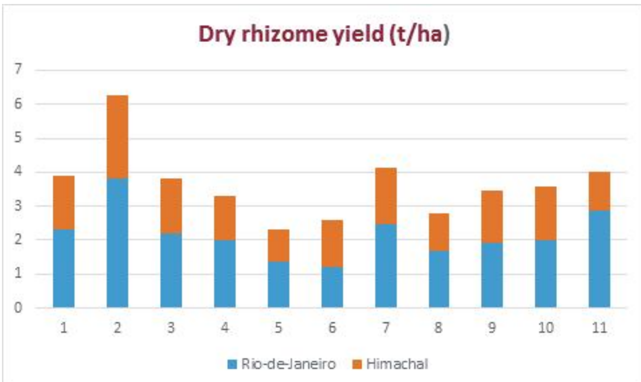

Fig. 9 : Effect of fertigation treatments on dry weight of rhizomes (t/ha) in ginger (Rio-de-Janerio and Himachal).

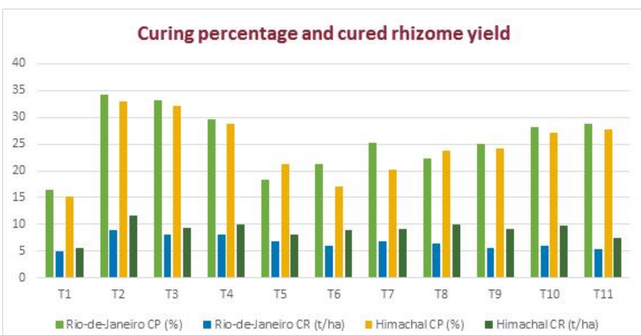

Fig. 10 : Effect of fertigation treatments on cured rhizome in ginger.

results are in agreement with recent findings indicating that higher fertilizer levels significantly enhance rhizome yield in ginger by Patra *et al.* (2022), Behera and Sial (2023), Aswani *et al.* (2025), Shende *et al.* (2024) and Shende *et al.* (2025).

Thus, the results of the present study clearly indicate that higher fertilizer levels supplied through fertigation along with organic amendments enhance nutrient availability and uptake, improve plant growth and rhizome development, and ultimately result in increased dry rhizome yield of ginger cultivars.

Curing percentage and cured rhizome yield: The observations on curing percentage and cured rhizome yield of ginger cultivars Rio-de-Janeiro and Himachal as influenced by different treatments are presented in Table 7 and Fig. 10.

Curing percentage: Curing percentage exhibited significant variation among treatments under RCBD in both cultivars. In the cultivar Rio-de-Janeiro, the highest curing percentage (34.20%) was recorded in T_2 [200% RDF (200:100:100 kg N:P_2O_5 :K_2O ha^{-1}) through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}], while the lowest curing percentage was recorded in T_1. Similarly, in parallel experiment with the cultivar Himachal, the highest curing percentage (32.93%) was also recorded in T_2, whereas the lowest curing percentage was observed in T_{11}. The differences among treatments were found to be statistically significant based on the F-test. The results indicate that higher levels of nutrients supplied through fertigation along with organic amendments improved curing percentage in both cultivars. Higher curing percentage observed under T_2 may be attributed to improved rhizome development and higher dry matter accumulation due to balanced nutrient supply through fertigation combined with organic amendments. Adequate supply of nitrogen, phosphorus and potassium enhances photosynthesis, carbohydrate synthesis and translocation of assimilates to rhizomes, which ultimately results in higher dry matter content and better curing recovery. Organic amendments such as FYM and neem cake improve soil fertility, microbial activity and nutrient availability, thereby enhancing nutrient use efficiency and crop performance.

The beneficial role of organic amendments was also reported by Gill *et al.* (1999), Kumar *et al.* (2015) and Kamal and Yousuf (2012). Similarly, Bahadur *et al.* (2000) and Sunil *et al.* (2014) reported improved growth and rhizome yield in turmeric with higher NPK levels. These results are in agreement with recent findings indicating that higher fertilizer levels and integrated nutrient management significantly improve rhizome development in ginger by Patra *et al.* (2022), Aswani *et al.* (2025) and Shende *et al.* (2025).

Therefore, the results of the present study clearly indicate that higher levels of nutrients supplied through fertigation along with organic amendments improve nutrient availability, enhance rhizome development and increase dry matter accumulation, which ultimately results in higher curing percentage in ginger cultivars.

Cured rhizome yield: Cured rhizome yield exhibited significant variation among treatments under RCBD in both cultivars. In the cultivar Rio-de-Janeiro, the highest cured rhizome yield (8.90 t ha^{-1}) was recorded in T_2

Table 7 : Effect of fertigation treatments on curing percentage and cured rhizome yield in ginger cultivars.

Treatments	Curing percentage and cured rhizome yield			
	Rio-de-Janeiro		Himachal	
	CP (%)	CR (t/ha)	CP (%)	CR (t/ha)
T_1	16.45	4.97	15.26	5.58
T_2	34.20	8.90	32.93	11.60
T_3	33.29	8.00	32.10	9.24
T_4	29.69	7.99	28.86	9.86
T_5	18.24	6.75	21.16	7.98
T_6	21.17	5.90	17.12	8.83
T_7	25.18	6.79	20.17	9.04
T_8	22.34	6.35	23.77	9.90
T_9	25.12	5.54	24.10	9.02
T_{10}	28.18	6.04	27.08	9.68
T_{11}	28.85	5.42	27.84	7.43
F-test	*	*	*	*
SEm±	1.52	0.34	1.44	0.51
CD at 5%	4.44	0.98	4.20	1.50

CP= Curing percentage; CR= Cured rhizome

[200% RDF through fertigation + FYM @ 30 t ha^{-1} + neem cake @ 2 t ha^{-1}], while the lowest yield (4.97 t ha^{-1}) was recorded in T_1. Similarly, in parallel experiment with the cultivar Himachal, the highest cured rhizome yield (11.60 t ha^{-1}) was recorded in T_2, whereas the lowest yield (5.58 t ha^{-1}) was recorded in T_1. The differences among treatments were found to be statistically significant based on the F-test. Treatments such as T_3, T_4, T_7 and T_{11} also recorded comparatively higher cured rhizome yield among the treatments. The higher cured rhizome yield in T_2 may be attributed to adequate nutrient supply through fertigation along with FYM and neem cake, which improved nutrient availability, plant growth and rhizome development. Improved soil fertility and nutrient use efficiency under integrated nutrient management might have contributed to higher yield. The lower yield in T_1 could be due to comparatively lower nutrient availability, resulting in reduced growth and rhizome formation.

These findings are consistent with recent studies in ginger and turmeric indicating that higher fertilizer levels and integrated nutrient management significantly enhance rhizome yield and nutrient uptake. The beneficial role of organic amendments was also reported by Gill *et al.* (1999), Kumar *et al*. (2015) and Kamal and Yousuf (2012), who observed improved growth and rhizome yield with application of FYM, neem cake and fertilizers. Significant increases in rhizome yield with higher and balanced NPK application have been reported by by Patra *et al.* (2022), Behera and Sial (2023) and Shende *et al.* (2025).

Thus, the results of the present study clearly indicate that higher levels of nutrients supplied through fertigation along with organic amendments enhance plant growth, rhizome development and dry matter accumulation, resulting in higher cured rhizome yield in ginger cultivars.

Conclusion

The present study demonstrated a significant positive influence of fertigation levels in combination with organic amendments on growth, biomass accumulation, yield, and curing characteristics of ginger cultivars Rio-de-Janeiro and Himachal in parallel experiments with RCBD. Among all treatments, application of 200% RDF (200:100:100 kg $N:P_2O_5:K_2O$ ha^{-1}) through fertigation along with FYM @ 30 t ha^{-1} and neem cake @ 2 t ha^{-1} (T_2) consistently recorded superior performance.

The maximum rhizome girth was observed under T_2 (7.96 cm in Rio-de-Janeiro and 7.81 cm in Himachal), along with the highest number of nodes per finger (4.68 and 4.81, respectively), indicating enhanced rhizome development. Biomass accumulation was also significantly higher under this treatment, with fresh weight of 198.83 g plant^{-1} in Rio-de-Janeiro and 269.35 g plant^{-1} in Himachal and corresponding dry weights of 68.25 g and 47.99 g plant^{-1}.

Yield parameters were markedly improved with T_2, recording the highest fresh rhizome yield (11.46 t ha^{-1} in Rio-de-Janeiro and 14.54 t ha^{-1} in Himachal). Similarly, dry rhizome yield was maximum (3.81 and 2.47 t ha^{-1}, respectively) accompanied by higher curing percentage (34.20% and 32.93%). Consequently, the highest cured rhizome yield was also obtained under this treatment (8.90 and 11.60 t ha^{-1}, respectively).

The improvement in growth and yield attributes can be attributed to the efficient and continuous nutrient supply through fertigation, which enhanced nutrient uptake and utilization. The addition of FYM and neem cake further improved soil physical properties, microbial activity, and nutrient availability, leading to better biomass production and translocation of assimilates to rhizomes.

Overall, the findings indicate that higher fertigation levels integrated with organic amendments significantly enhance productivity and curing efficiency of ginger. Hence, application of 200% RDF through fertigation in combination with FYM and neem cake can be recommended as a viable and sustainable nutrient management strategy for achieving higher yield and quality in ginger under similar agro-climatic conditions.

Limitations of the study

Despite the promising results obtained, the present study has certain limitations that should be considered while interpreting the findings which are given below:

- The experiment was conducted at one location, therefore, the results may vary under different agro-climatic conditions and years.
- Only two ginger cultivars (Rio de Janeiro and Himachal) were assessed, which limits the generalization of findings across a wider range of genotypes.
- Environmental aspects such as nutrient leaching, water use efficiency and sustainability indicators were not quantified.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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