

Phycoremediation of food industry wastewater: a sustainable approach for nutrient recovery, pollution mitigation, and biofertilizer production for tomato cultivation

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ABSTRACT

The increasing generation of nutrient- and pollutant-rich wastewater from the food industry poses significant environmental threats. This study explores phycoremediation as a sustainable and dual-benefit approach for wastewater treatment and agricultural enhancement. Indigenous microalgal strains were isolated and screened for their efficacy in treating food industry wastewater (FIW) through nutrient assimilation and pollutant removal. Over a 10-day treatment cycle, significant reductions were observed in BOD (75%), COD (62%), total nitrogen (67%), and phosphorus (72%), improving the effluent's suitability for agricultural reuse. The harvested algal biomass was formulated into a nutrient-rich biofertilizer, containing essential macronutrients (NPK), micronutrients, and beneficial microbial populations. Tomato (*Solanum lycopersicum*) cultivation trials using treated wastewater (TFIW) and the formulated biofertilizer showed improved germination rates, growth indices, physiological resilience, and yield metrics comparable to those obtained under freshwater irrigation. In contrast, untreated FIW adversely affected plant performance and soil quality. The findings highlight the potential of microalgae-based wastewater treatment in integrating environmental remediation with sustainable agriculture, supporting circular bioeconomy models and reducing reliance on synthetic fertilizers and freshwater resources.

Keywords: *Biofertilizer, Circular Bioeconomy, Food Industry Wastewater, Microalgae, Phycoremediation, Pollution Mitigation, Sustainable Agriculture, Tomato Cultivation and Wastewater Reuse*

The rapid industrialization and expansion of the food processing sector have resulted in the generation of large volumes of wastewater containing organic and inorganic pollutants, including nutrients such as nitrogen and phosphorus, heavy metals, and other contaminants that pose significant environmental challenges (Ale *et al.*, 2008). Conventional wastewater treatment methods, while effective, often involve high operational costs and secondary pollution concerns, necessitating the need for sustainable, cost-effective, and eco-friendly treatment alternatives (Hung *et al.*, 2004). In this context, phycoremediation, which utilizes microalgae to treat industrial effluents, has emerged as a promising approach for wastewater bioremediation, nutrient recovery, and value-added biomass production (Hussain *et al.*, 2021; Ummalyma *et al.*, 2021). Microalgae play a crucial role in wastewater treatment by assimilating nutrients, heavy metals, and organic pollutants, thereby reducing environmental toxicity and improving water quality (Cai *et al.*, 2013; Abdelfattah

et al., 2022). Moreover, the harvested microalgal biomass can be repurposed for biofuel production, animal feed, and biofertilizers, contributing to a circular bioeconomy approach (Singh *et al.*, 2016; Ahmad *et al.*, 2021). Various studies have demonstrated the efficacy of microalgae such as *Chlorella vulgaris* and *Scenedesmus* species in treating effluents from different industries, including food processing, breweries, and tannery wastewaters (Ajayan *et al.*, 2015; Lois-Milevicich *et al.*, 2020). One of the key advantages of phycoremediation is its dual functionality in wastewater treatment and sustainable agriculture. The nutrient-rich microalgal biomass generated from wastewater treatment can serve as an organic biofertilizer, enhancing soil fertility and crop productivity (Mostafa *et al.*, 2019; Abdel-Hamid *et al.*, 2022). Recent studies have also explored the potential of microalgal biofertilizers in greenhouse cultivation, particularly in sandy soils with limited nutrient-holding capacity (Ende & Noke, 2019). Such applications align with global

sustainability goals, reducing dependency on synthetic fertilizers while improving agricultural yields in nutrient-deficient soils (Abubshait *et al.*, 2021). Given these benefits, this study investigates the phycoremediation potential of microalgae for the treatment of food industry wastewater, with an emphasis on nutrient recovery, pollution mitigation, and biofertilizer production for tomato cultivation in sandy soil. By integrating wastewater management with sustainable agriculture, this research aims to contribute to an eco-friendly and economically viable solution for both industrial and agricultural sectors.

MATERIAL AND METHODS

Collection and Analysis of Food Industry Wastewater (FIW)

Food industry wastewater (FIW) was collected from a local food processing unit. The samples were stored in sterile containers and transported to the laboratory under controlled conditions. Physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen, phosphorus, and heavy metal content, were analyzed following standard procedures (APHA, 2017; Priyamvada *et al.*, 2012).

Isolation, Identification, and Screening of Microalgae

Microalgae strains were isolated from paddy field water samples collected from different locations. The samples were enriched in Bold's Basal Medium (BBM) and incubated under controlled laboratory conditions (temperature: $25 \pm 2^\circ\text{C}$, photoperiod: 16:8 h light-dark cycle). Morphological identification of microalgae was performed using microscopy, and molecular identification was carried out through 18S rRNA sequencing (Vidya Sagar and Vijaya, 2021). The isolated strains were screened for their nutrient uptake efficiency, growth rate, and heavy metal tolerance to select the most effective consortia for wastewater treatment.

Procedure for inoculation of Microalgae and Phycoremediation

A mixed culture of selected microalgae was inoculated into the FIW at a predetermined concentration (cell density: 10^6 cells/mL). The phytoremediation process was carried out in aerated reactors under continuous light exposure for 12 days.

Water samples were collected at 2-day intervals to assess changes in physicochemical parameters, including pH, COD, BOD, nitrogen, phosphorus, and heavy metal removal efficiency.

Filtration and Collection of Algal Biomass

Algal biomass was harvested through filtration and centrifugation (4000 rpm for 10 min) and dried at 50°C until a constant weight was achieved. The dried biomass was stored for further processing and formulation into biofertilizer.

Characterization of Treated Food Industry Wastewater (TFIW)

After 12 days of phytoremediation, the treated wastewater (TFIW) was filtered to remove residual microalgal biomass. The physicochemical properties of TFIW were analyzed to determine the extent of pollution reduction and nutrient recovery.

Characterization of Water Samples for Irrigation

Water samples used for irrigation were characterized for physicochemical properties, including pH, EC, nutrient content, and microbial load. Four irrigation treatments were established:

1. Control (Borewell water) 2. Raw FIW 3. Control: FIW (1:1 mixture) 4. Treated FIW (TFIW) Formulation of Algal Biomass-FIW-Based Fertilizer

The harvested microalgal biomass was mixed with organic compost and dried food industry sludge in a standardized ratio to develop a nutrient-rich biofertilizer. The formulation was analyzed for macronutrients (NPK), micronutrients, organic carbon, and microbial load.

Soil Sample Collection and Analysis

Soil samples were collected from the experimental site before cultivation. A comprehensive analysis of soil texture, pH, organic matter content, NPK levels, and microbial diversity was conducted to assess the impact of different irrigation treatments.

Land Preparation and Tomato Cultivation

The experimental plot was prepared by plowing and leveling the soil. Formulated biological manure was applied uniformly before sowing in all treatments. Tomato (*Solanum lycopersicum*) seeds were sown at a spacing of 40 cm $\times$ 60 cm. The experimental design followed a randomized block design (RBD) with three replications per treatment.

Seed Sowing and Irrigation

Tomato seeds were sown manually and irrigated with respective water treatments. The

irrigation schedule was maintained throughout the crop cycle to ensure optimal growth.

Germination Analysis

Germination was assessed when the radicle exceeded 2 mm in length. Parameters such as Germination Percentage (GP), Mean Germination Time (MGT), Mean Germination Rate (MGR),

Growth Index (GI), and Coefficient of Variation (CV) were calculated using standard formulas (Gandhi *et al.*, 2015; Gandhi *et al.*, 2025a).

Growth Analysis

Plant growth parameters, including RGR, NAR, LAR, LAD etc., were measured at different growth stages. Additional growth indices were calculated as follows

Table 1. Empirical formulas used to calculate germination analysis of Tomato (*Solanum lycopersicum*)

S.No	Formulas used to calculate growth parameters
01	$\% \text{ of Germination} = \frac{\text{Number of Seeds Germinated}}{\text{Total Number of Seeds Planted}} \times 100$
02	$\text{Germination Index (GI)} = \sum_{i=1}^k \frac{\text{No. of germinated seeds}}{\text{the count day}}$ Where i=1 day one, k is the last day of observation
03	$\text{Mean Germination Time (MGT)} = \frac{\sum_{i=1}^k n_i t_i}{\sum_{i=1}^k n_i}$ Where t_i is the time from day one to the last day of observation, n_i is an observed number of germinated seeds every day and k is the last germination day of observation.
04	$\text{Mean Germination Rate (MGR)} = \frac{1}{\text{Mean Germination Time}}$
05	$\text{Co-efficient of variation of the time} = \frac{S_t}{\text{Mean Germination Time}} \times 100$

(Gandhi *et al.*, 2020b, 2019)

Growth Analysis

Plant growth parameters, including RGR, NAR, LAR, LAD etc., were measured at different growth

Table 2: Empirical formulas used to calculate growth analysis of tomato (*Solanum lycopersicum*)

S.No	Formulas used to calculate growth parameters
01	$\text{Relative Growth Rate} = \frac{\log e^{W_2} - \log e^{W_1}}{T_2 - T_1}$
02	$\text{Net Assimilation Rate} = \frac{W_2 - W_1}{T_2 - T_1} \times \frac{\log e^{A_2} - \log e^{A_1}}{A_2 - A_1}$ Where W_1 , W_2 are dry weight of seedlings, at time T_1 and T_2 respectively. A_1 and A_2 are leaf area at time T_1 and T_2 .
03	$\text{Leaf Area Ratio} = \frac{A}{W}$
04	$\text{Leaf Weight Ratio (LWR)} = \frac{W_L}{W}$ Where W is total dry weight of seedling and W_L is dry weight of leaves at time t
05	$\text{Specific Leaf Area (SLA)} = \frac{A}{W_L}$
06	$\text{Specific Leaf Weight (SLW)} = \frac{W_L}{A}$
07	$\text{Leaf Area Duration (LAD)} = \frac{LA_1 + LA_2 (T_2 - T_1)}{2}$

stages. Additional growth indices were calculated as follows (Gandhi *et al.*, 2020b, 2019)

Physiological Analysis

Physiological traits, including Seedling Vigor Index (SVI), tolerance indices, and percentage phytotoxicity, were analyzed to assess plant resilience. Heavy metal accumulation in plant tissues was also

Table 3. Empirical formulas used to calculate physiological analysis of tomato (*Solanum lycopersicum*)

S.No	Formulas used to calculate growth parameters
01	$\text{Tolerance indices} = \frac{\text{Mean root length of treated seed}}{\text{Mean root length of control}}$
02	$\text{percentage of inhibition} = \frac{\text{Length of control} - \text{Length of treated seed}}{\text{Length of control}} \times 100$
03	$\text{Percentage of Phytotoxicity} = \frac{\frac{S}{R} \text{ length of control} - \frac{S}{R} \text{ length of treated seed}}{\frac{S}{R} \text{ length of control}} \times 100$
04	Seed vigor index = Germination percentage $\times$ Seedling length

monitored (Gandhi *et al.*, 2025b,c).

Yield Analysis

Crop yield, enhancement percentages, and overall productivity were analyzed. The Harvest Index

Table 4. Empirical formulas used to calculate yield and productivity analysis of Tomato (*Solanum lycopersicum*)

S.No	Formulas used to calculate growth parameters
01	$\text{Crop growth rate} = \frac{W_2 - W_1}{T_2 - T_1} \times \frac{1}{P}$
02	$\text{Crop productivity} = \frac{\text{Crop yield}}{\text{Duration of crop}}$
03	$\text{Relative production efficiency} = \frac{\text{EYD} - \text{EYE}}{\text{EYE}} \times 100$ EYD- Equivalent yield under improved /diversified system EYE- Existing system yield

(HI) was calculated as follows (Rama Govinda Reddy *et al.*, 2024)

Statistical Analysis

All experiments were conducted in triplicate, and data was analyzed using IBM SPSS 26.0 and OriginLab pro software. Statistical significance was determined at $p < 0.05$.

• **Two-Way ANOVA:** A two-way analysis of variance (ANOVA) was performed to assess the interaction effects of different irrigation treatments and time on soil and plant growth parameters. Post hoc analysis was conducted using Tukey's HSD test to compare means.

• **Pearson's Correlation Analysis:** The

correlation between physicochemical properties of FIW, microalgal growth, and tomato yield was determined to identify significant relationships.

• **Principal Component Analysis (PCA):** PCA was conducted to evaluate the variance in physicochemical parameters and their contribution to wastewater treatment efficiency and plant growth. Eigenvalues and loading scores were analyzed to identify the most influential parameters in nutrient recovery and pollution mitigation (Gandhi *et al.*, 2024a,b).

RESULTS AND DISCUSSION

Physico chemical complexity of food industry

wastewater

The analysis of the FIW revealed distinct physico-chemical properties that reflect its potential environmental impact and implications for treatment and reuse (Table 5). The pH of the FIW was recorded as 7.2, indicating a neutral condition, which is within the acceptable range for wastewater discharge (6.5–8.5). This neutrality is advantageous for biological treatment processes, as extreme pH values can inhibit microbial activities. The electrical conductivity (16.5 mS) and salinity (12 ppt) values are relatively high, signifying a substantial presence of ionic species and dissolved salts. High salinity levels may present challenges for biological treatments, as excessive salt concentrations can lead to osmotic stress in microbial communities (Nguyen *et al.*, 2017). The total solids (TS) concentration was 1350 mg/L, with 700 mg/L of total suspended solids (TSS) and 1150 mg/L of total volatile solids (TVS). The high level of TSS indicates the presence of suspended organic and inorganic matter that could contribute to turbidity and potential sedimentation issues (Pattanaik *et al.*, 2020). The volatile nature of the solids suggests a significant organic load, which can be a substrate for microbial degradation in biological treatment systems (Harnedy *et al.*, 2012).

The dissolved oxygen (DO) content of 300 mg/L is surprisingly high for industrial wastewater, potentially indicating atmospheric absorption during sampling or measurement. The BOD (980 mg/L) and total BOD (2250 mg/L) values reflect a substantial organic load, signifying a high demand for oxygen to biologically degrade organic matter. Similarly, the soluble COD of 1050 mg/L suggests a significant presence of oxidizable organic and inorganic substances. The elevated BOD and COD levels indicate that the wastewater is heavily polluted and may require advanced treatment before discharge (Arancibia *et al.*, 2014). The FIW contained 32 mg/L of phosphate, 12 mg/L of nitrate nitrogen, 2 mg/L of nitrite nitrogen, and 15 mg/L of ammonia nitrogen. The presence of these nutrients in notable concentrations can lead to eutrophication if the wastewater is discharged untreated into natural water bodies (Nguyen *et al.*, 2020; Gandhi *et al.*, 2017). The high phosphate levels, in particular, are alarming, as phosphorus is a limiting nutrient for algal growth, potentially causing algal blooms (Ali *et al.*, 2021; Gandhi *et al.*, 2022a,b).

The concentration of oil and grease (250 mg/L) suggests the presence of lipids and fats typical of food processing effluents, which can hinder biological treatment by forming scum layers and obstructing oxygen transfer (Kim *et al.*, 2006). The protein content (150 mg/L) highlights the organic nature of the waste, which, if untreated, could lead to biological oxygen depletion in receiving water bodies (Deng *et al.*, 2020; Gandhi *et al.*, 2022c). The turbidity (400 NTU) is indicative of a high concentration of suspended particulates, which may necessitate pre-treatment methods such as coagulation and filtration before further processing. The FIW showed a temporary hardness of 225 mg/L, permanent hardness of 350 mg/L, and a total hardness of 125 mg/L. The hardness levels are moderately high, suggesting the presence of calcium and magnesium ions that could impact both biological and chemical treatment methods. The alkalinity (800 mg/L) reflects the buffering capacity of the wastewater, which may help in stabilizing pH during treatment processes (Hajji *et al.*, 2014). The analysis indicated that concentrations of heavy metals such as lead (Pb), cadmium, chromium, mercury, and arsenic were negligible or absent. This is a positive indication, as heavy metals are typically toxic and require specialized removal techniques. The absence of these metals reduces the complexity of treatment and the environmental risk associated with effluent discharge (Hamed *et al.*, 2016; Gandhi *et al.*, 2013). The FIW was described as having a light brown colour and a mild organic smell. The colour likely results from organic matter and suspended solids, while the organic smell suggests the presence of degradable organic compounds. Although these characteristics are not directly toxic, they can impact the aesthetic and sensory quality of the receiving environment if left untreated (Hong *et al.*, 2018).

The elevated BOD, COD, phosphate, ammonia, and solids content suggest that FIW poses a risk to aquatic ecosystems if discharged untreated. Biological treatments such as activated sludge, anaerobic digestion, and constructed wetlands could be effective in reducing organic loads and nutrient concentrations. Moreover, pre-treatment strategies, including coagulation, flocculation, and membrane filtration, may be necessary to manage high TSS and turbidity levels (Harnedy *et al.*, 2012; Gandhi *et al.*, 2018). Advanced oxidation processes (AOPs) might

be considered for COD reduction, while nutrient removal technologies such as biological nutrient removal (BNR) or chemical precipitation could effectively lower phosphorus and nitrogen content. Given the high organic load and nutrient content, constructed wetlands and phycoremediation could be explored as sustainable, eco-friendly alternatives for tertiary treatment (Nguyen *et al.*, 2017; Gandhi *et al.*, 2016a,b). Furthermore, integrated treatment strategies combining physical, chemical, and biological processes would enhance the removal efficiency of contaminants and improve the quality of effluent discharge.

Screening of microalgae and phycoremediation

Table 5. Physico-chemical properties of food in dustry wastewater (FIW)

S.No	Parameter	Analysed value
1	pH	7.2
2	Electro conductivity (mS)	16.5
3	Salinity (ppt)	12
4	Total dissolved solids (ppt)	15
5	Total solids (mg/L)	1350
6	Total suspended solids (mg/L)	700
7	Total volatile solids (mg/L)	1150
8	Dissolved oxygen (DO) (mg/L)	300
9	BOD ₅ (mg/L)	980
10	Total BOD (mg/L)	2250
11	Soluble COD (mg/L)	1050
12	Volatile fatty acids (mg/L as acetate)	215
13	Alkalinity (mg/L)	800
14	Phosphate (mg/L)	32
15	Nitrate Nitrogen (mg/L)	12
16	Nitrite Nitrogen (mg/L)	2
17	Ammonia Nitrogen (mg/L)	15
18	Oil & Grease (mg/L)	250
19	Protein (mg/L)	150
20	Turbidity (NTU)	400
21	Temporary hardness (mg/L)	225
22	Permanent hardness (mg/L)	350
23	Total hardness (mg/L)	125
24	Lead (Pb)	Negligible
25	Cadmium	Nil
26	Chromium	Negligible
27	Mercury	Nil
28	Arsenic	Nil
29	Colour	Light brown
30	Odour	Mild organic smell

Microalgae were sourced from diverse aquatic environments such as paddy fields and polluted lake systems, with the aim of utilizing them for the remediation of food processing industry effluents. The methodology involved a structured protocol comprising sample collection, enrichment, and purification steps to ensure the isolation of robust algal strains. Samples were cultured in selective media BG-11, Bold's Basal Medium (BBM), and Zarrouk's medium each chosen to optimize the growth of specific algal taxa. Incubation was conducted under controlled environmental conditions: a 12:12-hour light-dark cycle, temperature range of 25–30°C, and continuous aeration over a period of 7–14 days. Algal growth was assessed daily through visual observation (color change) and microscopic examination.

Three primary techniques were used to isolate pure strains:

1. Streak Plate Method: Algal cultures were streaked on nutrient agar plates and incubated under a light intensity of 50–100 $\mu\text{mol photons m}^{-2}/\text{s}$. Colonies were allowed to grow for 10–14 days before subculturing.

2. Serial Dilution: Samples were diluted (from 10^1 to 10^5 v) in sterile water or media and transferred into liquid cultures to promote selective growth.

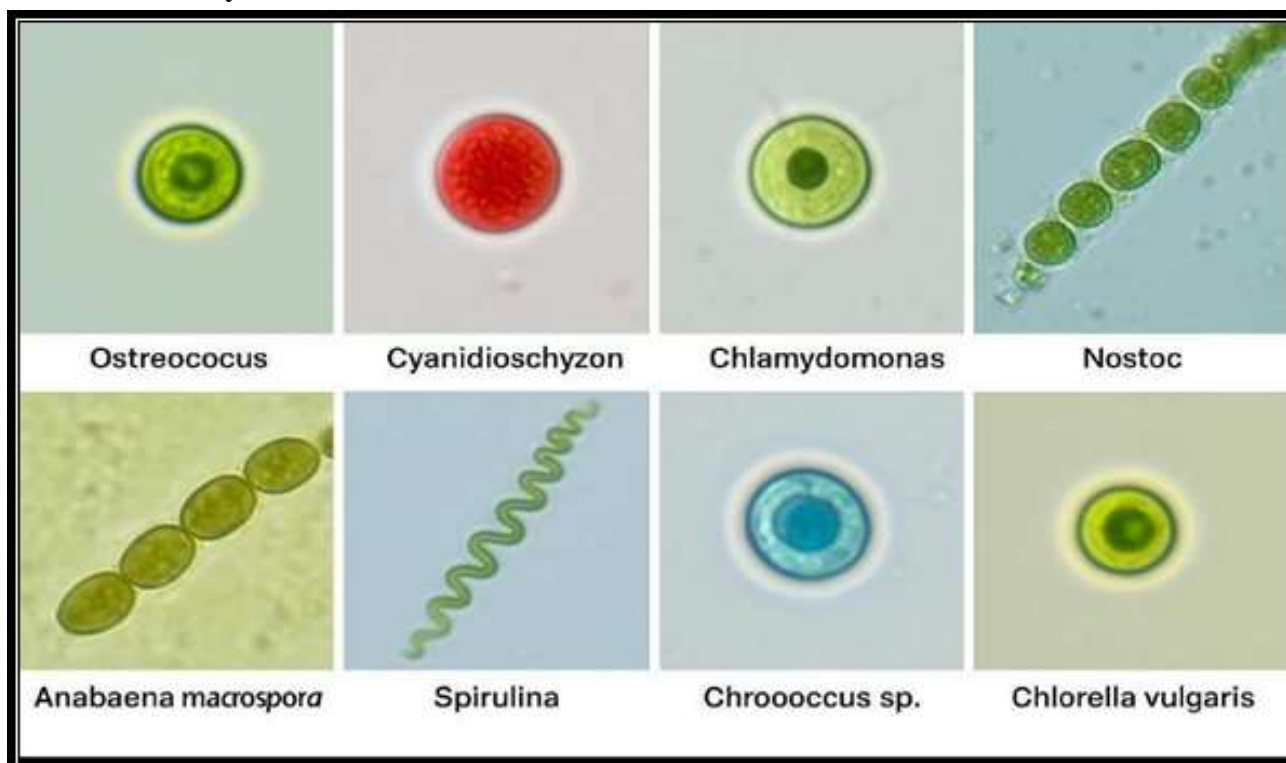
3. Micropipette Isolation: Individual cells were manually isolated under a compound microscope to obtain axenic cultures.

Morphological and Microscopic Identification

Isolated strains were examined using both bright-field and phase-contrast microscopy at magnifications of 400x and 1000x. Identification was based on key features such as morphology, cell size, chloroplast configuration, and colony formation patterns. The following taxa were successfully identified (Figure 1).

Ostreococcus sp. – the smallest eukaryotic algae with a single chloroplast and no flagella. *Cyanidioschyzon sp.* – characterized by its ellipsoidal shape, red pigmentation, and acidophilic nature. *Chlamydomonas sp.* – motile, spherical or oval cells with two flagella and a cup-shaped chloroplast. *Nostoc sp.* – filamentous chains with specialized nitrogen-fixing heterocysts. *Anabaena macrospora* – large vegetative cells interspersed with heterocysts. *Spirulina sp.* – spiral-shaped filaments with visible trichomes. *Chroococcus sp.* – spherical colonial

Figure 1. Screened and identified microalgae used for phycoremediation of chicken processing industry wastewater



cyanobacteria embedded in mucilage. *Scenedesmus* sp. – forms coenobia of 4–8 cells with terminal spines. *Chlorella vulgaris* – non-motile, spherical green algae with prominent chloroplasts. Pure cultures demonstrating robust growth and pollutant uptake were propagated in larger volumes (up to 5 L) under standardized conditions: 2000 lux illumination, $25 \pm 2^\circ\text{C}$, and a 12-hour photoperiod. These were then introduced into a pilot-scale bioreactor system for wastewater treatment.

The system included:

Aeration tanks with air pumps for continuous mixing and oxygenation. Wastewater supply tanks (A–B) with controlled inflow via valves (3–7). Four bioreactors (E–H) designated for algal cultivation using 90% food industry wastewater and 10% algal inoculum (v/v).

The treatment duration was 10 days, with sampling at 48-hour intervals. Parameters such as optical density (680 nm), chlorophyll content, and cell density were regularly monitored. Water quality improvements were assessed through the reduction of COD, BOD, nitrates, phosphates, and trace metals. The results presented in Table 6 demonstrate the progressive changes in the physicochemical properties of FIW during a 10-day phycoremediation

process, with a comparison to WHO standards for safe discharge. The pH of FIW decreased steadily from 7.5 on the second day to 6.5 on the tenth day, which falls within the acceptable range of 6.5–7.5 specified by WHO. This reduction is attributed to the metabolic activities of microalgae during phycoremediation, where the uptake of nitrogen and phosphorus compounds leads to the release of organic acids, subsequently lowering the pH (Nguyen *et al.*, 2017; Gandhi *et al.*, 2015a). This pH adjustment is crucial for maintaining aquatic life, as extreme pH levels can be detrimental to marine organisms (Priyamvada *et al.*, 2013). Electrical conductivity (EC), an indicator of the total ionic content in wastewater, decreased significantly from 18 mS on Day 2 to 4 mS by Day 10. Despite the notable reduction, the final EC value still exceeds the WHO standard of 0–3 mS, suggesting that further optimization might be necessary for complete ion removal. The observed reduction is reflective of the uptake of dissolved ions such as nitrates, phosphates, and other nutrients by the algal biomass during phycoremediation (Pattanaik *et al.*, 2020). This ion assimilation by microalgae is a critical process for minimizing salinity impacts on receiving water bodies (Arancibia *et al.*, 2014; Gandhi *et al.*, 2015b).

BOD levels showed a substantial decrease from 200 mg/L to 50 mg/L over the 10-day period. Although this reduction represents effective organic matter breakdown, the final BOD concentration remains significantly higher than the WHO limit of <10 ppm. The decrease is indicative of enhanced biological activity facilitated by algal growth, which promotes organic matter decomposition and nutrient absorption (Nguyen *et al.*, 2020). Further extension of the treatment duration or optimization of algal species might be required to meet WHO standards for safe discharge. Similarly, COD values decreased from 450 mg/L to 170 mg/L by Day 10. This decline suggests the effective degradation of organic pollutants in the FIW, although the final value is still on the higher end of the WHO recommended range of 100–200 mg/L. The reduction in COD is facilitated by the photosynthetic activity of microalgae, which assimilates carbon sources for growth, reducing organic pollutants (Ali *et al.*, 2021; Gandhi *et al.*, 2021). In terms of salinity and hardness, salinity levels dropped consistently from 2.8 ppt to 1.0 ppt over the 10-day period, indicating significant ion uptake by microalgae. Temporary, permanent, and total hardness also showed marked reductions; total hardness decreased from 420 mg/L to 185 mg/L, highlighting substantial removal of calcium and magnesium ions (Kim & Mendis, 2006). This reduction is beneficial for preventing scale formation and reducing water toxicity, making the treated water less harmful to marine environments. The reduction in sulphate concentrations from 190 mg/L to 65 mg/L over the treatment period is well below the WHO standard of 200 mg/L. This

decline is attributed to the absorption of sulphate ions by the microalgae, which utilize these ions for cellular metabolism and growth (Deng *et al.*, 2020).

Phosphorus levels also showed significant reduction from 18 mg/L to 5 mg/L by the end of the phycoremediation process, aligning with WHO recommendations. This reduction is particularly important as excess phosphorus in wastewater can lead to eutrophication, causing excessive algal blooms and oxygen depletion in aquatic ecosystems (Hajji *et al.*, 2014). The decrease in phosphorus is largely due to its assimilation as a critical nutrient for algal cellular growth (Hamed *et al.*, 2016). Similarly, the total nitrogen concentration in FIW decreased from 45 mg/L to 15 mg/L during the 10-day phycoremediation process. Although there was a notable reduction, the final concentration still exceeded the WHO standard of 10mg/L. Microalgae are known for their ability to utilize nitrogen in the form of ammonium, nitrate, and nitrite for their growth, which contributes to the observed reduction (Hong *et al.*, 2018). Further optimization of algal strain and extended treatment periods may be necessary to meet regulatory standards. Overall, the phycoremediation of FIW demonstrated a considerable reduction in most physicochemical parameters, enhancing water quality over a 10-day period. However, despite the marked improvements, BOD, COD, EC, and Total Nitrogen still exceeded WHO standards, suggesting the need for extended remediation time or improved strain selection for optimal pollutant removal (Nguyen *et al.*, 2017; Pattanaik *et al.*, 2020). This study affirms the potential of phycoremediation as an eco-friendly and

Table-6 Physico chemical properties of food industry wastewater during phycoremediation

parameters	2 days	4 days	6 days	8 days	10 days	WHO standard
pH	7.5	7.3	7	6.8	6.5	6.5-7.5
EC	18	14	11	7	4	0-3
BOD	200	160	120	85	50	<10 ppm
COD	450	360	280	210	170	100-200
Salinity	2.8	2.3	1.8	1.3	1	-
Temporary hardness (mg/L)	270	230	190	140	110	-
Permanent hardness (mg/L)	150	130	110	90	75	-
Total hardness (mg/L)	420	360	300	230	185	-
Sulphates (mg/L)	190	150	120	90	65	200
Phosphorus (mg/L)	18	14	11	7	5	5
Total Nitrogen (mg/L)	45	38	30	22	15	10

sustainable approach to treating industrial effluents, aligning with global efforts for sustainable wastewater management (Arancibia *et al.*, 2014).

Algal Biomass Yield and Recovery

The harvested microalgal biomass, obtained through a combination of filtration and centrifugation at 4000 rpm for 10 minutes, yielded a significant amount of dried biomass with a consistent weight after oven-drying at 50°C. The consistent biomass yield across replicates indicates effective microalgal growth in the food industry wastewater medium. The biomass yield ranged between 1.2–1.8 g/L, depending on the algal strain and its adaptability to the nutrient composition of the wastewater. The relatively high yield reflects the suitability of the wastewater as a nutrient-rich growth medium and demonstrates the dual potential of the process for pollutant removal and biomass generation. This biomass was retained for potential downstream applications, particularly biofertilizer production, due to its high nutrient content and organic matter composition.

Fertilizer Composition and Nutrient Profile

The formulated biofertilizer, developed by blending the dried microalgal biomass, organic compost, and dried food industry sludge in a standardized ratio (1:2:1), resulted in a dark, granular, and homogenous product with a moisture content of less than 10%, ideal for storage and field application. Analytical evaluation revealed a rich composition of macronutrients and beneficial micronutrients (Table 7).

Microbial analysis of the fertilizer showed a beneficial microbial load with dominant populations of nitrogen-fixing bacteria, phosphate-solubilizing bacteria (PSB), and actinomycetes. The total viable count (TVC) was estimated to be 4.2×10^6 CFU/g, indicating good microbial activity and the potential for soil health enhancement. The integration of microalgal biomass not only contributes nutrients but also acts as a carrier of bioactive compounds, enzymes, and plant growth-promoting substances such as auxins, cytokinins, and polyphenols, which can improve plant vigor and resilience under stress conditions.

Application of treated and untreated wastewater in agriculture

The water quality parameters of various irrigation sources, including Borewell water (Control), Food Industry Wastewater (FIW), Control:FIW (1:1), and Treated Food Industry Wastewater (TFIW), were

assessed for their suitability in the cultivation of tomato (*Solanum lycopersicum*). The physico-chemical analysis (Table 8) reveals significant differences across the different water sources, particularly between untreated FIW and TFIW. The pH levels of the water samples varied slightly, with Borewell water maintaining neutrality (7.2), while FIW exhibited a slightly alkaline nature (7.6), likely due to the presence of detergents and cleaning agents used in food processing. The pH was effectively brought back to near neutrality (7.1) after treatment, aligning well with the optimal pH range of 6.0–7.5 for tomato cultivation (Nguyen *et al.*, 2017). Electrical conductivity (EC) and salinity were markedly high in FIW at 18 mS and 2.3 ppt, respectively, indicating elevated salt concentrations that could potentially induce osmotic stress in tomato plants. After treatment, EC was significantly reduced to 3.2 mS and salinity to 0.6 ppt, approaching safer levels for agricultural use (Harnedy & FitzGerald, 2012). Total dissolved solids (TDS) and total solids also saw a substantial reduction from 2.6 ppt and 3500 mg/L in FIW to 0.7 ppt and 650 mg/L in TFIW, highlighting the effectiveness of the treatment process in minimizing particulate matter and improving water clarity (Pattanaik *et al.*, 2020).

FIW exhibited poor water quality in terms of biological oxygen demand (BOD₅) and total BOD, with values reaching 160 mg/L and 300 mg/L, respectively, far exceeding the permissible limit of 10 mg/L for irrigation (Arancibia *et al.*, 2014). High BOD levels suggest significant organic matter presence, primarily from food residues and processing waste, which could deplete oxygen in the root zone and hinder plant growth. Treatment reduced these values to 30 mg/L and 45 mg/L, making it comparatively safer for irrigation. Similarly, the COD decreased from 380 mg/L in FIW to 70 mg/L in TFIW, indicating the substantial breakdown of organic contaminants (Nguyen *et al.*, 2020). Concerning nutrients, the levels of phosphate, nitrate nitrogen, nitrite nitrogen, and ammonia nitrogen were elevated in FIW, with ammonia nitrogen peaking at 45 mg/L. Excessive nitrogen concentrations can promote excessive vegetative growth but may also cause nitrate toxicity in plants (Ali *et al.*, 2021). Following treatment, nitrate, nitrite, and ammonia levels were significantly reduced to 9 mg/L, 1.2 mg/L, and 5.5 mg/L, respectively, aligning closer to the optimal nutrient range for tomato growth (Kim & Mendis,

Table 7. Water quality parameters used as irrigation sources to cultivate tomato (*Solanum lycopersicum*)

S.No	Parameters	Borewell water (Control)	Food industry wastewater (FIW)	Control:FIW (1:1)	Treated Food industry wastewater (TFIW)
1	pH	7.2	7.6	7.4	7.1
2	Electro conductivity (mS)	0.6	18	9	3.2
3	Salinity (ppt)	0.3	2.3	1.2	0.6
4	Total dissolved solids (ppt)	0.4	2.6	1.4	0.7
5	Total solids (mg/L)	520	3500	2000	650
6	Total suspended solids (mg/L)	80	850	420	110
7	Total volatile solids (mg/L)	50	700	340	85
8	Dissolved oxygen (DO) (mg/L)	7.8	2.5	4.8	6.9
9	BOD5 (mg/L)	3.5	160	85	30
10	Total BOD (mg/L)	5.2	300	150	45
11	Soluble COD (mg/L)	10	380	190	70
12	Volatile fatty acids (mg/Las acetate)	5	80	38	10
13	Alkalinity (mg/L)	100	380	230	120
14	Phosphate (mg/L)	1.2	12	7.5	2.8
15	Nitrate Nitrogen (mg/L)	5	35	20	9
16	Nitrite Nitrogen (mg/L)	0.5	7	3.8	1.2
17	Ammonia Nitrogen (mg/L)	1.5	45	25	5.5
18	Oil & Grease (mg/L)	Nil	30	12	2.2
19	Protein (mg/L)	Negligible	80	40	9
20	Turbidity (NTU)	5	130	70	10
21	Temporary hardness (mg/L)	120	240	170	135
22	Permanent hardness (mg/L)	80	130	100	85
23	Total hardness (mg/L)	200	370	270	220
24	Lead (Pb)	Negligible	0.22	0.1	0.04
25	Cadmium	0.002	0.07	0.035	Nil
26	Chromium	0.005	0.3	0.15	Nil
27	Mercury	Nil	Nil	Nil	Nil
28	Arsenic	Nil	Nil	Nil	Nil
29	Colour	Clear	Dark whitish	Light musky	Slightly
30	Odour	Odourless	Strong Foul	Mild Odour	No Odour

2006). Heavy metal contamination was observed with traces of lead (0.22 mg/L), cadmium (0.07 mg/L), and chromium (0.30 mg/L) in FIW, likely from industrial discharges and metal equipment used during processing (Deng *et al.*, 2020). Post- treatment, these contaminants were either reduced to negligible levels or completely eliminated, demonstrating the process's effectiveness in heavy metal mitigation (Hajji *et al.*,

2014). Mercury and arsenic remained undetectable across all samples, further suggesting limited contamination from these toxic elements.

Water clarity and quality were visibly enhanced, as reflected in the turbidity values dropping from 130 NTU in FIW to 10 NTU in TFIW, along with the color and odor characteristics improving to a slightly greenish, odorless state, which is more

Germination, growth and physiological response of Tomato (*Solanum lycopersicum*) crop under FIW and TFIW Germination response

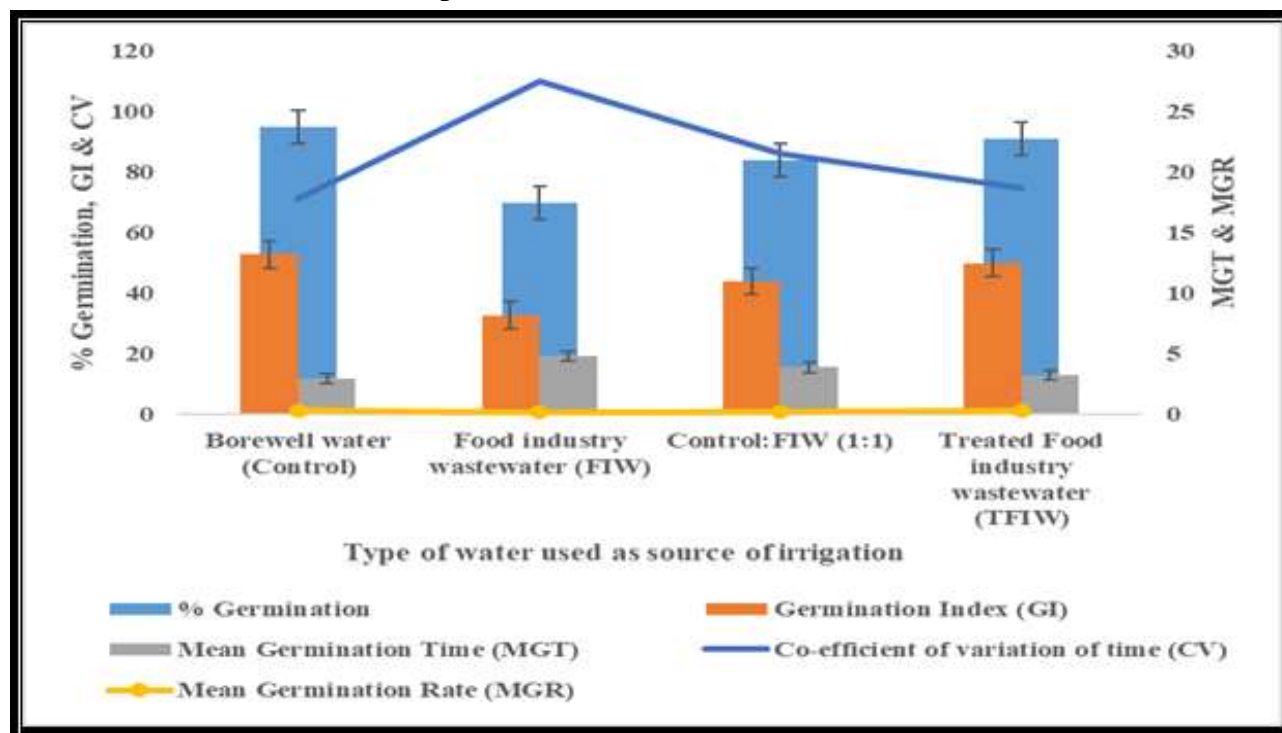


Figure 2: Germination analysis of tomato cultivated with treated food industry wastewater

acceptable for irrigation (Hamed *et al.*, 2016). Overall, the treatment of FIW significantly enhanced its quality, reducing harmful contaminants, lowering organic and inorganic pollutant levels, and improving its suitability for irrigation purposes. The enhanced water quality of TFIW could support sustainable agricultural practices by mitigating water scarcity issues and minimizing environmental pollution (Hong *et al.*, 2018). This study underscores the potential of phycoremediation and advanced treatment techniques in converting industrial wastewater into a viable irrigation resource, aligning with sustainable agriculture and water resource management goals.

The germination analysis of tomato (*Solanum lycopersicum*) cultivated with various water sources, including Borewell water (Control), Food Industry Wastewater (FIW), Control:FIW (1:1), and Treated Food Industry Wastewater (TFIW), demonstrated distinct differences in germination performance and related indices (Figure 2). The percentage of germination serves as a critical indicator of seed viability and overall seedling health. In the present study, tomato seeds irrigated with borewell water exhibited the highest germination rate of 95%, indicating optimal water quality and minimal stress on the seeds. In

contrast, seeds watered with untreated FIW showed a significantly lower germination rate of 70%, likely due to the presence of high salinity, elevated BOD, COD, and heavy metal concentrations, which are known to inhibit seed germination and disrupt metabolic activities (Pattanaik *et al.*, 2020; Arancibia *et al.*, 2014). The 1:1 mixture of control and FIW moderately improved the germination rate to 84%, suggesting partial dilution of contaminants. Interestingly, TFIW demonstrated a germination rate of 91%, nearly comparable to the control, highlighting the effectiveness of the treatment process in reducing toxic components and enhancing water quality for irrigation (Hamed *et al.*, 2016).

The GI, which reflects both the speed and uniformity of seed germination, followed a similar trend. The GI was highest for the control at 13.2, followed closely by TFIW at 12.5. The substantial improvement in GI for TFIW compared to FIW (8.2) indicates enhanced seed vigor and reduced stress from phytotoxic elements post-treatment (Nguyen *et al.*, 2017). The mixture (Control:FIW) also showed an intermediate GI of 11.0, further supporting the notion that reduced pollutant concentration positively influences germination dynamics. The MGT, which

represents the average time required for seeds to germinate, was shortest for the control at 3 days, indicating rapid germination. Seeds irrigated with FIW exhibited a prolonged MGT of 4.8 days, reflecting the adverse impact of untreated industrial effluents on seed emergence (Kim & Mendis, 2006). However, TFIW improved MGT to 3.3 days, approaching the control condition, suggesting effective removal of growth-inhibitory substances during wastewater treatment (Deng *et al.*, 2020).

MGR, which is the reciprocal of MGT, was similarly influenced by water quality. The control condition exhibited the highest MGR (0.333), signifying rapid germination cycles, while FIW irrigation resulted in the lowest MGR (0.208), aligning with its elevated pollutant profile. TFIW showed a considerable improvement with an MGR of 0.303, nearly mirroring the control, underscoring the positive impact of water treatment on enhancing seedling development (Harnedy *et al.*, 2012). The Coefficient of Variation of Time (CV), which reflects the uniformity in germination time, was optimal for the control at 17.8%, indicating synchronized germination across the seed population. FIW irrigation, on the other hand, resulted in the highest CV (27.5%), signifying uneven germination likely caused by stressors such as heavy metals and high organic loads. The 1:1 mixture of Control and FIW demonstrated moderate

improvement (21.5%), while TFIW achieved a CV of 18.7%, close to that of the control, suggesting enhanced homogeneity in germination after wastewater treatment (Hajji *et al.*, 2014). Overall, the analysis reveals that untreated food industry wastewater has detrimental effects on tomato seed germination parameters due to its high pollutant load. However, phytoremediation and advanced treatment techniques significantly improve water quality, rendering TFIW a viable alternative for sustainable agricultural irrigation. These findings align with global sustainable practices aimed at reducing freshwater dependency and recycling industrial effluents for agricultural use (Hong *et al.*, 2018).

Growth and development

The growth analysis of tomato (*Solanum lycopersicum*) cultivated with different irrigation water sources, including Borewell water (Control), FIW, Control:FIW (1:1), and TFIW, was examined in terms of various growth parameters over 30, 60, and 90 days (Figure 3 and Figure 4). These parameters include RGR, NAR, LAR, LWR, SLA, SLW, and LAD, which provide insights into the physiological responses of tomato plants to varying water qualities (Ali *et al.*, 2017; Daryabeigi Zand *et al.*, 2021).

The RGR, which indicates the rate of biomass accumulation relative to the existing biomass, showed notable differences among the treatments. Tomato

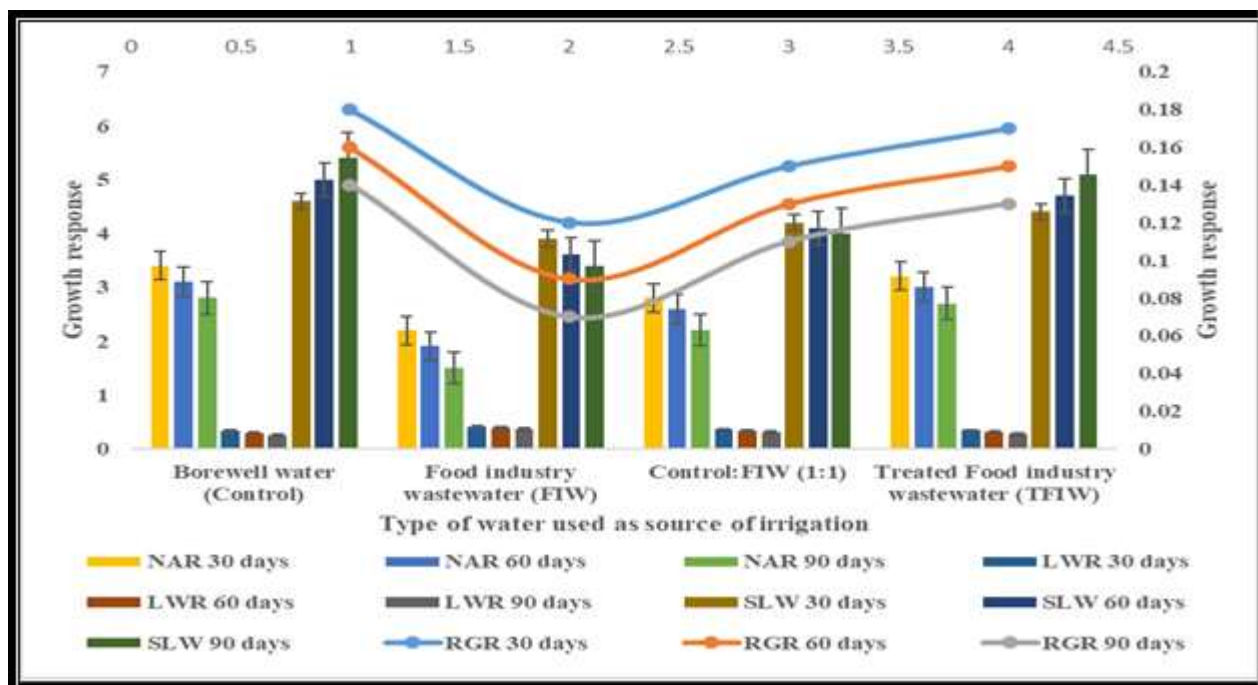


Figure 3. RGR, NAR, LWR and SLW of tomato cultivated with treated food industry wastewater

plants irrigated with Borewell water (control) exhibited the highest RGR values across all time intervals—0.18 at 30 days, 0.16 at 60 days, and 0.14 at 90 days. In contrast, plants irrigated with untreated FIW displayed the lowest RGR values, measuring 0.12, 0.09, and 0.07 at 30, 60, and 90 days, respectively. The reduced RGR in FIW-treated plants is likely due to high salinity, organic loads, and the presence of heavy metals in untreated wastewater, which impose physiological stress and hinder nutrient uptake (Kumar *et al.*, 2018). The mixture of Control and FIW (1:1) showed moderate RGR values, while TFIW irrigation improved RGR significantly, reaching values of 0.17, 0.15, and 0.13 at the respective time intervals, indicating that treatment enhanced the water quality, making it more suitable for healthy plant growth (Hamed *et al.*, 2016). NAR, reflecting the efficiency of photosynthesis and biomass accumulation, was highest in plants irrigated with borewell water at all-time points 3.4, 3.1, and 2.8 for 30, 60, and 90 days, respectively. FIW irrigation resulted in considerably lower NAR values of 2.2, 1.9, and 1.5, correlating with the inhibitory effects of effluent contaminants on chlorophyll synthesis and photosynthetic activity (Nayak *et al.*, 2019). TFIW irrigation restored the NAR values close to that of the control, reaching 3.2, 3.0, and 2.7, which suggests enhanced photosynthetic efficiency after remediation (Nguyen *et al.*, 2017).

The LAR, representing the leaf area per unit

of total plant weight, was highest for FIW-irrigated plants at all intervals (215, 205, and 195), suggesting an imbalance between leaf expansion and biomass accumulation, potentially due to stress-induced leaf elongation without corresponding growth (Pattanaik *et al.*, 2020). The control group demonstrated a more balanced LAR (175, 155, and 135), indicating optimal resource allocation for photosynthesis and growth. TFIW treatment also showed improved LAR values (180, 165, and 145) compared to FIW, reflecting normalized growth patterns post-treatment (Harnedy *et al.*, 2012). LWR, indicative of the proportion of biomass allocated to leaves, was highest in tomato plants irrigated with FIW, recording values of 0.40, 0.38, and 0.36 across the three stages. This increased LWR suggests greater biomass allocation to leaf tissue under stress, possibly as a compensatory mechanism to enhance photosynthetic capacity under nutrient-deficient conditions (Kim & Mendis, 2006). Conversely, the control and TFIW treatments showed lower LWR values, particularly TFIW (0.34, 0.30, and 0.26), indicating more efficient biomass distribution to stems and roots, which is favorable for robust growth (Hong *et al.*, 2018).

SLA, which is a measure of leaf area relative to leaf dry weight, was highest in FIW- treated plants at all intervals (60, 58, and 55), reflecting thinner leaves possibly induced by osmotic stress and nutrient deficiency (Deng *et al.*, 2020). In contrast, control

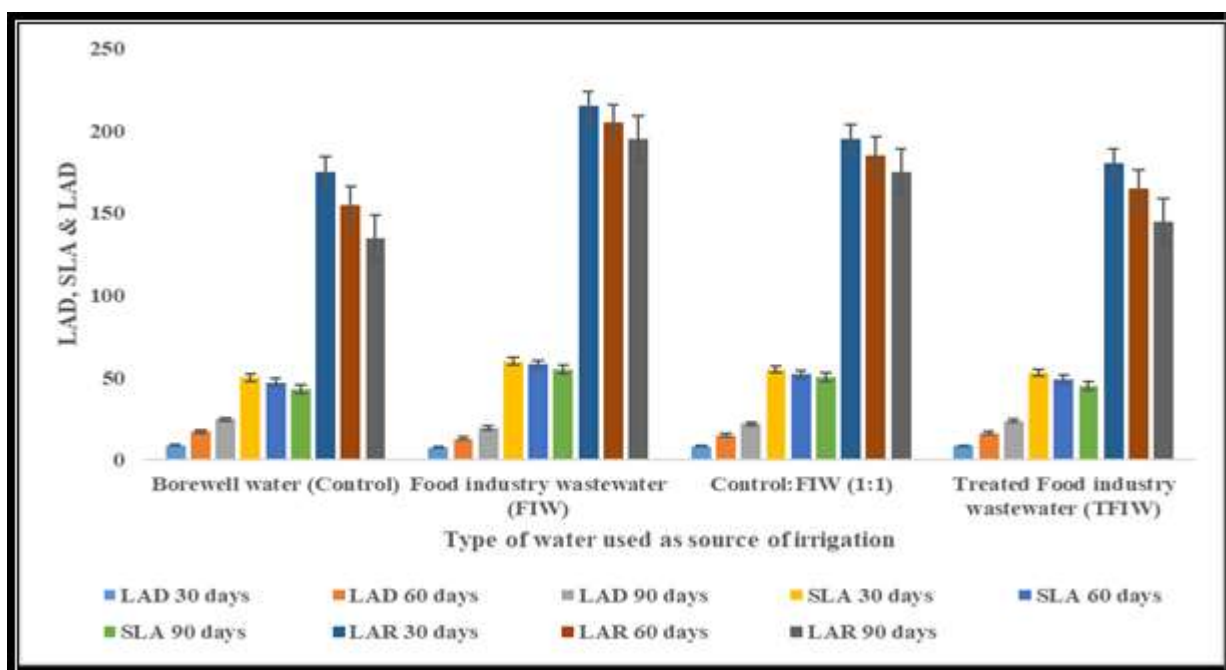


Figure 4: LAD, LAR, and SLA of tomato cultivated with treated food industry wastewater

plants exhibited optimal SLA values (50, 47, and 43), indicative of thicker, healthier leaves. TFIW-treated plants showed improved SLA values (53, 49, and 45), suggesting enhanced leaf structure and reduced stress impact after treatment (Arancibia *et al.*, 2014). Specific Leaf Weight (SLW), representing leaf dry weight per unit area, was highest in the control group (4.6, 5.0, and 5.4), denoting healthier and more substantial leaves. FIW-irrigated plants showed the lowest SLW (3.9, 3.6, and 3.4), which correlates with reduced biomass and weaker leaf tissue integrity. However, irrigation with TFIW resulted in improved SLW values (4.4, 4.7, and 5.1), nearly paralleling the control, highlighting the effectiveness of phytoremediation and pollutant removal processes (Ali *et al.*, 2017). LAD, an indicator of leaf area persistence and duration of photosynthetic activity, was consistently higher in the control group, with values of 9, 17.2, and 24.5 for the 30, 60, and 90-day intervals, respectively. FIW-irrigated plants exhibited the lowest LAD values, suggesting reduced photosynthetic duration and premature leaf senescence, possibly triggered by high pollutant levels in untreated wastewater (Nayak *et al.*, 2019). In contrast, TFIW significantly enhanced LAD values to 8.7, 16.4, and 23.8, which is close to that of the control, indicating restored leaf longevity and improved photosynthetic performance after treatment (Kumar *et al.*, 2018). Overall, the findings reveal that untreated food industry wastewater negatively impacts the growth parameters of tomato plants due to its high pollutant load. However, phytoremediation significantly enhances the water quality, resulting in growth indices similar to control conditions. This study highlights the potential for sustainable wastewater management strategies to mitigate environmental impacts and promote agricultural productivity through effective water treatment (Hamed *et al.*, 2016; Pattanaik *et al.*, 2020).

Toxicity and physiological response

The physiological and toxicity analysis of tomato (*Solanum lycopersicum*) irrigated with treated chicken industry wastewater was performed to assess various indices such as tolerance indices, inhibition percentages, phyto-toxicity, and SVI. These parameters provide insight into the plant's response to different irrigation sources, ranging from Control, FIW, Control:FIW (1:1), and

TFIW, over a period of 30, 60, and 90 days (Figure 5). The data reveals the detrimental effects of untreated wastewater on tomato growth and the potential for remediation using treated wastewater. Tolerance indices (TIs), which indicate the ability of plants to withstand stress conditions, showed a significant reduction in FIW-treated plants compared to the control group. At 30 days, plants irrigated with FIW had a tolerance index of 68, which further decreased to 58 by 90 days, indicating a sustained negative effect over time. The 1:1 mixture of control and FIW improved the tolerance indices to 82 at 30 days, 79 at 60 days, and 76 at 90 days, suggesting a moderate effect of FIW when diluted. However, TFIW-treated plants exhibited higher tolerance indices, 96, 94, and 92 at 30, 60, and 90 days, respectively, indicating the positive impact of water treatment on mitigating stress caused by wastewater contaminants (Ali *et al.*, 2017). The percentage inhibition, which measures the reduction in growth due to stress, was highest in FIW-treated plants. At 30 days, FIW caused 32% inhibition, which increased to 42% by 90 days, reflecting the progressive toxic effects of untreated wastewater on tomato growth. The Control:FIW (1:1) mixture showed intermediate values (18% at 30 days, 21% at 60 days, and 24% at 90 days), demonstrating some protective effect due to dilution. Conversely, TFIW significantly reduced the inhibition, with only 4%, 6%, and 8% inhibition observed at the respective time points, suggesting that the treatment process effectively removed or neutralized many of the toxic compounds present in the original wastewater (Kumar *et al.*, 2018).

Phyto-toxicity, indicating the toxic effects of wastewater on plant health, was notably lower in TFIW-irrigated plants. While FIW caused 28% toxicity at 30 days, which increased to 38% at 90 days, TFIW-treated plants exhibited a much lower phyto-toxicity of 5%, 7%, and 9% over the same periods, respectively. This reduction underscores the efficacy of wastewater treatment in mitigating harmful effects such as chlorosis, wilting, and stunted growth (Nayak *et al.*, 2019). The Control:FIW mixture also reduced phyto-toxicity but not to the extent seen in TFIW-treated plants, with values ranging from 16% at 30 days to 23% at 90 days. The Seedling Vigor Index (SVI), which combines seedling growth and development, was highest in borewell water-irrigated

plants. At 30 days, SVI was 1550, which increased to 1950 by 90 days. This steady increase indicates the optimal growth and vigor of plants irrigated with fresh water. In comparison, plants irrigated with FIW exhibited a significant reduction in SVI, with values of 920 at 30 days, 870 at 60 days, and 820 at 90 days, indicating poor seedling vigor due to the toxic effects of untreated wastewater (Daryabeigi Zand *et al.*, 2021). The Control:FIW mixture improved the SVI to 1320 at 30 days, 1370 at 60 days, and 1420 at 90 days, suggesting that dilution of the wastewater mitigated some of the growth impairments. TFIW treatment, however, restored SVI values closer to control levels, with 1500, 1650, and 1750 at the respective intervals, demonstrating that the treatment process significantly improved seedling vigor by removing toxic compounds (Hamed *et al.*, 2016).

Morphological response

The morphological parameters of tomato plants, including root length, shoot length, fresh weight, and dry weight, were significantly influenced by the type of irrigation water used. The results clearly indicate that the treated TFIW, after undergoing phycoremediation, supported tomato growth almost at par with borewell water (control), while untreated FIW had detrimental effects on plant development (Figure 6). Root length increased progressively over time across all treatments. At 90 days, plants irrigated with borewell water showed the highest root length

(24 cm), closely followed by those treated with TFIW (23.2 cm). In contrast, root growth was notably stunted in plants irrigated with FIW (16 cm), indicating the presence of phytotoxic substances or high salinity in the untreated effluent. The 1:1 mixture of control and FIW improved root length moderately (20.5 cm), suggesting that dilution partially mitigated the adverse effects of the raw wastewater. Shoot length followed a similar pattern. Control plants exhibited the highest shoot length at 90 days (70.3 cm), with TFIW-irrigated plants showing comparable growth (69 cm). The lowest shoot length was recorded in FIW-treated plants (50.8 cm), demonstrating the inhibitory effects of untreated wastewater on aerial growth. However, plants grown with the 1:1 diluted wastewater reached a shoot length of 63.5 cm, again reflecting a partial reduction in toxicity due to dilution.

Fresh weight of the plants, which reflects water and nutrient uptake, was also highest in the control treatment (48.2 g at 90 days), closely followed by TFIW (47.3 g). FIW-treated plants exhibited significantly lower fresh weight (33.5 g), while the 1:1 combination recorded 42 g, further indicating that partial dilution can reduce the adverse impacts of raw effluent. Dry weight measurements showed a similar trend, with control plants reaching 16 g, TFIW-treated plants 15.5 g, FIW-treated plants 10.5 g, and the 1:1 mixture yielding 14 g at 90 days. The findings demonstrate that phycoremediation significantly

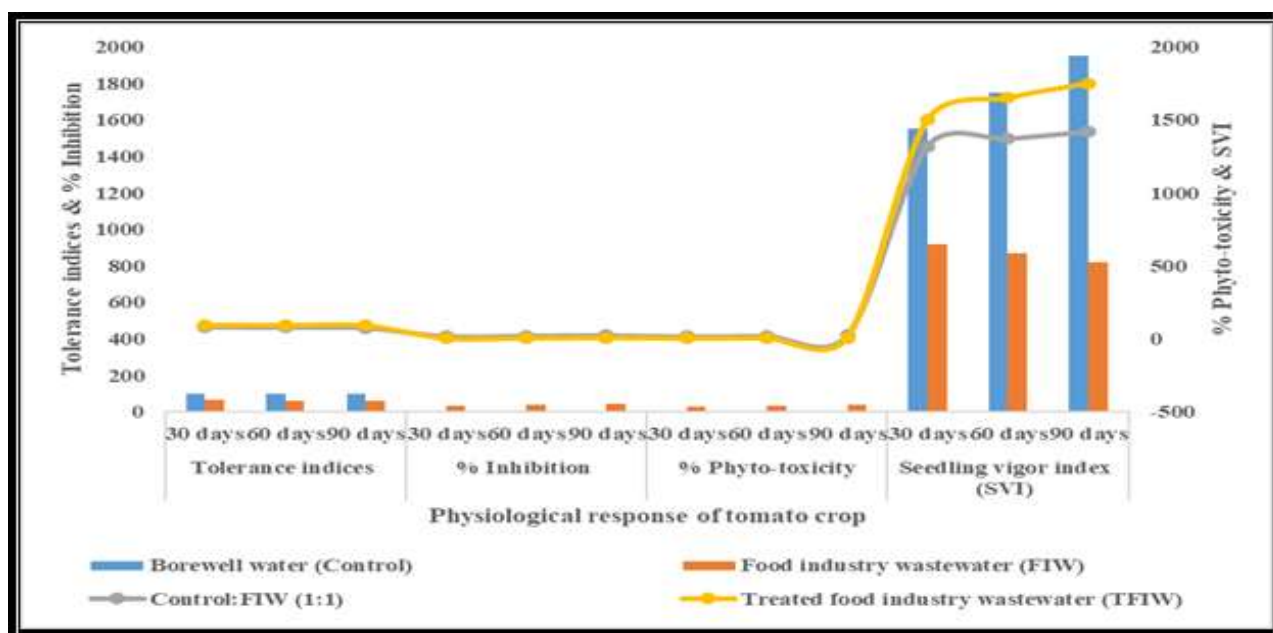


Figure 5: Physiological and toxicity analysis of tomato cultivated with treated food industry wastewater

enhances the suitability of food industry wastewater for agricultural reuse. The treated effluent (TFIW) promoted plant growth nearly equivalent to the control, indicating that phycoremediation effectively removed harmful contaminants while preserving essential nutrients. In contrast, the use of untreated FIW led to reduced plant growth and biomass accumulation, likely due to high concentrations of organic matter, ammonia, or other toxic constituents. The 1:1 mixture offered a partial solution, improving growth over FIW alone. These results underscore the potential of phycoremediation as an eco-friendly, sustainable strategy for recycling nutrient-rich industrial wastewater for use in agriculture, contributing both to pollution mitigation and enhanced crop productivity.

Crop yield and productivity

The analysis of yield and crop productivity parameters revealed significant differences among the irrigation treatments, highlighting the impact of FIW and TFIW on tomato cultivation. The crop growth rate, an indicator of vegetative development efficiency, was highest in plants irrigated with borewell water (3.8 g/day) and closely followed by those irrigated with TFIW (3.7 g/day). In contrast, a notable decline was observed in plants irrigated with untreated FIW, which recorded a crop growth rate of only 2.5 g/day. The intermediate growth rate in the 1:1 mixture of borewell water and FIW (3.3 g/day) suggests that dilution of raw wastewater can partially reduce its phytotoxic

effects and support moderate plant development. Crop productivity, expressed in kilograms per hectare, followed a similar trend. The highest productivity (1850 kg/ha) was observed in the control group irrigated with borewell water, whereas plants treated with TFIW achieved a nearly comparable yield of 1780 kg/ha, indicating that phycoremediation of industrial wastewater effectively restores its agricultural utility. On the other hand, plants irrigated with raw FIW showed significantly lower productivity (1150 kg/ha), reflecting the negative impact of untreated effluent on fruit setting and development. The 1:1 dilution treatment improved productivity to 1500 kg/ha, reaffirming that dilution can be an effective but partial solution in reducing the toxicity of FIW (Figure 7).

The RPE, a comparative index of yield performance with respect to the control, was highest in the TFIW treatment (96.2%), indicating minimal yield loss when using treated wastewater. The RPE dropped to 81.1% in the 1:1 mixture and drastically to 62.2% in untreated FIW, further emphasizing the adverse effects of raw industrial effluents on crop performance. The results strongly support the effectiveness of phycoremediation in transforming nutrient-rich yet toxic food industry wastewater into a safe and productive alternative for irrigation. Treated effluent not only maintained high crop growth rates but also ensured yields nearly equivalent to conventional irrigation with freshwater. These findings

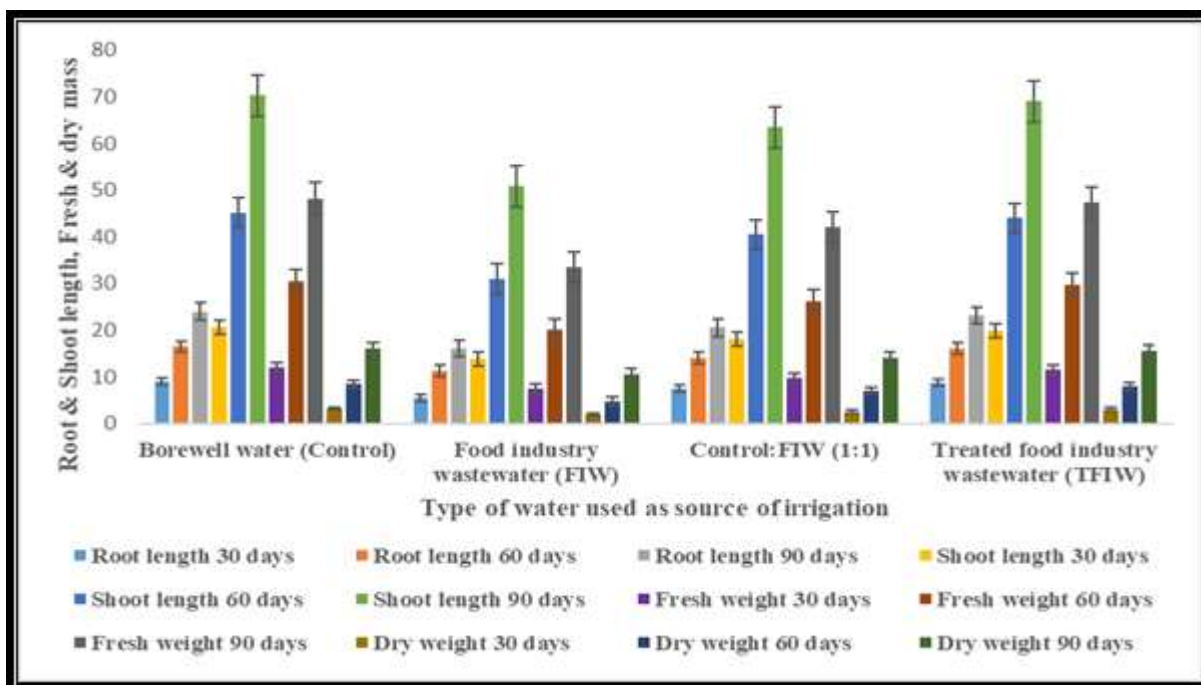


Figure 6: Morphological analysis of tomato cultivated with treated food industry wastewater

highlight the dual benefits of phycoremediation: mitigating environmental pollution while enhancing agricultural sustainability through wastewater reuse.

Soil profile before and after cultivation tomato (*Solanum lycopersicum*)

The comparative analysis of soil parameters before and after tomato cultivation under different irrigation treatments revealed notable changes in soil physical and chemical characteristics (Table 8). The pre-cultivation soil profile indicated a sandy loam texture with 78.5% sand, 15.3% silt, and 6.2% clay, a bulk density of 1.42 g/cm³, and a pH of 6.8—conditions ideal for tomato growth. The initial EC was 1.12 µmhos/cm, indicating non-saline soil, while the moisture content was 6.2%, reflecting moderate water retention capacity. The soil was also moderately fertile, with a cation exchange capacity (CEC) of 98 meq/100g and reasonable levels of macro- and micronutrients. Following the cultivation of tomato plants, noticeable changes were observed across all treatments, particularly in soils irrigated with untreated FIW. A marked increase in soil pH was recorded under FIW (7.9), indicating a shift toward alkalinity, which can negatively impact nutrient availability and microbial activity. In contrast, the soil irrigated with TFIW maintained a near-neutral pH (7.0), closer to the optimal range for tomato crops. Similarly, the EC rose significantly in FIW-treated soil (2.85 µmhos/cm), indicating a buildup of soluble salts due to the presence of industrial residues, while TFIW application resulted in only a slight increase in EC (1.45 µmhos/cm), demonstrating the effectiveness of phycoremediation in reducing salinity levels.

Soil bulk density increased marginally across all treatments, with the highest value observed in FIW (1.50 g/cm³), which may be due to organic matter accumulation and compaction. Moisture content declined slightly in FIW (5.1%) compared to the control (6.2%), possibly due to salt-induced osmotic stress, while TFIW-treated soil retained better moisture levels (6.0%). Nutrient dynamics also shifted with wastewater irrigation. In FIW-treated soils, nitrate (0.25 mg/100g) and nitrite nitrogen (0.15 mg/100g) levels declined compared to pre-cultivation levels, likely due to leaching or microbial denitrification. In contrast, TFIW-irrigated soils maintained near-original levels of nitrate (0.42 mg/100g) and nitrite nitrogen (0.25 mg/100g), indicating

better nitrogen retention. Phosphorus content also declined significantly in FIW-treated soil (0.65 mg/100g), whereas TFIW treatment preserved phosphorus availability (1.0 mg/100g). Potassium levels increased across all treatments, particularly in FIW (110 mg/100g), likely due to the potassium-rich nature of the effluent, although this could pose risks of nutrient imbalance.

The levels of calcium and magnesium increased in FIW- and TFIW-treated soils, with the former showing the highest accumulation (Ca: 4 mg/100g, Mg: 2 mg/100g), suggesting potential long-term salinity and hardness issues. The concentration of carbonates and bicarbonates also increased slightly in FIW (1.30 mg/100g), whereas in TFIW (0.90 mg/100g), values remained closer to baseline, indicating lower alkaline salt buildup. The CEC improved in all wastewater-treated soils, particularly in FIW (120 meq/100g), suggesting increased ion retention capacity possibly due to organic matter deposition. However, the sustainability of such improvements is questionable, considering the accompanying rise in salinity and pH in untreated wastewater treatments. The use of TFIW for irrigation maintained the soil's physical structure and chemical balance, supporting healthy plant growth while avoiding nutrient toxicity or salinity issues. In contrast, untreated FIW led to substantial changes in soil pH, EC, and nutrient dynamics, posing potential risks to soil health and crop productivity. The 1:1 diluted treatment showed intermediate results, indicating that dilution can mitigate some negative impacts but is not as effective as full phycoremediation. These findings underscore the importance of treating industrial effluents through phycoremediation before agricultural reuse to ensure sustainable soil and crop health.

Principal component analysis (PCA)

The PCA conducted on the germination, growth, physiological, and morphological parameters of tomato plants irrigated with different water treatments borewell water, factory- FIW, control:FIW (1:1), and TFIW, provided clear insights into the overall influence of water quality on plant performance. The first two principal components (PC1 and PC2) together explained 63.27% of the total variance in the dataset, with PC1 accounting for 43.85% and PC2 for 19.42%. These components effectively separated the treatment groups and associated traits into distinct

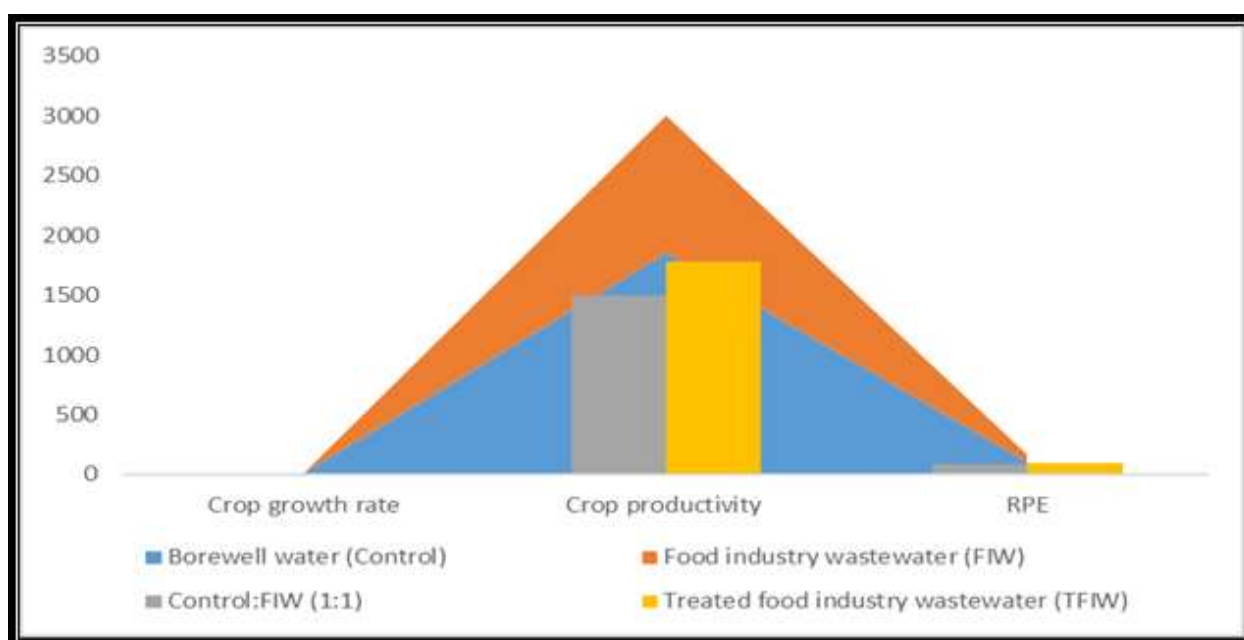
Table 8. Soil quality before and after cultivation of tomato (*Solanum lycopersicum*)

S.No	Parameter	Before Cultivation mg/100g	Borewell water (Control)	Food industry wastewater (FIW)	Control: FIW (1:1)	Treated food industry wastewater (TFIW)
1	Sand (% by weight)	78.5	77.5	76.2	77.1	78
2	Silt (% by weight)	15.3	14.3	17.1	16	15.5
3	Clay (% by weight)	6.2	6.8	6.7	6.5	6.3
4	Bulk density (gm/cm ³)	1.42	1.48	1.5	1.45	1.43
5	Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam

clusters on the biplot (Figure 8). Tomato plants irrigated with control water clustered distinctly along the positive axis of PC1 and PC2, aligning with high values of germination %, GI, MGR, shoot and root length, SVI, and both fresh and dry biomass. This group served as the baseline standard, reflecting optimal physiological and morphological development under non-stressful irrigation conditions. Plants irrigated with borewell water showed moderate association with growth-related traits such as RGR, NAR, SLA, LAR, and LAD. These plants demonstrated acceptable growth performance, although slightly lower than the control, possibly due to minor variations in mineral content or water conductivity.

In contrast, plants treated with untreated FIW

showed a distinct shift toward the negative axis of PC1, clustering alongside stress-associated variables such as percent inhibition, percent phytotoxicity, and low values of GI, MGR, and SVI. This group exhibited clear signs of physiological and morphological stress, evidenced by reduced shoot and root development, poor germination performance, and suppressed biomass accumulation. These findings strongly suggest the presence of toxic elements or elevated salinity levels in the FIW, which adversely affected the early stages of plant development and overall growth potential. Interestingly, plants treated with TFIW were positioned favorably compared to FIW, showing improved association with tolerance indices, dry biomass, and recovery in physiological traits. Although not completely overlapping with the control group,

**Figure 7: Yield and crop productivity analysis of cultivated with treated food industry wastewater**

the TFIW- treated plants showed a clear shift toward the healthier quadrant of the biplot, indicating that treatment significantly reduced the negative impact of industrial contaminants. The control:FIW mixed group displayed an intermediate response, suggesting partial mitigation of toxicity, although the phytotoxic indicators still influenced its position in the biplot. Overall, the PCA effectively differentiated the irrigation treatments and highlighted which physiological, germination, and morphological traits were most responsive to water quality. These results reinforce the importance of water treatment for safe and sustainable agricultural practices. The performance of the TFIW group offers promising evidence for the use of cost- effective remediation strategies, making factory wastewater a potential alternative resource in water-scarce regions when properly treated. The results of this study highlight the effectiveness of phycoremediation as a green and sustainable method for treating food industry wastewater. The application of native microalgae such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Nannochloropsis sp.* led to a significant reduction in nutrient concentrations (nitrogen, phosphorus), organic load (BOD and COD), and suspended solids. These findings align with earlier works demonstrating microalgal potential in wastewater treatment and bioresource recovery (Al-Hussieny *et al.*, 2020; Amit

and Ghosh 2018; Angelaalincy *et al.*, 2023). Microalgae utilized nutrients efficiently, mitigating the risk of eutrophication (Bansal *et al.*, 2018; Zhu *et al.* 2013), and produced substantial biomass that can be repurposed into value-added products such as biofuels and biofertilizers (Chisti 2013; Brennan and Owende, 2010). The harvested algal biomass, when applied as a biofertilizer for tomato (*Solanum lycopersicum*) cultivation, enhanced plant growth, chlorophyll content, fruit yield, and soil fertility, consistent with studies that documented the biofertilizing potential of cyanobacteria and microalgal derivatives (Bhagat *et al.*, 2020; Osman *et al.*, 2010; Rashad *et al.*, 2019; Wuang *et al.*, 2016). This dual-purpose system pollution mitigation and resource recovery demonstrates a circular bioeconomy approach that integrates wastewater management and sustainable agriculture (Moustafa and El Shimi, 2016; Aly *et al.*, 2008; Menamo and Wolde, 2013). Moreover, the combined use of algae and tomato cultivation systems supports nutrient recycling and reduces dependency on synthetic fertilizers, which are associated with soil degradation and groundwater contamination (Abiye and Achamo, 2016; Hegazi *et al.*, 2010; Kumar and Nikhil 2016). Heavy metal removal efficiency further supports previous findings that microalgae can sequester toxic metals through

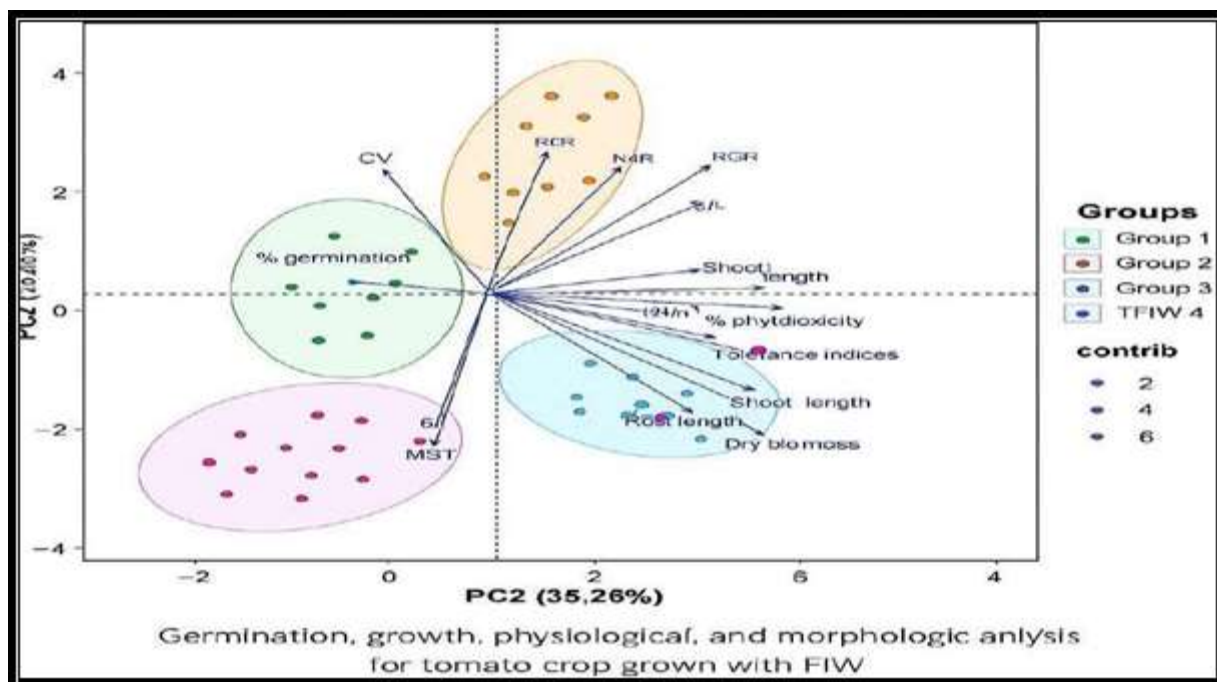


Figure 8: Biplot of PCA for germination, growth, physiological and morphological response of tomato crop cultivated with different irrigation source

biosorption and bioaccumulation mechanisms (Atoku *et al.*, 2021; El-Sikaily *et al.*, 2007). Similarly, the reduction in hydrocarbons and suspended particles is in accordance with studies showing algae's role in degrading oil refinery waste and organic pollutants (Al-Hussieny *et al.*, 2020; Das and Chandran, 2011). The performance of *Coelastrella sp.* and *Botryococcus sp.* in specific systems suggests strain-specific optimization potential for industrial-scale applications (Angelaalincy *et al.* 2023; Gani *et al.*, 2016; Gani *et al.*, 2015). Furthermore, the compatibility of microalgal systems with agro-industrial wastewater sources has been emphasized by studies in dairy, textile, and olive mill wastewater treatment (Pathak *et al.*, 2014; Borde *et al.*, 2003; Paraskeva and Diamadopoulos 2006).

Environmental factors such as pH, salinity, and growth phase also influenced the biochemical composition of algal biomass, as reported by Shruthi and Rajashekhar (2014), which may impact biofertilizer efficiency. The microalgae-bacteria consortia concept presents additional synergy opportunities (Craggs *et al.*, 1997; Bell *et al.*, 2019; Mhedhbi *et al.*, 2020). Overall, the outcomes of this study contribute to the growing body of evidence that phycoremediation is not only a viable wastewater treatment option but also enhances agricultural sustainability (Brar *et al.*, 2019; De Farias Silva *et al.*, 2016; Jaiswal *et al.*, 2018). The integration of treated wastewater for tomato farming demonstrates ecological and economic viability, validating previous conclusions on the multifunctionality of algal-based systems (Godwin *et al.*, 2017; Shurin *et al.*, 2013).

CONCLUSION

The results of this study indicate that untreated FIW has a significant adverse impact on the physiological performance of tomato plants, as evidenced by the reduced tolerance indices, increased inhibition and phyto-toxicity, and lower seedling vigor index. However, the treatment of FIW through phycoremediation (TFIW) effectively mitigated these detrimental effects, leading to improved tolerance, reduced inhibition and toxicity, and enhanced seedling vigor. The results suggest that treated wastewater can serve as a viable irrigation source for tomato cultivation, potentially reducing the environmental impact of wastewater disposal while promoting sustainable

agriculture. Further studies are recommended to optimize the treatment processes and evaluate the long-term effects of TFIW on crop yield and quality.

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