

Influence of Soil and Irrigation Water Quality on Plant Tissue Nutrient Status and Crop Performance of Nagpur Mandarin Grown in Vidarbha Region of Maharashtra

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Abstract: A comprehensive assessment of soil, irrigation water, and leaf petiole nutrient status was conducted in major citrus-growing areas—Katol, Chandur Bazar, Morshi, and Warud—of the Vidarbha region of Maharashtra (India) with special reference to Nagpur mandarin. Samples collected were analysed in a NABL-accredited laboratory at Nashik to evaluate deviations from desired standards for citrus production specially for Nagpur mandarin and to recommend region-specific nutrient management strategies.

Soil analysis revealed alkaline pH (8.11–8.82; desirable 6.0–7.5), high calcium carbonate content (up to 24%; desirable <5%), and low to moderate organic carbon (<1.2% in most locations; desirable >1.2%), indicating reduced nutrient availability as reflected in plant tissue analysis. Available phosphorus was critically low (4.96–17.30 kg ha⁻¹; desirable 17.5–30.5 kg ha⁻¹), while potassium levels in soil were high (530.41 to 1063.69) in most cases (desirable 400–435 kg ha⁻¹); however, leaf analysis indicated significant deficiencies of potassium (0.62–1.49%; desirable 2.12–2.51%), nitrogen (1.40–1.79%; desirable 2.49–2.81%), magnesium (0.25–0.44%; desirable 0.38–0.48%), sulphur (0.15–0.18%; desirable 0.18–0.30%), zinc (8–15 ppm; desirable 11.32–34.24ppm), and copper (5.34–9.96 ppm; desirable 10.4–18.6 ppm). Excessive calcium and magnesium in soil contributed to nutrient imbalance and restricted uptake of potassium, phosphorus, zinc, and copper. Elevated iron 291.18 to 841.51 ppm (desirable 108–180 ppm) and boron 27.59 to 45.15 ppm (desirable 2.05–3.0ppm) concentrations in leaves indicated toxicity stress, adversely affecting crop vigour and fruit quality.

Irrigation water analysis showed slightly alkaline pH (7.34–7.59; desirable 6–7), high electrical conductivity (up to 1.598dS m⁻¹; desirable <0.7dS m⁻¹), elevated total dissolved solids (up to 1170 ppm; desirable <500–1000 ppm), and high chloride content upto 203.86 ppm for some locations (desirable <100 ppm), contributing to soil salinity and nutrient imbalance. Farmer survey data indicated medium to low yields, moderate fruit quality, increased fruit drop, and higher incidence of diseases such as *Phytophthora* and Sooty mould, particularly under Ambiabahar (January Flowering) conditions.

The study highlights a significant disparity between soil nutrient reserves and actual plant uptake, primarily due to high soil pH, compaction, and nutrient imbalance or antagonism. Adoption of integrated nutrient management practices—including the use of organic manures, vermicomposting, green manuring, phosphorus- and potassium-solubilizing bacteria (PSB and KMB), mycorrhiza, foliar nutrient application, and use water conditioners—is essential to restore nutrient balance, improve fertilizer use efficiency, enhance fruit quality, and reduce fruit drop and post-harvest losses in citrus (Nagpur Orange) orchards of the Vidarbha region.



Keywords: Nagpur mandarin; Soil fertility; Leaf petiole analysis; Irrigation water quality; Nutrient imbalance; Alkaline soils; Phosphorus deficiency; Potassium uptake; Integrated nutrient management (INM); Bio fertilizers (PSB, KMB); Fruit drop; Citrus productivity

I. INTRODUCTION

Sustainable crop production and consistent yield improvement depend largely on the soil and water quality, balanced interaction between soil fertility, irrigation water quality, and efficient nutrient uptake by plants (Brady & Weil, 2017). In perennial fruit crops such as citrus, even minor deviations from optimum soil and water conditions can result in pronounced reductions in productivity, fruit quality, and tree longevity (Annon., 2006). To address this, researchers have established standard reference values for soil physico-chemical properties, irrigation water quality parameters and leaf nutrient composition (ICAR, 2019). Crop performance improves significantly when these parameters remain close to the recommended optimum ranges (Annon., 2017).

Regular monitoring through soil, water, and plant tissue analysis is therefore essential for diagnosing nutrient imbalances and formulating site-specific nutrient management strategies (Havlin *et al.*, 2014). Without such scientific assessment, fertilizer applications often remain inefficient, leading to nutrient fixation, poor uptake, and increased production costs. Leaf petiole analysis, in particular, provides a direct indication of nutrient availability to the crop and reflects the integrated effect of soil conditions, water quality, and fertilizer practices.

The Vidarbha region of Maharashtra, especially areas under Nagpur Mandarin cultivation, is characterized by alkaline soils with high calcium and magnesium content, which significantly influence nutrient availability (Dr. Panjabrao Deshmukh Krishi Vidyapeeth, 2018). Elevated soil pH and base saturation commonly result in reduced availability of phosphorus, potassium, zinc, copper, and other micronutrients, even when their total soil concentrations are high (Lindsay, 1979). This condition frequently leads to nutrient deficiencies in plant tissues, adversely affecting growth, yield, and fruit quality (ICAR-Central Citrus Research Institute, 2019). Additionally, soil compaction and low organic carbon content further restrict root development, water infiltration, and nutrient absorption (Havlin *et al.*, 2014). Irrigation water quality also plays a crucial role in determining soil chemical reactions and nutrient dynamics. High pH, electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), and chloride content in irrigation water can exacerbate soil alkalinity, impair nutrient uptake, and reduce the efficiency of agrochemicals applied through foliar sprays (USDA, 2011). Continuous use of such water without appropriate management accelerates nutrient imbalances and physiological stress in citrus plants (FAO, 2006).

In this context, the present study was undertaken to evaluate the soil fertility status, irrigation water quality, and nutrient composition of leaf petioles in major Nagpur mandarin-growing regions, namely Katol, Chandur Bazar, Morshi, and Warud. Soil, water, and leaf samples were collected and analysed at a NABL-accredited laboratory in Nashik. The analytical results were compared with established standard values (FAO, 2017; ICAR, 2015) to identify key constraints affecting nutrient availability and uptake. The findings aim to provide a scientific basis for corrective nutrient management practices, including the use of bio-fertilizers, organic amendments, and targeted fertilizer applications, to improve nutrient efficiency, crop health, and fruit quality in Nagpur mandarin orchards.

II. MATERIALS AND METHODS

1. Study Area

The study was conducted in six commercial orchards of Nagpur mandarin (*Citrus reticulata* Blanco) located in major citrus-growing regions of Amravati and Nagpur district, Maharashtra, India, namely:

Katol, Chandur Bazar, Morshi and Warud

Six orchards were purposively selected based on the severity of fruit drop reported by farmers during the Ambia and Mrigbahar seasons. All orchards were under bearing stage (8–15 years old) and managed under conventional fertilization practices.



2. Experimental Design and Sampling Strategy

This investigation followed a diagnostic survey approach to identify soil, water, and plant nutritional constraints associated with crop performance plant health and fruit drop.

2.1 Soil Sampling

From each orchard, soil samples were collected from the rhizosphere zone (0–30 cm depth).

Composite samples were prepared by collecting subsamples from 4–5 representative trees per orchard.

Samples were air-dried, sieved through a 2-mm sieve, and used for laboratory analysis in NABL accredited Laboratory.

2.2 Irrigation Water Sampling

Irrigation water samples were collected from the primary water sources (open wells and bore wells). As per standard sampling procedure.

Samples were collected in clean poly bottles.

Water samples were analysed within 48 hours to avoid chemical changes.

2.3 Leaf Petiole Sampling

Mature leaves from non-fruiting terminals were collected during the active growth period.

Leaf petioles were separated, washed with distilled water, oven-dried at 65°C, and ground for nutrient analysis.

Sampling was done from 4–5 representative trees per orchard.

3. Laboratory Analysis

All soil, water, and leaf samples were analysed in a NABL-accredited laboratory in Nashik, Maharashtra.

3.1 Soil Analysis

The following parameters were determined using standard analytical procedures:

Soil pH (1:2.5 soil-water suspension)

Electrical Conductivity (EC 1:2.5 soil water suspension)

Organic Carbon (%)

Calcium carbonate (%)

Available Nitrogen (Alkaline KMnO₄ method)

Available Phosphorus (Olsen's method)

Available Potassium (Flame photometer method)

Available Ca and Mg (EDTA titration method)

Available S (Turbid metric method)

Micronutrients (Fe, Mn, Zn, Cu) by DTPA extraction

Boron (Hot water extraction method)

3.2 Irrigation Water Analysis

Water samples were analysed for:

pH

Electrical Conductivity (EC)

Total Dissolved Solids (TDS)

Sodium Adsorption Ratio (SAR)

Chloride concentration

3.3 Leaf Nutrient Analysis

Leaf petiole samples were analysed for:

Nitrogen (%)

Phosphorus (%)

Potassium (%)



Calcium (%)
Magnesium (%)
Sulphur (%)
Iron (ppm)
Manganese (ppm)
Zinc (ppm)
Copper (ppm)
Boron (ppm)

4. Assessment of Orchard Performance

The following parameters were recorded from each orchard:

Yield status (low/medium)
Fruit quality
Fruit drop severity
Post-harvest losses
Disease incidence (e.g., Phytophthora/Dinkya, Sooty mould)
Occurrence of fruit cracking or granulation
Bahar season (Ambia or Mrig)
Fruit drop severity was recorded based on farmer observations and field assessment.

5. Data Interpretation

Soil, water, and leaf nutrient values were compared with standard recommended ranges for Nagpur orange. Nutrient imbalances were diagnosed based on deviations from optimum desired levels. Soil–leaf nutrient relationships were examined to identify uptake constraints. Major factors contributing to fruit drop were inferred from nutrient deficiencies, toxicities, soil alkalinity, and irrigation water quality.

6. Diagnostic Framework

Fruit drop in Nagpur mandarin orchards was evaluated in relation to:
Soil alkalinity and nutrient fixation
Phosphorus deficiency
Potassium uptake limitations
Boron and Manganese toxicity
Water quality constraints
Soil compaction and low organic carbon

III. RESULTS AND DISCUSSION

1. Soil Physico-Chemical Properties (Table 1)

Result

The study was conducted in six representative orchards of Nagpur Mandarin located in Katol, Chandur Bazar, Morshi, and Warud regions of Maharashtra, India. Soil analysis revealed that the dominant constraint across all orchards was alkalinity.

The soil analysis of selected Nagpur mandarin orchards revealed alkaline reaction with pH ranging from 8.11 to 8.82, exceeding the optimum desirable range (6.0–7.5) recommended for citrus cultivation. Electrical conductivity varied between 0.177 to 0.200 dsm m⁻¹, indicating non-saline to slightly saline conditions. which helped crop to perform under high p^H conditions.



Calcium carbonate content ranged from 7 to 24 %, falling under low to medium category. Available nitrogen levels ranged from 234 to 367.57 kg/ha which are near to the desirable range. Available phosphorus levels were recorded between 4.96 to 17.30kg ha⁻¹, indicating deficiency in most locations. Available potassium ranged from 372.60 to 1063.69kg ha⁻¹, showing medium to high status of available K in soil.

Exchangeable calcium levels ranged between 4324.84 to 6965.86 PPM, and free CaCO₃ content varied from 7 to 24 %, confirming the calcareous nature of the soils.

Among micronutrients, available Zinc ranged from 0.66 to 2.57 PPM, showing deficiency in several orchards. Iron ranged from 2.22 to 5.02 PPM, Manganese from 3.06 to 5.25 PPM, and Copper from 2.09 to 4.66 PPM, indicating variable sufficiency.

Discussion

The alkaline soil reaction (pH 8.11–8.82) observed in the soil might have influenced nutrient availability and uptake efficiency in citrus orchards. High pH reduces solubility of micronutrients such as Zinc and Iron due to precipitation and adsorption reactions (Brady & Weil, 2017). Similar alkaline soil conditions associated with micronutrient deficiencies have been reported in central Indian mandarin-growing regions (Srivastava & Singh, 2003).

Low available phosphorus (4.96- 17.30kg ha⁻¹) is likely due to phosphorus fixation in calcareous soils, forming less soluble calcium phosphates (Havlin *et al.*, 2014). This limitation has been documented in long-term mandarin cultivation under calcareous conditions (Srivastava, 2013).

Although soil potassium was medium to high (530-1063.69 kg ha⁻¹), high exchangeable calcium (4324.84 to 6965.86 PPM) may induce ionic antagonism, restricting potassium uptake (Marschner, 2012). This explains why leaf potassium (Table 3) was deficient despite adequate soil potassium.

Low soil calcium carbonate content (7–9%) indicates depletion of soil organic matter in the studied orchards. Soil organic matter plays a vital role in maintaining soil health by improving microbial activity, enhancing nutrient mineralization, and increasing soil buffering capacity. Reduced organic carbon limits microbial population and biological processes responsible for nutrient cycling, which ultimately affects nutrient availability to plants. Similar observations regarding the importance of soil organic matter in sustaining soil fertility and productivity were reported by Neil C. Brady and Ray R. Weil (2017).

Zinc concentration in soil ranged from (0.66 to 2.63 PPM), indicating Zinc deficiency in surveyed orchards. The deficiency is mainly associated with high soil pH and the presence of calcium carbonate (CaCO₃), which reduce zinc solubility and availability to plants. Under alkaline conditions, zinc forms insoluble compounds, making it less accessible for plant uptake. These findings are consistent with earlier reports by A. K. Srivastava and S. Singh (2003) and A. K. Srivastava (2013)

Zinc plays a critical role in plant physiological processes, particularly in enzyme activation, protein synthesis, and auxin (plant growth hormone) production. Deficiency of zinc adversely affects vegetative growth, flowering, and fruit set in citrus. In Nagpur mandarin orchards, inadequate zinc supply may lead to poor flowering, reduced fruit set, and increased incidence of fruit drop, ultimately affecting yield and fruit quality.

Table -1. Status of soil and available nutrient levels in selected Nagpur Mandarin orchards in Vidarbha area and their impact on crop performance.

		Location					
Parameters	Standard req.	1	2	3	4	5	6
pH	6.5-7.5	8.41	8.11	8.64	8.74	8.82	8.75
OC(%)	Higher than 1.2	1.131	1.092	0.975	0.624	0.663	1.053
EC (dsm)	Less than 1	0.177	0.198	0.199	0.199	0.200	0.195



CaCO ₃ (%)	Less than 10 %	11	7	14	9	12	24
N (kg/ha)	250-350	367.57	354.9	341.25	234.00	248.62	342.22
P (Kg/ha)	17.5-30.5	4.96	11.64	17.30	14.44	7.36	5.99
K (kg/ha)	400-435	372.60	530.41	782.77	817.20	766.62	1063.69
Ca (PPM)	800-1500	6700.44	6965.86	4324.84	5744.23	6684.24	6842.4
Mg (PPM)	50-120	1096.66	1043.23	1233.67	1292.32	855.55	1306.54
S (PPM)	8.5-15.8	21.41	36.96	31.57	16.34	19.51	18.24
Fe (PPM)	3.10-5.75	3.29	5.02	3.41	3.38	3.07	2.22
Mn(PPM)	5.18-9.14	3.42	5.25	3.26	3.06	3.89	1.95
Zn (PPM)	0.2-0.95	2.05	0.66	1.72	2.57	0.86	2.63
Cu (PPM)	0.3-1.5	2.42	2.61	4.66	2.46	2.09	3.40
B (PPM)	0.22-0.9	0.307	0.506	0.158	0.439	0.058	0.207
Yield level	L/M/H	Medium	Medium	Low	Medium	Medium	Medium
Average Fruit quality	Poor/M/Good	Moderate	Good	Moderate	Good	Moderate	Moderate
Waibar incidence	Yes/No	No	Yes	Yes	No	Yes	Yes
Post-Harvest loss level	Less/M/High	Moderate	Less	Less	Less	Moderate	Moderate
Phytophthora/ Dinkya Incidence	Yes/no	Yes	Yes	Yes	No	Yes	No
Fruit cracking or granulation occurrence	Yes/No	No	No	No	No	Yes	No
Fruit drop level	Less/More	Medium	More	More	Less	More	Less
Sooty mould/Kolshiocurrence	Yes/no	No	No	Yes	No	Yes	No
Fruit Bahar preferred by growers	Ambia/Mrig	Ambia	Ambia	Ambia	Ambia/mrig	Ambia/Mrig	Ambia



From above Table-1 it is seen that if selected orchards are considered as representative of Vidarbha area Maharashtra, 100 % soils are alkaline in nature, 66% soil have excess CaCO_3 and 100% have excess K, Exchangeable Ca and Exchangeable Mg. 100% soils are deficient in available P while 100% soils have excess S, 66 % excess Zn, 80 % excess K, 33 % excess N, 50 % soils have deficient level of B. Moderate level of orchard favourable soil EC may be supporting crop under such excess or deficient status of soil nutrient, as observed and given in Table - 1

3. Irrigation Water Quality (Table 2)

The irrigation water analysis revealed slightly alkaline pH ranging from 7.34 to 7.59. Electrical conductivity (EC) values reached up to 1.59 dS m^{-1} , indicating moderate salinity hazard in certain locations. Total dissolved solids (TDS) exceeded 1000 ppm in some samples, suggesting salt accumulation potential.

Chloride concentration was recorded up to 203 ppm, which is relatively high for citrus crops under prolonged irrigation. Sodium adsorption ratio (SAR) values were observed up to 4.02, indicating a developing sodicity hazard in some orchards.

Overall, the irrigation water quality in some locations falls under moderate salinity and chloride risk category.

Discussion

Slightly alkaline irrigation water (pH 7.34–7.59) may gradually increase soil alkalinity, particularly in already calcareous soils (Table 1). EC up to 1.59 dS m^{-1} indicates moderate salinity stress; citrus yield reductions may begin at $\text{EC} > 1.5 \text{ dS m}^{-1}$ (Srivastava, 2013). Elevated TDS ($>1000 \text{ ppm}$) poses a risk of salt accumulation in the root zone, disrupting nutrient uptake. TDS of irrigation water can be a game changer for plant and soil health. High TDS lead to water stress due to Osmotic imbalance which may result into nutrient deficiency or toxicity. Reduced growth, yield and fruit quality can be the result of high TDS of irrigation water. TDS levels less than 450 ppm are safe while 450 to 2000 ppm are to be properly Monitored as may lead to crop risk. While TDS above 2000 ppm poses high risk to crops.

High chloride in water (203 ppm) can get accumulated in leaves, causing marginal leaf burn, reduced photosynthesis, and premature fruit drop. SAR values up to 4.02 indicate emerging sodicity, reducing infiltration and root growth. Higher SAR of irrigation water leads to soil dispersion making water hard which results in less nutrient uptake. Reduced water infiltration affects root growth and Sodium toxicity causes leaf burn, defoliation and reduced yield. High Na also disrupt K, Ca and Mg uptake.

Table - 2. Status of irrigation water quality used in selected Nagpur mandarin orchards in Vidarbha area of Maharashtra, India.

		Location					
Water	Required Standard	1	2	3	4	5	6
Parameters							
pH	6-7	7.39	7.41	7.34	7.59	7.35	7.49
EC (dsm)	Less than 0.7	0.635	0.773	1.598	1.40	0.78	0.853
TDS (PPM)	Less than 500	570.00	560	1130	1170	590	730
SAR	Less than 3	0.72	0.86	2.5	1.34	4.02	1.35



Chlorides(PPM)	Less than 100	44.01	48.64	203.86	194.59	39.38	78.76
Water source	Well/Bore well/ Any other source	Well, Bore well	Well	Well	Well	Bore well	Well

From above Table 2, it is observed that 100 % cases have high water p^H and TDS, 80 % have high EC, 16 % have high SAR and 33% have high chlorides in irrigation water. This reflects an absorption of nutrition by plant and affects efficiency of spray if water used for spraying without treatment to balance P^H .

Leaf petiole analysis (Table no. 3)

Result

Leaf nutrient analysis revealed considerable deviation from established optimum standards for citrus. As the uptake of nutrients is influence by soil and water quality.

Nitrogen (N) content ranged from 1.40 to 1.79%, which is below the recommended desired range of 2.49–2.81%, indicating consistent nitrogen deficiency across all orchards.

Phosphorus (P) ranged from 0.102 to 0.20%, remaining near the lower limit of the standard range (0.11–0.36%), with some locations approaching deficiency.

Potassium (K) content ranged between 1.12 and 1.89%, which is markedly below the optimum range of 2.12–2.51%, indicating widespread potassium deficiency. Influencing fruit quality and post-harvest losses.

Calcium (Ca) levels were relatively higher and, in some samples, exceeded the desirable balance range. Magnesium (Mg) levels were moderate but close to sufficiency limits.

Among micronutrients, zinc (Zn) levels were below the critical limit in several orchards. Iron (Fe), manganese (Mn), and copper (Cu) showed variable adequacy. Boron (B) levels were comparatively elevated in certain samples, suggesting possible toxicity risk. It may also be due to excessive application of Boron through foliar sprays or it high B is present in irrigation water.

Overall, nitrogen and potassium deficiencies were the most pronounced nutrient constraints observed in leaf tissues. And K deficiency in particular might have influenced the fruit quality, increase fruit drop and reduced shelf life.

Discussion

Leaf nutrient composition reflects the integrated effect of soil (Table 1) and irrigation water (Table 2).

Nitrogen deficiency reduces chlorophyll synthesis, vegetative growth, and fruit retention (Srivastava, 2013).

Potassium deficiency despite adequate soil K suggests antagonism with high exchangeable calcium (Marschner, 2012).

Potassium is critical for carbohydrate translocation, enzyme activation, stomatal regulation, and fruit development; its deficiency increases premature fruit drop (Srivastava & Singh, 2003). Low potassium in plant tissue despite high soil K may occur due to high soil pH, nutrient antagonism (excess Ca, Mg, or Na), poor or compacted soil structure, water stress, or damaged roots, which reduce K uptake. Excess soil K can also create nutrient imbalance by limiting Ca and Mg uptake, affecting plant growth, fruit quality, and causing leaf scorching under high salt conditions.

Phosphorus near lower threshold may impair ATP formation, affecting flowering and fruit set.

Zinc deficiency is consistent with alkaline calcareous soils; zinc regulates auxin synthesis and flowering intensity (Srivastava & Singh, 2003).

Elevated boron can cause toxicity, disturbing membrane integrity and fruit development.



Table -3. Comparison of observed nutrient levels in plant tissues with standard sufficiency range for Nagpur mandarin.

		Location						
Parameters	Unit	Standard range	1	2	3	4	5	6
N	%	2.49-2.81	1.68	1.51	1.79	1.40	1.51	1.74
P	%	0.11-0.36	0.153	0.20	0.139	0.145	0.136	0.102
K	%	2.12-2.51	1.49	1.28	0.95	1.27	1.02	0.62
Ca	%	2.12-2.32	3.22	4.76	4.25	4.17	4.80	4.91
Mg	%	0.38-0.48	0.25	0.34	0.44	0.34	0.31	0.39
S	%	0.18-0.30	0.14	0.181	0.177	0.15	0.18	0.16
Fe	PPM	108-180	291.18	841.51	821.79	596.09	584.56	547.13
Mn	PPM	74-85	48.17	124.81	109.47	82.66	77.59	99.98
Zn	PPM	24.2-38.8	11.32	17.46	17.58	17.58	34.24	26.61
Cu	PPM	10.4-18.6	6.99	9.96	6.66	5.34	6.00	7.98
B	PPM	2.05=3.0	28.64	40.29	45.15	37.38	27.59	41.75

From above Table 3, it is observed that 100 % samples show deficiency of N, K and Cu, while 100 % samples show excessive levels of Ca, Fe and B. 16 % showed P deficiency, 66 % showed Zn, S and Mg deficiency which cause, 16 % showed Mg deficiency influence crop performance. While 50 % showed excess Mn. Which can cause Mn toxicity leading to leaf drop and reduced leaf size.



IV. CONCLUSIONS AND SUGGESTIONS

The present investigation clearly demonstrates that citrus productivity in Katol, Chandur Bazar, Morshi, and Warud regions is strongly influenced by soil chemical composition constraints, irrigation water quality, and nutrient imbalance between soil and plant tissues. Although several nutrients were found adequate or even excessive in soil analysis, their availability and uptake were significantly restricted due to high soil pH, elevated calcium carbonate (CaCO_3) levels, soil compaction, and poor organic carbon status.

Soil pH values (8.11–8.82) across all locations indicate moderately to strongly alkaline conditions. Under such alkaline environments, phosphorus fixation increases, micronutrient solubility declines, and nutrient antagonism becomes more pronounced. High concentrations of calcium and magnesium in soil have suppressed the uptake of potassium, nitrogen, zinc, and copper, as confirmed by leaf petiole analysis. This clearly shows that nutrient availability in soil does not necessarily reflect nutrient absorption by plants. However, to ensure the uptake of bio fertilizers and organic manures can improve the status.

Despite high soil potassium levels in several locations, leaf potassium concentrations were consistently below the desired range. This imbalance has contributed to reduced fruit size, thick rind formation, decreased juice content, increased fruit drop, and poor fruit quality in Nagpur mandarin. Similarly, widespread phosphorus deficiency in soil has limited root development, weakened pedicel strength, and increased fruit abscission causing more fruit drop.

The excessive accumulation of iron and boron in leaf tissues indicates nutrient toxicity risks, further aggravating physiological stress. Elevated iron concentrations appear to interfere with phosphorus, zinc, and manganese uptake, while excess boron has induced leaf scorching and decline in crop vigour. Additionally, irrigation water analysis revealed elevated EC, TDS, SAR, and chloride levels at certain locations, which may contribute to salinity stress and impaired nutrient uptake.

Low soil organic carbon content in most sites suggests insufficient organic matter management, leading to soil compaction, poor aeration, weak microbial activity, and reduced nutrient-use efficiency. The lack of balanced fertilization, insufficient bio-fertilizer application, and limited use of organic amendments have collectively contributed to declining nutrient absorption and productivity.

Overall, the study confirms that citrus yield and fruit quality in the surveyed regions are limited not by a single nutrient deficiency but by a complex interaction of following:

- High soil alkalinity
- Nutrient antagonism (Ca–Mg vs. K–P–Zn–Cu)
- Poor phosphorus availability
- Reduced potassium uptake despite adequate soil reserves
- Micronutrient imbalance
- Suboptimal irrigation water quality
- Low organic carbon and soil compaction

To restore productivity and reduce fruit drop in Nagpur mandarin, the following integrated corrective measures are essential based on analysis done and presented:

- Reduction of soil pH through sulphur application and organic acid-based amendments.
- Increased use of organic manures, green manures, and oil cakes to improve soil organic carbon.
- Application of phosphorus-solubilizing bacteria (PSB), potassium-mobilizing bacteria (KMB), zinc- and iron-solubilizing bio-fertilizers.
- Balanced and need-based fertilization guided by periodic soil and leaf analysis.
- Foliar correction of potassium, zinc, and copper deficiencies.
- Reduction in boron and iron inputs where excess levels are detected.
- Use of water conditioners and adjuvants during foliar spraying to improve nutrient and pesticide efficiency.



Maintaining optimum phosphorus levels is particularly critical in Nagpur mandarin, as phosphorus deficiency was closely associated with increased fruit drop and reduced fruit retention.

In conclusion, sustainable citrus production in the studied regions requires an integrated nutrient management strategy that synchronizes soil health, water quality, microbial activity, and plant nutrition. Continuous monitoring through soil, water, and leaf analysis should be institutionalized to prevent nutrient imbalance and ensure consistent yield and fruit quality. This will also help in reduce excess use of fertilizers and to improve soil health.

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