Enhancing Soil Health through Organic Inputs to Sustain Tomato Production under Saline Conditions

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Abstract. The study investigates the impact of organic amendments on tomato plant growth, yield, biochemical composition, and defense mechanisms. Results show that integrated application of various organic amendments (mustard cake, goat manure, poultry manure, farmyard manure, vermicompost, neem cake, Azotobacter, phosphorus-solubilizing bacteria), and reduced levels of fertilizers (14.3% of the recommended dose) significantly impacts plant growth and yield, balance C/N ration and N-metabolism, and maintains antioxidant levels and defense mechanisms in plants; however, saline water negatively affects nitrogen and phosphorus availability, affecting tomato production. The authors suggest that organic amendments from locally available sources improve tomato productivity, reduce salt stress, and sustain production.

Keywords: antioxidant enzymes, biochemical parameters, plant defense mechanisms, organic inputs, saline water stress, tomato production

Significance:

A blend of organic inputs and reduced fertilizer was created to balance defense mechanisms, regulate salt stress in tomatoes, and maintain soil health. The mixture effectively sustains tomato production by enhancing nitrogen assimilation and mitigating saline conditions.

1.0 Introduction:

Tomatoes, scientifically known as *Solanum lycopersicum*, hold a prominent place among vegetable crops globally due to their nutritional value and economic significance [1]. Organic amendments, such as farmyard manure and vermicompost, are widely used to improve soil fertility and enhance plant growth; however, the potential interactions between organic amendments and saline water, remain poorly understood [2]. Farmers and researchers are exploring organic amendments for tomato cultivation, which improve soil structure, water retention, and nutrient supply, leading to increased yields. Vermicompost, a specialized compost produced by earthworms, is also being explored for its nutrient-rich properties [3, 4]. Some studies have recommended the use of microbes and organic inputs in alleviating salt stress in plants [5, 6]; however, an integrated approach including reduced levels of fertilizers and enhanced levels of organic inputs is still lacking. The study aims to (i) evaluate the impact of organic amendments like farmyard manure and vermicompost on tomato plants under normal and saline conditions, (ii) reduce fertilizer applications, and assess their restoration abilities for soil health and plant nutrition, and (iii) develop sustainable cultivation practices that maximize tomato productivity in salinity-affected regions.

2.0 Materials and Methods:

2.1 Experimental site:

The study was conducted at Amity University Uttar Pradesh, Noida, from September 2020 to December 2022, focusing on the region's hot semi-arid, sub-tropical climate with an annual rainfall of 530 mm.The farm is situated at a latitude of 28.32°N, longitude of 77.20°E, and an altitude of 200 meters above mean sea level. June

is the warmest month with an average high temperature of 42 ℃, while January is the coldest month with the lowest average high temperature at 20.8 ℃. June also has the highest average low temperature at 31.7℃, while January has the lowest average low temperature at 9.1 ℃.

2.2 Experimental:

The experimental layout consisted of randomized block design or RBD, having five treatments and three replications. The spacing was 0.45m × 0.60m in a 7.65 × 3.6 m² plot area. Each plot size was 27.54 m², and the total experimental area was 413.10 m² (27.54 × 5 × 3m²), covering 1,125 plants, equivalent to 27,233 plants ha^{-1}. Each plot had 75 (15×5) tomato plants, ensuring uniform plant density across all treatments. Nutrients were applied on October 21, 2020, and October 21, 2021, respectively. The details of treatment combinations are presented in Table 1. To study and explore the impact of using organic manure to improve soil health and support tomato cultivation in saline environments, the authors implemented the same treatment combinations on the experimental farm presented in Table 1. The irrigation process involved using a known concentration (EC 4.0 dS m^{-1}) of sodium chloride (NaCl) or table salt dissolved in water sourced from the Amity Research Farm in Noida, Uttar Pradesh.

Table 1. Treatment combinations for the impact analysis of organic inputs under saline conditions.

Treatments	**Symbol**	**Treatment combinations**
Treatment 1	T_1	Farmyard manure (FYM 15 t ha^{-1}) and vermicompost (VC 3 t ha^{-1})
Treatment 2	T_2	Mixture of mustard cake (MC 0.429 t ha^{-1}), goat manure (GM 0.714 t ha^{-1}), poultry manure (PM 0.471 t ha^{-1}), FYM 4.286 t ha^{-1}, VC 0.857 t ha^{-1}, neem cake (NC 1.071 t ha^{-1}), Inorganic fertilizer (Urea 46.6, SSP 89.3, MoP 14.3, in kg ha^{-1}), biofertilizer *Azotobacter* (BF-*A* 1 kg ha^{-1}, and phosphorus solubilizing bacteria (PSB 1 kg ha^{-1}
Treatment 3	T_3	Saltwater having EC 4 dS m^{-1} of NaCl only
Treatment 4	T_4	FYM 15.0 t ha^{-1}, VC 3.0 t ha^{-1}, and SW of NaCl having EC 4.0 dS m^{-1}
Treatment 5	T_5	Mixture of MC 0.429 t ha^{-1}, GM 0.714 t ha^{-1}, PM 0.471 t ha^{-1}, FYM 4.286 t ha^{-1}, VC 0.857 t ha^{-1}, NC 1.071 t ha^{-1}, Inorganic fertilizer (Urea 46.6, SSP 89.3, MoP 14.3, in kg ha^{-1}), BF-*A* 1 kg ha^{-1}, PSB 1 kg ha^{-1}, and SW of NaCl having EC 4.0 dS m^{-1}

2.3 Soil analysis:

Initial physicochemical measurements were recorded before the experiment to establish a baseline. The soil was characterized as sandy loam, consisting of sand, silt, and clay, as mentioned in Table 2. Representative samples were collected and stored in a refrigerator for analyzing soil physicochemical parameters, as shown in Table 2. The soil texture was sandy loam (alluvial), with EC 1.13 dS m^{-1} and pH 7.89. Soil pH was determined using a glass electrode pH meter, with a soil: water ratio of 1:2.5.

Table 2. Baseline physico-chemical characteristics of the experimental soil before the experiment. Data are presented as mean ± standard deviation (SD).

Parameter	**Unit**	**Values**
Sand	%	69 ± 1.30
Silt	%	14 ± 0.40
Clay	%	17 ± 0.40
pH	-	7.89 ± 0.16
EC	dS m^{-1}	1.13 ± 0.08
Available nitrogen	kg ha^{-1}	236.3 ± 5 03
Available phosphorus	kg ha^{-1}	17.00 ± 1.30
Available potassium	kg ha^{-1}	41.83 ± 2.75
Available sodium	µg g^{-1}	11.96 ± 0.40
Organic carbon	%	0.55 ± 0.02

2.3.1 Determination of soil organic carbon and NPK:

The organic carbon content was assessed using the wet dichromate acid oxidation method. Initial measurements of available nitrogen, phosphorus, and potassium were taken before initiating the experiment to establish a baseline. Subsequently, following the post-experiment, the available NPK levels were evaluated to assess the impacts of the different treatments. Soil-available nitrogen was determined using the Kjeldahl apparatus [7]. Available phosphorus levels were measured using the Olsen method. Exchangeable potassium and sodium were assessed using a flame photometer (CL22D ELICO Ltd.) [8]. The soil's cation exchange capacity was determined using the 1N ammonium acetate method [8].

2.4 Growing tomato seedlings:
The seeds of tomato (*var.* Pusa Sheetal) were germinated in a seedbed prepared in a fenced area with a well-maintained soil mixture. Four- to five weeks old were then transplanted from the seedbed to the main plot prepared for tomato crop cultivation.

2.5 Farmyard manure, vermicompost, and mixture of organic inputs:
The farmyard manure used in treatments T_1, T_2, T_4, and T_5 was obtained from locally available organic sources. Vermicompost was manufactured on the farm using a mixture of in-farm plant waste and cow dung layers with the help of earthworms, *Eisenia fetida.* It was covered with a layer of leaf mulch to maintain moisture [7]. The organic manure mixture in T_2 consisted of various bulky organic manures, including FYM and VC, concentrated manure such as Neem-cake and mustard-cake, other organic residues such as decomposed poultry birds and goat litter, biofertilizer inoculation (Azotobacter and PSB), and 14.3 % inorganic fertilizers (in kg ha^{-1}), through urea (46.6), single Super Phosphate (SSP 89.4), and Muriate of potash (MOP 14.3) (Table 2).

2.6 Applying saline water:
The saline water was prepared by dissolving NaCl in distilled water maintaining an EC of 4.0 dS m^{-1}. In Treatment T_3, an exclusive EC 4.0 dS m^{-1} (NaCl) was prepared by dissolving 2560 milligrams of NaCl in one liter of distilled water [9]. Saline water treatment was combined with treatments T_1 and T_2, forming treatments T_4 and T_5, respectively, to study normal and saline conditions.

2.7 Biometric parameters:
Biometric parameters of tomato plants were observed during the growth stages of plants. including plant growth, branching and leaves per plant, fruit biomass, and yield.

2.8 Biochemical parameters
Ascorbate peroxidase test (APX):
To assess *APX* activity, we followed the method described by Oliveira et al. [10]. The enzyme's activity was measured by a decrease in ascorbate absorbance at 290 nm. Using a molar extinction value of 2.8 mM cm^{-1}, APX was determined and expressed (µmole H_2O_2 reduced min^{-1} g^{-1} FW).

2.8.1 Carotenoid content analysis (CCn):
The quantification of carotenoids was performed using spectroscopy at 470 nm [4]. In this procedure, tomato extract (1 ml) was combined with a mixture of ethanol, acetone, and hexane in a ratio of 1:1:2, and centrifuged at 1500x for 30 minutes. By utilizing molar extinction coefficients of 184900 M^{-1} cm^{-1}, the concentration of carotenoids was calculated and expressed as mg g^{-1} FW.

2.8.2 Hydrogen Peroxide Activity (H_2O_2):
The concentration of hydrogen peroxide (H_2O_2) was estimated by using potassium iodide (KI) oxidation and measuring it spectrophotometrically at an absorbance of 390 nm [11].

2.8.3 Lycopene test (LYC):
The lycopene content of the tomato fruit was determined by using homogenized tomato fruit puree and a UV-VIS spectrophotometer to measure the absorance at 563 nm [4]. Tomato samples (1 g) were mixed with butylated hydroxytoluene (10 mL BHT, prepared from hexane, acetone (0.05% v/v), and ethanol (95%)). The samples were shaken using a shaker at 4 ℃ for 5 minutes at 180 rpm at room temperature. After 5 minutes, a visible layer of hexane appeared on the upper phase of the samples. The absorbance was measured to determine the lycopene content.

2.8.4 Malondialdehyde levels (MDA):
To determine the level of oxidative stress caused by salinity, we measured the amounts of Malondialdehyde (MDA) and hydrogen peroxide, which are indicators of lipid damage, quantified using the method of thiobarbituric acid reactive substances (TBARS) [12]. The resulting MDA-TBAR complex was calculated as nmol g^{-1} FW at 532 nm, 660 nm, and 440 nm, using a molar extinction coefficient of 155 mM cm^{-1}.

2.8.5 Superoxide dismutase activity (SOD):
The efficacy of SOD activity (mg^{-1} protein) was assessed by inhibiting the photochemical reduction of nitroblue tetrazolium chloride (NBT) [7]. A reaction mixture of 50 mM phosphate buffer (pH 7.8), 0.1 mM EDTA, 13.5 mM methionine, 75 mM NBT, and 10 mM riboflavin

was prepared in a volume of 1.5 mL. The enzyme extract (50 µL) was examined spectrophotometrically and the absorbance of the reaction mixture was measured at 560 nm. .

2.8.6 Total Antioxidant Activity (TAA):
The ABTS technique was used to measure total antioxidant activity (µmol g^{-1} FW), gauging the efficacy of both lipophilic and hydrophilic antioxidants in quenching a radical cation of 2,2'-azinobis 3-ethylbenzthiazoline-6-sulphonic acid (ABTS) [13]. The novel solution, consisting of 7 mM ABTS and 140 mM potassium persulfate, was incubated for 16 hours in the absence of light. Absorbance was measured at 734 nm to confirm the presence of ABTS, with values close to 0.700. Adding 30 ml of extract to 3 ml of the innovative solution initiated the reaction, and monitored by measuring absorbance at 734 nm for 6 minutes. The reduction in absorption was used to calculate TAA. Trolox concentrations (100 to 2000 M) were assessed through a calibration curve.

2.8.7 Total Soluble Solids (degree °Brix):
The concentration of TSS can be accurately determined using the principle of light refraction [14]. This phenomenon occurs when a ray of light passes through different media, resulting in a change in direction. The degree of refraction is directly related to the density or soluble solids in the solution. Measuring the angle of incidence and refraction allows for the calculation of the refractive index using a hand refractometer.

2.8.8 Vitamin C (mg g^{-1} FW) TAA:
Ascorbic acid content (mg g^{-1} FW) was determined using a standard protocol [15]. Tomato pulp (1g) was homogenized and a 3% bromine water solution was added to the centrifuged samples to convert ascorbic acid into dehydroascorbic acid. The excess bromine was then eliminated using 10% thiourea. A 2,4-DNPH solution is introduced to create osazones. All standards, samples, and blank solutions were maintained at a constant temperature of 37 °C for 3 hours using a water bath. Samples were treated with 5 mL 85% H_2SO_4 (chilled) while being continuously stirred, and the absorbance was read at 521 nm.

2.9 Statistical analysis:
The data collected from the assessed variables satisfying the conditions of both tests over the course of two seasons were subsequently subjected to an average and then subjected to Origin6.1 for drawing figures and MS-Excel 365 for the ANOVA. Following this transformation, ANOVA and Tukey's mean comparison tests were conducted (with a significance level of $p \leq 0.05$).

3.0 Results:
The impacts of organic inputs under normal and saline conditions have been presented under the following headings.

3.1 Soil pH:
The experiment showed that soil pH decreases with the introduction of organic matter, while it increases with salts. Treatments T_1 and T_2 showed slight decreases, while treatment T_3 significantly increased pH. The combined treatments T_4 and T_5 showed slight reductions and slight increases, respectively. The presence of saline water had a significant adverse effect on soil pH, indicating that organic inputs maintain stable pH levels. This decrease can be attributed to the organic matter's buffering capacity, which maintain a neutral to slightly higher pH range (Figure 1A).

3.2 Soil EC:
Soil electrical conductivity exhibited minimal fluctuations, reflecting the stability of the soil's natural electrical conductivity (1.13 dS m^{-1}) under the control. Treatment T_1 showed a slight increase in soil EC (1.20 dS m^{-1}) after the treatments were applied (Figure 1B). Similarly, T_2 exhibited a slight increase in soil EC levels following the treatments were applied (1.26 dS m^{-1}). The addition of organic inputs and reduced synthetic fertilizer levels contributed to an increase in ion concentration, resulting in a minor increase in the EC. Treatment T_3, significantly elevated soil EC after the application of saline water, indicating a noticeable increase in EC levels due to the introduction of salts (2.83 dS m^{-1}). The combined treatments, T_4 and T_5, showed similar trends to T_3, with a significant increase in soil EC after the application of treatments (1.97 and 2.13 dS m^{-1}, respectively); however, the increase in EC level was mitigated by the application of organic inputs.

3.3 Soil organic carbon:
The pre experimental plots had a minimum level of soil organic carbon (5.52 g kg^{-1}). Treatment T_1 showed a significant increase in soil organic carbon content (7.98 g kg^{-1}). The integration of organic inputs into the soil promotes microbial activity and the decomposition of organic materials, ultimately resulting in higher levels of soil organic carbon [16]. Treatment T_2 involved combining manure and reducing synthetic fertilizers, resulting in a significant increase in soil organic carbon content (7.80 g kg^{-1} soil) (Figure 1C). Manure organic matter aids soil microbes in accumulating organic carbon, while saline water negatively affects soil organic carbon content. Despite saline water's negative effects, organic matter counteracts these effects by

providing microbial activity and promoting carbon retention in soils.

3.4 Soil-available nitrogen (N):

The soil before the experiment showed a nitrogen-deficient condition, with 98.5 mg N kg^{-1} soil, equivalent to 236 kg N ha^{-1}. Treatment T_1, which involved FYM enriched with vermicompost, demonstrated an increase in available nitrogen levels after the experiment. VC is known for its slow-release properties, contributing to elevated nitrogen availability (141.5 mg kg^{-1} equivalent to 340 kg N ha^{-1}). Choudhary et al. [17] applied Jeevamrut at 16.08 L and VC at 24.79 kg $plant^{-1}$ which produced significant yield and increased soil available-N up to 272.68 kg ha^{-1}. Similarly, treatment T_2 exhibited a significant increase in the available N levels after the experiment (145.8 mg kg^{-1} equivalent to 350 kg N ha^{-1}). This outcome is consistent with the input of nitrogen-rich materials through both manures and synthetic fertilizers, thereby increasing the nitrogen content available to the plants (Figure 1D).

The experiment showed a significant decrease in nitrogen levels (84.7 mg kg^{-1} equivalent to 203 kg ha^{-1}) due to the application of saline water. However, organic matter amendments in T_4 and T_5 likely compensated for potential losses, resulting in lower nitrogen levels.

3.5 Soil available phosphorus:

Prior to the experiment, the available phosphorus in the pre-experimental soil was 7.1 mg kg^{-1} soil equivalent to 17 kg ha^{-1} soil. Treatment T_1 displayed an increase in available phosphorus (9.4 mg kg^{-1} soil) after the experiment. Similarly, treatment T_2 showed a higher increase in the level of available phosphorus, recorded to the extent of 10.54 mg kg^{-1} soil, after the experiment. The introduction of phosphorus-rich materials through both manure and synthetic fertilizers has led to a significant increase in the phosphorus content available for plant uptake. Treatment T_3 with saline water negatively affected soil phosphorus levels, reducing them to 5.6 mg kg^{-1} (Figure 1E). Saline water forms complex P-compounds, hindering P-availability to plants; however, organic acids available in organic inputs convert triphosphates into monophosphates.

3.6 Soil available potassium:

The experiment showed that the available potassium in soil increased significantly after treatment T_1, with the maximum level reaching 30.0 mg kg^{-1}. Treatment T_2, a combination of manure and reduced synthetic fertilizers, showed the highest available potassiu;. however, the stability of potassium availability remained unaffected by the introduction of saline water and manure (Figure 1F). The study reveals that saline water has a marginal influence on potassium availability, resulting in consistent potassium levels [6].

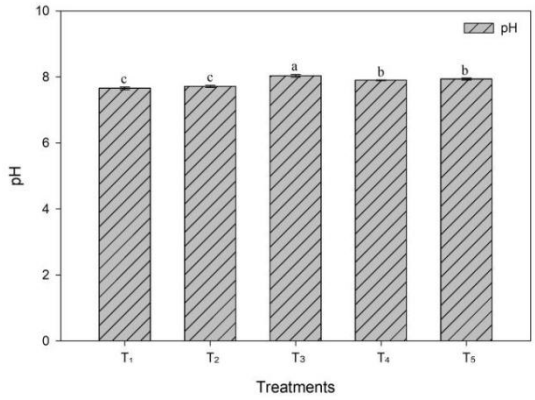

Figure 1A

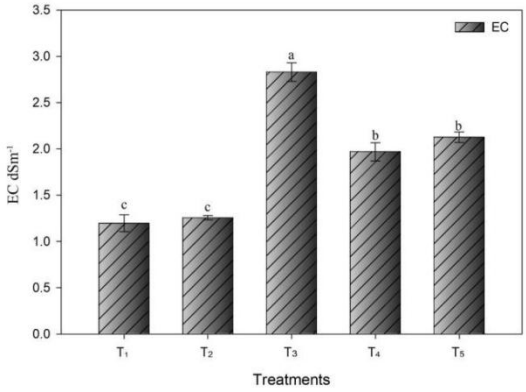

Figure 1B

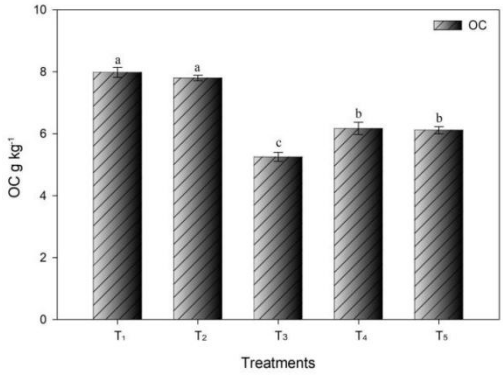

Figure 1C

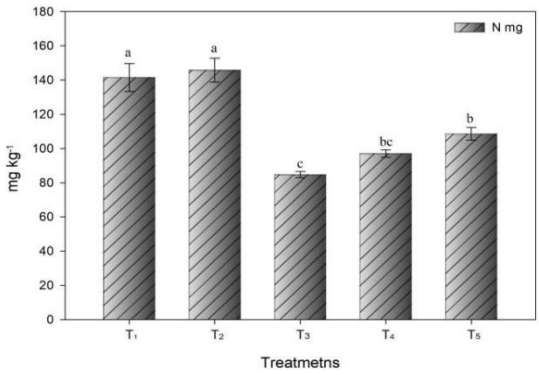

Figure 1D

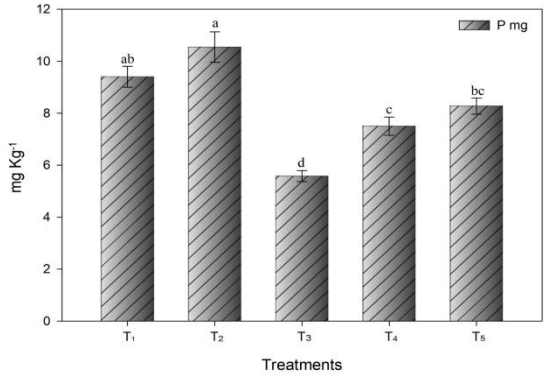

Figure 1E

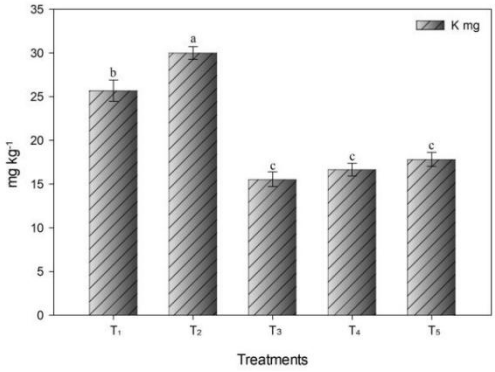

Figure 1F

Figure 1. The effect of organic inputs on (A) soil pH (F = 22.93, P < 0.0001) (B) soil electrical conductivity (EC) (F = 72.04, P < 0.0001), (C) soil organic carbon (F = 64.95, P < 0.0001), (D) soil available nitrogen (F = 26.84, P < 0.0001), (E) available phosphorus (F = 23.33, P < 0.0001), and (F) available potassium (F = 52.22, P < 0.0001) under both normal and saline conditions in tomato cultivation.

3.7 Plant height:

Treatment T_1 used farmyard manure and vermicompost to increase plant height up to 71.67 cm. Treatment T_2 combined bulky and concentrated manure with biofertilizers, reduced 14.3% dose of recommended NPK, achieved maximum plant height of 73.8 cm. The study reveals that well-composted manures may stimulate growth in salty water conditions (Figure 2A). Treatment T_4, involving only saline water (4 dS m^{-1}), displayed the least favorable outcomes, resulting in significantly shorter tomato plants with an average height of 39.06 cm. Saline water usage has led to a significant decrease in fruit growth and yield [18,19].

3.8 Number of branches:

Treatments T_1 and T_2 stood out with a significant number of branches, up to 12.67 on average per plant. The rich organic matter and better nutrient availability under FYM- and vermicompost-treated plots can justify this, as they provide ample resources for lateral branching and increase vegetative growth. Additionally, when a combination of manures and fertilizers was applied, enriching the soil with essential nutrients and producing more lateral branches. A fertigation with treated wastewater integrated with controlled pH (6.5-7.2), EC (< 2 dS m^{-1}), compost, and composite biochar can improve nutritional quality in crops [20]. Treatments T4 and T5 provided abundant N and essential nutrients, potentially stimulating growth and increasing branching compared to T3, which used saline water alone, with the least favorable outcomes (Figure 2B).

3.9 Number of leaves:

Two treatments, T_1 and T_2, displayed a significant number of leaves, up to 110.8 and 113.7 (mean basis), respectively, due to the long-term availability of nitrogen, moisture, and other essential nutrients (Figure 2C). This result can be attributed to the rich organic matter and nutrients in these materials, which likely provided essential resources for increased leaf development and foliage expansion. The diverse nutrient profile from the mixture treatment T_2 likely contributes to an increased leaf count. Treatments T_4 and T_5 yielded slightly better results than T_3, potentially contributing to an increase in leaf production.

Thus, soil salinity can hinder the plant's ability to produce new leaves and expand its foliage.

3.10 Number of fruits:

Treatment T_1 significantly increased fruit production, attributed to FYM and vermicompost's nutrient-rich organic matter. Treatment T_2 also showed a substantial increase, likely due to the diverse nutrient profile and reduced fertilizers, promoting floral-to-fruit development (Figure 2D). The addition of saline water (T_3) acted as a growth inhibitor, potentially inhibiting flower formation and leading to fewer fruits (mean of 10.33 fruits plant^{-1}). The adverse effect of saline water on fruit formation from flowers can be attributed to its potential negative impact on soil health, which can hinder the initiation and development of floral structures.

3.11 Fruit weight:

Treatment T_2 produced the maximum fruit weight gain (56.0 g); however, treatment T_1 was also found to be promising, resulting in an average fruit weight of 52.99 g (Figure 2E). The presence of rich organic matter and essential nutrients in these materials likely creates an ideal environment for fruit development, biochemical production, and gene expression, subsequently elevating fruit weight. Treatment T_3, involving saline water alone, yielded the least favourable outcomes for fruit weight (33 g), possibly due to the adverse effects of saline water on soil salinity, hindering fruit development due to toxicity and unavailability of nutrients.

3.12 Fruit yield:

The optimal combination of organic inputs, such as FYM, VC, poultry manure, goat manure, neem cake, mustard cake, and dual inoculation with Azotobacter and phosphorus-solubilizing bacteria, and reduced fertilizers, led to the highest fruit yield (428 q ha^{-1}). Similarly, treatment T_1 with FYM and VC delivered a higher fruit yield per hectare (419.3 q ha^{-1}). Conversely, treatment T_3, involving saline water alone, yielded the least favourable outcomes, potentially due to the abundant supply of saline water hindering fruit production [16, 19].

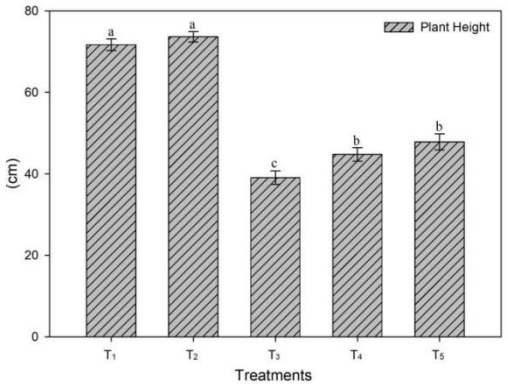

Figure 2A

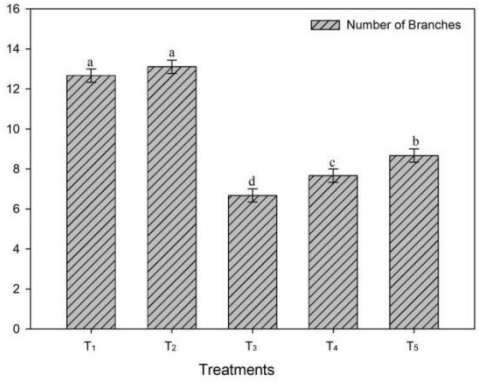

Figure 2B

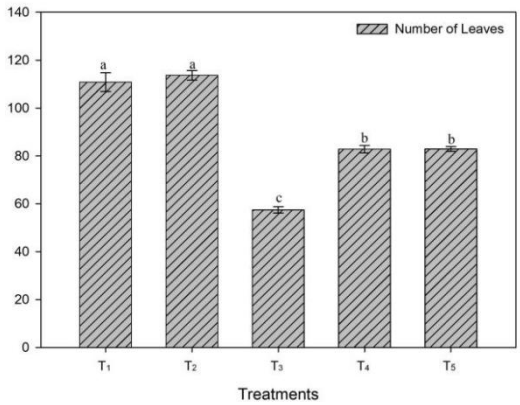

Figure 2C

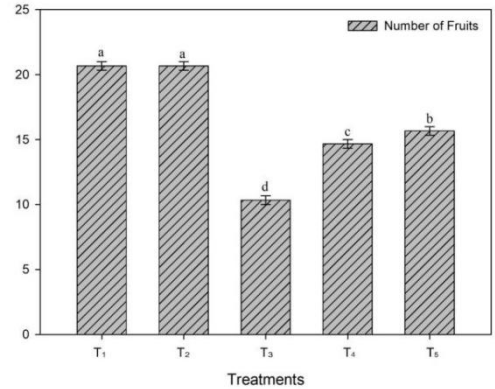

Figure 2D

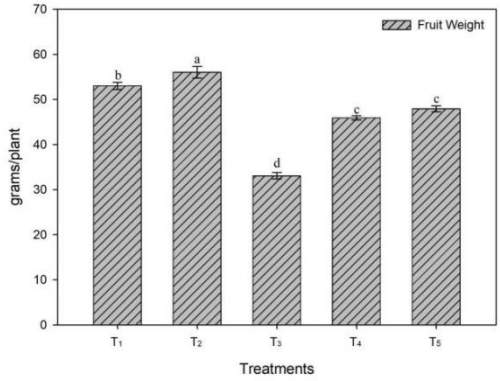

Figure 2E

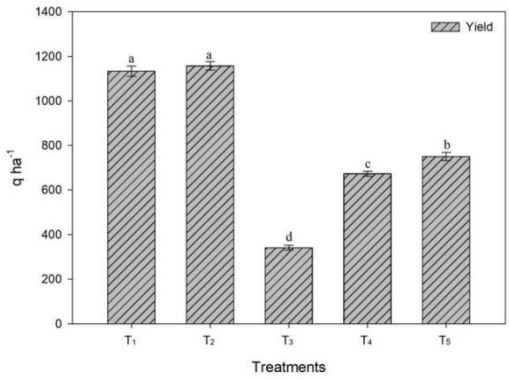

Figure 2F

Figure 2. The effect of organic inputs on (A) plant height (F = 98.66, P < 0.0001), (B) number of branches (F = 72.0, P < 0.0001), (C) number of leaves (F = 108.95, P < 0.0001), (D) number of fruits (F = 172.7, P < 0.0001), (E) fruit weight (F = 179.0, P < 0.0001), and (F) yield (F = 403.89. P < 0.0001) at 90 Days After Transplanting (DAT) under both normal and saline conditions in tomato cultivation.

3.13 Ascorbate Peroxidase Activity (APX):

Treatment T_2 exhibited the highest APX activity (352.1 µmol min^{-1} mg^{-1}) (Figure 3A). Treatment T_1 displayed the second-highest APX activity (349 µmol min^{-1} mg^{-1}). The organic matter in this combination, which comprises FYM and vermicompost, improves soil structure and microbial activity while maintaining optimal enzymatic activity, such as APX [21]. Treatment T_3, involving saline water alone, exhibited the lowest APX activity (199.3 µmol min^{-1} mg^{-1}). High soil salinity creates severe stress in plants, inhibiting enzyme activity, including APX. The increased osmotic stress from saline water reduces the plant's ability to maintain enzymatic processes, leading to significantly lower APX activity. Organic inputs contributes to enhanced soil microbial activity and nutrient availability, thereby stimulating APX production in plants and fortifying their defense mechanisms against oxidative stress, leading to. enhanced stress tolerance in plants.

3.14 Carotenoid content (CCn):

Treatment T_2 exhibited the highest level of CCn (65.9 mg g^{-1}). Treatment T_1 demonstrated the second-highest CCn value (64.7 mg g^{-1}) (Figure 3B). This result can be attributed to the synergistic effects of organic amendments. The organic inputs provide an enriched source of organic matter [22, 23], promoting the diverse microbial community, contributing to improved stress tolerance in plants, potentially resulting in elevated carotenoid levels. In contrast, treatment T_3 (saline treatment) exhibited the lowest CCn level (43.7 mg g^{-1}). Elevated soil salinity creates severe stress for tomato plants, hindering the production and accumulation of carotenoids.

3.15 Lycopene content (LYC):

Treatment T_2 resulted in a significant increase in LYC, highlighting the significance of nutrient balance in enhancing LYC to a maximum of 52 mg g^{-1}. Treatment T_1 exhibited the second-highest LYC value of 51 mg g^{-1}. Both these outcomes are attributed to the beneficial effects of organic amendments on nutrient availability and microbial activity. Treatments contaminated with saline water, T_4 and T_5, showed a moderate increase in LYC compared to the treatment T_3. This suggests that saline water was less effective under organic amendments and was unable to significantly reduce LYC. Treatment T_3 (saline water alone) yielded the lowest LYC level, emphasizing the detrimental effects of saline water on nutrient uptake and LYC levels (29.18 mg g^{-1}) (Figure 3C). In summary, treatments T_1 and T_2 were the most effective in enhancing LYC, while saline water treatments had a limited impact [22].

3.16 Superoxide Dismutase activity (SOD):

Treatments T_1 and T_2 displayed higher SOD activity (unit: mg $protein^{-1}$) in tomato plants, up to 44.73 and 44.87, respectively (Figure 3D). The increased SOD activity contributes to the plants' ability to scavenge superoxide radicals and mitigate oxidative stress. Treatment T_3 exhibited the lowest SOD activity, measuring 23.43 mg $protein^{-1}$. Treatments T_4 and T_5, which combined saline water with organic and inorganic amendments, also showed a reduction in SOD activity compared to non-saline treatments. This emphasizes the significant impact of saline water stress on the beneficial effects of organic and inorganic soil amendments, which hinders the plants' SOD activity.

3.17 Total Antioxidant Activity (TAA):

Treatment T_2 (the optimized mixture of organic inputs and reduced level of fertilizers) exhibited

the highest TAA level up to 162.9 µ mol g^{-1} (Figure 3E). The optimized treatment fosters robust plant growth and enhanced stress resilience. The organic matter in this combination enhances soil structure and microbial activity, while NPK fertilizer provides essential nutrients required for the synthesis of antioxidants, supporting increased TAA level. This approach aids in the maintenance of an efficient antioxidant defence system in tomatoes. Treatment T_1 highlighted the second-highest TAA level in tomato plants (161.5 µ mol g^{-1}). Organic matter boosts soil microbial activity and nutrient availability, stimulating antioxidant production in tomatoes [7]. The enriched TAA in this treatment highlights its potential to bolster the plants' antioxidant defense system and protect them against oxidative stress. Treatment T_3 (saline water alone) displayed the lowest TAA (86.46 µ mol g^{-1}). Treatments T_4 and T_5, which combined saline water with organic and inorganic amendments, exhibited a lower TAA level due to a competitive interaction between saline water and organic inputs in plants.

3.18 Total Soluble Solids (TSS):

TSS levels increased when organic treatments were used in tomato production. The organic inputs highlight their potential to enhance tomato quality by increasing TSS [18, 19], which is a crucial indicator of fruit sweetness and flavor. Treatments T_1 and T_2 exhibited a higher level of TSS (7.25 and 7.28 °Brix, respectively). These outcomes are a result of the balanced nutrient supply provided by the integrated nutrient management (Figure 3F). It is interesting to note that treatment T_3 (saline water treatment only) increased the TSS levels up to a maximum level of 7.35°Brix. High soil salinity exerts severe stress on plants, negatively affecting nutrient and water uptake, and fruit quality. The osmotic stress created by saline water significantly reduces the tomato's ability to absorb moisture, causing a drastic accumulation of total soluble solids up to the maximum level. Treatments T_5 and T_6, which combined saline water with organic and inorganic amendments, exhibited reduced TSS levels up to 5.63 and 6.19 (in °Brix), respectively, compared to their non-saline counterparts, underscoring the overriding impact of saline water stress on the beneficial effects of soil amendments on TSS.

3.19 Vitamin C:

Treatment T_2 exhibited the highest vitamin C content in tomato fruits (20.49 mg g^{-1} FW) (Figure 3G). Treatment T_2 stands out as a promising approach for enhancing the nutritional quality of tomatoes, making them richer in vitamin C, a vital antioxidant with health-promoting properties. Treatment T_1 displayed the second highest level of vitamin C (20.44 mg g^{-1} FW). This approach promotes the accumulation of vitamin C, further enhancing the nutritional value of the fruits [24].

Tomatoes treated with saline water (T_3) had the lowest vitamin C content (10.79 mg g^{-1} FW). The osmotic stress caused by saline water significantly reduces the tomatoes' ability to accumulate vitamin C, underscoring the detrimental impact of saline water stress on tomato nutritional quality. The study highlights the overriding impact of saline water stress on the beneficial effects of soil amendments on vitamin C content.

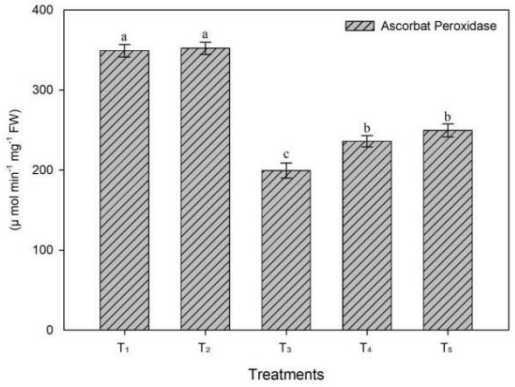

Figure 3A

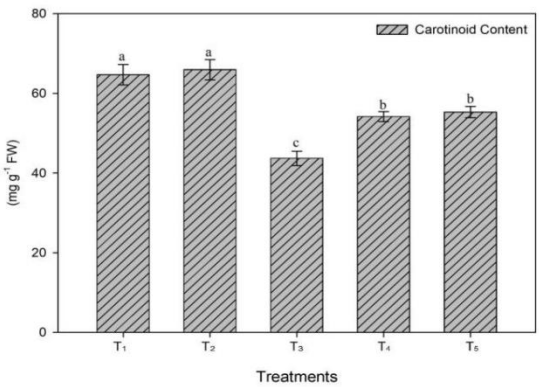

Figure 3B

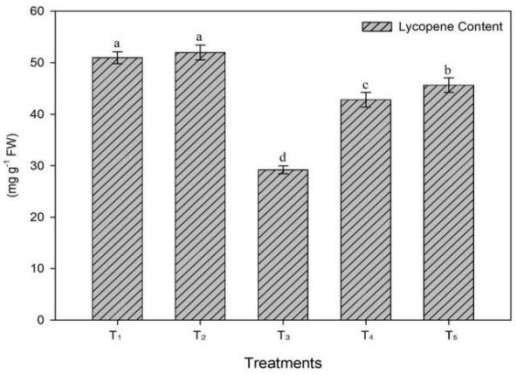

Figure 3C

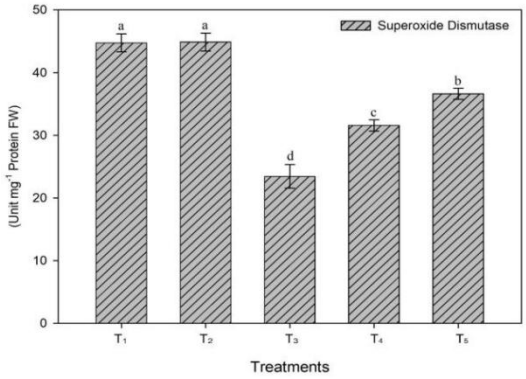

Figure 3D

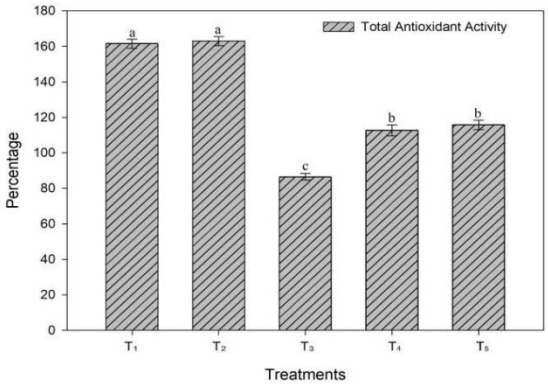

Figure 3E

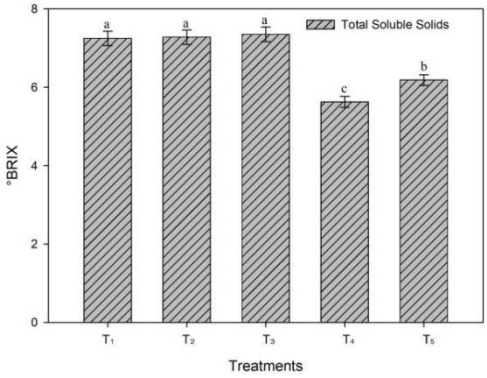

Figure 3F

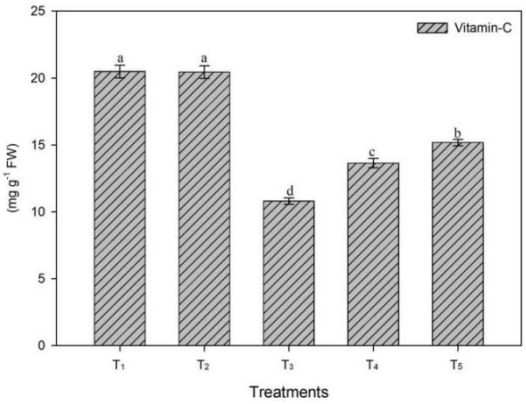

Figure 3. The effect of organic inputs on (A) ascorbate peroxidase (F = 75.42, P < 0.0001), (B) carotenoid content (F = 20.37, P < 0.0001), (C) lycopene content (F = 52.26, P < 0.0001), (D) superoxide dismutase (F = 45.0, P < 0.0001), (E) total antioxidant activity (F = 166.43, P < 0.0001), (F) total soluble solids (F = 21.71, P < 0.0001), and (G) vitamin C content (F = 132.84, P < 0.0001) at 90 Days After Transplanting (DAT) under both normal and saline conditions in tomato cultivation.

3.20 Reactive Oxygen Species (ROS):

Treatments T_1 and T_2 showed moderate levels of ROS (390.2-391.2 µ mol g^{-1} FW) in tomato plants. The microbial communities in vermicompost trigger enzyme activities that contribute to a balanced soil ecosystem, reducing oxidative stress on the tomato plants. Treatment T_2 provides a promising approach to reduce ROS levels in tomatoes, preserving plant health (Figure 4A). Ulikely, treatment T_3 (saline water alone) exhibited the highest levels of ROS in tomato plants (667.80 µ mol g^{-1} FW). High soil salinity places severe stress on plants, leading to an increased production of ROS due to oxidative damage. Treatments T_4 and T_5, which combined saline water with organic and mixed amendments, also displayed higher levels of ROS compared to non-saline treatments. This emphasizes the

overriding impact of saline water stress on oxidative stress in tomato plants [25].

3.21 Hydrogen Peroxide (H_2O_2):

Hydrogen peroxide (H_2O_2) levels in tomato production almost followed similar trends to ROS levels. Treatments T_1 and T_2 displayed lower levels of H_2O_2 in tomato plants, with values of 27.9 and 28.10 nmol g^{-1} FW, respectively. The balanced nutrient supply in treatment T_2, which integrates organic inputs with reduced NPK fertilizers, supports robust plant growth and stress resilience, thereby reducing oxidative stress. Treatment T_3 exhibited the highest level of H_2O_2 (60.80 nmol g^{-1} FW) in tomato plants (Figure 4B). High soil salinity places severe stress on plants, leading to increased H_2O_2 production as a result of oxidative damage. The osmotic stress created by saline water significantly reduces the plants' ability to regulate H_2O_2 levels, resulting in a higher accumulation of H_2O_2 in tomato plants.

3.22 Malondialdehyde (MDA):

Treatment T_1 demonstrated the lowest levels of MDA in tomato plants (71.40 TBAR's g^{-1} FW). This outcome can be attributed to the synergistic effects of different organic inputs which enhance soil microbial activity and nutrient availability, leading to improved plant health and reduced MDA production. The study reveals a promising approach for minimizing MDA levels in tomatoes, which is critical for reducing oxidative damage and maintaining plant health [3]. Treatment T_2 displayed a reduced MDA level (71.80 TBAR's g^{-1} FW) compared to other treatments. Treatment T_3, involving saline water alone, exhibited the highest levels of MDA in tomato plants (97.70 TBAR's g^{-1} FW). High soil salinity places severe stress on plants, leading to a significant accumulation of MDA due to oxidative damage and lipid peroxidation (Figure 4C). The osmotic stress created by saline water significantly impairs the plants' ability to regulate MDA levels, resulting in higher oxidative stress in tomato plants.

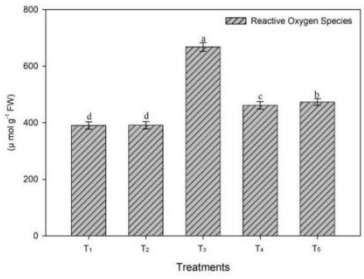

Figure 4A

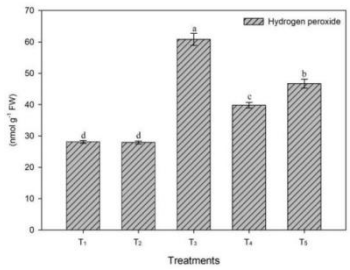

Figure 4B

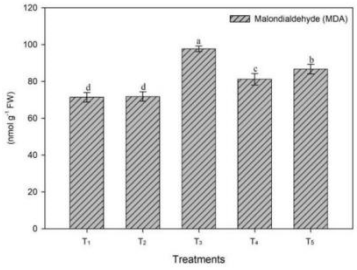

Figure 4C

Figure 4. The effect of organic inputs on the (A) reactive oxygen species ($F = 72.82$, $P < 0.0001$), (B) hydrogen peroxide ($F = 139.58$, $P < 0.0001$), (C) malondialdehyde content ($F = 19.14$, $P < 0.0001$) at 90 Days After Transplanting (DAT) under both normal and saline conditions in tomato cultivation.

4.0 Discussion:

Saline water treatment slightly increased soil pH levels, while organic inputs and a combination of organic and synthetic fertilizers slightly decreased pH. Saline water significantly increased soil EC levels, while organic matter and reduced synthetic fertilizers reduced EC levels. Organic inputs did not significantly alter nitrogen availability, but saline water negatively affected phosphorus levels [26]. Choudhary et al. [17] applied Jeevamrut at 16.08 L and vermicompost at 24.79 kg $plant^{-1}$ observing a significant increase in soil available phosphorus up to 23.90 kg ha^{-1}.

The study reveals the critical role of organic inputs in promoting increased plant height, branch numbers, leaf numbers, flower numbers, and fruit weight in tomatoes, as well as the need for a balanced approach to using saline water in agriculture. El-Mogy et al. [27] reported that NaCl treatment up to a bearable threshold (> 1 dS m^{-1}) causes reduced plant yield and product quality. An increase in salt concentration in soil and irrigation water negatively affects cell membrane integrity under mild salinity stress [21]; however, the activity significantly decreases at higher salinity conditions. Maharjan et al. [28] reported that vermicompost prepared using tea waste, cauliflower leaf waste, and mixed food waste increased the population density of Redworm (*Eisenia fetida*) up to 7.13, 3.06, and 0.2 times, respectively. An increase of 11.3 % in strawberry yield was reported using vermicompost and oil cakes [29]. The present findings reveal that the integrated application of organic inputs affects salt tolerance and defense mechanisms in plants. The study highlights the importance of balanced nutrient management and organic amendments in tomato cultivation to optimize chlorophyll, carotenoids, and lycopene contents. Ganugi et al. [23] reported that the application of microbial fertilizer can enhance biochemical parameters, such as carotenoids and lycopene, by increasing functional activity in tomatoes.

Organic inputs enhance plant SOD activity, counteracting oxidative stress. Saline water and high soil salinity cause osmotic stress, affecting antioxidant production and defense mechanisms. Saline water treatment reduces fruit yield but increases TSS content [19, 27]. Wang et al. [16] mentioned an increase in vitamin C content (47%) by the application of vermicompost. El-Mogy et al. [27] reported 19.4% decrease in vitamin C content of tomato under saline conditions. Organic inputs and reduced NPK fertilizers improve tomato plant health by reducing ROS levels and oxidative stress [30]. Saline water and organic amendments in tomato plants showed higher MDA levels, indicating the significant impact of saline water stress on lipid peroxidation and oxidative stress.

5.0 Conclusions

The study found that using farmyard manure, vermicompost, and a mixture of organic inputs with reduced fertilizers can improve tomato plant height, branching, leaf production, and fruit quality attributes. However, caution should be taken when using saline water and regulating irrigation water's electrical conductivity. Organic amendments can enhance tomato fruits' quality and yield by affecting biochemical pathways. The study emphasizes the importance of enriching soil management practices with organic inputs to maintain soil health and fertility in tomato cultivation.

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Ethical Statement:

Ethical issues are not applicable to this review article. The paper does not involve a study on animals.

7.0 Conflict of Interest:

The authors declare that there is no conflict of interest among authors for the publication of this manuscript in this journal.

7.1 Declaration Statement:

The authors deny any financial or personal influence on their work and have not published or submitted the manuscript for publication elsewhere.

7.2 Data Statement:

The data will be made available whenever required.

7.3 Contribution of authors:

Chitranjan Kumar (CK) and Shiv Bhushan Verma (SBV) proposed the idea and the topic of this research. CK, SBV, and Raghvendra Pratap Narayan (RPN), prepared the original draft and revised it. All authors have reviewed the final version of this manuscript.

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