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Assessment of brewery wastewater as an alternative irrigation source: impacts on soil health and nutrient uptake by maize in Tamil Nadu, India

Senthilraja Kandasamy[1], Udhaya Nandhini Dhandayuthapani[2], Venkatesan Subramanian[3*], Jothimani Palanisamy[4], Mohan Kumar Shanmugam[1], Dinesh Dhakshanamoorthy[5], Umesh Kanna Subramani[6] and Sriram Nagappan[3]

Abstract

Background The growing demand for sustainable water management in agriculture has led to the exploration of unconventional water sources, including treated industrial wastewater. Brewery wastewater (BWW), with its inherent nutrient content, seems promising for irrigation. Nevertheless, there is limited knowledge regarding the influence of BWW on soil properties, crop nutrients and overall productivity in the Tamil Nadu context. This study delves into the intricate relationship between BWW irrigation and its impact on soil properties, plant responses and, ultimately, suitability for sustainable agricultural practices. Comparing BWW with Narugampally River water (NRW) serves as a baseline to assess potential differences in its effects.

Methods Laboratory analyses were conducted on BWW and NRW to characterize their irrigation potential. A pot experiment was also carried out in a completely randomized design (CRD) with four treatments covering 100%, 75%, 50% and 25% BWW, along with an additional 100% control (NRW) treatment. The analysis of the BWW samples revealed elevated levels of TDS, BOD, COD, CO_3^-, HCO_3^-, K^+, NO_3^--N, SO_4^-, B^+, SSP, KR and TH beyond the permissible limits of the FAO irrigation water quality standards. However, the mean values of pH, EC, TSS, Ca^{2+}, Mg^{2+}, Na^+, Cl^- and MH remained below the permissible limits according to FAO standards. In the NRW, all the studied parameters fall within the allowable limits.

Results The results of the pot culture experiments revealed that the height and stem girth of the maize plants in the soils irrigated with different concentrations of BWW did not significantly differ ($P < 0.05$). Furthermore, 100% BWW irrigation significantly ($P < 0.05$) increased the leaf area, chlorophyll content, shoot and root biomass and uptake of NPK and other cations in maize leaves. The same treatment significantly increased the pH, EC, OC, available NPK, exchangeable Ca, Mg, Na and soil CEC compared with those of the soils irrigated with 100% NRW. Principal component analysis (PCA) was used to identify key properties contributing to variance, highlighting the positive impact of organic carbon on soil properties and plant growth.

*Correspondence:
Venkatesan Subramanian
svengat95@gmail.com
Full list of author information is available at the end of the article

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Conclusion This study provides a comprehensive assessment of the impact of BWW on soil and crop productivity in Tamil Nadu, filling a critical knowledge gap in sustainable water management for agriculture in water-scarce regions.

Keywords Brewery waste water, Crop productivity, Irrigation potential, Nutrient uptake, Soil properties, Sustainable water management

Background

Water, the most important natural resource for the agricultural sector, is expected to face increasing challenges in the future due to climate change and its associated scarcity [1]. In recent years, climate change has altered rainfall patterns and intensified water scarcity across India. In regions such as Tamil Nadu, residents often pay approximately ₹10 per bucket to meet daily water needs due to severe shortages [2]. According to the Ministry of Water Resources, demand for water is projected to surpass supply by 2050, driven by rising industrial and agricultural needs. Given that unutilized water sources are depleted rapidly, it is crucial to restore and upgrade existing small water bodies, such as tanks, particularly in Tamil Nadu, where water scarcity is already critical. Regions such as the Palakkad and Coimbatore regions are currently experiencing severe shortages of drinking and irrigation water due to the depletion of the Bharathapuzha River and Siruvani River, which serve as lifelines for the people of Palakkad and Coimbatore, respectively [3]. However, owing to minimal rainfall in its catchment areas, water levels in all major irrigation reservoirs have decreased significantly and are becoming increasingly dysfunctional. This has compelled farmers to adopt alternative irrigation methods and seek new water sources, such as brackish groundwater and treated municipal wastewater, to meet their irrigation needs. This pressing requirement has encouraged the scientific community to expand beyond conventional scopes and study the utilization of industrial effluent, which is usually released into bodies of water [4–6].

In such situations, the considerable amounts of wastewater generated by agro-processing industries, such as breweries, can be used to increase freshwater resources and make it possible to resolve local near-order water deficits for agricultural purposes. Brewery wastewater (BWW), with its inherent nutrient content, seems promising for irrigation. The brewery industry is characterized by the use of a large amount of water in beer production, including malting, mashing, wort filtration, wort boiling, fermentation, maturation, stabilization, and clarification [7–9]. It represents one of the most significant sectors within the agricultural industry, generating a substantial volume of residues annually [4]. BWW contains biodegradable [10] organic compounds such as sugars, starch and ethanol that can be recycled and reused for agricultural purposes [5]. Additionally, the solid byproducts generated from breweries, such as spent grains, hops and yeast, are also characterized by their biodegradability. These solid wastes are recycled and reused, making them suitable for agricultural purposes.

This eco-friendly feature of brewery effluent distinguishes it from other industrial effluents [11]. However, elevated concentrations of organic pollutants in untreated wastewater systems lead to increases in various parameters, such as biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), and toxic metals, including lead (Pb), zinc (Zn), cadmium (Cd), manganese (Mn), iron (Fe), copper (Cu), nickel (Ni), cobalt (Co), arsenic (As), and mercury (Hg) [12, 13]. Studies have demonstrated that the continuous utilization of wastewater for irrigation purposes results in heightened toxicity levels [14, 15], diminished crop potential [16], and phytotoxicity attributed to the presence of heavy metal ions [17, 18]. The discharge of untreated or minimally treated wastewater by industries into nearby environments not only significantly contributes to ecological pollution issues [19–21] but also poses a threat to lake ecology and all forms of life in water bodies [22]. Consequently, the treatment of brewery water is imperative.

Wastewater irrigation may lead to greater productivity than irrigation with fresh water, most likely because more nutrients, especially nitrogen, phosphorus and potassium, are carried in wastewater [23, 24]. Recent studies have indicated that the growth and development of diverse crops may be influenced by the application of brewing wastewater. A study conducted by Gorfie et al. [13] explored the impact of brewing wastewater on lettuce crop growth in Ethiopia. These findings suggest that this type of wastewater is saline-sodic, which can alter soil properties and affect lettuce crops. Consequently, corrective measures such as the application of gypsum are needed. It is also recommended that regular assessment and monitoring of brewery wastewater quality should be undertaken prior to its utilization for irrigation purposes. A separate study carried out by Senthilraja et al. [25] revealed that sunflower and sesame crops thrive better when higher concentrations of brewery wastewater are applied. Research has further demonstrated that an increase in the concentration of this wastewater resulted in increased soil enzyme activities within soils irrigated with brewery wastewater. Furthermore, a study by Garcia and Barco [26] revealed that applying both brewery wastewater and solid residues produced by the brewing industry could enhance the physical and chemical properties of soil when it is used on agricultural lands. This practice also led to an increase in the organic carbon and nitrogen contents within the soil.

The increasing problem of water scarcity cannot be neglected, and farmers in water-scarce states such as Tamil Nadu are more inclined to look for alternatives for irrigation. Industrial wastewaters, particularly BWW, have high plant-available nutrient contents and are considered attractive sources for irrigation. Nonetheless, little is known about how BWW application affects soil properties, plant responses and agricultural productivity in this region. This knowledge gap is particularly pertinent in view of the urgency with which sustainable water management practices are needed to address both current global problems related to water scarcity and environmental pollution.

Consequently, this study intends to concentrate on the potential applications of brewing effluent in agriculture. The aims of this study were as follows: (i) to analyse the physical–chemical properties and heavy metal concentrations of brewery wastewater intended for irrigation in comparison with the FAO quality standard limits; (ii) to assess alterations in basic soil properties in soil samples subjected to brewery wastewater irrigation; and (iii) to examine the impact of brewery wastewater irrigation on the growth, physiological characteristics and nutrient composition of maize.

Methods

Description of the study area

The research was undertaken at United Breweries Ltd., which is located in Kanjikode West, Palakkad, Kerala, India. The geographical coordinates of the site are 10.7901° N latitude and 76.7211° E longitude, with an elevation of 114 m above sea level. A location map of the research area is depicted in Fig. 1. This area falls within the Western Ghats and Coastal Plains Agro-Ecologic Zone of India and experiences a temperature range that varies annually from 19.0 to 29.8 °C. The average

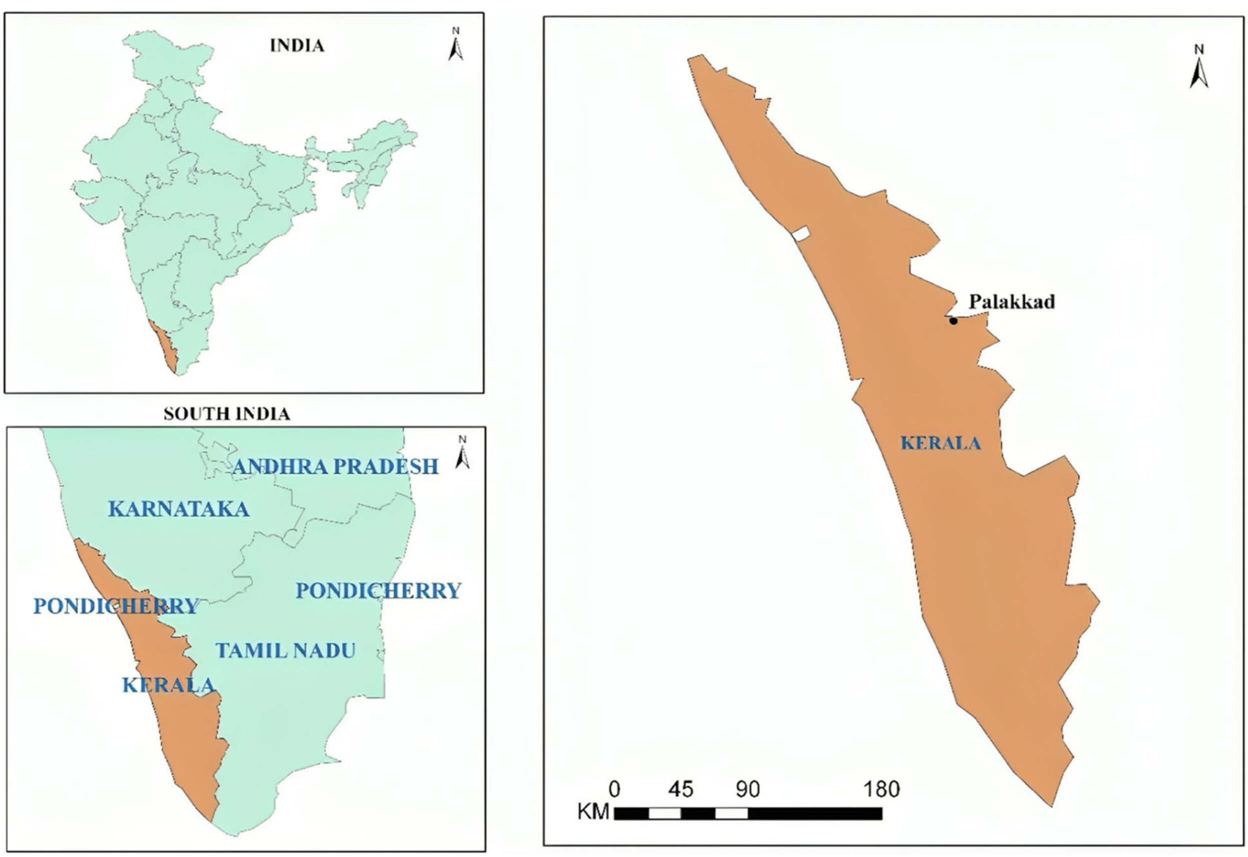

Fig. 1 Location of the study area

annual minimum and maximum air temperatures are 28.8 °C and 19.5 °C, respectively. The region receives an annual precipitation amount of 1297.4 mm $year^{-1}$, with a major contribution from the southwest monsoon season (63.0%) on the basis of climatological means from 1991–2020 (Source: India Meteorological Department).

Sampling methods and data collection

Samples of NRW and BWW were procured from United Breweries Ltd., which is located in Kanjikode West, Palakkad, from March 2020-June 2020. These samples were subsequently analysed for their physicochemical and biological attributes. Each liter of river water or brewery water was collected in a plastic bottle that had been meticulously cleaned with distilled water and rinsed with the corresponding wastewater prior to sample collection.

The procedure for sample collection at each point adhered strictly to the guidelines set forth by the World Health Organization (WHO) in 1989 [27] pertaining to water quality assessment. This process also complied with standard methodologies for examining both water and wastewater as well as those outlined in the Water Laboratory Manual [28]. The collected samples were preserved at a temperature of 4 °C within a refrigerated room pending further analysis; bottles were only unsealed at the time of sampling. The average values of parameters within NRW and BWW were compared against widely accepted irrigation water quality standards established by the Food and Agriculture Organization (FAO) [29] (Table 1).

Chemical analyses of these samples were performed within the laboratory facilities at the Department of Environmental Science, Tamil Nadu Agricultural University, Coimbatore. The levels of pH, TDS and EC were determined via portable pH meters (Model: Lab India-PICO+) [30]. Each thoroughly mixed sample was filtered through standard filter paper.

To measure the BOD, the initial dissolved oxygen concentration of each sample was measured. The sample was then incubated in the dark for 5 days, during which time the microorganisms consumed organic matter, reducing the amount of dissolved oxygen. After incubation, the final dissolved oxygen content was measured, and BOD was calculated as the difference between the initial and final concentrations, indicating organic pollution in the water. Adherence to standard protocols is crucial for accurate BOD measurements [31]. COD measures the amount of oxygen needed to chemically oxidize substances in water. A strong oxidizing agent is added to a sample, which reacts with organic and inorganic compounds. The remaining oxidizing agent is titrated, and the consumed amount indicates the COD, reflecting the water pollutant level [31].

The Bremner method was used to analyse ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) [30]. HCO_3^- and CO_3^- were measured following acid titration [32]. A sample was prepared, a mixture of versenate (EDTA) was added for complex formation, and titration was performed with an indicator (Eriochrome Black). The endpoint, signalled by a color change, determines the ion concentration [33].

Chemical analysis of various inorganic constituents, including anions and cations, involves immediate filtration through 0.22 μm cellulose membranes. A flame photometer (Model: S-935) was used to examine the presence of Na^+ and K^+ ions [28]. Spectrophotometric methods (Dual Beam UV–VIS AU2603) were used to determine the sulfate and nitrate levels [28]. Boron analysis was carried out via the colorimetric method [33]. The concentrations of these chemically analysed constituents are expressed in milligrams per liter (mg L^{-1}). A sample that had been digested with a triacid mixture underwent heavy metal analysis via atomic absorption spectroscopy, following the guidelines set by the USEPA [34]. The AAS (Model: [Thermo Fisher, iCE 3000 Series) was calibrated at optimal wavelengths specific to each element: 283.3 nm for Pb and 228.9 nm for Cd, with a consistent lamp current of 10 mA for each hollow cathode lamp. To increase the sensitivity and reduce interference, the slit width was set at 0.7 nm. An air–acetylene flame was used with an optimized fuel-oxidant ratio and a burner height of 7.5 cm to ensure complete atomization. Calibration curves for each element were constructed using certified standard solutions in the range of 0- 10 ppm, achieving linearity with R2 values above 0.99. To maintain accuracy, quality control samples and blanks were analysed between sample batches, with certified reference material recoveries ranging from 95–105%. Samples were prepared through digestion and analysed in triplicate to ensure repeatability, maintaining a coefficient of variation below 5%.

Irrigation water quality indices

Total hardness (TH)

The subsequent equation, denoted as (1), is used to ascertain the total hardness (TH) measured in milligrams per liter (mg L^{-1}), as outlined by Todd and Mays [35].

$$TH = 2.497Ca^{2+} + 4.11Mg^{+} \tag{1}$$

Percent sodium (Na %)

The concentration of sodium in irrigation water is typically denoted as Na%. These parameters have been established considering the chemical variability of water samples [36]. To compute Na%, one would utilize Eq. (2).

Table 1 Characterization of treated brewery industrial wastewater and river water

Parameters	Unit	Treated brewery industrial wastewater	Control (river water)	FAO Standards (Ayers and Westcot, 1985)
pH	-	7.85	7.20	6.5–8.5
Electrical conductivity	$dS\ m^{-1}$	1.86	0.41	< 3
Total suspended solids	$mg\ L^{-1}$	1.20	0.61	< 50
Total dissolved solids	$mg\ L^{-1}$	1320	258	< 450
Biochemical oxygen demand	$mg\ L^{-1}$	22.0	2.00	< 10
Chemical oxygen demand	$mg\ L^{-1}$	135	12.0	< 60
Ammonical nitrogen	$mg\ L^{-1}$	3.50	2.40	< 5
Nitrate nitrogen	$mg\ L^{-1}$	44.5	3.00	< 30
Phosphate	$mg\ L^{-1}$	6.20	1.10	< 2
Carbonate	$mg\ L^{-1}$	46.0	7.00	< 0.1
Bicarbonate	$mg\ L^{-1}$	69.0	22.0	< 10
Calcium	$mg\ L^{-1}$	77.0	32.0	< 400
Magnesium	$mg\ L^{-1}$	41.0	12.0	< 60
Sodium	$mg\ L^{-1}$	213	68.0	< 900
Potassium	$mg\ L^{-1}$	29.0	11.0	< 2
Chloride	$mg\ L^{-1}$	245	62.0	< 350
Sulfate	$mg\ L^{-1}$	58.0	8.00	< 20
Boron	$mg\ L^{-1}$	2.50	0.06	< 0.75
Chromium (VI)	$mg\ L^{-1}$	BDL*	-	-
Total chromium	$mg\ L^{-1}$	BDL*	-	-
Cadmium	$mg\ L^{-1}$	BDL*	-	0.01
Lead	$mg\ L^{-1}$	BDL*	-	-
Nickel	$mg\ L^{-1}$	BDL*	-	0.2
Mercury	$mg\ L^{-1}$	BDL*	-	-
Percent sodium	%	67.2	33.2	< 20
RSC	$Meq.\ L^{-1}$	−3.00	−15.00	< 1.25
SAR	-	27.7	14.5	< 15
Kellis ratio	-	1.81	1.55	< 1
Magnesium hazard	-	34.7	27.3	< 50
Total hardness	$mg\ L^{-1}$	361	129	< 60

* *BDL* Below detectable level

$$\mathrm{Na\%} = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+}} \times 100 \tag{2}$$

Sodium adsorption ratio (SAR)

The sodium adsorption ratio (SAR) is calculated utilizing both the absolute and relative concentrations of the primary cations, as outlined by Richards [37]. The concentrations are expressed in milliequivalents per liter, as indicated in Eq. 3.

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2}}} \tag{3}$$

Kelley's ratio (KR)

The Kelly ratio (KR) is an essential metric utilized in the evaluation of surface irrigation water quality. This ratio is derived through a comparison of the concentration of sodium ions against that of calcium and magnesium ions. A Kelly ratio value exceeding 1 signifies a heightened presence of sodium within the water, as per Kelly's research [38]. Finally, this ratio, also known as Kelly's ratio (KR), is depicted in Eq. (4) as follows:

$$\mathrm{KR} = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} \tag{4}$$

Residual sodium carbonate (RSC)

The residual sodium carbonate (RSC) is used to evaluate the detrimental impacts of bicarbonate and carbonate on the quality of groundwater intended for irrigation [39]. The calculation of the RSC is conducted via Eq. (5), with the concentrations represented in milliequivalents per liter.

$$RSC = \left(HCO_3^- + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (5)$$

Magnesium hazard (MH)

The magnesium adsorption ratio (MAR) was used to assess the impact of elevated magnesium levels present in irrigation water, as described by Eaton [39]. The computation of this ratio is carried out via Eq. (6), where the concentrations are expressed in milliequivalents per liter.

$$MH = \frac{Mg^{+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (6)$$

Experimental species

Certified seeds of Zea mays (CoH(M)5) were procured from the Esteemed Millet Breeding Station at Tamil Nadu Agricultural University, Coimbatore. The maize seeds were subjected to surface sterilization via 0.1% $HgCl_2$ for five minutes, accompanied by continuous agitation. The samples were subsequently thoroughly rinsed with sterile water multiple times to guarantee the complete removal of any residual $HgCl_2$.

Pot culture studies

The pot experiment was carried out within the Department of Environmental Science at Tamil Nadu Agricultural University, Coimbatore, during the 2023 off-season. Seeds were sown at a depth of 1 cm in plastic pots measuring 20.5×24.0 cm, each filled with 2 kg of garden soil. Various dilutions of BWW were employed to promote seedling growth under pot culture conditions. The following treatments were administered in the course of the pot culture experiment: T1-NRW; T2-Irrigation using a blend of BWW and water at a ratio of 1:3 (25%); T3-Irrigation using a blend of BWW and water at an equal ratio (50%); T4-Irrigation using a blend of BWW and water at a ratio favouring BWW three times (75%); and finally, T5-exclusive use of BWW (100%). The experimental design was completely randomized (CRD), with five replications for each treatment. Upon full emergence, the seedlings were thinned to maintain only two plants per pot. Regular irrigation was performed via BWW to maintain a sixty percent capacity for soil water retention, which equated to approximately 173 ml per irrigation session. The initial characteristics pertaining to the soil are detailed in Table 2.

Plant observations

The following findings were documented 45 days after sowing: leaf area (in millimetres), stem girth (in centimetres), plant height (in centimetres), number of leaves, total chlorophyll content (measured in milligrams per gram), and dry matter production (measured in grams). The content of ethanol-soluble protein was ascertained via the method described by Lowry et al. [40], whereas proline accumulation within the third fully expanded leaf was estimated via the methods of Bates et al. [41]. Both measurements were denoted in milligrams per gram of fresh weight.

Chemical characteristics of leaves

The collected leaf samples were thoroughly cleaned with water, followed by the addition of an ample amount of distilled water to eliminate any dust or waxy residue. These samples were then left to air dry on a pristine plastic tray at ambient temperature for one week in an environment free from dust. Next, the samples were subjected to oven drying at 65 °C for 72 h until a stable weight was reached. The samples were subsequently pulverized via an electric stainless-steel mill, sifted through a sieve with 1 mm openings, and preserved in glass desiccators until analysis [42]. This meticulous procedure was undertaken in preparation for the laboratory nutrient composition analysis of maize. Triple acid digestion was employed for samples at temperatures ranging from 80 to 150 °C [43]. Following digestion, the samples were filtered. The phosphorus content was determined via a spectrophotometer, the K and Na contents were

Table 2 Initial characteristics of the experimental soil

Parameters	Unit	Values
pH	-	7.40
EC	dS m^{-1}	0.28
Organic carbon	percent	0.43
Available N	kg ha^{-1}	145
Available P	kg ha^{-1}	15.8
Available K	kg ha^{-1}	174
Exchangeable Ca^{2+}	cmol (p^+) kg $^{-1}$	4.26
Exchangeable Mg^{2+}	cmol (p^+) kg $^{-1}$	2.96
Exchangeable Na^+	cmol (p^+) kg $^{-1}$	0.86
Exchangeable K^+	cmol (p^+) kg $^{-1}$	0.21
Cation Exchange Capacity	cmol (p^+) kg $^{-1}$	8.29
Exchangeable Sodium percentage (ESP)	percent	10.39

determined via flame, and the N content was assessed via the Kjeldahl method. In addition, the Na^+/K^+ ratio was determined.

Plant anatomy

The crop plants were collected for analysis 30 days after sowing. The stems and roots were carefully detached and thoroughly rinsed with distilled water. The plant tissues were subsequently cut into small pieces approximately 4–5 mm in length and then preserved in a mixture composed of five parts 35% formalin, five parts glacial acetic acid, and ninety parts ethyl alcohol (commonly known as FAA fixative) for 24 h. Following this preservation process, the tissues were dehydrated through a sequence of baths containing water, ethyl alcohol, and tertiary butyl alcohol prior to being embedded in wax. Thin sections were prepared via an expert rotary microtome and positioned on slides that had been previously treated with Haupt's adhesive [44]. The wax was subsequently removed by gently immersing the slides in xylol for ten minutes. This was followed by rehydration through an ordered series of baths containing pure xylol (two changes), a blend of xylol and ethanol (50:50 ratio; one change), and pure ethanol (two changes). After each ten-minute immersion period, the slides were stained with safranin dye [45] before being examined under a Nikon light microscope at ten times magnification.

Soil analysis

Soil samples, each weighing 500 g, were obtained from the pot culture at 45 days after sowing (DAS) for the purpose of evaluating their physicochemical properties via the aforementioned methods. Soil analysis was conducted at the Department of Environmental Science Laboratory, Tamil Nadu Agricultural University Coimbatore. Composite soil samples were prepared through a process that involved air drying them at ambient temperature, pulverizing them with a mortar and pestle, and subsequently passing them through a sieve with a diameter of 2 mm.

The pH level of the soil was ascertained through the application of the pH-water method, which involves forming a suspension of soil to water at a 1:2.5 ratio and subsequently measuring it with a pH meter [30]. The analysis of soil organic carbon (OC) was conducted via the rapid titration method [46], with the organic matter (OM) content being computed by multiplying the OC content by 1.724 [47]. The parameters for calcium (Ca), magnesium (Mg), and sodium (Na) were evaluated via the Mehlich-3 extraction method [48]. The soil mineralizable nitrogen was extracted with 2 M KCl for one hour and determined via the Kjeldahl technique [49]. Available phosphorus was extracted via Olsen's reagent-specifically, 0.5 M $NaHCO_3$-at a pH of 8.5 and a soil-to-extractant ratio of 1:10; this was then quantified via molybdenum-blue colorimetry [50]. Finally, the available potassium was extracted with neutral normal ammonium acetate at a pH of 7.0; this measurement took place via flame photometry [51].

Statistical analysis

The pot culture experiment was conducted in a completely randomized design with five replications for each treatment. The data obtained from the various treatments involving different types of irrigation water on plant and soil properties were statistically analysed via analysis of variance (ANOVA). Mean comparisons were conducted via the least significant difference (LSD) test at a significance level of 5% ($P < 0.05$). The statistical analysis was performed via WASP software version 2.0 [52], following the methods outlined by Gomez and Gomez [53]. Additionally, principal component analysis (PCA) and heatmaps were generated via the free online platform software SRTools [54] to further explore the relationships among variables and the influence of different treatments.

Results

Chemistry of NRW and BWW

The comprehensive analysis of treated BWW in comparison with NRW reveals a spectrum of disparities across various water quality parameters, shedding light on the intricate nature of industrial effluent and its potential environmental implications (Table 1). BWW has a higher pH (7.85) than does NRW (7.20), suggesting a potential alkaline influence on receiving ecosystems. The EC in the BWW is markedly elevated at 1.86 dS m^{-1}, whereas the NRW registers a lower value of 0.41 dS m^{-1}. The total suspended solids in the BWW, at 1.20 mg L^{-1}, surpassed those in the NRW (0.61 mg L^{-1}). Additionally, the concentration of TDS is significantly greater in BWW (1320 mg L^{-1}) than in NRW (258 mg L^{-1}), highlighting the persistence of dissolved contaminants even after treatment.

With respect to the biochemical parameters, BWW presented substantially higher levels of BOD and COD at 22.0 and 135 mg L^{-1}, respectively, than did river water at 2.00 and 12.0 mg L^{-1}. Among the nutrients, the N and K contents were greater, followed by those of P. The nutrient concentrations in the BWW, including those of NH_4–N (3.50 mg L^{-1}), NO_3–N (44.5 mg L^{-1}), and phosphate (6.20 mg L^{-1}), surpassed those in the NRW (2.40, 3.00 and 1.10 mg L^{-1}), suggesting potential impacts on nutrient balance in aquatic ecosystems receiving industrial discharge. In terms of cation and anion concentrations, BWW presented higher levels of Ca^{2+} (77.0 mg L^{-1}), Mg^{2+} (41.0 mg L^{-1}), Na^+ (213 mg L^{-1}), Cl^- (245 mg

L^{-1}), SO_4^{2-} (58.0 mg L^{-1}) and other elements than did river water.

Notably, indices reflecting the suitability of water for irrigation, such as the SAR, KR and MH, indicate potential risks associated with the BWW. SAR is substantially greater in the BWW at 27.7 than at 14.5 in the river water, suggesting an increased risk of soil structure degradation. The KR, which measures the risk of sodium-induced problems, also has a higher value of 1.81 in the BWW than in the river water (1.55). The MH exceeds the critical value of 30 in BWW (34.7), indicating potential hazards associated with magnesium content, whereas it is lower in NRW at 27.3.

Effect of BWW on maize in the pot culture experiment

A pot culture experiment was conducted to study the effects of BWW on soil and crops under controlled conditions. The following results were obtained from the pot culture experiment.

Growth and physiological attributes of maize

The outcomes of the experiment, which focused on plant morphological parameters, including plant height (cm), stem girth (cm) and leaf area (cm^2), across the different treatments are presented in Table 3. The plant height varied among the treatments, with T2 resulting in the highest mean value of 76.8 cm, whereas T4 resulted in the lowest value of 69.9 cm. However, these differences were not statistically significant. The stem girth measurements also showed no significant differences among the treatments, with values ranging from 3.20 (T2) to 3.40 cm (T4). In terms of leaf area, T1 presented the highest mean value of 351 cm^2, which significantly differed from those of the other treatments. Conversely, T5 presented the smallest leaf area, with a mean value of 263 cm^2.

In the pot experiments, the dry matter produced by the various treatments ranged from 2.47 to 2.99 g and from 1.72 to 1.92 g, respectively, in maize for shoot and root biomass production. Compared with the other treatments, the application of BWW resulted in significantly greater dry matter production ($P < 0.05$). Furthermore, at relatively high concentrations of BWW, a significant increase in dry matter production was observed, with maize showing the most pronounced response in the present study. Interestingly, the results of treatment T4 were comparable to those of treatment T5.

These results underscore the influence of different treatments on plant morphology, particularly on leaf area and dry weight, suggesting potential implications for overall plant development and health. T4 presented the highest total chlorophyll content, with a mean value of 3.09 mg g^{-1}, which was significantly ($P < 0.05$) different from that of the other treatments. In contrast, T5 presented the lowest total chlorophyll content, with a mean value of 2.66 mg g^{-1}. T3 was comparable to T2, which had a value of 2.91 mg g^{-1}. These findings suggest variations in the total chlorophyll content among the treatments, reflecting the influence of different experimental conditions on this important biochemical parameter.

Chemical characteristics of the plants

The application of BWW significantly increased the uptake of nutrients in maize (Table 3). The uptake of cations varied from 19.2 to 24.6, 3.40 to 3.90, 2.10 to 2.50,

Table 3 Effects of treated brewery wastewater on maize growth attributes, physiological traits and nutrient uptake in pot culture experiments

Treatments	T1	T2	T3	T4	T5
Plant height (cm)	71.9 ± 0.99^{ns}	76.8 ± 0.41^{ns}	73.5 ± 0.91^{ns}	69.9 ± 1.04^{ns}	70.8 ± 0.71^{ns}
Stem girth (cm)	3.40 ± 0.02^{ns}	3.20 ± 0.01^{ns}	3.28 ± 0.02^{ns}	3.40 ± 0.03^{ns}	3.36 ± 0.03^{ns}
Leaf Area (cm^2)	272 ± 1.4^{c}	263 ± 4.1^{c}	308 ± 3.8^{b}	290 ± 4.7^{bc}	325 ± 4.8^{a}
Total Chlorophyll content (mg g^{-1})	2.66 ± 0.03^{d}	2.91 ± 0.05^{bc}	2.86 ± 0.04^{c}	3.04 ± 0.05^{ab}	3.09 ± 0.04^{a}
Shoot biomass (g $plant^{-1}$)	2.67 ± 0.05^{b}	2.47 ± 0.03^{c}	2.84 ± 0.04^{a}	2.87 ± 0.05^{a}	2.99 ± 0.07^{a}
Root biomass (g $plant^{-1}$)	1.87 ± 0.01^{c}	1.82 ± 0.04^{bc}	1.72 ± 0.00^{a}	1.86 ± 0.02^{ab}	1.92 ± 0.02^{a}
Total Nitrogen (g kg^{-1})	19.2 ± 0.34^{a}	21.0 ± 0.49^{bc}	20.2 ± 0.23^{cd}	21.7 ± 0.32^{b}	24.6 ± 0.03^{a}
Total Phosphorus (g kg^{-1})	3.40 ± 0.01^{c}	3.40 ± 0.07^{c}	3.80 ± 0.01^{ab}	3.70 ± 0.08^{b}	3.90 ± 0.04^{a}
Total Potassium (g kg^{-1})	2.10 ± 0.05^{c}	2.20 ± 0.05^{bc}	2.30 ± 0.05^{b}	2.30 ± 0.04^{b}	2.50 ± 0.05^{a}
Sodium (g kg^{-1})	2.00 ± 0.00^{d}	2.50 ± 0.04^{c}	2.50 ± 0.02^{c}	2.70 ± 0.01^{b}	2.90 ± 0.03^{a}
Calcium (g kg^{-1})	5.20 ± 0.03^{b}	5.60 ± 0.13^{a}	5.70 ± 0.07^{a}	5.00 ± 0.12^{b}	5.70 ± 0.05^{a}
Magnesium (g kg^{-1})	3.00 ± 0.07^{a}	2.80 ± 0.06^{b}	2.80 ± 0.07^{b}	2.80 ± 0.02^{b}	3.10 ± 0.06^{a}
Na^+/K^+ Ratio	0.95 ± 0.02^{c}	1.14 ± 0.02^{ab}	1.09 ± 0.01^{b}	1.17 ± 0.02^{a}	1.16 ± 0.03^{a}

The data are the mean values of five replicates ± standard error. Means followed by the same letter within each row are not significantly different at the 0.05 level. ns indicates nonsignificant

2.00 to 2.90, 5.00 to 5.70 and 2.80 to 3.10 g kg^{-1} for N, P, K^{+}, Na^{+}, Ca^{2+} and Mg^{2+}, respectively, in maize. The crops grown under relatively high concentrations of BWW (100%) presented greater macronutrient and cation uptake than did the plants grown in NRW. In terms of phosphorus uptake, T3 was on par with T4 and T5.

Furthermore, the Na^{+}/K^{+} ratio significantly differed among the treatments, with T5 having the highest ratio of 0.95–1.17. The progressive increase in the sodium (Na) concentration from 25 to 100% BWW correspondingly increased the Na^{+}/K^{+} ratio in the seedlings. Among all the treatments, T1 notably resulted in a significantly reduced Na^{+}/K^{+} ratio of 0.95.

Plant stem and root anatomy

The stem and root anatomy of maize is depicted in Fig. 2. Maize presented a typical anatomical structure irrespective of the treatment under which it was grown or the amendment applied.

In terms of stem anatomy, numerous vascular bundles were observed. The cortex, pericycle and pith were indistinct due to the scattered distribution of bundles throughout the axis. Each vascular bundle is enveloped by a well-developed sclerenchymatous sheath and typically has an oval shape. The phloem was identified solely by sieve tubes and companion cells. The xylem parenchyma was located adjacent to the water cavity (lysigenous cavity). No significant differences in stem anatomy were noted among the different treatments.

The maize root anatomy revealed numerous xylem groups (12) in both the control and BWW-only pots. No changes were recorded in the pericycle or vascular tissue of the roots. The pith of the roots was well developed in both the control plants and the plants treated with BWW alone. The thin-walled parenchyma cells have sufficiently developed with intercellular spaces among them.

Chemical analysis of BWW- and NRW-irrigated soils

The soil organic carbon content varied between 0.48 and 0.64%. T5 (BWW alone) presented the highest soil organic carbon content at 0.64%, closely followed by T4 at 0.60%. T1 (NRW) had the lowest recorded value at 0.48% (Table 4).

The changes observed in soil pH due to BWW irrigation were not different among the treatments. However, numerically higher pH values were associated with T5. In general, an increasing trend in soil pH was observed due to increasing BWW concentrations.

The soil electrical conductivity (EC) significantly differed ($P<0.05$) as a result of BWW irrigation. T1

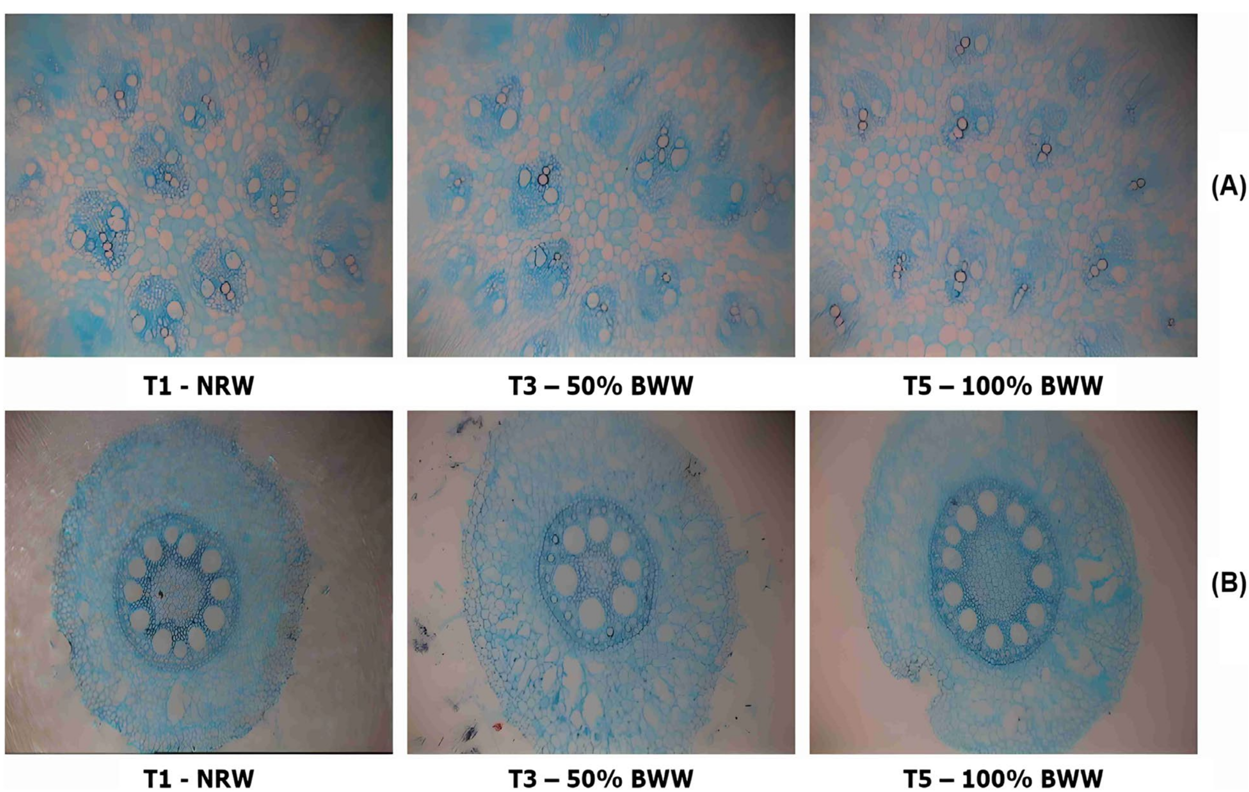

Fig. 2 Anatomical changes in maize due to brewing wastewater application **A**. Stem changes and **B**. Root changes

Table 4 Chemical analysis of the brewery wastewater irrigated and control soils

Parameters	T_1	T_2	T_3	T_4	T_5
pH	7.55 ± 0.10^{ns}	7.89 ± 0.04^{ns}	7.82 ± 0.10^{ns}	7.89 ± 0.13^{ns}	7.98 ± 0.15^{ns}
EC (dS m^{-1})	0.32 ± 0.00^{d}	0.43 ± 0.00^{d}	0.62 ± 0.01^{c}	0.80 ± 0.01^{b}	1.15 ± 0.08^{a}
Organic carbon (%)	0.48 ± 0.00^{d}	0.51 ± 0.00^{cd}	0.55 ± 0.01^{bc}	0.60 ± 0.01^{ab}	0.64 ± 0.02^{a}
Available N (kg $ha^{-1)}$	118 ± 0.59^{c}	140 ± 0.43^{b}	146 ± 0.74^{b}	157 ± 1.09^{ab}	168 ± 1.04^{a}
Available P (kg $ha^{-1)}$	16.3 ± 0.0^{d}	20.5 ± 0.06^{c}	22.0 ± 0.11^{c}	24.5 ± 0.17^{b}	26.9 ± 0.17^{a}
Available K (kg $ha^{-1)}$	186 ± 0.94^{ns}	184 ± 0.56^{ns}	181 ± 0.91^{ns}	178 ± 0.25^{ns}	189 ± 1.17^{ns}
Exchangeable Ca (cmol (p^{+}) kg^{-1})	4.30 ± 0.06^{b}	4.70 ± 0.02^{ab}	4.90 ± 0.06^{a}	5.10 ± 0.08^{a}	5.00 ± 0.04^{a}
Exchangeable Mg (cmol (p^{+}) kg^{-1})	0.30 ± 0.00^{d}	0.40 ± 0.00^{d}	0.8 ± 0.01^{c}	1.30 ± 0.02^{b}	1.50 ± 0.04^{a}
Exchangeable Na (cmol (p^{+}) kg^{-1})	0.35 ± 0.00^{1}	0.70 ± 0.00^{c}	0.89 ± 0.01^{b}	1.07 ± 0.02^{a}	1.15 ± 0.03^{a}
Soil CEC (cmol (p^{+}) kg^{-1})	5.27 ± 0.07^{c}	6.00 ± 0.03^{c}	6.91 ± 0.09^{b}	7.69 ± 0.13ab	7.94 ± 0.15^{a}
SAR					

The data are the mean values of five replicates ± standard error. Means followed by the same letter within each row are not significantly different at the 0.05 level. ns indicates nonsignificant

presented the lowest soil EC value at 0.32 dS m^{-1}, which was statistically similar to that of T2 at 0.43 dS m^{-1}. Conversely, T5 presented the highest recorded value at 1.15 dS m^{-1}.

The soil available NPK markedly improved ($P < 0.05$) due to the application of BWW (Table 2). The available NPK contents ranged from 118–168, 16.3–26.9 and 178–189 kg ha^{-1}, respectively. The highest values of soil available N and P (168 and 26.9 kg ha^{-1}) were recorded in T5, which were significantly different from those in all the other treatments. The lowest values (118 and 16.3 kg ha^{-1} of N and P, respectively) were recorded at T1. Irrespective of the treatment, the K concentration decreased significantly in T4 but again increased in T5, followed by T1 (186 kg ha^{-1}).

The soil exchangeable Ca and Mg contents increased with increasing concentrations of BWW. The increased concentration of BWW significantly increased the soil exchangeable Ca and Mg in all the treatments. The maximum soil exchangeable Ca and Mg contents were recorded in T4 and T5 (5.1 and 1.5 cmol (p^{+}) kg^{-1} Ca and Mg, respectively). With respect to the Ca content, T3, T4 and T5 were on par with one another. Minimum values (4.3 and 2.8 cmol (p^{+}) kg^{-1}) of Ca and Mg were recorded at T1. With respect to the Mg content, treatment T5 significantly differed from all the other treatments. The soil exchangeable sodium content gradually increased from the control to BWW alone, corresponding to the increasing concentration of BWW, ranging from 0.35 to 1.15 cmol (p+) kg^{-1} among the treatments. The transition from the control (5.27 cmol (p+) kg^{-1}) to T5 (7.94 cmol (p+) kg^{-1}) resulted in a gradual upwards trend, emphasizing the impact of BWW on enhancing the soil cation exchange capacity.

Principal component analysis and heatmaps

The physicochemical properties and plant traits of all the BWW- and NRW-irrigated soils were subjected to principal component analysis, revealing that 75% of the data variance was associated with the first two components (Table 5). Figure 3 depicts the score plot of the PCA for all the treatments via the first two principal components (PCs). The score plot visually represents clusters of soils with similar physicochemical properties.

The first PC accounted for 60.835% of the variance, with negative loadings on plant height (−0.191), leaf area (−0.731), and total chlorophyll content (−0.286) and positive loadings for the remaining parameters (Table 5). These attributes are crucial indicators of plant growth and development. OC, available NPK, exchangeable Ca^{2+}, Mg^{2+} and Na^{+} and CEC are the primary properties exhibiting high positive loadings, making substantial contributions to the variance in PC1. An elevated OC content leads to increased concentrations of anions and cations in the soil solution. These alterations are expected to have a positive impact on soil properties and promote enhanced plant growth.

PC2 explained 14.871% of the variance, with negative loading on exchangeable Ca^{2+} and Na^{+}. BD was also associated with PC2, with a negative loading of −0.37. The clay content, BD and K influence water transport through the soil. PC3 accounted for 12.273% of the variance, with negative loadings on exchangeable Mg^{2+} and Na^{+}, stem girth, and leaf area, whereas PC4 explained 7.366% of the variance, with positive loadings on pH, height, stem girth and total chlorophyll. PC5 explained 4.655% of the variance in the total variance.

A heatmap was employed as a visualization tool to illustrate the distribution of data among the treatment

Table 5 Principal component analysis of wastewater-irrigated soil properties and plant characteristics

Principle components	PC1	PC2	PC3	PC4	PC5
Eigne value	13.992	3.650	2.593	1.694	1.071
% variance	60.835	14.871	12.273	7.366	4.655
Cumulative variance	60.835	75.706	88.979	95.345	100
Rotated component matrix (Varimax rotation)					
pH	.690	.342	.597	.224	.020
EC	.882	.276	-.194	-.298	.138
OC	**.943**	.260	-.102	-.085	.161
Avl. N	**.983**	.113	.058	-.126	.032
Avl. P	**.981**	.108	-.013	-.154	.040
Avl. K	.018	**.841**	.521	-.077	.126
Ex. Ca	**.955**	-.039	.181	.188	.136
Ex. Mg	**.915**	.173	-.309	-.094	.168
Ex. Na	**.988**	-.060	-.048	-.110	.076
CEC	**.975**	.065	-.105	-.032	.183
Ht	-.191	.028	**.956**	.120	-.187
SG	.180	.696	-.066	.546	.425
LA	-.731	.155	-.091	.411	.515
N	.821	.489	.066	-.264	-.111
P	.790	.193	.122	-.106	.560
K	.862	.345	.182	-.223	.233
Na	**.975**	.087	.129	-.141	-.079
Ca	.212	.154	.799	-.500	.207
Mg	.064	**.947**	.049	-.201	.237
TC	-.286	.009	.002	**.958**	-.001
SB	.673	.356	-.171	.012	.625
RB	.246	**.928**	-.038	.211	-.182
Na + /K	**.934**	.010	.249	.069	-.247

Bolded loadings are highly weighted

groups (Fig. 4). In this depiction, three distinct clusters are discernible, and the color gradient from blue to orange serves as a representation of the data variation. Specifically, blue is indicative of negative trends, whereas orange signifies positive trends within the dataset.

Discussion

Chemistry of brewery waste water and NRW

Wastewater irrigation has both favourable and unfavourable impacts on soil characteristics. The results revealed that the highest pH was recorded in BWW, suggesting a slight alkaline influence on the receiving ecosystems, whereas the lowest pH (7.20) was in NRW water, indicating a generally neutral pH. Previous studies by Gorfie et al. [13], Thapliyal et al. [55] and Bhutiani et al. [56] consistently reported an increase in soil pH under wastewater irrigation. Mojiri [57] reported an initial decrease followed by a subsequent increase, and Abegunrin et al. [58] reported a reduction in soil pH as a result of wastewater irrigation. In contrast, the present study revealed a consistent increase in soil pH across all the wastewater treatment methods. This increase in pH could be attributed to several processes, such as decarboxylation and deamination involving organic anions and amino acids, nitrogen mineralization and denitrification [59]. Additionally, the presence of compounds such as carbonate, bicarbonate or hydroxide derived from industrial procedures may increase the alkalinity of wastewater, thereby influencing the soil pH.

The data from our current study emphasize a substantial difference in the EC values between the brewery and NRW samples. The increased EC in BWW suggests the presence of surplus dissolved solids and signifies a strong correlation between water conductivity and the concentration of dissolved ions. An increase in BWW conductivity serves as a potential indicator of the introduction of dissolved ions during industrial processes, thereby serving as a potential marker for identifying pollution sources. Moreover, our findings resonate with those of [13], who similarly documented elevated EC values in BWW samples compared with those in NRW samples.

The TDS stands out as a crucial parameter in assessing the agricultural suitability of water for irrigation [60]. In our study, the TDS content markedly differed between the NRW and BWW samples. The elevated levels of TDS can be attributed to the substantial quantity of pollutants such as carbohydrates, alcohols, suspended solids, and yeast in industrial effluent [61]. The TSS also followed a similar trend. Irrigation with high TDS can result in soil pore clogging, which inhibits water infiltration and reduces permeability. This can lead to more surface runoff and eventually degrade the soil structure [62]. In long-term irrigation planning for BWW, to counteract its negative effects, farmers are encouraged to blend fresh water whenever possible for irrigation to maintain soil health and improve water retention.

The results revealed a 90% decrease in BOD in NRW water over BWW. Indeed, BOD serves as a valuable indicator of water quality, and its interpretation aligns with the understanding that a lower BOD value corresponds to better water quality, whereas a higher BOD value suggests lower water quality for irrigation purposes, as observed by Tomas et al. [63]. The rationale behind this correlation lies in the fact that a lower BOD value implies a reduced demand for oxygen by microorganisms during the decomposition of organic matter in water, indicating a cleaner and less polluted aquatic environment. Furthermore, the relationships between BOD and the presence of pollutants, including TSS, TDS, and COD, are emphasized by Singh et al. [64]. A higher BOD value is indicative of elevated concentrations of these pollutants

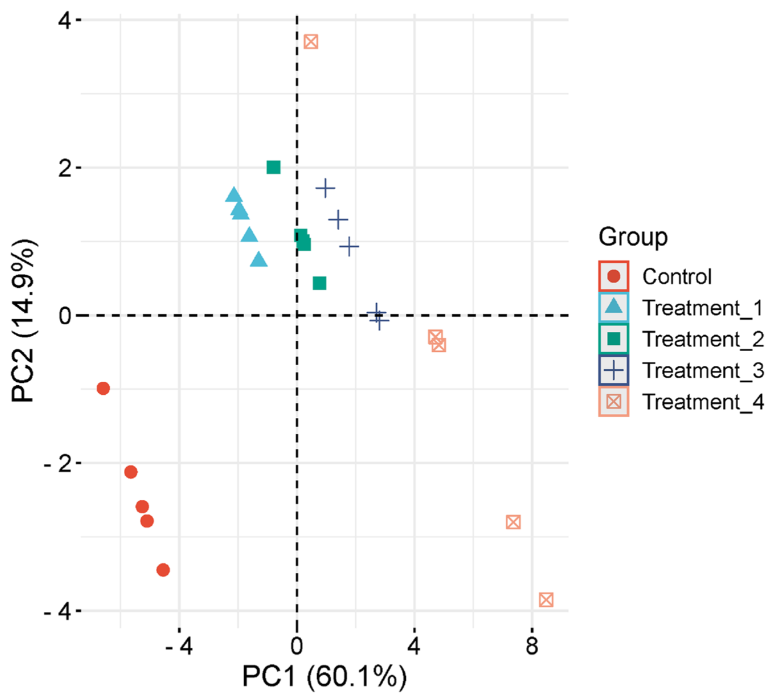

Fig. 3 Score plot of PCA

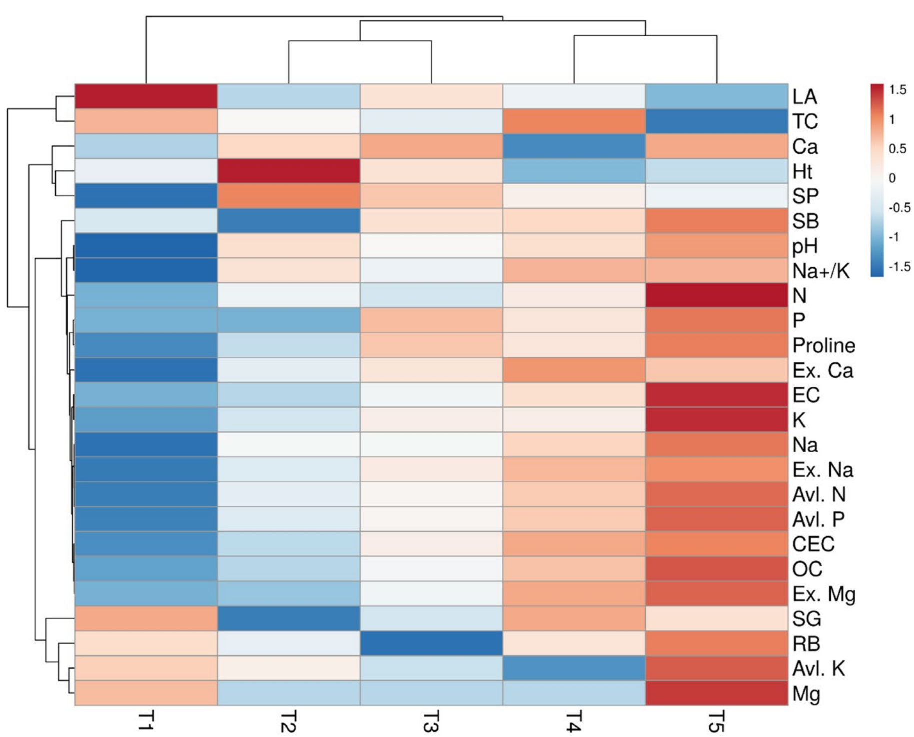

Fig. 4 Heatmap representing the changes in the studied parameters related to the five treatments, which were drawn via the SRplot platform. Each treatment is shown as a single column in the heatmap, and each parameter is shown as a single row. Different shades represent parameter accumulation, whereas the blue color represents a decreasing trend, and the orange colour represents an increasing trend (color key scale on the right of the heatmap)

in BWW, reflecting a greater organic load that microorganisms need to oxidize.

The COD value measured in BWW was 125% higher than the safe limit recommended by the FAO (60 mg L^{-1}), indicating that BWW is unsuitable for irrigation purposes. This elevated COD level signifies a substantial load of organic compounds in the BWW, surpassing the threshold for safe agricultural use. Analogous to BOD, higher COD levels impact the availability of oxygen for the decomposition of organic matter and lead to an insufficient oxygen supply for soil microorganisms [65].

Elevated concentrations of NO_3-N in water can have multifaceted implications for both human health and the environment. The presence of high nitrate levels often indicates groundwater contamination, frequently stemming from agricultural runoff, fertilizers, or septic system discharges, with potential repercussions for both surface and groundwater quality. Additionally, elevated nitrate concentrations can lead to over-fertilization of crops, causing nutrient imbalances and soil acidification [66]. This could be attributed to the high nutrient content of BWW, which is largely derived from malts, yeast cells and sanitizing chemicals used during the treatment process [67]. The BWW in this study contained 6.2 mg L^{-1} of phosphorus, which is above the FAO limit. In this case, prolonged use of phosphorus-rich BWW for irrigation can disrupt soil phosphorus dynamics, leading to agricultural runoff (Liu et al., 2017), which can cause eutrophication or toxicity in nearby ecosystems [68].

The level of HCO_3^- in BWW was higher than the recommended threshold set by the Food and Agriculture Organization (FAO), thus rendering it inappropriate for irrigation purposes. However, organic manures, especially those from animal sources, provide calcium, which can help counteract the negative effects of bicarbonates. Ca^{2+} displaces Na^+ (which is often linked with high bicarbonate levels) on soil particles, improving the soil structure and reducing salinity problems. Additionally, farmers are advised to lend BWW with a cleaner water source (lower in bicarbonates) to reduce the overall concentration, making it safer for irrigation for a certain period.

The average cation values (Ca^{2+}, Mg^{2+}, Na^+, K^+) for both NRW and BWW were observed to be within the permissible limits established by the FAO, suggesting that their concentrations are suitable for irrigation and do not substantially affect soil or crop growth [69]. However, laboratory analysis revealed that the K^+ value surpassed the FAO standard, indicating that its concentration may not be suitable for irrigation purposes.

The SAR elucidates the extent of the Na^+–Ca^{2+}/Mg^{2+} exchange process between water and fine soil particles. This process involves the displacement of adsorbed Mg^{2+} and Ca^{2+} ions by Na^+ ions, consequently leading to soil hardness and diminished permeability. The SAR serves as an effective assessment criterion for the majority of irrigated agricultural areas [70]. SAR values exceeding 18 signify a sodium hazard [71], and the observed value for BWW was 27.7, placing it in the hazard category. Conversely, an SAR value below 18 for NRW is deemed favourable [35]. Wastewater-induced salinity can reduce crop productivity by causing nutrient imbalances and growth inhibition due to toxic ions. For example, maize is moderately sensitive to salinity. Therefore, the effective and sustainable use of effluent for irrigation requires the periodic monitoring of soil salt levels and proper management practices, such as leaching, the application of green manure, or the use of gypsum [72].

Conversely, the SSP values for BWW and NRW stand at 59.2% and 55.3%, respectively, indicating a range from fair to poor water quality. As a result, these SSP values suggest that between 50–80% of the water samples are of poor quality, whereas only 20–40% demonstrate fair water quality appropriate for irrigation purposes.

KR is an evaluative measure that considers the contents of Na^+, Ca^{2+}, and Mg^{2+} to assess surface water suitability for irrigation purposes and typically deems surface water with a KR less than one fit for irrigation. Nevertheless, in instances where the KR exceeds one in value, the water is not suitable for irrigation use.

Effects of BWW and NRW on maize growth and physiological traits

The findings demonstrated that, compared with NRW-irrigated soil, soil irrigated with 100% BWW significantly enhanced growth traits such as shoot and root biomass by 12 and 3%, respectively. This increase in measured traits could be attributed to the higher nutrient content, particularly N, present in BWW than in NRW. For example, the continuous supply of N in two forms, ammonium (NH_4^+) and nitrate (NO_3^-), found in wastewater could have been instrumental in maintaining an appropriate cation–anion ratio, thereby influencing plant fresh weight. The presence of N not only impacts above-ground biomass but also promotes increased root biomass and soil volume proliferation, thereby affecting below-ground biomass. These observations are corroborated by Awe [73]. The current results align with those of studies carried out by Gorfie et al. [13] and Gatta et al. [74], who suggested that wastewater irrigation can enrich soils with essential nutrients, thus improving soil fertility and increasing crop growth, productivity, and quality.

Mojiri et al. [57] and Parveen et al. [75] reported an increase in the shoot length of *Lepidium sativum* and *Brassica rapa*, respectively, when they were irrigated with wastewater. However, in this study, there was no significant difference in plant height or stem girth among the treatments applied. This finding receives strong support from the results reported by Kobaissi et al. [76]. The consistent plant height across treatments can be attributed to two potential reasons: first, the NRW-irrigated soil provided optimal conditions for plant growth, and second, the higher concentration of total nitrogen recorded in the BWW treatments contributed to increased vegetative growth.

A 20% increase in leaf area was observed with 100% BWW over NRW irrigation. This can be attributed to the higher nutrient content in soils irrigated with BWW than in those irrigated with NRW. Omotade [77] reported that hot pepper plants irrigated with treated wastewater presented significantly greater leaf areas, attributed to increased photosynthesis, which ultimately resulted in greater plant yields.

Our findings are supported by those of Mousavi and Shahsavari [78] and Younas et al. [79], who reported that maize plants irrigated with biotreated textile effluents had more leaves than did those irrigated with untreated effluents. The increased number of leaves, along with their healthier condition, contributes to a greater leaf area.

The elevated total chlorophyll content (16% increase over NRW) observed under 100% BWW irrigation may be attributed to an increased rate of chlorophyll biosynthesis from wastewater [80]. In this study, the higher Mg^{2+} content of BWW may be considered a contributing factor to the increased total chlorophyll values. Magnesium, an essential macronutrient found in wastewater, plays a pivotal role as a component of the chlorophyll molecule, which is crucial for the process of photosynthesis in green plants [81]. Additionally, nitrogen, another component of chlorophyll, is present in two forms (NH_4^+ and NO_3^-) in BWW (Table 1) and is considered a significant factor supporting the increased chlorophyll content in leaves [82]. Owing to its greater photosynthetic activity than other crops, maize, a C_4 crop, can effectively metabolize more nitrogen from wastewater [83]. These findings are supported by various studies [83–85]. However, in contrast, Rasheed et al. [86] reported a low chlorophyll content in wastewater-irrigated soil in maize.

Root and stem anatomy

The root and stem anatomy of maize was examined, and all the treatments, including the control, presented the same structure. The typical anatomical features of a crop are likely influenced by genetic characteristics such as the size and shape of each layer. Visual observations [87] revealed a reduction in the cortex region in CO_3 (Napier grass) and guinea, which is considered a desirable trait. Similarly, halophytic species presented a marked reduction in the development of the primary root cortex [88]. In contrast, there were no differences in the root or stem anatomy among maize plants subjected to different wastewater treatments.

Effect of BWW on the nutrient composition of maize leaves

The leaf concentrations of total nitrogen, phosphorus, potassium, calcium, magnesium and sodium were significantly ($P < 0.05$) influenced by 100% BWW, resulting in increases of 28%, 15%, 19%, 10%, 3%, and 45%, respectively, over those of the control. This could be linked to the high concentration of nutrients present in land irrigated with wastewater [89]. Notably, the macronutrient content was greater in the BWW irrigation system than in the NRW irrigation system. These results are consistent with those reported by [85], who reported significantly higher macronutrient contents in silage maize under wastewater irrigation conditions than under freshwater irrigation conditions, emphasizing its nutrient-rich nature. Numerous researchers [76, 90–92] have emphasized that the nutrient richness of wastewater is responsible for the accumulation of nutrients in crops.

Effect of BWW on soil chemical properties

The practice of wastewater irrigation has been observed to have both advantageous and disadvantageous impacts on soil properties. One such property, soil pH, plays a pivotal role in determining nutrient availability, the potency of potentially harmful substances and the physical attributes of the soil [93]. In this particular study, an increase ranging from 4 to 6% in soil pH was noted across all applications involving wastewater compared with those that did not. The initial pH value of 7.40 increased by approximately 8% after irrigation with treated wastewater. Consistent with these findings, Disciglio et al. [94] reported an increase in soil pH under wastewater irrigation due to the accumulation of exchangeable cations [95] and the release of OH^- ions through ligand exchange facilitated by the high organic matter content in wastewater [69]. The same was highlighted by Thapliyal et al. [55] and Jahan et al. [96]. On the other hand, Osakwe [93] and Abegunrin et al. [58] reported a decline in soil pH as a consequence of wastewater irrigation.

Research has revealed that the EC value of BWW was greater than that of NRW. Consequently, it is anticipated that, compared with NRW, the use of BWW will lead to elevated soil EC levels. The peak EC was noted in soil irrigated with 100% BWW, whereas the minimum value was documented in soil irrigated with NRW. This discrepancy can be attributed to the movement of ions, their valences, and their actual and relative concentrations, as elucidated by Feigin et al. [97]. This observation aligns with a parallel study by Jahan et al. [96], which indicated an increase in EC values concurrent with the concentration of physicochemical constituents in BWW compared with freshwater. Research conducted by Mohammad and Mazahreh [98] revealed a rise in soil EC over a decade-long period of wastewater irrigation compared with soil irrigated with potable water. In contrast, our study revealed a swift surge in EC within merely two months, which was correlated with escalating concentrations of BWW. This is attributed to the BWW electrical conductivity (EC) of 1.86 dS $m^{-}1$. When applied continuously, it causes a sudden increase in the soil EC. However, the EC of BWW remains within the safe limits outlined by FAO standards, indicating its potential suitability for crop cultivation [69]).

An increased OC content results in an increase in organic matter within the soil, which subsequently increases the CEC within it; this phenomenon has been reported by Ramos et al. [99].

Soil organic matter is instrumental in several soil processes, such as nutrient storage and exchange capacity, maintaining soil structural stability, porosity, water retention, and pollutant degradation [72]. The average organic carbon content was 33% greater in soil irrigated with treated wastewater than in soil irrigated with nonrecycled water. Research has also revealed a significant increase of 47.9% in organic carbon within topsoil (0–15 cm) exposed to industrial wastewater for irrigation compared with that in soil irrigated with nonrecycled water [100]. These findings were further corroborated by Abd-Elwahed [101], who proposed that the introduction of nutrients and organic matter via sewage irrigation could increase soil microorganism activity and increase organic carbon levels in soils irrigated with treated wastewater compared with those in nontreated wastewater for irrigation.

The concentration of cations was significantly greater in the soils irrigated with BWW than in those irrigated with NRW. This suggests that the levels of cation concentration in land irrigated with BWW surpass those found in farmland watered with NRW. This observation aligns seamlessly with the research findings of Jahan et al. [96] and Galavi et al. [102]. These researchers reported an increase in the levels of exchangeable cations such as Na^+, K^+, Ca^{2+} and Mg^{2+} in soil when irrigation was performed with BWW instead of NRW.

The nitrogen content in the soil, as per the study, experienced an average increase of 29% across all wastewater treatments compared with nonrecycled water (NRW). This increase in nitrogen levels can be attributed to the process of nitrogen mineralization, which is initiated by the introduction of organic matter. The variety and abundance of microorganisms involved in degrading this organic matter can indirectly influence soil organic matter (SOM) and, subsequently, its nitrogen content [103]. Similar observations regarding increased nitrogen levels in soils irrigated with wastewater have been reported by Osakwe [93] and Thapliyal et al. [55]. Compared with that of NRW, a significant increase of nearly 65% was observed in the phosphorus content in soil irrigated with 100% brewery wastewater. This aligns with the findings of Osakwe [104], who reported high phosphorus values in soils irrigated with cassava effluent. However, potassium availability only marginally increased by approximately 1.6% over that of NRW. The increase in cation levels can be attributed to the plentiful nutrients present in domestic wastewater. This observation aligns with the research conducted by Boruah and Hazarika [105], which demonstrated that wastewater-irrigated soil contained the highest concentration of available nutrients. The persistent application of wastewater to soils rich in cations, nutrients, and anions may influence certain crops, especially when moderate to high concentrations of specific ions are present in the irrigation water or soil solution [106]. Consequently, it is imperative to conduct further research to obtain a thorough understanding of the increased levels of certain ions. Notably, no such effects were observed either in the short term or within a single season.

The soil CEC directly correlates with its capacity to absorb or exchange cations [104]. The observed 50% increase in CEC in soil treated with 100% BWW can be attributed to the relatively high SOM resulting from wastewater addition. Abd-Elwahed [69] posited that the CEC of soils is predominantly determined by the composition of organic matter and clay. OM, which possesses a negative charge, increases the availability of negatively charged surfaces, thereby attracting a greater number of positively charged ions or cations [107]. The observed increase in the concentrations of Ca^{2+}, Mg^{2+} and K^+ after wastewater application aligns with the findings of Bastida et al. [108] and Thapliyal et al. [55]. These researchers similarly noted an increase in these elements following irrigation with wastewater.

Principal component analysis & heatmap

The goal of PCA is to diminish the dataset's dimensionality, as typically, only a small number of the new components typically no more than the first three principal components can account for the majority of the data's variation. The information presented in Table 5 illustrates that the initial five principal components (with eigenvalues $\geq$ 1) have values ranging from 1.071 to 13.992, collectively revealing 100% of the variability within the dataset concerning the studied parameters. Notably, the first three components collectively describe almost 88% of the variance observed in the dataset. Reducing our initial dataset, comprising five objects and 23 experimental variables, to three dimensions results in an approximately 11% loss in explaining the variation in the data. Alternatively, reducing it to four dimensions incurs only a 5% loss in data variation. Within each principal component, the variable exhibiting the highest factor loading was identified as the most significant contributor to the total variation.

PCA identifies key properties contributing to variance, highlighting the positive impact of OC on soil properties and plant growth. Furthermore, the soil OM content significantly increased with wastewater irrigation, and this increase was more pronounced with an extended irrigation period, indicating a positive shift in soil quality. These results align with those of previous studies [100, 101], which highlighted the positive impact of prolonged wastewater use on soil organic matter content, attributed to increased microbial activity in degradation processes and the presence of biodegradable substances in wastewater. The observed increase in CEC has a positive effect on soil quality, as it enhances the soil nutritional capacity and, consequently, improves overall soil productivity.

Three cluster groups were formed according to the dendrogram derived from the heatmap. Cluster one (T1-NRW) exhibited a more distinct grouping, suggesting a greater dissimilarity in parameter concentrations among the clusters. Compared with the samples in clusters one and two, those in cluster three (T4-75% BWW & T5-100% BWW) presented a more orange color, indicating greater diversity among the parameter concentrations.

A comprehensive field-level study was conducted to elucidate the impact of BWW along with organic amendments on field conditions. This in-depth investigation included a thorough analysis of crop productivity and various other relevant parameters. The outcomes of these extensive investigations are presented in a separate research article. The intention is to provide a detailed account of the specific findings related to crop performance, soil characteristics and other pertinent aspects arising from the application of BWW in the field.

Conclusion

This study demonstrates the potential of brewery wastewater (BWW) as an irrigation source in water-scarce regions such as Kerala and Tamil Nadu, providing valuable insights into its effects on soil properties, nutrient dynamics, and maize productivity. Laboratory analysis revealed that while some BWW parameters exceeded FAO irrigation standards, key indicators such as pH, EC, TSS, $Ca2^{+}$, $Mg2^{+}$, Na^{+}, Cl^{-}, and MH were within acceptable limits, and NRW consistently met all standards. Pot experiments revealed no significant effect of BWW irrigation on maize plant height or stem girth; however, there were positive effects on leaf area, chlorophyll content, shoot and root biomass, and nutrient uptake. Soil irrigated with 100% BWW also presented increases in pH, EC, organic carbon (OC), available NPK, exchangeable Ca, Mg, Na, and cation exchange capacity (CEC), underscoring the potential for BWW to improve soil fertility. To improve the feasibility and sustainability of BWW reuse, future research should focus on technical, economic, and operational improvements. First, technical advancements, such as the development of more affordable filtration and treatment technologies tailored to BWW and real-time quality monitoring devices, could improve irrigation safety and efficiency. Second, economic viability could be enhanced by conducting cost-benefit analyses for farmers, providing financial incentives, and fostering industry-government partnerships to fund necessary treatment infrastructure. Finally, optimizing production processes through research on ideal BWW dilution ratios, exploring soil amendments to mitigate sodium effects, and conducting long-term field trials would enable more sustainable BWW applications. This study emphasizes the need for stringent standards and effective policies to manage industrial wastewater discharge, reduce contamination, and promote environmental sustainability. BWW reuse offers a promising solution for addressing water scarcity and pollution when carefully managed. Continued research and targeted improvements will help ensure that BWW serves as a sustainable resource, supporting agricultural productivity in water-limited regions.

Abbreviations

AAS	Atomic Absorption Spectrometry
ANOVA	Analysis of variance
As	Arsenic
BOD	Biological Oxygen Demand
BWW	Brewery Waste Water
Cd	Cadmium
CEC	Cation-Exchange Capacity
Co	Cobalt
COD	Chemical Oxygen Demand
CRD	Completely Randomized Design
Cu	Copper
DAS	Days After Sowing
EC	Electrical Conductivity
EDTA	Ethylenediamine Tetraacetic Acid
FAO	Food and Agriculture Organization
Fe	Iron
Hg	Mercury
KR	Kelly's Ratio
LSD	Least significant difference
Mn	Manganese
Ni	Nickel
NPK	Nitrogen, Phosphorus, and Potassium
NRW	Narugampally River water
OC	Organic Carbon
Pb	Lead
pH	Potential of Hydrogen
SAR	Sodium adsorption ratio

SSP	Soluble Sodium Percent
TDS	Total Dissolved Solids
TH	Total hardness
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
Zn	Zinc

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Authors' contributions
Senthilraja Kandasamy: methodology, software, discussion, resources, writing, editing and reviewing. Udhaya Nandhini Dhandayuthapani: conceptualization, methodology, analysis, validation, writing-original draft preparation, and software. Venkatesan Subramanian: contributed to the writing, analysis, data acquisition and visualization. Jothimani Palanisamy, Mohan Kumar Shanmugam, Dinesh Dhakshanamoorthy, Umesh Kanna Subramani and Sriram Nagappan: validation, visualization, data acquisition and supervision.

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Data availability
The authors declare that the data supporting the findings of this study are available within this article and that all simulation datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

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Author details
[1]Centre of Excellence on Climate and Disaster Resilient Agriculture, Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India. [2]Centre of Excellence in Sustaining Soil Health, Anbil Dharmalingam Agricultural College & Research Institute, Trichy, Tamil Nadu 620 027, India. [3]Directorate of Research, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India. [4]Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India. [5]ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Vasad, Gujarat, India. [6]Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India.

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