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Effect of shade management and agronomic management including soil types, fertigation levels and intervals on yield and biochemical-quality parameters of ginger

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Abstract
Ginger (*Zingiber officinale*), a globally valued spice and medicinal crop, exhibits significant variability in growth, yield, and quality depending on environmental and agronomic conditions. This review synthesizes current research on the effects of shade levels, soil types, and fertigation practices on ginger cultivation. Moderate shade (20-40%) enhances physiological parameters, such as photosynthetic efficiency and dry matter accumulation, leading to improved rhizome yield and higher volatile oil content, while excessive shade may reduce crude fiber and curing efficiency. Soil characteristics, particularly texture, pH, bulk density, and organic matter content, play a pivotal role in determining yield and bioactive compound profiles, with well-drained sandy loams and loamy laterites proving most favorable. Fertigation strategies, including 100-125% of the recommended dose of fertilizers (RDF) integrated with organic inputs, improve nutrient uptake, growth traits, and quality attributes like essential oils, oleoresins, and gingerols. Stage-specific and frequent fertigation intervals further optimize nutrient utilization, enhancing both productivity and crop quality. The findings highlight that integrated management of shade, soil, and fertigation offers a sustainable and high-return approach to ginger cultivation.

Keywords: Agronomy of ginger: Review, yield, quality & biochemical parameters, shade management, soil types, fertigation levels & intervals

Introduction

Scientifically known as *Zingiber officinale*, ginger is a spice and medicinal plant cultivated for many centuries. It belongs to the family Zingiberaceae and is native to Southeast Asia. The peculiar flavor and aroma of ginger have made it very popular in cuisines all over the world. Ginger is one of the better-known and useful plants of the world, being consumed for centuries as a spice for flavouring food and as a medicinal plant. Ginger can be used for different food or medicine items and is used in the making of soft drinks, beverages, such as ginger beer, ginger tea, ginger wine, cordials, liquors, ginger ale and candies, soda, pickles, preserves and baking products. Ginger oil is employed in pharmaceutical preparation as a carminative and also as a stimulant during alcoholic gastritis etc. It holds a very esteemed position in Indian cuisine and traditional medicine. The rhizome, which is aromatic in nature, is used fresh, dried, or powdered in cooking for flavor and aroma. Besides, ginger is valued for its medicinal properties, which are anti-inflammatory, digestive, and antioxidant in nature (Anonymous, 2023; Anonymous, 2024) [11, 12]. The production of ginger in India accounts for about 54% of the total world production. India not only has a huge share in the globe supply but also is one of the largest producers of ginger. Further, it is followed by Nigeria, China, Nepal, Indonesia & Thailand. Indonesia tops the list of ginger growers. Major ginger growing states of India include Madhya Pradesh, Karnataka, Assam, Maharashtra, West Bengal, Orissa, Gujarat, Sikkim, Kerala, Meghalaya, Mizoram, Manipur and Nagaland. The ginger shall be sold both in and out of the country, fresh as well as in dried states (Anonymous, 2022) [10].
Shade management plays a crucial role in optimizing ginger yield, biochemical composition, and quality parameters.

Research has shown that moderate shade levels, particularly 20-40% shade, can significantly enhance ginger production and quality compared to open cultivation (Ajithkumar and Jayachandran, 2003; Zhang and Xu, 2008) [4, 108]. Under 20-40% shade, ginger plants exhibit improved photosynthetic efficiency, increased dry matter production, and enhanced rhizome yield (Ajithkumar and Jayachandran, 2003; Sreekala, 1999) [4, 92]. This moderate shading creates a favorable microclimate that reduces photo-oxidative stress and promotes efficient translocation of photosynthates to the rhizomes (Sreekala, 1999) [92]. The biochemical composition of ginger is also influenced by shade levels. Volatile oil content tends to increase with higher shade intensities, with maximum levels observed under 60-80% shade (Ajithkumar and Jayachandran, 2003; Sreekala, 1999) [4, 92]. However, non-volatile ether extract (NVEE) content is optimized under 20-40% shade, contributing to the overall quality and pungency of ginger (Ajithkumar and Jayachandran, 2003) [4]. Interestingly, starch and crude fiber content are generally higher in open-grown ginger, while moderate shade (20-40%) strikes a balance between yield and quality parameters (Ajithkumar and Jayachandran, 2003; Sreekala, 1999; Padmapriya *et al*., 2007) [4, 92, 65]. The color of shading material also impacts ginger growth and yield, with green film-shading at the seedling stage promoting higher leaf photosynthesis, plant growth, and ultimate yield compared to other colors (Zhang and Xu, 2008) [108]. Careful shade management not only affects yield and quality but also influences plant morphology, chlorophyll content, and disease susceptibility (Lashley IV *et al*, 2024; Shende *et al*., 2024) [48, 85]. By optimizing shade levels, growers can create an ideal balance between vegetative growth, rhizome development, and biochemical composition, ultimately producing high-quality ginger with desirable yield and organoleptic properties.

The highest ginger and turmeric yield found in sandy loam soil having the minimum bulk density, moderate acidic reaction, and high organic matter and available potassium (Sahu and Mitra, 1992) [77]. Pruthi (1993) [71] reported that ginger can be grown in a wide range of well-drained soils of at least 30 cm depth, ranging from heavy laterite loams to clayey loam. Laterite loams containing not more than 30 percent sand or 20 percent clay and free from gravel have given higher yields. Growth, yield and quality of ginger were superior to the ginger grown in friable, loose, well drain soils having moderate fertility and humus which included red sandy loams, red loamy soils, lateritic soils, alluvial-colluvial soils in the northern part of Nagaland (Kanjilal *et al*., 1997) [42]. Turmeric cultivated on dark-red and grey soils had high curcumin content and fat content higher than that in red soil. To gain a high yield and high contents of curcumin, fat, protein and Fe, cultivation of turmeric in dark-red soil in Okinawa was recommended (Hossain and Ishimine, 2005) [35]. The type of soil and its management play a crucial role in determining the yield and quality of ginger. Different soil types and nutrient management practices can significantly influence the physical and biochemical properties of the soil, which in turn affect ginger's growth, yield, and quality parameters such as essential oil and gingerol content (Azizah *et al*., 2019; Srinivasan *et al*., 2018) [17, 96]. Ginger thrives in well-drained, loamy soils rich in organic matter with an optimal pH of 6.0-6.5 (Anedo *et al*, 2017; Lashley IV *et al*., 2024) [9, 48]. Poor soil fertility, erosion, and improper nutrient management can reduce yields by up to 40% due to nutrient depletion and increased susceptibility to diseases like bacterial wilt (Anedo *et al*, 2017; Wang *et al*., 2023) [9, 104]. Thus, adopting site-specific soil management strategies not only ensures higher yields but also improves the economic value of ginger through superior quality parameters.

Fertigation levels and intervals play a critical role in optimizing ginger yield, biochemical properties, and quality parameters. Fertigation ensures precise and efficient delivery of nutrients like nitrogen, phosphorus, and potassium directly to the root zone, enhancing nutrient uptake and utilization efficiency. Fertigation regimes and nutrient management significantly impact ginger yield and quality parameters. Higher levels of fertigation, such as 200% RDF with organic amendments, enhance essential oil, oleoresin, gingerol, and crude fiber content in ginger (Manjunatha *et al*., 2023_a; Manjunatha *et al*., 2023_b) [53, 54]. Optimal irrigation scheduling combined with integrated nutrient management (75% inorganic + 25% organic) improves growth, yield components, and quality parameters (Patra *et al*., 2022) [68]. Proper fertigation levels, such as 100% or 125% of the recommended dose of fertilizer (RDF), have been shown to significantly improve growth parameters, including plant height, tiller number, and leaf area, while also boosting rhizome yield by up to 25-50% compared to conventional methods (Patra *et al*., 2022; Manjunatha *et al*., 2023_a) [68, 53]. Increased levels of NPK fertilizers (125 kg N + 60 kg P_2O_5 + 60 kg K_2O ha^{-1}) result in higher fresh rhizome yield, oil content, and oleoresin content (Seyie *et al*., 2013) [82]. Organic fertilizers, particularly biofertilizers like Azospirillum, can match or exceed inorganic fertilizers in terms of rhizome yield while significantly improving quality attributes such as dry matter, oil, and oleoresin content (Rana & Korla, 2010) [74]. The frequent fertigation during early vegetative stages promotes shoot development through nitrogen supply, while moderate intervals during rhizome bulking stages ensure potassium availability for rhizome development (Billi *et al*., 2021; Shende *et al*., 2024; Manjunatha *et al*., 2023_b) [21, 85, 53]. Reduced intervals in later stages prevent excessive vegetative growth, redirecting energy toward rhizome ripening (Mekonnen and Garedew, 2019; Shende *et al*., 2024) [57, 85]. These studies collectively emphasize the importance of balanced fertigation and nutrient management in optimizing ginger yield and biochemical parameters. Therefore, adopting optimal fertigation levels and intervals is essential for sustainable ginger cultivation with higher yields and superior quality.

Materials and Methods

I) Data and Literature Reviews Collection

To study the impacts of shade conditions, different soil types, fertigation levels and intervals on ginger as a agronomic management in ginger, we have collected the several research literature reviews, information papers and research article related to our study. We have selected the literature through out the world, the latest and new literature reviews are selected and presented in this review paper. Based on these literature reviews we have presented the results and discussions in this paper from their studies and information. We have taken help from our Department of Agronomy and University Library at Central Campus of Mahatma Phule Krishi Vidyapeeth, Rahuri, the software facilities like JateGate, Sera and other database management systems in the library were used to collect data and literature reviews.

II) Data and Literature Reviews Arrangement and Management

We have used the relevant databases such as PubMed, Scopus, Elsevier and ScienceDirect database, Springer Data base, Web of Science, Google Scholar, ResearchGate, Academia, Semantic Scholar, Willey Library, Consensus, SciSpace, Perplexity, Elicit, etc. to collect the literature reviews. Also, we have used reference management tools like EndNote, Zotero, Mendeley etc. for proper reference management and literature cited. We have used these for selecting databases and literature reviews systematically, and recorded search results and presented in this paper.

Results and Discussions

I) Effect of Shade Management on Ginger

A. Effect of Shade Management on Yield Parameters and Yields of Ginger

Plant height and tiller number were increased with shade treatment, while the severity of iron chlorosis was reduced. Ginger growth under 66% saran netting, inter-cropped with orchard or okra and inter-cropped with corn and peas, significantly out-yielded those plants intercropped with corn only and those with no shade (Wilson and Ovid, 1993) [105]. The plant growth and rhizome yield was not reduced significantly by providing 25 percent shade, and the yield obtained from open and low shade (25 percent) was on par. The mango-ginger recommended for intercropping situations and as a crop component in homesteads where multi-species crops are grown (Jayachandran and Nair, 1998) [39]. Plants grown under moderate shade (60 to 70%) produced longer and more numerous rootlets, more bud primordia, and had greater rhizome mass and healthier leaves than plants grown under extreme shade (95%) or in full sun. Decreasing shade density had a major impact on plant condition and growth. Those plants grown with the greatest sun exposure displayed 100% scorch damage to the foliage, in comparison to <35% damage in the moderate shade (30 to 40%). The results suggest that moderate shading may double yield in rhizome mass, and promote increased bud proliferation in subsequent seasons. Late season leaf vigour is not correlated with rhizome mass (Quigley and Mulhall, 2002) [72]. The shade levels 20 and 40 percent were favourable for obtaining higher dry ginger yield. The dry ginger yields of plants grown under 20 an 40 percent shade were on par but produced significantly higher yield when compared to open condition, and other shade during both the seasons. 60 and 80 percent shade levels reduced the yield, however, open condition was found to be better than 60 and 80 percent shade levels for rhizome yield (Ajithkumar and Jayachandran, 2003) [4].

The shading increased the root activity and the chlorophyll contents and stomatic size of upper cuticulae of ginger leaves, but decreased the stomatic density and size of their lower cuticulae. Water stress influenced the growth and yield of ginger significantly, but the effects of light intensity on ginger growth and yield were different under different water contents. Under normal water content, ginger grew better and yield was higher in natural sunlight, while under water stress, ginger grew better and yield was higher in shading (Xu *et al*., 2003) [107]. The ginger in shadenet condition showed increased total chlorophyll content, total phenol content and registered the highest yield but provision of shade decreased the curing percentage as compared to open condition (Padmapriya *et al*., 2007) [65]. The fresh mass of root, stem, leaf, and rhizome decreased in the order of green, white, red, and blue film-shading, also shading with green film at seedling stage could increase the leaf photosynthesis, plant growth, and yield of ginger (Zhang and Xu, 2008) [108]. The increasing the intensity of shade could increase the number of leaves, the number of stems, the leaf area index, and the dry weight of the top of the plant, which was highest in 25 and 50% shade. Without shade and 75% shade form a quadratic curve, with the optimum point of the leaf greenness index at the dose of fertilizer K 139.83 and 200.5 kg ha^{-1}, respectively, while in shade of 25 and 50% forming a linear curve, the greenness of the leaves increases in line with the increase in the dose of fertilizer K. Elephant ginger plants are tolerant to shade and are suitable for intercropping with other crops that give opportunities to plants with shade intensity of 25 and 50%, with a dose of fertilizer K 50-100 kg ha^{-1} (Pamuji and Busri, 2010) [66]. Shading of ginger reduces wilting during the hottest part of the day, and this would be expected to positively influence yields. However, shading caused reduced rhizome yields in this experiment. Covering the crop with a permanent shade screen reduces light throughout the day, including those periods (early to mid-morning and later afternoon) when light intensity is less than optimal for the maximum photosynthetic rate, and this negative effect appears to predominate over any positive effects of shading (Kratky *et al*., 2013) [44].

Studies indicate that shade levels of 20% and 40% are favorable for higher dry ginger yield, with volatile oil content increasing with more shade. However, crude fiber content decreases as shade intensity increases, suggesting a trade-off between yield and certain quality parameters Research indicates that shade management significantly influences ginger yield and quality. Low to moderate shade levels (20-40%) generally result in higher dry ginger yields, increased volatile oil content, and improved physiological parameters such as dry matter production and leaf area index (Ajithkumar & Jayachandran, 2015; Sreekala & Jayachandran, 2015). The weight of rhizomes per plant and fresh rhizome yield together with VC ratio were noted to be significantly higher (229.9 g and 22754 kg/ha) in improved cultivar Suprabha with integrated nutrient management (INM) in partial shade than the same genotype with INM without shade (216.4 g and 21692 kg/ha). The lowest rhizome per plant and fresh rhizome yield was recorded in farmers' practice (without shade) with Local cultivar (154.7 g and 16698 kg/ha). The technology gap and technology index were minimum in improved cultivar Suprabha with INM due to partial shade resulting an additional 5 employment (Singh *et al*., 2015) [87]. Low shade levels, such as 20%, have been associated with higher dry matter production, leaf area index, net assimilation rate, and crop growth rate, which contribute to increased yield. This suggests that moderate shading can positively influence physiological parameters critical for ginger growth (Sreekala and Jayachandran, 2015) [93].

The growth and yield performances of turmeric plants were better under 50% shade level, 50% shade level is suitable for the cultivation of turmeric in the Batticaloa district of Sri Lanka (Srikrishnah and Sutharsan, 2015) [95]. The partial tree shade proved that the growth and yield of rhizome was statistically significant, However, number of tillers per plants was not statistically significant (Meena and Singh, 2017) [56]. Rhizome yield was increased with increasing levels of shade. The growth of ginger plants enhanced with decreasing light transmission and increasing relative humidity and air temperature. Higher shade levels (60-80%) can also enhance growth and yield, particularly when combined with plastic covers or intercropping systems (Aly, 2019) [6]. The ginger growth and yield were increased under shadenet condition. the ginger varieties Suprabha, Himachal, Pundibari, Zaherabad local were the good varieties for the yield attributing parameters like growth, rhizome and yield characters. Suprabha variety is performed best under shade net cultivation (Babu *et al*., 2017 and Babu *et al*., 2019) [18, 19]. The 60% shade level might have been excessive to increase the rhizome yield of ginger and turmeric plants. However, lower shading percentages might be beneficial for these crops and should be evaluated in future studies, especially when considering that SPAD index values were generally higher in plants grown under shade than under full sun (Cordero *et al*, 2022) [29]. The green shade significantly improved both growth and yield compared to non-shaded conditions. This suggests that not only the amount of shade but also the quality (colour) of light can affect ginger cultivation outcomes (Roslan *et al*., 2024) [75]. In a high tunnel study, different cultivars showed varying responses to shade, with some producing higher yields under 0% and 40% shade in one year, and 22% shade in another, indicating that optimal shade conditions may vary annually and by cultivar (Lashely IV *et al*., 2024) [48]. Ginger is an excellent intercrop because in shaded conditions it uses PAR efficiently and has low light reflection. As a result, it accumulates more photosynthates under shaded conditions because of its larger leaf area values. This increases the crop's bulking rate, net assimilation rate, and growth rate, all of which increase the production of rhizomes (Thakur and Kumar, 2024) [100].

B. Effect of Shade Management on Biochemical-Quality Parameters of Ginger

Volatile oil content showed an increasing trend with increasing levels of shade. Volatile oil was maximum under heavier shade levels in general (60 and 80 percent), non-volatile ether extract was higher under 20 percent shade. Maximum non-volatile ether extract was recorded in the plants grown under 20 and 40 percent shade levels. Higher starch content was observed in plants grown under 20 percent shade levels. Crude fibre content gradually reduced as the intensity of shade increased and found maximum in open condition which was at par 20 percent shade levels. Starch as well as crude fibre content was more in plants grown under open condition. lowest volatile oil content was recorded under open condition during growth stages. (Sreekala, 1999; Ajithkumar and Jayachandran, 2003) [92, 4].
In the glasshouse experiment, total flavonoids biosynthesis was highest under 310 μmol m^{-1} s^{-1} light intensity and total phenolics was high under 790 μmol m^{-1} s^{-1} light intensity. Also, antioxidant activities increased significantly with increasing total flavonoids and high antioxidant activity was observed under 310 μmol m^{-1} s^{-1}. The ferric reducing (FRAP) activity of the rhizomes was higher than that of the leaves in 310 μmol m^{-1} $s^{-1}$of sun light in glasshouse (Ghasemzadeh *et al*., 2010) [32]. Flavonoid compounds (quercetin, apigenin, luteolin, and myricetin) and phenolic acids (gallic acid, vanillic acid, ferulic acid, tannic acid and caffeic acid) were identified with different concentration in leaves and rhizomes of ginger varieties. The most abundant phenolic acid in ginger was gallic acid, and flavonoids were quercetin and apigenin. Accordingly, accumulations of flavonoids in the leaves were high under 60% shade, while most phenolic acids were observed in the rhizomes under 0% shade. Furthermore, caffeic acid was only detected from ginger grown under 0% shade, while tannic acid only accumulated in the leaves of ginger grown under 60% shade level. The results indicated phenolic acids and flavonoids absolutely light dependent and them biosynthetic rate is related to light intensity (Ghasemzadeh and Ghasemzadeh, 2011) [31]. Studies indicate that shade levels of 20% and 40% are favorable for higher dry ginger yield, with volatile oil content and non-volatile ether extract (NVEE) increasing with more shade. However, crude fiber content decreases as shade intensity increases, suggesting a trade-off between yield and certain quality parameters (Ajithkumar & Jayachandran, 2015) [5].
Moderate shading (50%) increases the expression of proteins related to light-harvesting complexes and enhances photosynthetic electron utilization, potentially improving drought tolerance. Shading significantly increased the expression of proteins related to the light harvesting complex, even under drought stress. In addition, shading increased the expression of proteins related to the oxygen evolution complex, plastocyanin, and ferredoxin-$NADP^+$ reductase (FNR), thereby enhancing the efficiency of photosynthetic electron utilization. The shading and drought combination treatment appeared to enhance ginger's drought tolerance by reducing the expression of FNR and enhancing cyclic electron flow (Lv *et al*., 2020) [50]. The application of shade nets was found to have a positive impact on essential oil yield and can be recommended for commercial cultivation of *K. parviflora* (Black Ginger). For direct sunlight conditions *K. parviflora* were planted in an open field and for partial shade (75% sunlight) under a green polyethylene agro shade net during the year 2020. The essential oils extracted by hydro-distillation were chemically profiled by gas chromatography/mass spectroscopy (GC/MS) which revealed linalool as the major compound in both *K. parviflora* essential oil under shade cultivation (KPEOSH) and *K. parviflora* essential oil under direct sunlight cultivation (KPEOS) with significantly higher linalool content in KPEOSH (43.35%). The essential oil yield of KPEOSH (0.92% w/w) was found to be higher than KPEOS (0.76% w/w) (Begum *et al*., 2022) [23].
The ginger grown under either 22% or 40% shade conditions demonstrated more vigorous (healthy looking) plant growth. Ginger grown under shade can potentially boost growth and yield, and improved quality which can increase profit (Lashely IV *et al*., 2024) [48]. Moderate shade levels (20-40%) optimize photosynthesis and dry matter production, while excessive shade can increase disease risks and reduce curing and fiber content (Shende *et al*., 2024) [85]. Ginger is an excellent intercrop because in shaded conditions it uses PAR efficiently and has low light reflection. As a result, it accumulates more photosynthates under shaded conditions because of its larger leaf area values. This increases the crop's bulking rate, net assimilation rate, and growth rate, all of which increase the

production of rhizomes. Ginger grown under partial shade in various cropping systems, can be a very profitable spice crop with superior yield and quality rhizomes (Thakur and Kumar, 2024) [100].

II) Effect of Soil Types on Ginger

A. Effect of Soil Types on Yield Parameters and Yields of Ginger

The yield parameters of ginger *viz*., rhizome number, rhizome yield, dry rhizome yield were found maximum when cultivated in sandy loams, clay loams and laterite soil than clayey soils having more clay content and poor drainage (Paulose, 1972) [69]. The optimum soil temperature for germination is between 25-26 °C and for growth 27.5 °C and nutrient need for ginger is in the following order: N, K, P, Ca and Mg. Lighter soils having uniform loam texture provide optimum and best soil conditions for proper and maximum growth and yield of ginger (Hackett and Carolane, 1982) [34]. Ginger cultivation in light soils *viz*., sandy, sandy loam, sandy clay loam, loamy and clay loam soils had shown significant effects on its yield and yield parameters and also suggested that to cultivate ginger in light and medium deep soils having optimum porosity, bulk density, moisture storage and well-draining capacity for better growth and quality parameters of ginger under Uttarakhand region (Kumar and Joshi, 1984) [46]. Ginger and turmeric grown in well drain, friable and loose soil recorded highest yield attributes including numbers of rhizome, rhizome yield and dry yield. Sandy loams or sandy clay loams and loamy laterite soils were found best for ginger and turmeric cultivation to get maximum yield and production (Nair, 1982) [59]. In a sandy loam red soil, the cultivar Thingpuri gave the highest yield of 22 t/ha and the lowest yield (30 q/ha) was recorded in the cv. Rio-de-Janeiro on clay soil (Panigrahi and Patro, 1985) [67]. Ginger yield was higher in alluvial plain areas than in local fan, hilly or mountain foothill areas, and was higher on fine sandy loam than on sandy loam, clay or clay loam.

Yields were high on soils with good drainage and with a soil depth of >100 cm, and were negatively correlated with slope and soil hardness and positively correlated with ploughing depth and soil moisture content (Cho *et al*., 1987) [28]. The highest yields of fresh rhizomes (6.61-12.78 t/ha) in each clone were obtained with the highest planting and fertilizer rates in the laterite soils of Eastern Ghats Highland Zone of Orissa (Mohanty *et al*., 1988) [58]. Carrot shape was more conical at high bulk density under low moisture conditions. The yield was always higher in the high than in the low water treatment. The highest yield of 92.3 g plant^{-1} was recorded at 1.40 Mg m^{-3} in the high-water regime (Shri Anung and Blair, 1989) [94]. The highest ginger and turmeric yield found in sandy loam soil having the minimum bulk density (1.20 g/cc), moderate acidic reaction (pH 5.7), and high organic matter (organic carbon 1.1 percent) and available potassium (351 kg/ha). The yield decreased with increase in soil clay content and decrease in pH (Sahu and Mitra, 1992) [77]. The ginger variety Nadia yielded the highest (67.0 q/ha-fresh ginger) followed by Chekerella (57.0 q/ha) in clay loam soil of Assam. Growth attributes like leaves per clump, tillers per clump and shoot height were positively correlated with yield (Saikia and Shadeque, 1992) [81].

Turmeric yield was significantly higher when the rhizomes were planted at a depth of 4, 8 and 12 cm in a glasshouse, and at a depth of 8 and 12 cm in fields, than when planted at a shallower depth of the dark red soil. Turmeric planted at a 16 cm depth showed a slightly lower yield than that planted at 8 and 12 cm, and it was comparatively difficult to harvest rhizomes, probably due to the higher compactness or bulk density in deeper soil (Ishimine *et al*., 2003) [37]. Turmeric on dark-red soil had the highest yield with the favorable colour of the deep yellow and high curcumin content (0.20%). To gain a high yield and high contents of curcumin, fat, protein and Fe, cultivation of turmeric in dark-red soil in Okinawa was recommended (Hossain and Ishimine, 2005) [35]. The rhizome and straw yield of ginger increased significantly with the application of farmyard manure and K levels over control, however, the differential response of K levels beyond 100 kg K_2O ha^{-1} was at par under acid Alfisols sandy loam soil (Majumdar *et al*., 2005) [52]. The soil with low bulk density promoted the growth of ginger and improved yield. The fresh weight of root, stem, leaf and rhizome were higher by 43.3, 24.4, 28.1 and 35.2%, respectively (Shang *et al*., 2006) [83]. Vermicompost amendments improved net yield, fresh and dry biomass of shoot and rhizome yield of plants and their chlorophyll, carbohydrate and protein contents were increased under vermicompost amendment both in the saline and non-saline conditions in sandy loam soil. Ginger plant performed well in non-saline soil in case of growth, physiological and yield parameter as compared to saline soil condition maintained in sandy loam soil (Ahmad *et al*., (2009) [3]. Combined application of chemical N fertilizer N_2 (50 kg N ha^{-1}) and Azospirillium B_2 (20 g 10 kg^{-1} seed bit) produced a much higher rhizome and cured yield (22.8 and 4.3 tons ha^{-1}) than with either N_2 (20.3 and 4.0 tons ha^{-1}) or B_2 (20.4 and 3.8 tons ha^{-1}). These observations suggested that the optimum quality production of ginger can be obtained with N_2B_2 treatment in acid Alfisol soils (Singh and Singh, 2009) [90]. The application of a recommended dose of fertilizer + 25 t FYM ha^{-1} to ginger planted on the flatbed in clay loam soil is the best combination for higher rhizome yield (Shaikh *et al*., 2010) [84].

The mixture of coir dust and burnt paddy husks significantly affected plant height, shoot biomass, rhizome yield, and rhizome to shoot ratio. Media containing high amount of coir dust (70-100%) showed good growth and increased the rhizome yield up to 36% compared to those containing high amount of burnt paddy husks. Plants grown in 100% coir dust gave the best growth performance and yield compared to the other treatments. They produced the highest rhizome yield (5,480±325 g per plant). The lowest rhizome yield (2,570±135 g) was obtained from plants planted in 30% coir dust + 70% burnt paddy husks (Suhaimi *et al*., 2015) [97]. The higher turmeric rhizome yield was recorded in the one-day interval of irrigation at 80% PE (T_2) (42.79 t ha^{-1}) which was on par with two days interval of irrigation at 80% PE (T_3) (42.51 t ha^{-1}) black clay loam soil (Chitra *et al*., 2017) [27]. The mulch significantly affected the yield parameters of ginger as it increased number of rhizome fingers, fresh and dry weight of rhizomes in sandy loam soil (Kumara and De Silva, 2019) [47]. The land characteristics-controlled yield and diameter of ginger rhizome through soil properties both chemical (e.g. CEC) and physical (e.g. soil texture). The production potential including rhizome yield/plant, rhizome yield/ha, rhizome length, rhizome diameter and gingerol content of small white ginger was large in low-mid lands having clay, silty clay and silty clay loam soil whereas for big white and red gingers was higher in the uplands having clay loam, silty, silty clay and loamy soil (Azizah *et al*., 2019) [17]. The application of N.P.K. (15:15:15) fertilizer at the rate of 150 kg/ha gave significantly higher rhizome plant^{-1} rhizome length (cm), rhizome weight (g) and rhizome yield (t ha^{-1}) under sandy loam soil of tropical ultisol of Nigeria rainforest (Ojikpong, 2019) [63]. The biochar (15 t/ha), PM (15 t/ha) and NPK fertilizer (200 kg/ha) alone or combination of biochar with PM or with NPK fertilizer increased the yield (number of rhizomes and fresh rhizome yield) of ginger significantly compared to control in tropical alfisol with sandy loam soil (Adekiya *et al*., 2020) [2].

The highest flower number (320.3 n m^{-2}), stigma yield (2.0 g m^{-2}), daughter corm production (7.9 kg m^{-2}), and horizontal diameter (3.1 cm) were derived from loamy and sandy loam soils. Stigma length, stigma fresh & dry weight, stamen fresh & dry weight, tepal fresh & dry weight, by-products dry weight, number of daughter corn, daughter corn weight, daughter corn diameter and daughter corn yield were also found superior when saffron cultivated in loamy and sandy loam soils (Cardone *et al*., 2020) [25]. The media of Cocopeat + sand (75:25) recorded maximum rhizome yield plant^{-1}, rhizome yield ha^{-1} and dry recovery (576.40 g/clump, 34.58 t ha^{-1} and 24.85% respectively) of ginger, while the minimum was recorded in the media cocopeat + perlite (75:25) (Supriya *et al*., 2020) [99]. The sowing depth significantly affects ginger (*Zingiber officinale* Roscoe) yields, and sowing depth can affect rhizosphere community structure through root exudates. Sowing depth at 10 cm (SD_{10}) significantly increased ginger yield, which is related to the development of vascular bundles and the expression of aquaporin (Lv, *et al*., 2021) [51]. The production of red ginger using oil palm empty fruit bunch compost media was higher than other compost media. The planting media including top soil + compost of empty palm oil bunches (1:1) recorded significantly highest rhizome weight, rhizome numbers, rhizome yield and ultimately improved the rhizome production of red ginger (Sijabat *et al*., 2021) [89]. For accessing the land evaluation for the cultivation of ginger, pepper and maize the soils were classified as Alfisols (soil order), Ustalf (suborder), Rhodustalf (greatgroup) and Kanhaplic Rhodustalfs (subgroup). The pedon 11 was very highly suitability for ginger cultivation, management practices such as organic matter and mineral fertilizer incorporation are recommended. Underlying the sandy loam is sandy clay loam with weak Fine crumbs to moderately sub angular blocky structures which make the sites suitable for ginger production (Abagyeh *et al*., 2022) [1].

The application of 300 kg K ha^{-1} rate had a higher rhizome diameter, rhizome weight per plant, and total yield per ha compared with other K fertilizer rates. The 300 kg K ha^{-1} rate also had the highest yield (per plant and per hectare) compared with other K fertilizer rates. The increases in K from 100 to 300 kg ha^{-1} enhanced yield by 127% to 153% (3.3 to 5.5 t ha^{-1}) during the first and second seasons; this indicated the important role of K in red ginger yield in the alfisol with loamy clay texture (Azizah *et al*., 2022) [16]. The fertilization of 75% RDF as inorganic fertilizers + 25% RDF as vermicompost recorded the maximum finger length (3.70 cm) and green rhizome yield (10.62 t ha^{-1}) over the other nutrient management in sandy soil of inceptisols of West Bengal (Patra *et al*., 2022) [68]. The significantly maximum number of primary and secondary finger clump^{-1}, fresh weight of mother, primary and secondary rhizomes clump^{-1}, length and breadth of mother, primary and secondary rhizomes and dry matter production ha^{-1} at harvest were recorded with 200% RDF (200:100:100 N:P_2O5:K_2O kg ha^{-1}) through drip fertigation + FYM 30 t ha^{-1} + Neem cake t ha^{-1} in well drained red sandy loam soils (Manjunatha *et al*., 2023$_a$) [53]. The greater vegetative growth and seed production was found in coarser, sandier soils with lower microelement concentrations. The nutritional traits of leaves varied, with soil organic matter and macronutrient content associated with reduced leaf Na, protein and phenolic (mainly flavonoid) concentrations, whereas soils with lower pH and Fe concentrations, and higher clay content yielded plants with lower leaf Zn concentration and greater accumulation of hydroxycinnamic acids (Noguerol *et al*., 2023) [61].

B. Effect of Soil Types on Biochemical-Quality Parameters of Ginger

Nadia yielded the highest (67.0 q/ha-fresh ginger) followed by Chekerella (57.0 q/ha) in clay loam soil of Assam. Growth attributes like leaves per clump, tillers per clump and shoot height were positively correlated with yield. Moran, Wynad and Jorhat hard yielded higher carbohydrate, fibre, volatile oil, acetone extract, oleoresin and volatile oil under clay loam soil in Assam (Saikia and Shadeque, 1992) [81]. Growth, yield and quality of ginger grown in Wokha, Mon, Mokokchang and Tuensang districts were superior to the ginger from other districts of Nagaland which having friable, loose, well drain soils having moderate fertility and humus which included red sandy loams, red loamy soils, lateritic soils, alluvial-colluvial soils in the northern part of Nagaland (Kanjilal *et al*., 1997) [42]. The protein content of turmeric in dark-red soil was 5.2%, which was around 40% higher than that in other soil types. Turmeric cultivated on dark-red and grey soils had high curcumin content (0.20%) and fat content 71% higher than that in red soil. To gain a high yield and high contents of curcumin, fat, protein and Fe, cultivation of turmeric in dark-red soil in Okinawa was recommended (Hossain and Ishimine, 2005) [35]. The crude protein content increased significantly up to 100 kg K,O/ha while all the K levels increased the oleoresin content significantly and the maximum values of crude protein (8.90%) and oleoresin content (9.65%) were recorded with 200 kg K_2O ha^{-1} and 5 tonnes of FYM ha^{-1} under acid alfisols sandy loam soil (Majumdar *et al*., 2005) [52]. The soil with low bulk density promoted the growth of ginger and improved yield. The yields of the control, 1.36 g cm^{-3} BD (T_1) and 1.20 g cm^{-3} BD (T_2) were 2534.1, 3017.7 and 3326.8 kg, respectively. Moreover, the content of rhizome dry matter, starch and volatized oil increased with the increase in soil bulk density, while the content of protein and amino acid decreased. The change in soil bulk had little effect on the content of fibre, sugar and VC (Shang *et al*., 2006) [83].

Combined application of chemical N fertilizer N_2 (50 kg N ha^{-1}) and Azospirillium B_2 (20 g 10 kg^{-1} seed bit) produced a much higher volatile oil which was 0.48% with B_2 and 0.49%with N_2 improved to 0.58% with N_2B_2. The oleoresin content of 4.38% with N_2B_2 was much higher than either N_2 (4.26%) or B_2 (4.27%) alone. These observations suggested that the optimum quality production of ginger can be obtained with N2B2 treatment in sandy loam acid Alfisol soils (Singh and Singh, 2009) [90]. The vermicompost amendments improved net yield, fresh and dry biomass of shoot and rhizome yield of plants and their chlorophyll, carbohydrate and protein contents were increased under vermicompost amendment both in the saline and non-saline conditions in sandy loam soil. The yield factors *viz*., fresh and dry weight of rhizome as well as biochemical parameters *viz*., carbohydrate, protein, nitrogen, sodium and potassium content were significantly increased only in ginger plants under non-saline condition provided by Vermicompost as fertilizer, its concentration was reduced under saline water irrigation and remained more or less equal even in those plants provided with organic fertilizers under sandy loam soil (Ahmad *et al*., 2009) [3]. The yield and total reducing sugar were decreased by increasing bulk density as an important soil property, on the other side raw ash content of tobacco increased. Increasing bulk density value, one of the important physical properties of the soil, decreased the tobacco yield and sugar content of the tobacco. Also decrease in yield is determined. In contrast, raw ash content of tobacco has increased. In terms of tobacco quality, high sugar content, low raw ash content is desired. According to this, with preventions reducing the bulk density value in the tobacco soils, tobacco yield and quality can be increased (Delibacak *et al*., 2014) [30].

The essential oil content in organic nutrient management and chemical nutrient management was almost identical (1.0-1.7%), while it was slightly higher at 1.32-4.0% in integrated nutrient management. Rhizome oil components showed that pinene, d-camphene and-phellandrene contents were higher in chemical nutrient management,-citral (neral) and citronellol in organic nutrient management and-citral (geranial) in integrated nutrient management under Ustic Humitropept with clay loam textured soil (Srinivasan *et al*., 2018) [96]. The land characteristics-controlled yield, quality and diameter of ginger rhizome through soil properties both chemical (e.g. CEC) and physical (e.g. soil texture). The production potential including rhizome yield/plant, rhizome yield/ha, rhizome length, rhizome diameter and gingerol content of small white ginger was large in low-mid lands having clay, silty clay and silty clay loam soils whereas for big white and red gingers was higher in the uplands having clay loam, silty, silty clay and loamy soils (Azizah *et al*., 2019) [17]. Kumara and De Silva (2019) [47] carried out a study in a field at the Intercropping and Betel Research Station, Department of Export Agriculture, Narammala in 2017 on the efficacy of different mulching materials in influencing growth, yield, soil and quality parameters of ginger cultivated in the low country intermediate zone (il1) of Sri Lanka in sandy loam soil with a pH ranging from 5.74 to 6.58, having total nitrogen 0.13%, available phosphorus 320 ppm and available potash 0.017% and found that mulch significantly affected quality of ginger as it decreased soil pH and pungency levels in sandy loam soil.

According to International Organization for Standardization (ISO) references, although all spice samples belonged to the first qualitative category, clay, loam, and clay-loam soils recorded the highest value for colouring power (290.5, 289.1, and 287.6 $A^{1\%}_{1cm}$ 440 nm, respectively). The highest values of bittering (109.2 $A^{1\%}_{1cm}$ 257 nm) and aromatic (26.6 $A^{1\%}_{1cm}$ 330 nm) power were reached by loam soil. Positive correlations were found both between colour with clay and organic matter, and aroma with total calcium carbonate (Cardone *et al*., 2020) [25]. The high antioxidant content because of its gingerols was found in the optimal K use, which was reflected by K fertilizer application at approximately 180 and 300 kg K ha^{-1}. This result indicated that antioxidant content in red ginger can increase by optimizing the K fertilization rate in the alfisol with loamy clay texture (Azizah *et al*., 2022) [16]. The fertilization of 75% RDF as inorganic fertilizers + 25% RDF as vermicompost recorded the highest content for essential oil (0.45%) and oleoresin (3.74%) and also improved carbohydrate, and fibre quality over the other nutrient management in sandy soil of inceptisols of West Bengal (Patra *et al*., 2022) [68]. The nutritional traits of leaves varied, with soil organic matter and macronutrient content associated with reduced leaf Na, protein and phenolic (mainly flavonoid) concentrations, whereas soils with lower pH and Fe concentrations, and higher clay content yielded plants with lower leaf Zn concentration and greater accumulation of hydroxycinnamic acids. The nutritional value of the seed oil composition appeared to be enhanced in soils with coarser texture and lower micro-element concentrations. The accumulation of specific phenolic compounds in the seed was influenced by a wide range of soil properties including texture, pH and some microelements (Noguerol *et al*., 2023) [61].

III) Effect of Fertigation Levels and Intervals on Ginger:
A. Effect of Fertigation Levels and Intervals on Yield Parameters and Yields of Ginger

The highest yields of fresh rhizomes (6.61-12.78 t/ha) in each clone were obtained with the highest planting and fertilizer rates in the laterite soils of Eastern Ghats Highland Zone of Orissa. The same trending data were also highlighted on growth components contributing to the yield and on economic returns in soils of Eastern Ghats Highland Zone of Orissa (Mohanty *et al*., 1988) [58]. The N, P and K rates influenced yield, with yield increasing with increasing rates of N and P, and highest yields in the K treatments observed at the lowest K dose. Interactions between 2 fertilizers also influenced yield, with high yields (15.62-22.53 t/ha) observed in the following combinations: 150 kg N + 75 kg P/ha; 150 kg N + 50 kg K/ha; and 25 kg P + 50 kg K/ha (Gowda *et al*., 1999) [33]. The positive effect of higher, doses of N and K on the yield. Among the 16 levels of N and K, 3 combinations *viz*.,150 kg N, 50 kg K; 150 kg N, 100 kg K and 75 kg N, 150 kg K ha^{-1} were found to be significantly superior with respect to yield. The optimum dose ·of N and K derived from the quadratic equation was 144 kg and 109 kg ha^{-1}, respectively under acidic clay loam soil (Pradeepkumar *et al*., 2001) [70]. The rate of fertilizer-N utilization by ginger was quite different in different fertilizer-N application stages. The results indicated that the rate of fertilizer-N utilization increased with the delay of application. The highest utilization rate, 45.24% was observed when fertilizer was applied during the middle period of vigorous growth, while the utilization rate was only 28.09% when applied at seedling stage (Xu *et al*., 2004) [106]. The rhizome and straw yield of ginger increased significantly with the application of farmyard manure and K levels over control, however, the differential response of K levels beyond 100 kg K_2O ha^{-1} was at par. The initial K status of the experimental soil was low; hence, the application of K might have influenced the yield of ginger. The rhizome yield was increased by 14.2% with farmyard manure application could be because of additional supply of plant nutrients as well as reduction of soil acidity and physical condition of the soil which in turn makes the crop more responsive to K (Majumdar *et al*., 2005) [52].

The application of nitrogen at 175 kg ha^{-1} significantly increased the fresh rhizome yield, dry rhizome yield, dry recovery, curcumin content of turmeric during both years (Kandiannan and Chadaragir 2006) [41]. The fertigation of 300 kg N ha^{-1} significantly increased the shoots and fruits of tomato, number of fruits plant^{-1}, fruit weight and fruit yield plant^{-1}. The rate of fertilizer-N utilization by ginger was quite different in different fertilizer-N application stages. The results indicated that the rate of fertilizer-N utilization increased with the delay of application. The highest utilization rate, 45.24% was observed when fertilizer was applied during the middle period of vigorous growth, while the utilization rate was only 28.09% when applied at seedling stage (Xu *et al*., 2004) [106]. (Badr and El-Yazied, 2007) [20]. The wet rhizome yield significantly increased with increasing levels of NPK and when applied in the form of tablets (Jagadeeswaran *et al*., 2008) [38]. The treatment in which 100% RDF was applied through drip recorded the maximum plant height (99.36 cm), number of tillers per plant (3.41) and fresh rhizome yield (12.24 t acre^{-1}) (Sadarunnisa *et al*., 2010) [76]. The treatments of drip irrigation once in two days at 80, 60 and 40% of PE along with fertigation levels of 125, 100 and 75% of N and K produced higher rhizome yields (34.31 to 41.96 t ha^{-1} during 2004-05 and 32.90 to 34.76 t ha^{-1} during 2005-06) and were superior over surface irrigation (28.12 and 22.50 t ha^{-1}) in 2004-05 and 2005-06 years, respectively. Drip irrigation at 80 and 60% of PE once in 2 days and fertigation levels of 125, 100 and 75% of N and K produced higher yields (32.9 to 41.96) t ha^{-1} during first and second crop) which were superior over other levels of irrigation. Irrigating at 60% PE with 125% of N and K will produce profitable yield as compared to other treatments (Thiyagarajan *et al*., 2011) [101]. To increase yield and the utilization for water and fertilizer, the effects of different irrigation styles such as conventional irrigation without fertilization (CK_0), conventional irrigation and fertilization (CK), drip fertigation (T_1) and 20% reduction of fertilizer in drip fertigation (T_2) on the growth as well as water and NPK utilization were analysed in the cultivar 'Laiwu large ginger'. Compared with conventional irrigation and fertilization (CK), the economical yield of ginger increased by 17.94% and 15.78%, respectively, but the biological yield of ginger in drip fertigation (T_1) and 20% reduction of fertilizer in drip fertigation (T_2). Conventional irrigation and fertilization (CK) did not show a significant difference in case of economical yield (Liu *et al*., 2012) [49].

The NPK (106 g urea + 76 g TSP + 68 g MP) plot^{-1} + 1.2 kg poultry litter recorded significantly maximum weight of mother rhizome plant^{-1}, number of primary finger plant^{-1}, weight of primary fingers plant^{-1}, number of secondary finger plant^{-1}, weight of secondary fingers plant^{-1} and yield ha^{-1} of turmeric (Amin *et al*., 2013) [8]. The increase in N and P level had very highly significant effect on all the growth parameters and yield characters. Increasing rate of N and P levels recorded significantly highest ginger yield (rhizome/tuber). The nitrogen level increase reveals progressive increment for all ginger yield components (Bosha *et al*., 2014) [22]. The application of 270:135:180 kg N:P_2O_5:K_2O ha^{-1} recorded higher yield attributes over other levels. Weight of mother, primary, secondary and tertiary rhizome per plant and yield of turmeric were found significantly superior with the application 270:135:180 kg N:P_2O_5:K_2O ha^{-1} over other levels (Satyareddi and Anagadi, 2014) [79]. Surface irrigation (5 cm depth) + soil application of fertilizers at 100% RDF was the control. The result indicated that higher turmeric yield was noticed under drip irrigation at 120% PE + fertigation with 100% RDF which is statistically on par with micro-sprinkler irrigation at 120% PE + fertigation with 100% RDF (Archana and Maragatham (2017_a) [13].

The uptake of nitrogen, phosphorus and potassium was significantly increased with higher rate of application. Higher uptake of nutrients was attributed to better availability of nutrients which was reflected in better growth and rhizome yield. Higher turmeric yield was noticed under DI at 120% PE + fertigation with WSF at 100% RDF (28.56 t/ha) which is comparable with MSI at 120% PE + fertigation with WSF at 100% RDF (28.14 t/ha). The lower yield was noticed under surface irrigation (5 cm depth) + soil application of fertilizers at 100% RDF (20.87 t/ha). This might be due to the maximum available nutrient present in drip and micro sprinkler fertigation with 100% RDF compared to surface irrigation. The applied nutrients at any stage of the crop should properly reflect in terms of available nutrient in the soil, so that crop could absorb these nutrients without hindrance (Archana and Maragatham (2017_b) [14]. The fertigation applied in 30-40 splits doses at 2-3 days interval resulted in maximum dry matter partitioning, corm diameter, corm length and corm yield plant^{-1} of elephant foot yam (Nedunchezhiyan *et al*., 2017) [60]. The number of fruits (22) and yield (42.25 t ha^{-1}) of tomato were significantly maximum in drip irrigation with daily application of fertilizers than rest of the treatments. The Drip irrigation with every two days application of fertilizers also reported high yield characters of tomato but less than drip irrigation with daily application of fertilizers (Nut *et al*., 2017) [62]. The fertigation treatment with 125% levels of N and K through water-soluble fertilizers recorded significantly superior yield characters *viz*., yield per plant (406.27 g), yield per plot (109.76 kg/25 m^2), estimated yield (43.90 t ha^{-1}) and estimated cured rhizome yield (7.96 t ha^{-1}) of turmeric transplants. Based on a good performance on yield, fertigation with 125% levels of N and K through water-soluble fertilizers can be employed for turmeric transplants (Sangeetha *et al*., 2017) [78]. The application 270:135:180 kg N:P_2O_5:K_2O ha^{-1} resulted in higher fresh rhizomes, mother rhizomes and cured finger rhizome yield which was on par with application of 225:112.5:135 kg N:P_2O_5:K_2O ha^{-1} (Satyareddi and Anagadi, 2017) [80]. The maximum average curd weight (851 g), curd yield (244 q ha^{-1}) of cauliflower and fruit weight per fruit (3.7 g) and fruit yield (159 q ha^{-1}), respectively of chili with at 75% RDF through fertigation + 2 foliar spray 1% urea phosphate over 50% RDF through fertigation. The combined effect of drip irrigation and fertigation significantly increased yield of cauliflower and chili. Combination of 80% PE drip irrigation along with 75% RDF through fertigation + 2 foliar sprays of 1% urea phosphate significantly increased yield (280 and 170 q ha^{-1}) of cauliflower and chili as compared to the combination of 40% PE at drip irrigation along with 50% RDF (Singh *et al*., 2017) [56]. Fertigation of 100% RDF recorded a significantly higher number of fruits plant^{-1} (100.83) and fruit weight plant^{-1} (54.17 g) as compared to the rest of fertigation levels. However, it was on par with fertigation of 80% RDF. The lowest number of fruits and fruit weight plant^{-1} was noticed under fertigation of 60% RDF during the study of experimentation, this might be because of the enhanced supply of nitrogen, phosphorus and potassium in the root rhizosphere which increased the uptake of nutrients. Among the fertigation schedules, fertigation of 40 equal splits of NPK at every 3 days interval up to 120 DAT exhibited a significantly maximum number of fruits plant^{-1} (100.83), fruit weight (54.17 g) and fruit yield (71.89 t ha^{-1}). While the lowest number of fruits plant^{-1} and fruit weight plant^{-1} was noticed under fertigation of 30 equal splits of NPK every 8 days (Vasanthi *et al*., 2017) [103]. The combined applications of 125% NPK (188: 75: 135 kg ha^{-1}) significantly increased weight of rhizome, number of shoot and dry yield of rhizome of turmeric (Raizada *et al*., 2018) [73].

All the nutrient management schedules were applied in split doses at planting, 45 and 90 DAP. The mean yield across the five years indicated almost identical performance by both organic nutrient management and integrated nutrient management treatments (18.64 & 18.50 Mg ha^{-1}, respectively) and was greater by 67.3% and 66.1%, respectively, compared with chemical nutrient management (11.14 Mg ha^{-1}) among all the years (Srinivasan *et al*., 2018) [96]. The nutritional sources at 50% inorganic + 50% organic fertilizers increased the yield attributes *viz*., number and weight of mother, primary and secondary rhizomes plant^{-1} and fresh rhizome yield (Tripathi *et al*., 2019) [102]. The fertilizer level of 150:100:100 kg ha^{-1} resulted the highest fresh yield (17855.03 kg ha^{-1}) and dry yield (3.91 t ha^{-1}) on all periods and obtained at harvest followed by 100:75:75 NPK kg ha^{-1} + 19:19:19 foliar spray @ 0.5% at 1, 3, 4 MAT (17455.58 kg ha^{-1}, 3.58 t ha^{-1}) and 75:50:50 kg ha^{-1} + 19:19:19 foliar spray @ 0.5% at 1, 3, 4 MAT. The more secondary rhizomes per plant and higher dry yields of rhizome. The enhanced nitrogen application from 75 kg ha^{-1} to 150 kg ha^{-1} increased rhizome yield to 290 kg ha^{-1} and application of phosphorus significantly increased the rhizome yield and enhanced P application, from 50 kg ha^{-1} to 100 kg ha^{-1} increased rhizome yield to 202 kg ha^{-1} (Mathew and Sreekala, 2019) [55]. The three times split application of 115 kg N ha^{-1} produced significantly higher values for mother and finger rhizome numbers and weights, fresh rhizome yield of turmeric. The three times split application of 115 kg N ha^{-1} produced significantly higher values for mother and finger rhizome numbers and weights, fresh rhizome yield of turmeric (Mekonnen and Garedew, 2019) [57]. The application of N.P.K. (15:15:15) fertilizer at the rate of 150 kg/ha gave significantly higher rhizome plant^{-1} rhizome length (cm), rhizome weight (g) and rhizome yield (t ha^{-1}) of ginger (Ojikpong, 2019) [63]. The fertilizers improved all the agronomic parameters of sweet potato compared to the control treatment. The application of 400 kg ha^{-1} NPK (12:22:22) and 500 kg ha^{-1} (12:22:22) produced significantly maximum number of small and big tuberous roots, number of tuberous roots plant^{-1}, mean weight of tuberous roots, crop index, dry matter content and fresh tubers yield (Sidiky *et al*., 2019) [86]. The drip fertigation with 125% RDF significantly improved all the yield of turmeric. Single plant rhizome weight, rhizome yield plot^{-1}, fresh rhizome yield (t ha^{-1}) significantly increased with the application of 125% RDF drip fertigation in all varieties of turmeric (Soman *et al*., 2019) [91].

The fresh rhizome yield and cured rhizome yield were significantly improved by the nutrient management and nutrient schedules. The application of 50% RDF + 25% FYM + 25% VC produced maximum fresh rhizome yield (21.10 and 22.62 t ha^{-1} during first and second year, respectively) and cured rhizome yield (4.21 and 4.46 t ha^{-1} during first and second year, respectively) (Tripathi *et al*., 2019) [102]. The biochar (15 t/ha), PM (15 t/ha) and NPK fertilizer (200 kg/ha) alone or the combination of biochar with PM or with NPK fertilizer increased the yield (number of rhizomes and fresh rhizome yield) of ginger significantly compared to the control in tropical alfisol with sandy loam soil (Adekiya *et al*., 2020) [2]. The 75% RDN + 25% N through VC on an equivalent basis and 75% RDN + 25% N through FYM on an equivalent basis also 100% RDN + recommended dose of FYM recorded significantly higher biomass yield, rhizome number, rhizome yield and harvest index (Kakar *et al*., 2020) [40]. The application of irrigation at 6 times per day resulted in better rhizome yield regardless of the nutrient volume. Similar results also were observed in the cherry tomato plant that resulted in the higher yield, the number and the weight of fruits with the application of 1,500 ml of water per day. Overall, the highest irrigation frequency is more efficient for plant growth and yield regardless of the nutrient level, with four-six times a day and has a significant effect on rhizome yield compared to twice a day, stated that the frequency of fertigation has an important influence on plant yield (Suhaimi and Zaliha, 2020) [98].

The nutrients were supplied through drip fertigation twice a week and nutrient levels were N_1-80%, N_2-100%, N_3-120% and N_4-140% of RDF and secondary nutrient and micronutrients added to all nutrient levels and they found that the nutrient level N_4 recorded the maximum yield per plant (565.92 g / clump) and dry recovery (27.40%). The nutrient levels were found significant with yield and dry recovery percent of ginger (Supriya *et al*., 2020) [99]. The maximum number of fruits per plant (83.42), weight of fruits (88.53 g), volume of fruits (90.88 cc), length of fruit (5.88 cm), yield per plant (7385.04 g) and yield per square meter (17.72 kg) were reported under fertigation of 125% RDF three days interval followed by at two days fertigation interval (Ameta *et al*., 2021) [7]. The higher instantaneous efficiency of water use in the mist treatment was caused mainly by the higher net photosynthetic rate, the maximal quantum yield of photosystem II and the actual photochemical efficiency of photosystem II in ginger in the shading treatment were significantly higher which is further reflected by the higher rhizome yield of ginger under the mist culture and frequent fertigation system. Therefore, the mist cultivation with frequent fertigation system improved the physiological characteristics and yields of ginger (Bili *et al*., 2021) [21]. The fertigation interval at 3 days interval significantly gave the highest number of bulbs at 2 WAP, 4 WAP, 6 WAP. Red onion growth was mainly affected by interval of fertigation. With 3 days interval, plant will receive more nutrient than those treated with 6 days or 9 days interval, regardless the daily frequency of the application. With more nutrient supply, red onion can grow higher, produced more leaves and more bulbs. However, the yield was affected more by the frequency of daily nutrient supply. Red onion treated with nutrient 3 times/day significantly produced the highest yield. The application of nutrient three times/day provided the highest yield (economical dry weight) (Brotodjojo *et al*., 2021) [24]. With different seed sizes and spacings have better growth, yield and quality potential, in fertilization of 200:75:100 kg NPK ha^{-1} yield plant^{-1} increases with narrow spacing, its mainly reflected in yield hectare^{-1} owing to the effect of density. However, using of smaller seed sizes with high multiplication ratio is preferable where planting material is scarce or limited planting material is to be multiplied under fertilization of 200:75:100 kg NPK ha^{-1} (Chandrashekhar and Hore, 2021) [26].

The application of 3.6 t ha^{-1} organo-mineral fertilizer gave the highest rhizome yield and return on investment in both years. The application of 3.6 t ha^{-1} organo-mineral fertilizer produced significantly highest stand count ha^{-1}, rhizome fresh yield (t ha^{-1}), number of rhizomes ha^{-1} which was found at par with the application 2.4 t ha^{-1} organo-mineral fertilizer (Osunleti *et al*., 2021) [64]. The number of primary (9.56) and secondary fingers per clump (10.91), length of rhizomes (23.22 cm), width of rhizomes (10.64 cm), fresh rhizome yield (48.69 t/ha), of ginger were found maximum with 180% of RDF + 180% Secondary nutrients + Micronutrients (Arif *et al*., 2022) [15]. The 300 kg K ha^{-1} rate had a higher rhizome diameter, rhizome weight per plant, and total yield per ha compared with other K fertilizer rates. The 300 kg K ha^{-1} rate also had the highest yield (per plant and per hectare) compared with other K fertilizer rates. The increases in K from 100 to 300 kg ha^{-1} enhanced yield by 127% to 153% (3.3 to 5.5 t ha^{-1}) during the first and second seasons; this indicated the important role of K in red ginger yield (Azizah *et al*., 2022) [16]. The two-time fertilization practices using NPK (20:10:10 + trace nutrients) and three times foliar fertilization practices using NPK (15:12 + trace nutrients) per orchard increased the yield. The mean values of percent increase in yield and yield parameters by the NPK fertilization were obtained as 8.3% in yield, 13.3% in shelled nut weight, 10.0% in kernel weight and 5.1% in percent kernel efficiency (Kizilkaya *et al*., 2022) [43]. The fertilization of 75% RDF as inorganic fertilizers + 25% RDF as vermicompost recorded the maximum finger length (3.70 cm) and green rhizome yield (10.62 t ha^{-1}) over the other nutrient management in sandy soil of inceptisols of West Bengal (Patra *et al*., 2022) [68]. The growth and yield (plant height, number of leaves and number of fruits) of red chili were significantly affected by combinations of fertigation interval and frequency. Three days interval in once and twice a day frequency resulted in higher of fruit number of chili. The interval and frequency of fertigation didn't significantly affect to the weight and storability of chilies (Padmini *et al*., 2021) [24]. The significantly maximum number of primary and secondary finger clump^{-1}, fresh weight of mother, primary and secondary rhizomes clump^{-1}, length and breadth of mother, primary and secondary rhizomes and dry matter production ha^{-1} at harvest were recorded with 200% RDF (200:100:100 N:P_2O5:K_2O kg ha^{-1}) through drip fertigation + FYM 30 t ha^{-1} + Neem cake t ha^{-1} (Manjunatha *et al*., 2023$_a$) [53].

B. Effect of Fertigation Levels and Intervals on Biochemical-Quality Parameters of Ginger

The crude protein content increased significantly up to 100 kg K,O/ha while all the K levels increased the oleoresin content significantly and the maximum values of crude protein (8.90%) and oleoresin content (9.65%) were recorded with 200 kg K_2O ha^{-1} and 5 tonnes of FYM ha^{-1} (Majumdar *et al*., 2005) [52]. The application of nitrogen at 175 kg ha^{-1} significantly increased the fresh rhizome yield, dry rhizome yield, dry recovery, curcumin content of turmeric during both years (Kandiannan and Chadaragir, 2006) [41]. The treatment with 100% level of N and K application by fertigation through water soluble fertilizers were recorded higher quality contents *viz*., curcumin (4.4%), oleoresin (9.6%) and essential oil (3.8%) with increased carbohydrate and fibre quality which was on par with the treatments N+K @ 100% level by fertigation using straight fertilizers (Urea and MOP) and N+K @ 75% level by fertigation using water soluble fertilizers (Urea and Multi 'K') which registered curcumin contents of 4.2% and 4.3% respectively (Krishnamoorthy *et al*., 2015) [45].

The essential oil content of ginger in organic nutrient management and chemical nutrient management was almost identical (1.0-1.7%), while it was slightly higher at 1.32-4.0% in integrated nutrient management. Rhizome oil components showed that pinene, d-camphene and-phellandrene contents of ginger were higher in chemical nutrient management,-citral (neral) and citronellol in organic nutrient management and-citral (geranial) in integrated nutrient management (Srinivasan *et al*., 2018) [96]. The three times split application of 115 kg N ha^{-1} produced significantly higher values for oleoresin and essential oil contents of turmeric (Mekonnen and Garedew, 2019) [57]. The nutrient management practices have a significant effect on nutrient concentration in the above ground and rhizome part of ginger. Besides nutritive value, essential oil and oleoresin contents affect the economic value of ginger rhizome and integrated nutrient management helped in significantly improving their contents. Essential oil content ranged from 0.47% to 2.46%, with an average content of 1.85%, while oleoresin content varied from 2.20% to 5.78%. Crop quality index based on nutritive and quality aspects, varied from 13.1 to 20.0. The highest crop quality index (20.0) was obtained with the application of 75% RDN + 25% N through VC on an equivalent basis; while organic nutrient management recorded significantly lower CQI (15.0) (Kakar *et al*., 2020) [40].

The higher rhizome yield of ginger under the mist culture and frequent fertigation system. Lower superoxide anion, hydrogen peroxide, and malondialdehyde contents were also found after mist treatment and fertigation system Lower ammonium avoids the potential risk of ammonium toxicity and is based on higher nitrate reductase, glutamine synthetase, and glutamate synthase activity but lower glutamate dehydrogenase activity. Therefore, the mist cultivation with frequent fertigation system improved the physiological characteristics, yields and quality of ginger (Bili *et al*., 2021) [21]. The highest essential oil content (1.40%), oleoresin content (10.20%) and crude fibre content (4.70%) as well as improved carbohydrate in rhizomes were found with 180% of RDF + 180% Secondary nutrients + Micronutrients (Arif *et al*., 2022) [15].

The high antioxidant content because of its gingerols was found in the optimal K use, which was reflected by K fertilizer application at approximately 180 and 300 kg K ha^{-1}. This result indicated that antioxidant content in red ginger can increase by optimizing the K fertilization rate (Azizah *et al*., 2022) [16]. The fertilization of 75% RDF as inorganic fertilizers + 25% RDF as vermicompost recorded the highest content for essential oil (0.45%) and oleoresin (3.74%) with enhanced carbohydrate and fibre quality in rhizomes over the other nutrient management in sandy soil of inceptisols of West Bengal (Patra *et al*., 2022) [68]. The significantly maximum essential oil, oleoresin, crude fibre and gingerol content at harvest in the both the varieties (Rio-de-Janeiro and Himachal) were recorded with 200% RDF (200:100:100 N:P_2O5:K_2O kg ha^{-1}) through drip fertigation + FYM 30 t ha^{-1} + Neem cake t ha^{-1} (Manjunatha *et al*., 2023$_b$) [54].

Conclusion

Ginger cultivation is highly responsive to optimized agronomic practices, particularly shade management, soil selection, and fertigation strategies. Moderate shade levels (20-40%) consistently enhance rhizome yield, photosynthetic activity, and volatile oil content, while mitigating heat stress and promoting efficient translocation of assimilates. Excessive shade, however, reduces crude fiber and overall yield, indicating a need for balance. Similarly, ginger thrives best in well-drained, friable soils such as sandy loams and loamy laterites, with low bulk density, moderate acidity (pH 6.0-6.5), and high organic matter, which collectively enhance nutrient uptake and improve quality traits like essential oils, oleoresins, and gingerols. Fertigation at 100-125% RDF, especially when integrated with organic inputs and applied at stage-specific intervals, significantly improves growth, yield, and biochemical composition. Early frequent fertigation supports vegetative vigour, while controlled application during bulking optimizes rhizome development. Collectively, the integration of moderate shade, ideal soil conditions, and targeted fertigation schedules ensures sustainable ginger production with superior yield and quality, offering a robust strategy for maximizing both agronomic and economic returns.

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