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Multiple nutrient stress in fruit crops : road to soil health-mediated quality production — a review

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Abstract

Fruit crops by the virtue of their extended juvenility , sharply delineated crop phenological growth stages , and ability to produce biomass per unit use of inputs, higher than cereal crops , are infact more mechanistically tailored to tolerate multiple nutrient stress. Productivity of fruit crops depends essentially on two premier facts, nutrient balance and biological activity , provided optimum soil moisture is maintained . Though , fruit crops are highly microbes -responsive , but combination of microbes-mycorrhizas produced much better crop responses , an indication of nutrient-constraint-neutral production system. Of late, paradigm shift from inorganic to organic manures-inorganic nutrients -microbes mediated associative crop response have aided in developing the far sustainable and climate -resilient fruit production system. Our long term data (2007-19) accrued on response of organic manures versus inorganic fertilizers demonstrated that important soil quality indices like soil microbial diversity, soil microbial biomass nutrient, and organic carbon partitioning displayed significant changes, but without much difference in quantum of fruit yield (but coupled with a-grade size fruits) when compared with purely inorganic fertilizer schedule. Combination of inorganic fertilizers -vermicompost -microbial consortium aided in saving 30-40% of crop nutrient requirement without any compromise on fruit yield or quality , besides lower rate of CO2 release compared to inorganic fertilizers , an evidence of carbon deposited in passive soil organic carbon pool, in addition to reducing the fertilizer doses by 30-40% and elevating the post-harvest shelf life of citrus fruits. We further introduced the concept of “rhizosphere hybridization” to harness the value -added benefits of nutrient -microbe synergy, besides providing better crop responsiveness to microbial consortium suiting to wide range of perennial fruits under both optimum as well as soil water deficit stress. Role of biochars (more recalcitrant carbon source) and arbuscular mycorrhizas-mediated glomalins (glycoproteins) have to be increasingly brought into the regular practice while addressing the multiple nutrient stress backed up with crop phenology -based 8-10 pulse fertigation schedules . These attempts could be translated into developing a robust toolbox (catering to 4R X 4W principles) for addressing multiple nutrient stress on a mutually exclusive basis , provided current methods of diagnosis of soil fertility constraints en-route precision diagnosis.

Key words: Fruit crops, Carbon sequestration, Customized fertilizer mixture, Integrated soil fertility management, Nutrient-microbes synergy, Microbial consortium, Multiple nutrient stress, Nutrient schedules, Organic manures evaluation

Globally, fruit crops occupy an area of 65.29 million ha with a production of 883 million tons (average productivity of 13.52 tons/ha) and fresh fruit market of USD 726.20 billion to further expand at an annual growth rate of 6.58% from 2024 onwards (FAO, 2023). The world trade of fruits is dominated by apple-pears, bananas, berries -grapes, and citrus fruits accounting 74.20% of fresh fruit market, with other fruits contributing only 25.80%. Approximately 1.7 million (2.8%) human deaths worldwide are attributable to micronutrient deficiency induced through suboptimum consumption of fruits and vegetables, and regarded as one of the top 10 selected risks for global mortality (WHO, 2021).

In the current era of climate change on continuous rampage triggering an upsurge in aridity , nutrient-efficient plants will play a major role in sustaining the crop yield compared to yesteryears , amidst newer challenges like shrinking land and water resources available for fruit crop production (often comes from competitive cereal-based land uses) , higher cost of inorganic fertilizer inputs, declining trends in crop yields globally, and increasing environmental concerns (Srivastava , 2013c; Srivastava and Pongener , 2023). Furthermore, at least 60% of the world's arable lands have mineral deficiencies or elemental toxicity problems and, on such soils, fertilizers and lime amendments are essential for achieving improved crop yields (Pathak and Nedwell, 2011). In the light of climate change related issues, fruit trees besides being severely challenged by multiple nutrient deficiencies, are widely claimed to play an important role in carbon cycle of terrestrial ecosystems and sequestering atmospheric CO_2 (Lobell *et al.*,2005; Guimãraes *et al*., 2014) as a part of sustaining the ongoing growth of fruit industry. According to Wu *et al.* (2012), net C- sink and C- storage in biomass of apple orchard ranged from 19 to 32 Tg C and from 230 to 475 Tg C in 20- years period, amounting to 4.5% of total net C sink in the terrestrial ecosystems in China. In an estimate, Lakso (2010) observed that an acre of apple

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orchard fixed about 20 tonnes of CO_2 from the air each season, and provided over 15 tonnes of CO_2, equivalent to over 5 billion BTU of cooling power. The atmospheric carbon fixing ability of fruit crops under soil waster deficit stress is, hence considered quite instrumental in negating the impact of multiple nutrient stress.

In sustaining the productivity potential of fruit crops under soil water deficit conditions, there will be an increasing importance of nutrient efficient cultivars (higher yields per unit of nutrients applied or absorbed than standard cultivars under similar agroecological conditions) that are higher producers under multiple nutrient stress (Srivastava, 2013a; Malhotra and Srivastava, 2015) . In the past, much research has been conducted to identify and/or breed nutrient efficient plant species or genotypes/cultivars within different fruit species, but the success in releasing nutrient efficient cultivars has been far limited (Dong *et al*., 2023). The main reasons for limited success are the genetics of plant responses to nutrients and plant interactions with environmental variables, not so well understood even today (Fageria *et al*., 2008). Fruit crops by the virtue of their perennial nature of woody framework (nutrients locked therein), extended physiological stages of growth, differential root distribution pattern (root volume distribution), growth stages from the point of view of nutrient requirement, and preferential requirement of some nutrients by specific fruit crop, collectively make them different than the annual crops (Srivastava and Singh, 2008a ; Srivastava and Malhotra, 2017).

Rengel *et al*. (1996) observed that the total number of bacterial colony forming units increased in the rhizosphere of Zn-efficient genotypes of wheat under Zn-deficiency and in Mn-efficient genotypes under conditions of Mn-deficiency. In contrast, a Zn-deficiency treatment acted synergistically with the number of fluorescent *Pseudomonas* in the rhizospheres. These studies provide strong clues that fruit crops exposed to varying nutrient stresses recruit plant growth promoting microorganisms, playing an important role in producing crop responses through number of mechanisms comprised of biological nitrogen fixation, growth hormone production, phosphate solubilization , siderophore production, hydrolytic enzymes production, and antagonistic activityAnother group of microorganisms, popularly known as arbuscular mycorrhizal fungi (Wu *et al*., 2013 ; 2014; Zhang *et al*., 2015) are equally effective in substantially improving the nutrient acquisition capacity of fruit crops, in addition to enriching the rhizosphere biologically in a much activated form (Liu *et al*., 2014; Huang *et al*.,2014; Zou *et al*., 2014).

A still bigger question emerges, whether rhizosphere competent microbes could collectively contribute towards improved resilience of plant's rhizosphere (Wang et al., 2014). And if those microbes are so successful in promoting growth response, addition of starter nutrients in such combination may further magnify the magnitude of response called nutrient-microbe synergy. Our earlier studies have shown that rhizosphere effective microbes have the tendency to play multiple roles (Keditsu and Srivastava, 2014 ; Wu *et al*., 2013) to overcome various biotic and abiotic stresses while interacting with an environment. Mineral fertilizers on the other hand as a main stream of direct nutrient supply, their application can enhance the soil biological activity via increases in system productivity, crop residue return, and soil organic matter (Khandelwal *et al*., 2013). Therefore, a sound understanding of nutrient-microbe synergy could possibly lay a solid foundation in unlocking the productivity potential of perennial fruit crops, besides safeguarding the soil health, both physico-chemically as well as biologically. In this background, systematic efforts were made to analyse the relationship between inorganic nutrients (macronutrients versus micronutrients) -organic manures (manures versus green manure) -microbial inoculants (single versus microbial consortium) and fruit crops as a holistic approach to address multiple nutrient stress jeopardizing the production sustainability , either under optimum soil moisture or water deficit stress during any growth stage of crop .

Nutrient-microbes relationship, a toolkit to neutralize multiple nutrient stress

The microbial communities associated with plants are known as the plant microbiome or phytobiome, comprised of an array of microorganisms such as bacteria , fungi, oomycetes, viruses, and different microbial habitats known by the terms like rhizosphere, phyllosphere, and endosphere (Berg, 2009). The phytobiome is an emerging field of research aimed at generating a system slevel understanding of plant-microbe interactions which influence plant health and plant productivity. The study of phytobiomes is currently in its infancy, and most research focuses on profiling plant microbiomes in different hosts and environments. The interactions between the microbiome and plant are highly complex and dynamic. The interactions among plant and microbes can be beneficial (mutualistic), neutral (commensalism), or detrimental (parasitic). Consequently, the plant microbiome dramatically affects plant health and productivity (Guttman *et al*., 2014). Hence, soil microbial count-related traits are more sensitive to soil fertility parameters.

Microbes and macronutrients bioavailability: The rhizosphere supports large and active microbial populations capable of exerting beneficial, neutral, or detrimental effects of plant growth. Plant growth promoting microbes have been reported to enhance plant growth directly by a variety of mechanisms; fixation of atmospheric N that is transferred to the plant, production of siderophores that chelate Fe and make it available to the plant root, solubilization of minerals such as P, and synthesis of phytohormones (Dobbelaere *et al*,. 2003). Direct enhancement of mineral uptake due to increases inspecific ion fluxes at the root surface in the presence of PGPR has also been reported (Bertrand *et al*., 2015 ; Tilak *et al*., 2005). Okon and Labandera-Gonzalez (1994) evaluated worldwide data accumulated over the previous 20 years on field inoculation with *Azospirillum,* and concluded that these bacteria are capable of promoting the yield of crops in different soils and climatic areas. *Azospirillum* spp. are involved in the biological fixation of N and the increased activity of glutamate dehydrogenase and glutamine synthetase (Ribaudo *et al*., 2006 ; Thaler *et al*., 2003). *Azospirillum brasilense* produces high quantities of extracellular indole-3-acetic acid (IAA), increasing root elongation, root surface area, and root dry matter (Molla *et al.,* 1984). However, considering the vital role of microbes in the maintenance and buildup of soil fertility, their utility is indispensable.

The phosphate-solubilising microorganisms popularlyknownasPSMinvolvephosphate sources, mainly of two types, : i. mineral (fluorapatite, hydroxyapatite, tircalcium phosphate, mono- and dicalcium phosphate, rock phosphate, and iron phosphate) and ii. organic nature (phytin, lecithin, hexose monophosphatic ester, phenyl phosphate, and calcium glycerophosphate) according to Joseph *et al.* (2015). Various species of *Trichoderma* as dual purpose microbe (phosphate solubilizer as well as microbial antagonist) were also effective in the promotion of growth and yield in various crops (Kalayu , 2019). Both the species of *Trichoderma,* viz., *T. harzianum* and *T. virens* promoted growth of variety of fruit crops (Joseph *et al.,* 2015 ; Chen *et al.* , 2023) . On the other hand, application of *Trichoderma* was not conducive to increased yields of some annual crops (Wang *et al*., 2022), suggesting some kind of inconsistency in response. Unfortunately, many studies carried out in the past have not been given due consideration due to exploitation of the potassium solubilising ability of microbes. Latest critical reviews (Bist *et al*., 2020 ; Afify, 2022) stated that although K is released from silicates by microorganisms, the process is not active enough to complete provision of the plants with this element.

Microbial solubilisation of micronutrients: Microorganisms attached to soil mineral surfaces ably create micro-environments where concentration of ligand, acidity and redox activity is substantially improved compared to the bulk soil, thus effecting mineral exchange reactions (Rogers and Bennett, 2004; Barker *et al.*, 1997). The so-called fluorescent pseudomonads *Pseudomonas aeruginosa*, *P. fluorescens*, and *P. putida* produce a water- soluble yellow-green fluorescent (under UV light) pigment called pyoverdine (Meyer and Abdallah, 1997). This pigment is responsible for the characteristic fluorescence of the cell and has also been identified as an iron-chelating siderophore (Schalk and Guillon , 2012).

Another important factor for the colonization of plant roots, especially under iron-limiting condition, is the synthesis of siderophores from *Pseudomonas*, which are iron-chelating compounds (Cornelius and Dingemans, 2013). Pseudomonas siderophore have a high affinity for iron, and when they chelate this micro-nutrient, they make it less available for other microorganisms, including plant pathogens (Ahmad *et al.*, 2008 ; Olanrewaju *et al*., 2017). The synthesis of siderophores is, therefore, important to confer an advantage in the competition for nutrients and space with regard solubilization of micronutrients in the rhizosphere .The bacterial genera viz.,, *Azotobacter, Azospirillum*, *Bacillus*, *Gluconacetobacter*, and *Pseudomonas*, have all been identified as Zn solubilizers (Lindsay and Norvell, 1978). Arbuscular mycorrhizae and the genus Trichoderma are the two groups of fungi possessing Zn-solubilizing activities in soil (Li *et al*., 2015). Recently, the discovery of Zn nanoparticles from the cell-free culture filtrates of *Pseudomonas*, *Bacillus*, and *Azospirillum* strains suggested that these microbes might solubilize Zn by producing nanoparticles to mobilize nutrients in the rhizosphere (Sultana *et al*., 2020).

Endophytes are generally known as non-pathogenic microbes that colonize inside plant tissues including roots . The beneficial effects of root endophytes on plant growth has been extensively discussed (Gouda *et al*., 2016; White *et al*., 2019) . Besides plant growth, there is emerging evidence showing the involvement of endophytic fungi in biofortification. The symbiotic mechanism involves extensive interactions between plants and endophytes . Plants excrete metabolites to initiate the symbiosis with these fungi. Endophytes can enhance the accumulation of nutrients including Fe, Zn, vitamin-B, vitamin- C, flavonoids, and saponins. In addition, endophytes can also enhance the accumulation of nitrogen and minerals in crops. Since the adverse effects of nitrogen fertilizer on the environment has been well known , microbe-mediated biofortification could be a "greener" alternative to provide (Khan *et al*., 2009).

Trichoderma species are not only found to solubilize phosphorus but other important nutrients- through various mechanisms. They react to limiting iron conditions by using a high-affinity iron uptake system based on the release of iron chelating molecules called siderophores. This chelated iron is not available to plant pathogens, whose activity is thereby reduced (Baker *et al*,. 2003), while plant roots can take up chelated irons either directly or after reduction of Fe^{3+} by plasma membrane reductases (Welch *et al.,* 1993).

Mycorrhizal dependence of fruit crops :Soil microorganisms are a major driving force in soil fertility transformations (Xuan *et al*., 2011; Srivastava , 2023). And of them, arbuscular mycorrhizal fungi (AMF) are the ubiquitous root symbiotic fungi that belong to the phylum Glomeromycota, possess a distinctive role in soil processes such as nutrient cycling and soil structural improvements (Rillig , 2004) , including the gobal carbon dynamics (Hawkins *et al*., 2023) due to their widespread presence in soils. AMF fungi can form mutualistic relationships with over 80% of land's plants, namely, arbuscular mycorrhizas (AMs). This symbiosis is the most common mycorrhizal association in natural ecosystems , and partly undertakes the absorption and delivery of mineral nutrition and water from the soil to the host plant by mycorrhizal hyphae (Begum *et al*., 2019). Therefore, AMs are critical for plant health, survival, and restoration in fruits -based agro-ecosystems (Liu *et al*., 2024).

The rhizosphere properties governing the crop performance are characterized by changes in soil fertility (available nutrients), nature of proteins binding soil particles into different aggregate sizes commonly known as water-stable aggregate and soil carbon pool (Ngullie *et al*., 2015) . Different species or communities of AMF have been observed to promote soil aggregation to varying degrees . However, the mechanisms involved are still inconclusively understood. Extensive hyphae of AMF enmesh soil particles and increase soil water repellency , thus, facilitating the formation and stabilization of soil aggregates. These hyphae also release an insoluble N-linked glycoprotein, called as glomalin, which contains ~60% carbohydrates and showed 3–10 times higher soil aggregating ability than hot-water-extractable carbohydrates (Wu *et al*., 2015).

Glomalin in soils is defined as glomalin-related soil protein (GRSP) (Rillig, 2004). Studies have proven the highly positive correlate on of GRSP with aggregate stability, irrespective of soil types (Wu et al., 2014). In citrus rhizosphere, we have found significantly positively correlation of GRSP with water stable aggregates at the size of 0.25–0.50 mm in field (Wu *et al*., 2017), and the contribution of GRSP to soil aggregate stability lied on water stable aggregates fractions (Wang et al., 2014). Recently, GRSP was classified into three fractions : fraction 1 of Bradford-reactive soil protein (BRSP) (highly labile GRSP, corresponding to easily-extractable glomalin-related soil protein), fraction 2 of BRSP (relatively more recalcitrant in soil, corresponding to difficultly-extractable glomalin-related soil protein), and total BRSP (fraction 1 + fraction 2 = T-BSRP) according to studies by Wu *et al*. (2015).

Plants can synthesize specific microbial structure according to their metabolic requirement and consequently the root exudates to varying composition, thereby, influencing rhizosphere properties on various accounts (Wu *et al.,* 2017). On the other hand, besides GRSP, AMF also develop an extraradical hyphae network to enmesh soil aggregates and induced more SOC to cement aggregates (Wu *et al*., 2014; 2015) . In principle, fruit crops have been observed highly AM-dependent crops evident from various kinds of soils-plant health -related parameters. Mycorrhizae have also been helpful in improving the uptake of diffusion limited micro nutrients such as P, Zn, Cu, Mn, and Fe by the host plants on account of their ability to dissolve and promote absorption of these nutrients . This is accomplished primarily by extension of root geometry through symbiotic association in which fungus utilizes carbohydrates produced by the host plants, and plants in turn benefit by increased nutrients uptake,

Organic manures-based fruit production system

Organic manures play a critical role in both short-term nutrient availability and long-term maintenance of soil organic matter vis-a-vis production sustainability, especially in small holder farming systems (Srivastava and Bora, 2023) via improvements in agrobiology-driven soil fertility changs. Despite this importance, there is little predictive understanding for the management of organic inputs in different fruit-based agro-ecosystems. Crop yields are a fundamental factor of economic success, and depend very much on balanced fertilization to address multiple nutrient constraints (Srivastava and Singh , 2004a) . A crucial question is how to guarantee optimum nutrition along with production on a sustained basis by organic measures only. An array of microorganisms present in manure and manure extracts such as *Trichoderma, Rhizobacteria,* and fluorescent *Pseudomonas* are known to stimulate plant growth (Bora and Bora , 2020) . Such composts having microbes of twin utility hold more promise in integrated nutrient management package (Srivastava and Singh , 2008c) .

Agronomic response of organic manures : The nutrient composition of different organic manures (Srivastava *et al*., 2002 ; 2019) and green manure (at flowering stage) showed a large variation in their nutrient value viz., FYM (1.42% N, 0.14% P, 1.20% K, 640 ppm Fe, 108.2 ppm Mn, 94.2 ppm Cu and 227.0 ppm Zn); vermicompost (1.91%

N, 0.16% P, 0.88% K,2850 ppm Fe, 113.2 ppm Mn, 67.0 ppm Cu and 72.4 ppm Zn); and poultry manure (2.15% N, 0.14% P,1.32% K, 28560 ppm Fe, 115.4 ppm Mn, 45.6 ppm Cu and 325.0 ppm Zn). The yield of green manure (sunhemp) on Typic Ustochrept soil varied from 5.17 to 11.12 tons/ha, adding 101.97 -229.68 kg N/ha, 4.1-9.28 kg P/ha, 87.55 -197.20 kg K/ha, 1.24 - 2.78 kg Fe/ha, 300.24-676.28 g Mn/ha,116.90-263.32 g Cu/ha, and 112.27-252.88 g Zn/ha into the soil (Kohli *et al.*, 1998; Srivastava and Singh, 2009a). A long term replicated trial laid out with different organic manures and green manuring treatments using Nagpur mandarin as test crop. Different treatments consisted of T_1 (Farmyard manure as FYM). T_2 (Vermicompost), T_3 (Poultry manure), T_4,(Green manuring - Sunhemp), and T_5(Inorganic fertilizers) : The requirement of organic manure was computed on N-equivalent basis using recommended doses of fertilizers (600 g N - 200 g P_2O_5, 100 g K_2O - 200 g $FeSO_4$, - 200 g $ZnSO_4$,) as guiding principle. The results obtained are summarized briefly as below:

Maximum increase in canopy volume was recorded with green manure (24.94 m^3) statistically on par with vermicompost (23.72 m^3) and , inorganic fertilizers (22.46 m^3) with farmyard manure (18.72 m^3) displaying the most inferior response. These observations suggested green manure and vermicompost as two most effective treatments (Table 1). The magnitude of different treatments on yield response was of comparatively lower order including those with inorganic fertilizers. Quality-wise, the maximum size of fruit was recorded with green manuring and vermicompost , while treatments carrying farmyard mansure , poultry manure or inorganic fertilizers , though display on-par response, but magnitude of response was far inferior over either vermicompost or green manure treatment. A constant increase, although at a slow rate, in organic carbon buildup was observed in all the treatments. After 6- years of consistent manuring , maximum organic carbon of 0.86% was observed with vermicompost treatment which was significantly higher than rest of the treatments viz., farmyard manure (0.68%), poultry manure (0.72%), green manure (0.86%) or inorganic fertilizers (0.61%).The maximum buildup of 0.38% was computed with vermicompost treatments compared to 0.28% with either green manuring treatment or only 0.10% with exclusive use of chemical fertilizers.

Table 1. Response of organic manures vs inorganic fertilizers on growth, yield, and fruit quality (pooled data 2008-14)

Treatment	Net increase in canopy volume (m^3)	Fruit yield (kg/plant)	Quality parameters (%)		
			Juice content	TSS	Acidity
Farmyard manure	18.72d	11.92cd	44.82c	9.21b	0.82a
Vermicompost	23.72b	26.20a	47.02a	9.86a	0.86a
Poultry manure	17.50e	12.05c	44.36cd	8.69d	0.84a
Green manure	24.94a	18.96b	46.05ab	9.02c	0.79a
Inorganic fertilizers	22.46c	11.49de	44.15de	8.79de	0.80a
C.D. (P=0.05)	1.14	5.20	1.28	0.14	NS

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments . CD stands for critical difference.

Source: Srivastava *et al.* (2002).

The available pool of nutrients was significantly affected by different organic manuring treatments (Table 3). Net increase in available N over initial value was observed in the order 123.8 mg/kg N and 7.9 mg/kg P, respectively, with K- depleting to 50.8 mg/kg with vermicompost treatment. This magnitude of increase in available N (120.7 mg/kg) and P (2.2 mg/kg) was not observed even with straight inorganic fertilizers, and decrease in available K was similarly on the declining side (Srivastava *et al.*, 2007). The availability of DTPA-extractable micronutrients displayed an overall improvement with all the treatments except inorganic fertilizers . These response in available supply of micronutrient indicated that all the organic

Table 2. changes in plant available pool of nutrients (mg/kg) in response to long-term application of organic manures (pooled data : 2008-14)

Treatment	Macronutrients			Micronutrients		
	N	P	K	Fe	Mn	Zn
Farmyard manure	196.2e	14.2d	207.0d	17.1bc	12.1d	0.82cd
Vermicompost	226.2a	21.3a	286.2a	22.2a	26.8a	1.08a
Poultry manure	210.3c	15.3c	190.1e	14.cd2	16.2c	0.94b
Green manure	219.4b	16.1b	243.7b	17.1b	18.3b	0.90bc
Inorganic fertilizers	204.7d	14.2d	238.3c	14.0de	10.8e	0.80de
C.D. (P = 0:05)	2.8	0.80	4.3	1.0	0.80	0110

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2002), Srivastava and Singh (2005) manures have excellent mobilizing capacity of otherwise unavailable micronutrients in soil (Srivastava *et al.*, 2007) . Except Cu, all the micronutrients attained a concentration within optimum range, irrespective of different treatments (Table 3) .

The studies so far carried out provided two cardinal explanations *viz.*, i. organic manures (vermicompost, green manure, and farmyard manure as FYM) hold good promise to meet crop nutrient requirement, and ii. Qualitywise , fruits from organic manuring were not inferior to those from inorganic fertilizers (Srivastava and Singh , 2009b ; Srivastava *et al.*, 2008). In such studies, it is more important to see the response of legacy carbon of soil (passive soil carbon stock) on production sustainability by working out the periodicity of organic manuring as a part of crop manuring holiday under both soil moisture limiting and optimum moisture availability to simulate the nutrient release pattern . The crop responses of different organic manures under two divergent soil moisture conditions are likely to originate through intensity of recalcitrance of carbon (Agegnehu *et al.*, 2017; Mousavi *et al.*, 2023).

Optimising nutrient (organic and inorganic)-microbe synergy: our experiences

The long-term experiments conducted around the world indicated that chemical fertilizer alone is not enough to improve or maintain soil fertility at high levels and the soil acidification problem caused by over-application of synthetic N fertilizers can be reduced if more fertilizer N is applied as NO3 relative to ammonium- or urea-based N fertilizers (Pathak and Nedwell, 2011). Organic amendments comprising manures have helped in increasing the fruit yield coupled with quality, effectively replacing mineral fertilizers in the nutrient management of commercial fruit tree orchards through associated changes in soil C pool, microbial pool and available nutrient pool of soil. Nutrient (nutrient as well as inorganic source)-microbe as tripartite association on the other hand is better known in fruit crops (Singh and Banik, 2011; Srivastava and Ngullie, 2009 ; Khehra and Bal, 2014) with respect to both agronomic response as well as soil health. An array of fruit crops have been reported to respond to the synergies originated through combination of organic nutrient- microbe-inorganics (Table 7) either under soil water deficit or an optimum soil moisture conditions. And such associations have invariably witnessed substantially higher productivity than any single component alone. However, there is a greater need to expand such plant response advantages using more rhizocompetent microbes preferably in consortium mode, plant response as well as soil health response both have to be sustained on a long term basis (Srivastava and Bora, 2023) .

Our long term studies on microbial consortium (mixture of *Bacillus pseudomycoides* , MF113272 ; *Acinetobacter radioresisten s,* MF113273 ; *Micrococcus yunnanensis* , MF113274 ; *Paenibacillus alvei,* MF113275 ; and *Aspergillus flavus* , MF113270), inorganic fertilizers, and vermicompost- mediated integrated soil fertility management (ISFM) in relation of sustained quality production of Nagpur mandarin (*Citrus reticulata* Blanco) under field condition during 2007-16 were initiated with five treatments viz., Module I (T_1)- 100% RDF (recommended doses of fertilizers: 600 g N – 200 g P – 300 g K - 200 g $ZnSO_4$ – 200 g $FeSO_4$ – 200 g $MnSO_4$/tree/year), Module II (T_2) -75 % RDF + 25% vermicompost; Module III (T_3)-75% RDF + 25% vermicompost + microbial consortium; Module IV(T_4)-50% RDF + 50% vermicompost; and Module V (T_5) – 50 % RDF + 50% vermicompost + microbial consortium. These modules representing various forms of ISFM were evaluated in terms of vegetative growth, fruit yield, fruit quality, plant available pool of nutrients in soil, leaf nutrients composition, soil carbon stock, and soil microbial load on a black clay soil (Typic Ustochrept) , and presented below through pooled data (Table 4- 7) :

Table 3. Nutrient profile of index leaves in response to long-term application of different organic manures (Pooled data: 2008-14)

Treatments	Macronutrients (%)			Micronutrients (mg/kg dry)drymatter)		
	N	P	K	Fe	Mn	Zn
Farmyard manure	2.38c	0.091d	1.20e	106.2d	28.2e	19.2bc
Vermicompost	2.63a	0.114a	1.34c	121.2a	40.3a	23.1a
Poultry manure	2.10e	0.080e	1.24d	118.1b	32.8d	20.4b
Green manure	2.52b	0.100b	1.54a	108.4c	36.1b	19.2bc
Inorganic fertilizers	2.28d	0.094c	1.45b	99.6e	34.0c	17.0d
C.D. (P = 0:05)	0.08	0.008	0.08	2.2	1.2	1.0

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2002), Srivastava and Sigh (2005)

Response ISFM modules on plant growth, fruit yield, and quality: All the ISFM-based treatments displayed significant response on changes in canopy volume (Table 4). Maximum cumulative increase in canopy volume was observed with module-III (18.67 m^3) followed by module-IV(17.16), Module-V(16.93 m^3), on part with module-II (16.70 m^3) and canopy volume with either module-III or module-V which were better than either module-II or module-IV compared to module-I which comprised of only inorganic fertilizers. Module I- T_1 (11.50 m^3). Incorporation of microbial consortium either with module-III or with module –V invariably induced higher canopy volume suggesting better response on fruit yield was observed to be significantly affected by different ISFM-based treatments (Table 5).The maximum fruit yield of 88.8 kg/tree was observed with treatment module-V which was better than 83.2 kg/tree with T_4 or 80.5 kg/tree with module-III than 71.0 kg/tree with treatment module-II. However, all these modules were observed far superior in magnitude of response when compared with 100% RDF as module-I (67.7 kg/tree). Hence, different ISFM-based modules (71.0-88.8 kg/tree) were much better than exclusive inorganic fertilizer treatment like module (67.7 kg/tree).

Different fruit quality parameters, except peel thickness (Table 5) displayed significant response in relation to different treatments. There was much high fruit weight with different ISFM-based treatments modules I-V 101.4-114.6 g compared to inorganic RDF module-I (101.4), showing that incorporation of both organic manure as well as microbial cultures improved the efficiency of organic fertilizers. The other three fruit quality related parameters such as juice content, acidity, and TSS expressed the similar pattern of response. While on the other hand, acidity observed a significant reduction with those superior treatment, e.g. module-III (0.86%) and module-V (0.80%) compared to module-II (0.93%) and module-IV(0.91%) highlighting the favorable changes in different fruit quality in response to different ISFM-based treatments.

Response of ISFM modules on response on soil health: Rational soil use practices must allow economically and environmentally sustainable yields, which will only be reached with the maintenance or

Table 4. Growth attributing parameters in response to different vermicompost - based modules of ISFM (Pooled data :2007-16)

ISFM modules	Plant height(m)	Tree spread (m) E-W	Tree spread (m) N-S	Canopy volume (m^3)	Cumulative increase in canopy volume over 2007-08 (m^3)
Module I	3.82 (2.02)	2.52 (1.27)	2.50 (1.20)	13.04e (1.54)	11.50e
Module II	5.09 (2.10)	2.98 (1.39)	2.89 (1.25)	18.51bc (1.81)	16.70cd
Module III	3.87 (2.13)	3.00 (1.27)	3.22 (1.23)	20.28a (1.61)	18.67a
Module IV	3.76 (2.10)	3.73 (1.30)	2.93 (1.30)	19.78ab (1.62)	17.16ab
ModuleV	3.86 (1.87)	2.97 (1.18)	2.96 (1.22)	18.33cd (1.40)	16.93bc
C.D. (P=0.05)	0.49	0.38	0.51	1.18	1.32

Figures in parentheses indicates the value obtained in 2007-2008

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source: Srivastava *et al.* (2019)

Table 5. Fruit yield and quality parameter in response to different vermicompost based modules of ISFM- treatments (pooled data:2007-16)

ISFM module	**Yield (kg/tree)**	**Fruit weight (g/fruit)**	**Peel thickness (mm)**	**Fruit quality parameters** **Juice content (%)**	**TSS (^{0}Brix)**	**Acidity (%)**	**TSS/ Acid ratio**
Module I	67.7e	101.4e	4.1a	40.2cd	8.4cd	0.96a	8.92de
Module II	71.0d	104.1d	3.0bc	39.6de	8.6bc	0.93ab	9.23cd
Module III	80.5c	106.2c	3.4b	41.5bc	9.5a	0.86cd	10.05b
Module IV	83.2b	109.1b	3.4b	42.7b	8.4cd	0.91bc	9.56bc
Module V	88.8a	114.6a	3.0bc	44.2a	9.3ab	0.80de	11.62a
C. D. (P=0.05)	2.1	1.4	0.50	2.1	0.30	0.10	1.10

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2019) recovery of the soil health (Lehman *et al.*, 2020) . Thus, a healthy soil has been defined as "The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran and Zeiss, 2000). To understand and use soil health as a tool for production sustainability, physical, chemical, and biological properties must be employed to verify the soil use and management within a desired timescale.

The soil microbial load in terms total bacterial count and fungal count in response to different ISMF-based treatments showed variable higher soil microbial load with module III and module V compared to either module II or module IV including module I . In our study changes in soil fertility indices with regard to available macro- as well as micronutrients were observed highly significant, but of variable nature in response to different treatments (Table 6). Module-I involving exclusive inorganic fertilizers registered lowest test values as against treatment like module-V registering maximum values, validating the supremacy of those treatments which carry all the three components of ISFM. The soil properties such as soil pH and soil EC were not affected by any of the ISFM-based treatments (Table 8). While, amongst different fractions of soil carbon viz., organic-C (SOC), inorganic-C (SiC), and total-C (TC) only SOC and TC were significantly affected . These observations showed that changes in soil carbon stock are more governed by organic fraction than inorganic fraction.

Maximum SOC and TC of 7.43 g/kg and 9.14 g/kg were observed with module-V. Likewise, module-III much SOC and TOC than module-II, displaying the significant role of microbial consortium in improving the carbon sink capacity of soil. Different ISFM-based modules were also observed to aid in improving the total soil N stock, being maximum with treatment like module- III- V(0.741-0.748%) compared to rest of the treatments like module-I, module-II or module-IV (0.721-0.738%). However, soil C:N ratio in the range of 12.00-12.32, without displaying significant changes in response to different treatments (Table 7). These modules provided us the strong clues about the effectiveness of developed microbial consortium . We further laid out the field experiment to evaluate in 10-year-old Nagpur mandarin (*Citrus reticulata* Blanco raised on *Citrus jambhiri* Lush rootstock) , how much nutrients saving can be achieved through microbial consortium , with treatments comprising, i. 50% RDF + 50% RDF equivalent vermicompost + microbial consortium, ii. 45% RDF + 45 % RDF equivalent vermicompost + microbial consortium, iii. 40% RDF + 40% RDF equivalent vermicompost + microbial consortium, iv. 35% RDF + 35% RDF equivalent vermicompost + microbial consortium, and v. 30% RDF + 30% RDF equivalent vermicompost + microbial consortium. Incorporation of microbial consortium in ISFM showed a minimum of 30% of RDF (35% RDF + 35% RDF equivalent vermicompost + microbial consortium) could be saved without any compromise on either fruit yield , quality or soil fertility status (Srivastava *et al.*, 2019).

Customized micronutrient mixtures: development and field evaluation

A number of principles are involved in developing customized fertilizers, which include: soil fertility-based variogram measuring spatial variability, defining different production management zones along with soil fertility gradient, nutrient budgeting based on nutrient removal and addition, nutrient logging data relation to phenology of a crop and blending nutrients- based spatial and temporal crop specific nutrient removal pattern (Srivastava and Das, 2017) . Needless to elaborate on advantages of customized fertilizers than straight fertilizers. Unfortunately, not much inroads have been made with respect to developing specialty fertilizers or these fertilizers customized as per crop nutrient demand

Table 6 . Changes in soil fertility status in response to different modules of ISFM-based treatments (Pooled data: 2007-16)

ISFM modules	**Plant available nutrients (mg/kg)**						
	Macronutrients			**DTPA-micronutrients**			
	$KMnO_4$-N	**Olsen-P**	**NH_4OAc-K**	**Fe**	**Mn**	**Cu**	**Zn**
Module I	140.0e	9.32a	185.2e	10.35e	10.54e	2.2a	0.98
Module II	143.5d	9.27a	196.6d	12.57d	11.54cd	2.3a	1.00
Module III	155.7bc	9.15a	203.6c	15.18bc	12.45c	2.7a	1.10
Module IV	161.0b	9.57a	209.2b	16.56b	11.67b	2.8a	1.18
Module V	178.5a	9.55a	212.6a	19.50a	12.93a	2.5a	1.32
CD (P=0.05)	6.2	NS	1.3	1.32	1.01	NS	0.46

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.
Source: Srivastava *et al.* (2019)

depending upon soil and climate (Srivastava *et al.*, 2010). We made some sincere efforts to highlight some efforts to develop specialty fertilizers and customize them like citrus, with the help of other fruit crops :

Specialty fertilizer, a tool for site specific nutrient management (SSNM) : Conventionally designed long term fertilizer trials revealed that: i. omission of limiting macro- or micronutrients led to their progressive deficiencies due to heavy removals; ii. Sites initially well supplied with P, K or S become deficient when continuously cropped using N alone and iii. Fertilizer rates considered optimum still resulted in nutrient depletion at higher productivity levels, if continued, become sub-optimum rates (Tiwari *et al.*, 2007a) . There is a strong necessity to keep overall nutrient balance in relation to total crop load (Tiwari 2007b). Most of the existing fertilization guidelines have been derived from experimental data on yield responses to individual nutrients after controlling for other soil conditions by way of randomization. But , soil conditions in farm fields, former being more heterogeneous in soil fertility, is distinctly very different from those in the experimental fields, and soil data collected from a farm fields cannot be analyzed using the statistical method developed for experimental data (Srivastava *et al.*, 2006) .

Knowing the nutrients required for all stages of growth, and understanding the soil's ability to supply those needed nutrients, are critical to profitable crop production. The recommendations on fertilizer application may not, however, produce the same magnitude of results when practiced on an orchard of large area, because of its inability to accommodate large spatial variation in soil fertility (Srivastava *et al.*, 2006). Application of uniform single rate of nutrients, hence, most often result in over-application of nutrients at some sites and under-application at other sites, cumulatively leading to reduced fertilizer use efficiency (Jeyabaskaran *et al.*, 2021). Under such circumstances, SSNM as a dynamic concept of nutrient management exploits indigenously and spatially available nutrients within bigger orchards requiring differential fertilizer treatments in patches so as to improve the orchard efficiency (average yield of specified trees in relation to average orchard yield) in ultimate terms (Srivastava and Singh , 2008a). The success of SSNM during the last 15- years has been prominently realized on a number of fruit crops viz., avocado (Salaza-Garcia and Lazcano-Ferrat 2003), citrus (Srivastava *et al.* 2006 ; 2009) etc. to cite few success stories. In this background, the present review attempts to highlight certain pertinent issues on the necessity of developing SSNM concept as rationale of fertilizer use to harness better fertilizer use efficiency with emphasis on perennial crops.

The following steps are involved in arriving at fertilizer requirement based on the principles of SSNM (Srivastava 2013b): step i.: estimating target yield; step ii. estimating nutrient requirement to get target yield, step iii. estimating indigenous nutrient supply from soil (based on our earlier studies dealing with progressive nutrient response experiment), step iv : calculating fertilizer requirement. Working out the nutrient requirement : defined as the amount of nutrients added for producing the target yield minus the amount of indigenous nutrient (soil and other sources)and fertilizer recovery (%) defined as the percentage of nutrients absorbed by a crop out of the total amount of fertilizers applied (Srivastava *et al.*, 2014) .

Future gains in productivity and input- use-efficiency will require soil and crop management technologies that are knowledge-intensive, and are tailored to specific characteristics of individual farms or fields to manage the variability that exists between and within them (Tiwari 2007a). The SSNM approach is one such option that has been tried successfully in India using different approaches. In subsequent sections we discuss the principles and strategies that could be effectively used developing customized fertilizers use strategy, leading to development of specialty fertilizers. We developed a specialty micronutrient mixtures for Nagpur mandarin grown in central India and evaluated during 2012-20 in Vertic Ustochrept (Soil facing multiple nutrient deficiencies in form of N, P,Fe, MN, Zn and B. The treatments involving a total of four treatments viz.,$T_{1:}$ Micronutrient mixture (Citrus special, IIHR Bangalore, T_2 : Macronutrients (Soil application) + Micronutrients (Foliar application); T_3 : Micronutrient mixture-1(Soil application) + Macronutrients (Soil application) and T_4 : Micronutrient mixture-2 (Soil application) + Macronutrients (Soil application) were tested in field with 6 replications. The responses were evaluated in terms of vegetative growth, changes in soil fertility status and nutrient composition of index leaves to identify the best treatment during the fifth year of evaluation. The results obtained are as follows:

Response on vegetative growth and quality: Vegetative growth response using different growth contributing parameters were evaluated and expressed as canopy volume, responded significantly to the different treatments, as in preceding years. Among all the treatments, the most striking increase in canopy volume over 2018 – 19 was observed with the treatment T_4 (0.96 m^3) followed by the treatment T_3 (0.92 m^3), T_2 (0.85 m^3) and T_1 (0.46m^3). These responses in canopy volume suggested the superiority of both the micronutrient mixtures (T_3 and T_4) over conventionally used fertilizer (T_1 and T_2) application. Similarly, the yield response with treatments T_4 (58.2 kg tree or 16.2 tons /ha) and T_3 (46.3 kg /tree or 12.9 tons /ha) were of much higher magnitude over T_2 (42.4 kg/ tree or 11.8 tons/ha) and T_1 (40.4 kg/ tree or 11.1 tons/ha), suggesting that our prepared mixtures have out-yielded the conventionally used fertilizer doses (Fig. 1).

Changes in soil fertility and plant nutrition: The soil fertility and leaf nutrients composition were significantly available nutrients, with an exception of DTPA-Cu a affected by different treatments. Amongst plant available nutrients , with the exception of DTPA-Cu , all the nutrients viz., $KMnO_4$-N, Olsen-P, NH_4OAc-K, DTPA-Fe, DTPA-Mn, and DTPA-Zn showed a signification response of different treatments. The treatments T_4 observed significantly higher plant available macronutrient than treatment T_3 compared to treatments T_2 . These observations suggested the far superior response of micronutrient mixtures (Treatment T_3 and T_4) than treatments involving T_1 and T_2 . The treatment T_4 and T_3 registered a significantly higher plant available micronutrient than T_2 and T_1. Similar responses were observed in leaf nutrient status, where T_4 treatment showing the best response over T_3, T_2 or T_1 . Our observations strongly lend support shortly support towards better efficacy of micronutrient mixtures compared to conventionally used fertilizers (Fig 1) Hence our long term studies showed that micronutrient mixture developed by simply mixing straight micronutrient fertilizers such as ferrous sulphate , manganese sulphate , zinc sulphate and borax in ratio of 1:1:0.50:0.20 that stoichiometrically coincided with the similar concentration ratio of micronutrients present in fruits. Interesting, our developed micronutrient mixture at the rate of 100g/plant overtaken the response of these micronutrients when applied at the rate of 100g ferrous sulphate , 100g manganese sulphate , 100g zinc sulphate and 50g borax/plant/year (total micronutrients at the rate of 350g /plant proved far inferior over 100g customized micronutrients mixture) .

Changes in fruit quality index: Fruit quality index developed for citrus fruits displayed varying response. The treatment T_4 showed a maximum index value (69/100) followed by T_3 (66/100) , T_2 (62/100), and T_1 (59/100) in decreasing order. These observations suggested the far significant response of customized micronutrient mixtures compared to straight fertilizers involving treatment T_1 (Srivastava , 2012 ; Srivastava and Pandey , 2021) .

Microbial response of rhizosphere hybridization

Soil region adhering to plant root system is claimed to display the maximum microbiome diversity, responsible for changes in soil bio-physico-chemical properties influenced by root growth and their elevated activity, popularly known as rhizosphere . The term "Rhizosphere" was coined by German scientist, Hilter (1904) from two Greek words, i.e. rhiza (root) and sphere (field of influence). There are three broad classifications describing three different tiers of rhizosphere properties, viz., i. root tissues enclosing endodermis and cortical layers (endorhizopshere), ii. root surface adhering soil particles and microbes (rhizoplane), and iii. soil immediately adjacent to root (ectorhizosphere). Plant roots release various organic compounds through exudation, secretion, and deposition, starting from the

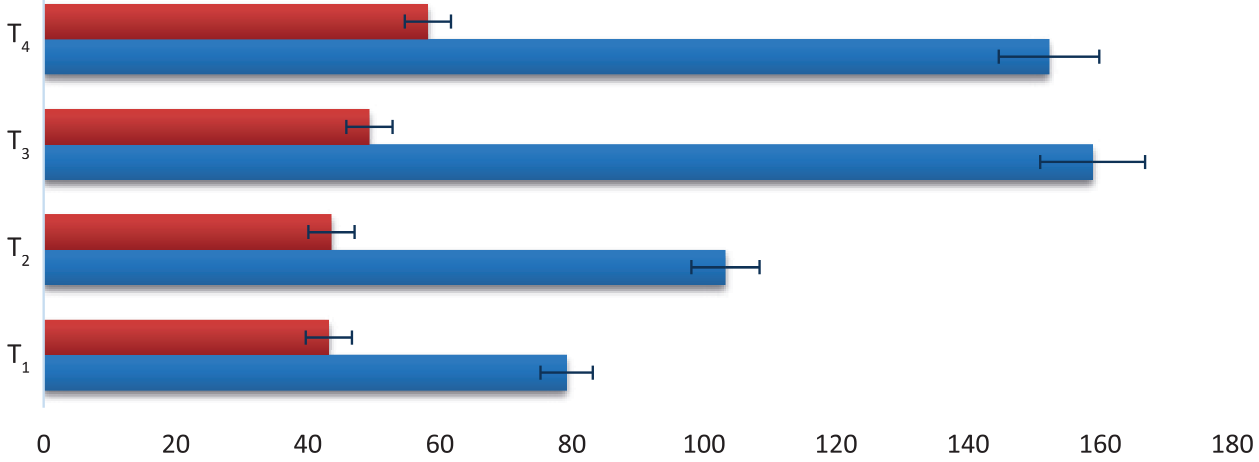

Fig. 1. Response of customized micronutrient mixtures on changes in canopy volume and fruit yield of Nagpur mandarin (2007-2019)
T_1 – Micronutrient mixture (Citrus special, IIHR Bangalore); T_2 -Macronutrients (Soil application) + Micronutrients (Foliar application; T_3- Micronutrient mixture-1 (Soil application) + Macronutrients (Soil application); T_4- Micronutrient mixtur-2 (Soil application) + Macronutrients (Soil application)
Source : Srivastav and Pandey(2021)

seed germination to growth of an adult plant, thereby, transforming rhizosphere biologically more active than bulk soil (Moshiri *et al.*, 2019). In this process, plant recruits active microbial communities within rhizosphere along and within the rootzone.

While addressing this important issue, comparative studies (Wang *et al.*, 2022; Xie *et al.*, 2024) on monoculture versus intercropping cultivation patterns of fruit crops have shown significant differences in reshaping the microbial communities and metabolism of beneficial microbes alongside microbial antagonists. The evidences accrued through worldwide studies are strong enough about a strong possibility of microbial communities conditioned by root exudates of main crops and intercrops undergoing mutational changes via different trophic interactions , thereby giving birth to another term (Fig 2 as a conceptual framework) , we propose as "Rhizosphere Hybridization" . Rhizosphere hybridization is hence a concept that involves combining the microbial diversity of different crop rhizospheres to improve the rhizosphere function of targeted crops for improvised plant growth and development. In this background information, efforts were made to take stock of the work done on the rhizosphere microbiome of different promising tree plants that could be fitted into the concept of rhizosphere hybridization and put forth some future lines of research on an issue, very limited clues are presently available at the international arena.

Rhizosphere hybridization is new concept to modify the rhizosphere ecology to create an optimum environment for PGPMs to show the positive effect of plant agronomy . The concept of "rhizosphere hybridization" is therefore, advocated to harness the value- added benefit of nutrient-microbe synergy, besides providing dynamism to microbial consortium suiting to wide range of perennial fruits (Srivastava and Singh , 2006) . Our studies on response of different treatments involving rhizosphere soil of three perennial trees viz., *Ficus racemosa* L. (Umber tree), *Ficus benghalensis* L. (Banyan tree), and *Ficus religiosa* L. (Pipal tree) along with rhizosphere soil of healthy and highly productive sweet orange trees in sweet orange buddlings showed differential response in terms of agronomic parameters, changes in soil physical properties, and pool of plant available nutrients (Cheke *et al.*, 2018). However, hybridized rhizosphere of sweet orange and *Ficus racemosa* L. out-smarted the response over other rhizosphere hybridization treatments . These studies lend some support to the fact that inoculation of soil or crops with rhizospheric or endophytic microbes, respectively, can enhance the micronutrient contents in various plant tissues including roots, leaves, and fruits (Fig. 3). In field , the rhizosphere hybridization can be

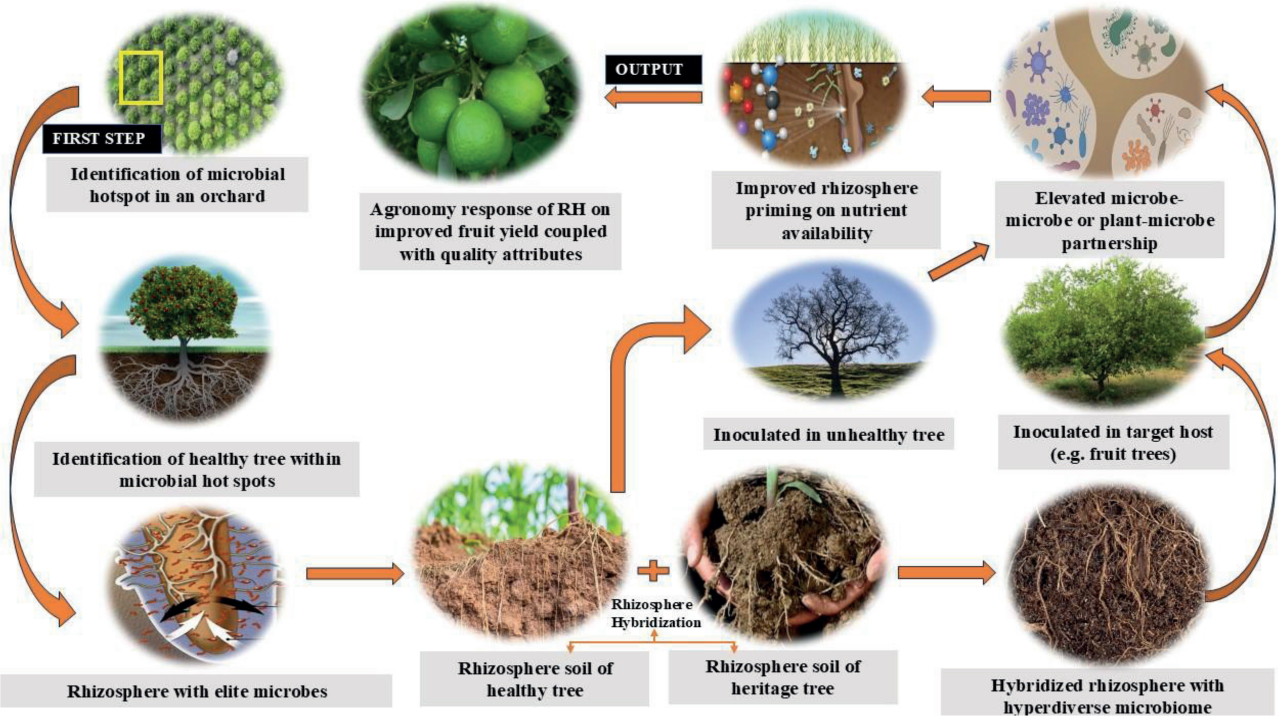

Fig.2. Schematic representation of rhizosphere hybridization proposed for using agrobiology-driven rhizosphere fortification of microbes in citrus (Srivastava *et al.*, 2025)

implemented by collecting rhizosphere soil of healthy trees and injected into weaker trees to rationalise distribution of microbes across field /orchard as a part of natural farming with agro-ecology exploited as its best .

Strategies and opportunities

No doubt , magnitude and distribution of nutrient stress are likely to expand with soil water deficit stress (Shirgure and Srivastava, 2003), warranting for a reoriented strategies to sustain the fruit production when compared with optimum soil moisture condition (Shirgure *et al.*, 2001) and optimum fruit load (Srivastava *et al.*, 2000). Despite many cutting edge technologies, addressing a variety of core issues on role of soil management-based nutrient- use -efficiency (integrating right dose of fertilizers in right place at right crop growth stage using right source as 4R and right amount of irrigation water in right place at right crop growth stage using right source as 4W) using sensor-based subsurface fertigation amidst multiple nutrient deficiencies (Meshram *et al.*, 2025a ; 2025b) in raising the productivity of perennial fruits is the major research and developmental issue. Microbes are most diverse soil organisms, yet very little is known about them (Hota *et al.*, 2020). Until recently, research has focused on those organisms that are culturable. However a wealth of information is now being collected from both culturable and, as yet, unculturable organisms. Functions of the soil microbial population impact many processes and, therefore, productivity , if mechanisms involved in the plant-microbe interaction are better understood. Researchers are still looking forward to schedule function-specific microbial inoculation , in line with nutrients partitioning as per crop critical growth stages . If fertigation (as a prudent option to neutralize soil water deficit stress) is a nutrient saving exercise , biofertigation could still be a better option, provided value -chain of microbial inoculants is precisely developed.

fertilizers, an understanding on nutrient acquisition and regulating the water relations would help switch orchards to CO_2 sink (expanding carbon capturing capacity of rhizosphere) so that a more sustainable fruit-based integrated crop production system under biotic and abiotic stress could be evolved. Role of mycorrhizas

in providing an additional resilience to rhizosphere's ability of carbon accredition through within rhizosphere and associated development of plant's antioxidant profile

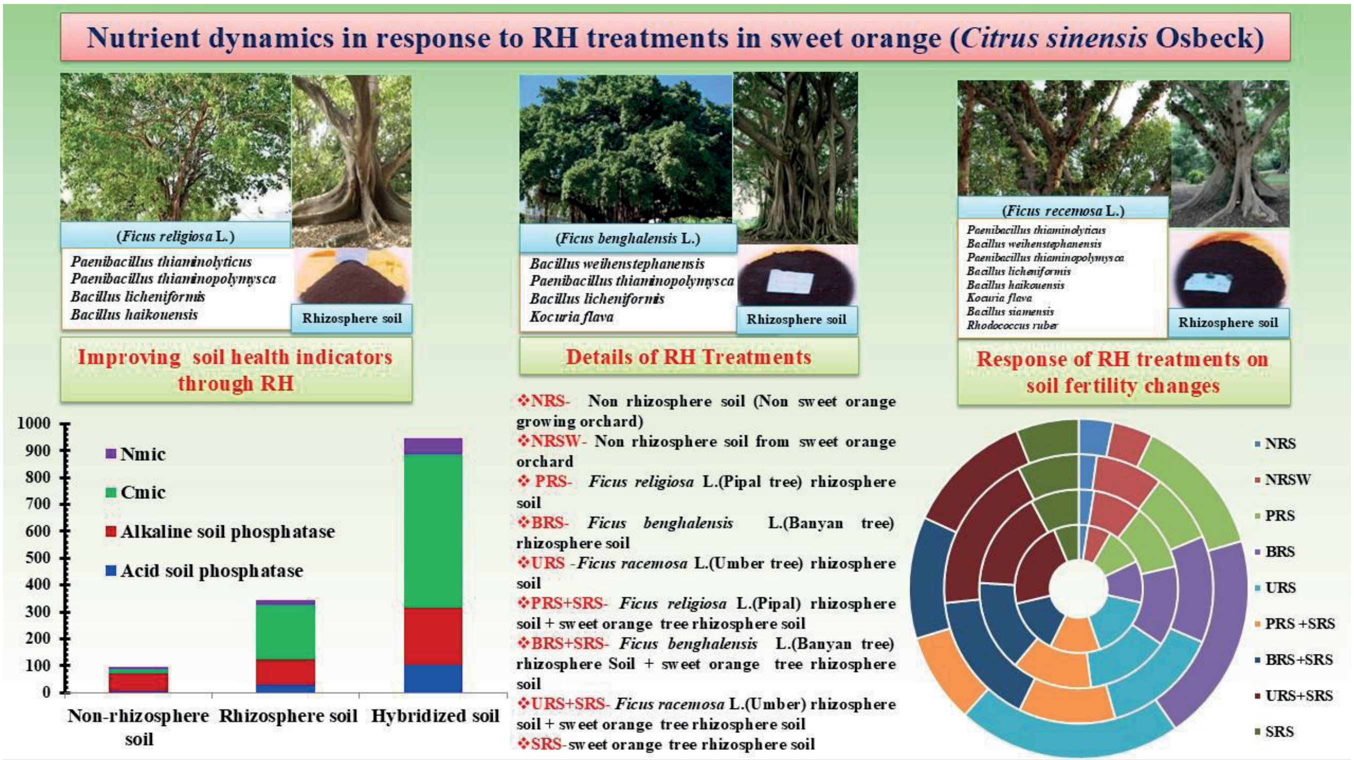

Fig. 3: Diagrammatic representation on response of RH in sweet orange (*Citrus sinensis* Osbeck) grafted on Rangpur lime (*Citrus limonia* Osbeck) rootstock for improved rhizosphere health indicators (microbial biomass nitrogen, Nmic; microbial biomass carbon, Cmic; alkaline soil phosphatase; and acid soil phosphatase) and soil fertility changes (inner most circle represents organic carbon, followed by $KMnO_4$-N, Olson-P, and NH_4OAc-K as we move on from inner circle). Hybridized soil (URS + SRS) involving inoculation of rhizosphere of *F. recemosa* (URS) into the rhizosphere of sweet orange trees (SRS) proved to be far superior over either of two. Based on data used generated through studies by Cheke *et al.* (2018) and Srivastava *et al.* (2021)

as a defense mechanism should divert the research studying strong mycorrhizal dependency of fruit crops. Rhizosphere specific AMF-based microbial consortium (mass multiplication technology, however still a lot desired to be addressed) would add a new dimension in providing newer options for raising the productivity potential of fruit crops. The framework on soil biodiversity effects from field to fork comprises: i. recognizing both direct and indirect mechanisms of soil biodiversity effects on crops properties, ii. identifying postharvest processes that affect biodiversity legacy effects on crop properties; and iii. pinpointing biodiversity-related crop properties that influence the efficacy and success of operations occurring in the agrifood chain..

In addition, another novel concept called "Rhizosphere Hybridization" where we succeeded in developing a microbially hybridized rhizosphere (Hota *et al*., 2020 ; Sivastava *et al*., 2022; Srivastava *et al*., 2025) by inoculating rhizosphere soil from healthy plants into the rhizosphere those unhealthy plants , eventually resulted in complete recuperation from untimely decline in productivity (Dzvichu *et al*., 2023) on account of aided biochemical preparedness of thus treated plants (Srivastava , 2023 ; Srivastava and Singh , 2004b) . These strategies are anticipated to develop a resilience to soil water deficit stress without nutrient constraints jeopardizing the possible gains in crop-response linked productivity. The work related to microbial inoculants for mass production, formulation coupled with innovative marketing, interaction and signaling with the plant and soil environment need further redressal to reorient nutrient-microbe synergy in fruit scientists. In another persuit to develop a nutrient-efficient fruit crop, engineering microbial genepool could play an important role by combining nutritional physiology with functional genomics and simultaneously solve the recurrent problem of crop response under soil water deficit stress.

The fall out of a generalized fertilizer s recommendation over large areas of small-scale farming very frequently leads to the possibility of over or under-application of nutrients, by and large, coupled with its economic and environmental consequences . The more apparent consequences of falling productivity and nutrient efficiency, multi-nutrient deficiencies, increasing pace of nutrient mining, and falling farm income are highlighted by earlier researchers (Srivastava and Singh , 2004b ; 2009a). The environmental impacts are not very apparent yet, probably because of the generally low nutrient application rates, except few crops of very high commercial importance. The SSNM using crop-customized fertilizers on the other hand, is another approach for feeding crops with nutrients, as and when they are needed, considering inherent spatial variability associated with fields under crop production. The most important step towards the calibration of site specific fertilizer requirement is the estimation of the indigenous nutrient supplies, which we define as the cumulative amount of nutrient originating from all indigenous sources . The major challenges for SSNM research and extension in future will be two-folds: i. to retain the demonstrated potential of the approach and ii. to build upon what has already been achieved while reducing the complexity of the technologies as it is disseminated to farmers . However, Zhang *et al*. (2010) suggested that the regionalized maps are practical alternative to site-specific soil nutrient management approaches in areas where it is not practical to implement SSNM due to small field size or other constraints to use intensive soil sampling and chemical analyses (Srivastava and Patil, 2014 ; Srivastava *et al*., 2015 ;Srivastava and Singh , 2001 ; 2002). These strategies would go a long way in offering some fruitful solution in mitigating multiple nutrient deficiencies (regardless of soil moisture) using specialty fertilizers, with an eye on the soil agroecology playing a pivotal role in ensuring a sustained productivity in the backdrop of climate change as an approach of slogan-to-solution for future redressal of soil health-mediated multiple nutrient stress in fruit crops. .

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