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REVIEW ARTICLE

Nutrient efficiency unlocked: Water-soluble fertilizers in horticultural crop production

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Abstract

Horticultural crops are invaluable to the lands of small and marginal farmers across the nation, making a substantial contribution to the national economy. The significant productivity gap in horticulture is mostly attributable to the inefficient utilization of water and fertilizer resources. Soil fertility has been declining, driven by nutrient depletion and excessive fertilizer application with low nutrient-use efficiency, which hampers productivity despite the steady increase in cultivated area. Numerous research has investigated the application of water-soluble fertilizers to enhance the yield of horticulture crops, achieving greater profitability while minimizing environmental effects. Water-soluble fertilizers are closely linked to improvements in growth, yield attributes and soil fertility in various horticultural crops. These fertilizers offer numerous advantages, such as controlling weed growth, reducing the need for herbicides and enhancing the quality of vegetables and fruits, leading to widespread adoption. Additionally, drip irrigation systems in horticulture have conserved nearly half of the fertilizers and water resources used. Achieving self-sufficiency and sustainability in food production further supports precision farming through water-soluble fertilizers. Consequently, higher nutrient use efficiency (NUE) can be attained, making water-soluble fertilizers an essential component of precision agriculture and site-specific nutrient management.

Keywords

water soluble fertilizers; horticultural crops; nutrient use efficiency; fertigation; water use efficiency

Introduction

Holding the second position globally in total vegetable and fruit production and ranking first in the production of onion, ginger and okra, India also stands 14th in vegetable export and 23rd in fruit export. The horticultural sector is pivotal in supporting global food production and improving the nation's nutritional diet (1). This sector holds immense potential to double farmers incomes, improve livelihoods and boost foreign trade by exporting quality produce (2). Water and nutrients are fundamental to enhancing horticultural yield and quality, yet the lack of studies on their interaction remains a crucial factor behind lower productivity (3). Fertilizers are essential for the growth and production of horticultural crops by supplying necessary plant nutrients and their timely application significantly improves produce quality.

The area under horticultural production had seen significant growth, expanding from 15.69 Mha in 2000 to 28.08 Mha in 2022, with yield increasing from 150.2 Mt in 2000 to 342.3 Mt over the same period (4). This trend is expected to continue. Mineral fertilizer use in agriculture is also projected to rise, from 175 Mt in 2015 to 199 Mt by 2030 (5). However, marginal farmers face challenges with reduced nutrient use efficiency due to high rates of leaching and volatilization, which result in significant nutrient loss and hinder the cultivation of high-yield horticultural crops. Many horticultural crops also deplete soil nutrients extensively, exacerbating this issue.

Water scarcity poses another major threat to sustainable horticultural production, requiring careful management. Because horticultural crops are typically spaced more widely, improper water conveyance can lead to substantial water loss, creating deficits during critical phases such as flowering and fruit development. This, in turn, leads to lower yields and reduced quality (6). Balanced nutrition improves nutrient use efficiency (NUE), increases litter production and enhances biomass generation, indirectly supporting microbial population growth (7, 8) and fostering beneficial nutrient-microbe interactions. This tripartite association has shown benefits in crop yields-for example, papaya under 50% of the recommended fertilizer dose with Azotobacter @ 50g per plant (9) and banana under 100% of the recommended dose of fertilizers with farmyard manure @ 10 kg/plant, *Azospirillum* @ 25 g/plant and phosphate-solubilizing bacteria @ 250g/plant (10). Conversely, lower nutrient use efficiency can reduce crop quality and harm environmental health by diminishing microbial communities, which are essential for nutrient cycling.

Water-soluble fertilizers (WSFs) offer a breakthrough in addressing these 'Twin Threats' by improving nutrient and water use efficiencies. Water soluble fertilizers provide site-specific, timely nutrient delivery, minimizing losses compared to conventional fertilizers (11). High nutrient use efficiency is achieved even with small quantities of WSFs, reducing both cultivation costs and environmental risks. Fertigation facilitates multiple applications, addressing crop requirements at various growth phases, hence enhancing productivity and sustainability in horticulture production. Utilizing WSFs in place of traditional fertilizers improves nitrogen absorption by plants, decreases nutrient leaching from the soil and alleviates problems such as eutrophication in aquatic environments. Increased nutrient uptake enhances nutrient use efficiency, ultimately benefiting farmers financially by reducing cultivation costs. This report highlights the importance of WSFs in improving water productivity and nutrient use efficiency, thereby supporting high-quality horticultural production.

Emerging multi-nutrient deficiencies in soils

Intensive cultivation and imbalanced nutrient application over the past forty years have led to the widespread emergence of secondary and micronutrient deficiencies in addition to primary nutrients like nitrogen, phosphorus and potassium (12, 13). Table 1 presents a statistical summary of available sulphur and micronutrients in Indian soils.

Studies estimating plant and soil samples across various regions of India indicate that approximately 49%, 12%, 5%, 3%, 33% and 11% of Indian soils are deficient in zinc, iron, manganese, copper, boron and molybdenum, respectively (14). The significance of micronutrients in crop growth and development is highlighted, as even minor deficiencies can lead to substantial agricultural challenges (15). In particular, horticultural production on widespread alkaline/calcareous soil presents a severe challenge in maintaining adequate iron levels in the soil (16). Factors such as root morphology, root secretions, plant-microbe associations, and the nature of the plant system also play crucial roles in determining micronutrient availability (17, 18).

It is essential to tailor fertilizer applications to maximize the benefits of horticultural crops. Excessive nitrogen application contributes to the eutrophication of water bodies, while excess phosphorus can exacerbate soil micronutrient deficiencies (19). Therefore, efforts should focus on improving fertilizer use efficiency based on sound scientific principles, rather than indiscriminately increasing fertilizer quantities for horticultural crops.

Nutrient requirement and fertilizer consumption in the horticultural sector

Optimizing fertilizer utilization is a crucial measure for attaining sustainable fruit and vegetable cultivation (3). Fertilizer consumption in India has grown significantly, from 1.54 million tons in 1967-68 to 29.84 million tons in 2022-23 (4). Horticultural crops are heavy consumers of nutrients, accounting for 6% of the country's total fertilizer use-similar to that of sugarcane and cotton and just below the usage for oilseeds (10%) and food grains (69%) (3). The cultivation of various fruits and vegetables typically requires 500-1000 kg ha^{-1} of primary nutrients (nitrogen, phosphorus and

Table 1. Descriptive Statistics of available sulphur and micronutrients in Indian soil **Source:** (13)

Nutrients	Minimum	Maximum	Mean	SD	CV (%)	Skewness	Kurtosis
Sulphur (mg kg^{-1})	0.02	822	27.0	29.9	111	4.28	35.6
Zinc (mg kg^{-1})	0.01	59.8	1.40	1.60	118	7.35	118
Boron (mg kg^{-1})	0.01	109	1.40	4.70	338	12.8	189
Iron (mg kg^{-1})	0.01	964	31.0	52.2	168	5.53	47.3
Copper (mg kg^{-1})	0.01	99.2	2.30	3.50	153	10.8	186
Manganese (mg kg^{-1})	0.01	483	17.5	21.4	122	5.72	59.7

potassium) (20), with an average fertilizer consumption of 219 kg ha^{-1} in India, compared to a global average of 259 kg ha^{-1} (21). Unbalanced fertilizer application is a concern in horticultural crops. Soil surveys in vineyards across Maharashtra and Karnataka have shown that excessive fertilizer application-up to 3 tons per hectare-intended to boost yield has led to reduced fruit quality, environmental degradation and groundwater contamination (22). While perennial crops such as guava and mango receive minimal fertilization, crops like vineyards, pomegranate groves and vegetables in some Indian states are often over-fertilized (23). Beyond water pollution, excessive chemical fertilizers disrupt microbial populations, increase soil acidity and degrade soil quality. Heavy metal contamination from such fertilizers also poses severe health risks and contaminates groundwater (24). The decadal shift in the nitrogen, phosphorus and potassium requirements of horticultural crops is shown in Table 2. Table 3 highlights major horticultural crops and their nutrient removal, while Table 4 provides generalized fertilizer recommendations.

Water Soluble Fertilizers and Use Efficiency

Fertigation is rapidly gaining traction in the horticultural sector due to its ability to improve both water and fertilizer use efficiencies, which in turn is increasing the demand for water-soluble fertilizers (WSFs). In fruit plantations, fertigation provides dual benefits, conserving up to 30-50% of nutrients and water (1). Fertigating crops with WSFs aligns nutrient application with crop needs, significantly reducing leaching and runoff losses (11). Table 5 presents data on improved fertilizer use efficiency across different application methods.

With the introduction of an advanced fertilization programme, WSFs have become a preferred choice for farmers due to their numerous benefits, including high solubility, nutrient delivery and compatibility with micro-irrigation systems. The complete solubilization and low salt index of WSFs help prevent clogging from precipitate formation in lateral systems. In sprinkler systems, fertilizers applied as a fine mist cover plant surface, enabling faster nutrient uptake, while drip fertigation effectively controls weed growth (11). WSFs provide essential plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K), along with secondary

Table 2. Decadal change in NPK requirement (t) of horticultural crops **Source**: (23)

Sector	2003-04				2013-14				% increase over the	2018-19				% increase over
	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total		N	P_2O_5	K_2O	Total	
Fruits	738857	393081	683162	1815100	1724261	1080930	1777036	4582226	153	1623217	1015340	1710995	4349551	140
Vegetables	475215	450647	506230	1432093	1032882	922450	1033186	2988518	109	941199	855918	970401	2767517	93
Flowers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Aromatic and medicinal crops	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Plantation crops	322500	157645	525940	1006085	383350	185130	607560	1176040	17	389630	186720	608210	1184560	18
Spices	NA	NA	NA	NA	226,785	151493	181486.5	559764	-	268651	192316	239645	700611	-
Grand Total	1536572	1001373	1715332	4253277	3367278	2340003	3599269	9306548	119	3222697	2250294	3529251	9002239	112

Table 3. Nutrient removal by horticultural crops **Source**: (23)

Crop	Yield (t ha^{-1})	Nutrient removal (kg ha^{-1})		
		N	P	K
		Fruits		
Mango	15.0	100	25	110
Banana	57.5	322	73	1180
Citrus	20.0	22	12	57
Guava	20.0	120	50	150
Pomegranate	40.0	44	8	70
Apple	29.0	18	2	40
Pineapple	84.0	150	45	530
Papaya	80.0	225	60	180
Grapes	20.0	160	40	180
		Vegetables		
Potato	28	202	50	225
Brinjal	60	175	40	300
Tomato	37	104	22	141
Cauliflower	35	250	100	350
Cabbage	25	112	28	112
Beans	30	130	40	160
Green peas	25	55	20	40
Lettuce	30	160	30	234
Spinach	25	120	45	200
Celery	20	140	55	220
Onion	30	73	36	68

Table 4. General fertilizer recommendations of horticultural crops **Source**: (70)

Crops	Recommended dose of NPK (kg ha^{-1})		
	N	P_2O_5	K_2O
Fruits			
Banana	620	310	620
Mango	75	20	70
Citrus	110	35	55
Papaya	925	925	925
Guava	250	175	175
Apple	320	320	320
Pineapple	275	70	200
Sapota	100	50	50
Grapes	300	300	600
Pomegranate	500	425	975
Litchi	50	50	25
Vegetables			
Potato	60	100	120
Tomato	180	120	150
Onion	125	75	125
Brinjal	180	150	120
Tapioca	45	90	120
Cabbage	150	125	100
Cauliflower	150	100	100
Okra	100	50	50
Peas	25	75	60
Sweet potato	20	40	60
Chilli	150	75	75
Plantation crops			
Coconut	100	55	210
Cashew nut	100	40	60
Arecanut	140	55	200
Cocoa	70	30	100
Spice crop			
Garlic	40	75	75
Turmeric	150	60	108
Ginger	37.5	50	37.5
Cumin	30	20	20
Coriander	10	40	20
Tamarind	20	15	25
Fenugreek	30	25	40
Fennel	50	10	10
Pepper	110	50	155
Cardamom	75	75	150
Ajwan	40	20	20
Nutmeg	187.5	187.5	600

Table 5. Fertilizer use efficiency under different methods of application

Source: (70)

Nutrient	Fertilizer use efficiency (%)		
	Soil application	Drip	Fertigation
Nitrogen	30-50	65	95
Phosphorus	20	30	45
Potassium	50	60	80

nutrients like calcium, magnesium, sulfur and various micronutrients, making them adaptable to soils with diverse fertility levels and different climatic conditions. A schematic illustration of fertigation with WSFs is shown in Fig. 1. WSFs offer several advantages, including 100% solubility, absence of inert materials, high purity, readily available nutrients, a low salt index and an acidic reaction that enhances nutrient use efficiency (3). Although the popularity and usage of WSFs in India remain limited compared to developed countries (25), there is considerable potential for expansion within the horticultural sector. As of now, the Fertilizer Control Order (FCO) of 1988 has sanctioned eighteen grades of fully water-soluble fertilizers (Table 6). The solubility of common WSFs is provided in Table 7.

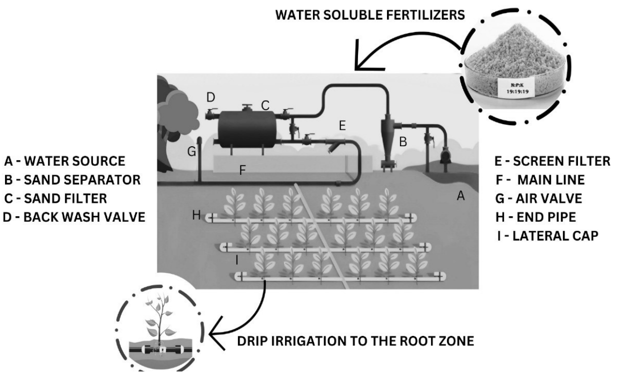

Fig. 1. Fertigation with water-soluble fertilizers

Source: Data collected from various sources)

Table 6. Nutrient composition of Fertilizer Control Order approved water-soluble fertilizers **Source:** (3)

Name of the product (Grade)	Nutrient Composition (%)						
	Nitrogen	P_2O_5	K_2O	S	Ca	MgO	Zn
Potassium Nitrate (13-0-45)	13	0	45	-	-	-	-
Mono Potassium Phosphate (0-52-34)	0	52	34	-	-	-	-
Calcium Nitrate	15.5			-	18.8	-	-
NPK (13-40-13)	13	40	13	-	-	-	-
NPK (18-18-18)	18	18	18	-	-	-	-
NPK (13-5-26)	13	5	26	-	-	-	-
NPK (6-12-36)	6	12	36	-	-	-	-
NPK (20-20-20)	20	20	20	-	-	-	-
NPK (19-19-19)	19	19	19	-	-	-	-
Potassium Magnesium Sulphate			22	20	-	18	
Mono Ammonium Phosphate (12-61-0)	12	61	-	-	-	-	-
Urea Phosphate (17-44-0)	17	44	-	-	-	-	-

Table 7. Solubility of different water-soluble fertilizers **Source:** (3)

Fertilizer	Grade	Solubility (g/l) at 20°C	pH (1 g/ l @ 20°C)
Water Soluble special fertilizers			
Mono Ammonium Phosphate (MAP)	12-61-0	282	4.9
Poly feed (PF)	19-19-19		
Mono potassium phosphate (MKP)	0-52-34	230	5.5
Potassium nitrate (multi-K)	13-0-46	316	7.0
Sulphate of potash	0-0-50		
Orthophosphoric acid	0-52-0	457	5.5
Conventional fertilizer			
Urea	46-0-0	1100	3.7
Ammonium nitrate	34-0-0	1920	5.7
Calcium nitrate	16-0-0	1290	5.8
Potassium chloride (Red)	0-0-60	347	7.0
Potassium sulphate (White)	0-0-50	110	3.7
Ammonium sulphate	21-0-0	760	5.5

Effect of WSFs on growth and yield attributes of horticultural crops

Water-soluble fertilizers (WSFs) enable precise nutrient delivery and are thus absorbed by plants more efficiently than traditional fertilizers. Studies have reported that growth indicators, such as the number of branches, plant height and yield attributes, were higher in tomatoes when treated with five foliar sprays of WSFs (26-29). Similar beneficial effects of WSF application have been observed across various horticultural crops, including banana (30), watermelon (31), guava (32), lettuce (33), onion (34), chili (35, 36), okra (36, 37), bottle gourd (38-40), cucumber (41, 42), potato (43), carrot (44), cabbage (45), tuberose (46), marigold (47-49) and coconut (50). Moreover, WSF application has been shown to reduce the number of days to reach 50% flowering in these studies. The contribution of WSFs to yield improvement in horticultural crops is illustrated in Fig. 2.

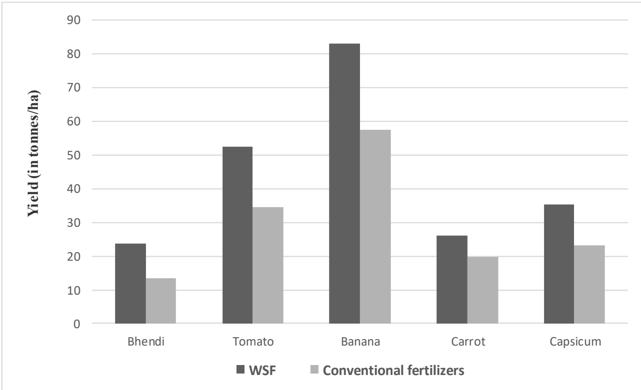

Fig. 2. Contribution of WSF to yield improvement of crops

Source: (Data collected from various sources)

Effect of WSFs on the quality of horticultural crops

Applying water-soluble fertilizers (WSFs) has been shown to improve the quality of horticultural crop production. For example, WSFs have been reported to increase total soluble solids in bananas (30), tomatoes (29) and carrots (44), as well as lycopene content in tomatoes (29). Similarly, WSF use has enhanced ascorbic acid and total phenol content in eggplant (51), vitamin C content in capsicum (52), soluble protein and sugars in lettuce (33) and total titratable acidity in watermelon (31) compared to conventional fertilizers.

Effect of WSFs on soil nutrient availability, nutrient use efficiency and water use efficiency

Water-soluble fertilizers (WSFs) have improved the availability of both macronutrients and micronutrients in the soil (26, 38, 53, 54). Since WSFs are applied through drip or foliar methods, there are minimal losses due to leaching and evaporation. This application method helps sustain healthy dry matter production, which is crucial in maintaining satisfactory soil organic carbon levels (55). Fertigation, which involves the direct supply of nutrients at the root zone, makes nutrient application and plant uptake highly efficient (56). Water-soluble fertilizers facilitate the implementation of the 4Rs of nutrient application: applying the right product at the correct rate, at the right time and in the right place. Reports demonstrate that tomato exhibits the highest water use efficiency and maximum nitrogen use efficiency (29, 57), although elevated phosphorus and potassium use efficiencies have been recorded in Syngonium and lettuce with the administration of WSFs via a drip method (54, 58). Additionally, the nitrogen, phosphorus and potassium content were higher in chilli when WSFs were applied (35).

The foliar application enhances the movement of sugars and other exudates from the root portion to the surrounding soil (rhizosphere) (59). These exudates attract beneficial microbial communities to the root zone, promoting increased biological activity around the roots, which helps maintain nutrient availability. An experiment investigating the nutrient content of coriander leaves concerning different fertigation levels using various WSFs revealed that the application of 125% recommended dose of fertilizers (RDF) through WSF resulted in higher nitrogen (3.36%), phosphorus (0.25%) and potassium (4.39%) content (60). Fertigated papaya plants treated with WSFs exhibited improved nutritional content, stomatal conductance, physiological efficiency, relative water content, photochemical efficiency, net photosynthesis and water productivity compared to non-fertigated plants (61-63). Additionally, enhanced nutrient uptake and use efficiency of 38.96 kg ha^{-1} was observed in onion under fertigation with TNAU-WSF at 125% RDF, along with sulphur and TNAU-LMM (Liquid Multi Micronutrient) (64). The contribution of WSFs to various attributes of horticultural crops is presented in Table 9.

Effect of WSFs on cost economics

The highest benefit-cost ratio (BCR) of 4.46 for tomatoes was observed with the foliar application of WSFs (28). In chilli, the highest BCR of 3.27 and the most significant net returns of Rs.1,83,196 per ha were achieved through fertigated with WSF at 100% RDF (36). Additionally, a maximum BCR of 2.99 was recorded under wider spacing and 2.83 under closer spacing of bhendi, both fertigated with WSFs at 100% RDF (37). Similarly, the highest BCRs have been documented for cucumber, ridge gourd (65), tomato (66), bitter gourd (67, 68) and cauliflower (69) under fertigation with WSFs at 100% RDF, primarily due to the provision of balanced nutrition. The economics of conventional fertilizers compared to WSFs is presented in Table 8.

Table 8. Economics of water-soluble fertilizers and conventional fertilizers

Crop	Water Soluble Fertilizers	Conventional fertilizers/ control	References
Tomato	4.12	2.83	(71)
Chilli	3.27	2.4	(36)
Bhendi	2.99	1.46	(37)
Soybean	2.45	1.84	(72)
Cauliflower	4.40	0.71	(69)
Bitter gourd	4.99	4.03	(67)
Cucumber	1.69	1.27	(73)
Onion	3.25	2.21	(64)

Table 9. Contribution of WSFs in improving various attributes of horticultural crops

Crop	Influence of WSF on various attributes of horticultural crops	References
	Growth attributes	
Guava	Maximum plant height of 390 cm under fertigation of 100% Recommended Dose of Fertilizer through WSF	(32)
Tomato	Maximum number of branches (12.3), maximum plant height of 84.5 cm under 100% WSF	(27, 71)
Chilli	Maximum number of branches (8.4), maximum plant height (62.2 cm) with fertigation through WSF	(35)
Carrot	Maximum plant height of 43.27 cm, higher leaf production (10.4) under foliar application of 2% WSF	(44)
Cabbage	The highest leaf length of the outer leaf (22.46) and maximum leaf area (504.90 cm^2) under fertigation of WSF	(45)
Bitter gourd	Increased vine length and number of primary branches with fertigation of WSFs	(74)
	Yield attributes	
Tomato	Maximum fruit yield of 70.77 t/ha and maximum fruit weight of 8.7 g under fertigation of 100% Recommended Dose of Fertilizer through WSF	(28)
Chilli	Maximum fruit weight of 8.7 g under fertigation of 100% Recommended Dose of Fertilizer through WSF	(36)
Bhendi	Enhanced pod yield of 23.79 kg ha^{-1} under fertigation with WSF	(37)
Lettuce	Maximum yield of 16.82 t/ha under fertigation of WSF.	(33)
Tuberose	Highest spike yield of 39.40/m^2 under application of 75% RDF as WSF	(46)
Bottle gourd	Maximum fruit yield of 39.19 t/ha under 100% Recommended Dose of Fertilizer of WSF.	(40)
Cucumber	Highest fruit yield of 25.5 t/ha under fertigation with WSF	(42)
	Qualitative attributes	
Capsicum	The highest vitamin C content of 28.27 under the 100% Recommended Dose of Fertilizer through WSF	(52)
Cocoa	Maximum number of cushions and pollen diameter under fertigation of 125% Recommended Dose of Fertilizer through WSF	(75)
Tomato, Banana, Carrot	Enhanced Total Soluble Solids of 4.41° Brix through fertigation with WSF	(26, 30, 44)
Brinjal	The Total phenolic content of 0.14 g was recorded under 100% RDF with 1% WSF as a foliar spray.	(51)
Watermelon	Total Titrable Acidity was higher under fertigation with 150 % RDF as WSF.	(31)
Lettuce	Highest vitamin C content of 110.65 µg/g, soluble protein (6.78 mg/g), soluble sugars (13.09 mg/g) at 100% Recommended Dose of Fertilizer through fertigation of WSFs	(33)
Banana	Improved fruit texture with a rating of 8.25, colour and appearance of 7.90 under fertigation with 100% WSF	(30)
Ridge gourd	Highest ascorbic acid content (8.14 mg/100g) under fertigation of 125% Recommended Dose of Fertilizer through water soluble fertilizers	(65)

Conclusion

Water-soluble fertilizers used in drip fertigation systems have become a game-changer in modern horticultural practices, offering numerous advantages over traditional farming methods. The amalgamation of WSFs with drip irrigation facilitates the accurate delivery of vital nutrients straight to the root zone while enhancing nutrient accessibility for plants. This method markedly improves nutrient usage efficiency (NUE), decreasing fertilizer requirements and mitigating nutrient runoff and leaching losses, which are prevalent challenges in traditional fertilization practices. In water-scarce situations, combining WSFs with drip irrigation can lead to substantial water savings, ensuring that crops receive only the necessary amount of water, thereby avoiding over-irrigation and water wastage. The precise delivery of nutrients results in higher crop yields and better-quality produce, improving the market value for horticultural products. Moreover, WSFs diminish the necessity for manpower and machinery commonly linked to the use of conventional fertilizers, hence significantly reducing operational expenses for farmers.

Regarding crop health, WSFs positively influence both growth parameters and quality attributes of fruits and vegetables. Benefits include enhanced chlorophyll content, improved fruit size, higher total soluble solids (TSS) and increased concentrations of vitamins and nutrients. This quality improvement, combined with better yields, ensures that farmers enjoy higher profits as their produce becomes more appealing to consumers and meets export market standards. Providing high-quality produce enhances the purchasing power of local communities and has a positive impact on maintaining food security at the grassroots level. Furthermore, WSFs play a crucial role in environmental conservation by reducing the pollution associated with excessive fertilizer use. Research indicates that by switching to WSFs, farmers can achieve cost savings of 40-60% on fertilizer expenses while simultaneously increasing crop productivity. By installing micro-irrigation systems under the Pradhan Mantri Krishi Sinchayee Yojana, the farming community can benefit and the provision of WSFs at subsidized rates by government bodies should be encouraged.

Future Strategies

With the paradigm shift in the acreage of horticultural crops, there is significant potential for speciality fertilizers and water-soluble fertilizers (WSFs), as many farmers have transitioned to micro-irrigation systems to optimize water and fertilizer use. Given their high nutrient use efficiencies, the recommendation of nutrients through WSFs must be standardized by crop and growth stage. Research should concentrate on elucidating the interaction effects of irrigation water and WSFs, given India's various water quality regulations. Customized formulations must be developed to address multiple nutrient deficiencies. Additionally, fertigation schedules and benefit-cost ratios for WSFs should be established for all horticultural crops. Ensuring quality control of WSFs is essential to prevent the entry of non-standard materials into the market. Furthermore, increasing awareness among farmers about the benefits of WSFs in precision agriculture is crucial.

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Authors' contributions

JL drafted the original manuscript, while CS contributed to the final drafting and critically revised it for important intellectual content. US provided final approval for the version to be published. RKK assisted in the literature collection necessary for developing the manuscript, and CIR supervised the project and contributed to the visualization of the original work. Finally, PL reviewed and oversaw the editing process to ensure the manuscript's accuracy and coherence.

Compliance with ethical standards

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