



RESEARCH ARTICLE

# Effect of dechlorination and defluoridation of treated sewage water on soil fertility and french bean (*Phaseolus vulgaris* L.) productivity

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## Abstract

An experiment was conducted to evaluate low-cost, locally available amendments for dechlorination and defluoridation of treated sewage water and to assess their effect on soil properties, growth and yield of French bean (*Phaseolus vulgaris* L.). Treated sewage water from Chintamani taluk was amended with different amendments like activated alumina and alum (known for ligand exchange and surface complexation of chloride and fluoride), charcoal and biochar (possessing high surface area, porosity and negatively charged functional groups favouring halide adsorption) and calcium-based compounds such as calcium silicate, calcium carbonate and calcium sulphate (which promote fluoride removal through precipitation and ion exchange mechanisms) at a 1:1 (w/v) ratio and the supernatant was analysed after 24 hr. Pot culture trials of French bean compared irrigation with groundwater, untreated treated sewage water and dechlorinated and defluoridated (DC and DF) waters. Activated alumina, alum, charcoal and biochar reduced chloride and fluoride content markedly, with charcoal and biochar offering an economically attractive option. Plants irrigated with DC and DF water showed improved growth, yield components and higher nutrient status compared to untreated sewage and groundwater irrigations. Soil properties, including organic carbon, available N, P, K, Ca, Mg, S and DTPA-extractable micronutrients, were enhanced under certain DC and DF treatments. The study demonstrates that the effectiveness of low-cost amendments is governed by their adsorption capacity, surface chemistry and precipitation mechanisms, highlighting their potential to reduce halide toxicity in reclaimed irrigation water and to improve crop performance, yield and soil fertility in water-scarce regions.

**Keywords:** activated alumina; alum; biochar; calcium carbonate; calcium silicate; charcoal

## Introduction

Irrigation is a crucial component of agriculture, as it plays a vital role in sustaining crop production and productivity. Increasing water scarcity and declining freshwater quality have intensified the reuse of treated sewage water for agricultural irrigation in arid and semi-arid regions. Although treated wastewater provides a reliable water source and nutrients, its long-term use without adequate quality control can adversely affect soil health, crop productivity and environmental safety (1, 2). Among water quality constraints, residual chlorine and fluoride are of particular concern. Chlorine is widely used for disinfection in wastewater treatment plants; however, excess residual chlorine ( $>0.5 \text{ mg L}^{-1}$ ) can cause phytotoxicity and react with organic matter to form carcinogenic disinfection by-products such as trihalomethanes (THMs) and haloacetic acids (3). The WHO recommend residual chlorine concentrations  $\leq 0.5 \text{ mg L}^{-1}$  in reclaimed water intended for irrigation. Similarly, fluoride concentrations exceeding  $1.5 \text{ mg L}^{-1}$  (WHO

permissible limit) impair plant physiological processes, reduce nutrient uptake and pose serious risks to soil quality and human health (3).

Chloride (Cl) is a micronutrient essential for photosynthesis, osmoregulation and turgor regulation, but excessive chloride can cause toxicity, leading to nutrient imbalances and reduced photosynthetic efficiency (4). Similarly, fluoride (F), a naturally occurring halogen, is beneficial in trace amounts but toxic in excess. High fluoride levels impair plant growth, nutrient uptake and enzyme activity, causing chlorosis, necrosis and reduced seed production (5). Various dechlorination and defluoridation techniques have been reported, including membrane filtration, chemical precipitation and electrocoagulation; however, their high cost and operational complexity limit field-level adoption (6). Consequently, low-cost, locally available amendments offer a practical alternative. Activated alumina and alum remove chloride and fluoride primarily through ligand exchange and surface

complexation, while calcium-based materials such as calcium carbonate, calcium sulphate and calcium silicate facilitate chloride and fluoride removal via precipitation and ion exchange reactions (7). Charcoal and biochar possess high surface area, porous structure and functional groups that enhance the adsorption of halide ions, making them economically viable and environmentally sustainable options (8).

Despite their potential, comparative evaluations of these amendments under agricultural irrigation conditions and their combined effects on soil fertility and crop productivity remain limited, particularly in water-scarce regions of southern India. Therefore, the present study was undertaken to evaluate the effectiveness of selected locally available amendments for dechlorination and defluoridation of treated sewage water and to assess their influence on soil properties, growth and yield of French bean (*Phaseolus vulgaris* L.), to identify affordable and sustainable solutions for safe wastewater reuse in agriculture.

## Material and Methods

### Collection of irrigation water samples

Treated sewage water samples were collected from the Bengaluru-Kolar canal at Chintamani taluk during the *rabi* season of 2024 (Fig. 1). A total of three representative water samples were collected from the canal at the sampling location. Sampling was carried out using clean, sterile polyethene bottles by submerging them 15–30 cm below the water surface, avoiding surface scum and debris. Immediately after collection, 2–3 drops of toluene were added to each bottle to prevent microbial activity. The bottles were sealed airtight, properly labelled and transported to the laboratory. The collected samples were filtered through Whatman No. 1 filter paper to remove suspended impurities. All samples were subjected to chemical analysis for different parameters following standard analytical procedures.

### Methods followed for analysing water quality parameters

The pH of water samples was determined by the potentiometric method using a calibrated digital pH meter and electrical conductivity (EC) was measured by the conductometric method using a

conductivity meter following standard procedures (9). Calcium and magnesium were estimated by the EDTA complexometric titration method, while sodium and potassium were determined using a flame photometer (9). Carbonates and bicarbonates were analysed by acid-base titration using standard indicators (9). Chloride concentration was estimated by the argentometric (Mohr's) titration method (9). Fluoride was determined by the zirconyl acid-SPADNS spectrophotometric method using a UV-Visible spectrophotometer (10). Phosphate was analysed by the ascorbic acid spectrophotometric method and sulphate was estimated by the turbidometric method following standard procedures (9, 11).

### Dechlorination and defluoridation of treated sewage water using different amendments.

Dechlorination and defluoridation studies were carried out using a batch adsorption process, low-cost, locally available amendments viz., activated alumina, calcium silicate, calcium carbonate, alum, gypsum, biochar and charcoal. The treatments were prepared on a weight/volume (w/v) basis, where the amendment dose was expressed as grams of amendment per litre of treated sewage water. For each treatment, one litre of treated sewage water was mixed with the respective amendment at a ratio of 1:1, 2:1, 3:1, 5:1 and 10:1 (amendment: volume, v/w), corresponding to 1, 2, 3, 5 and 10 g of amendment per litre of water, respectively. For bulk preparation, the same ratio was proportionately scaled to 20 litres of treated sewage water.

The mixtures were thoroughly stirred and allowed to stand undisturbed for 24 hr at room temperature to provide sufficient contact time for adsorption, ion exchange and precipitation reactions between the amendments and chloride and fluoride ions. A contact period of 24 hr was selected based on preliminary trials and earlier studies, which indicated that equilibrium removal of chloride and fluoride ions is generally attained within this duration. After the contact period, the supernatant was decanted, filtered and analysed for physico-chemical parameters, with special emphasis on chloride and fluoride concentration. Based on the efficiency of removal and economic feasibility, the 1:1 ratio was found to be most effective and was therefore selected for use in the pot culture experiment of French bean (*P. vulgaris* L.).

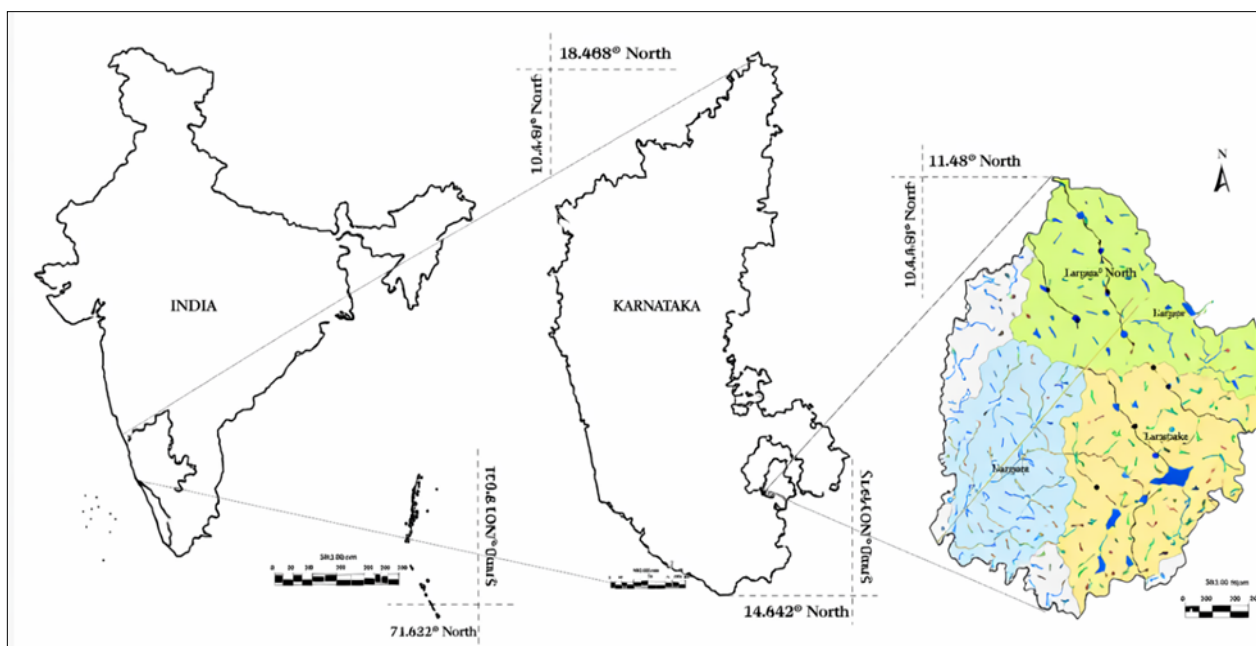


Fig. 1. Location of the study area.

### Adsorption isotherm equation for the chloride ion

Freundlich adsorption equation is fitted for the adsorption of chloride by activated alumina, alum, calcium silicate, charcoal, biochar, calcium carbonate and calcium sulphate.

### Effect of dechlorinated and defluoridated water on the growth and yield of French bean

French bean (*Phaseolus vulgaris* L.), Anupama variety collected from College of Sericulture, Chintamani. It is a bush bean improved and stringless variety. Plants and strong, dense foliage with fruits are thick & tender. It is short duration variety (70–75 days).

#### Details of the experiment

A pot culture experiment was conducted at the College of Sericulture, Chintamani, Karnataka, using French bean (*P. vulgaris* L.) as the test crop. The experiment was laid out in a completely randomised design (CRD) with nine treatments and three replications. Data were analysed using analysis of variance (ANOVA) appropriate for CRD and treatment means were compared using the critical difference (CD) test at the 5 % level of significance. Treatment details are presented in Table 1. Earthen pots (30 cm diameter and 30 cm height) were used, each filled with 10 kg of air-dried, sieved sandy loam soil collected from the experimental field of the College of Sericulture, Chintamani. The initial properties of the soil are presented in Table 2.

**Table 1.** Treatment details of the experiment

T <sub>1</sub>	Irrigation water (untreated irrigation water)
T <sub>2</sub>	Irrigation with treated sewage water
T <sub>3</sub>	Irrigation of DC and DF water by activated alumina
T <sub>4</sub>	Irrigation of DC and DF water by calcium silicate
T <sub>5</sub>	Irrigation of DC and DF water by calcium carbonate
T <sub>6</sub>	Irrigation of DC and DF water by alum
T <sub>7</sub>	Irrigation of DC and DF water by gypsum
T <sub>8</sub>	Irrigation of DC and DF water by biochar
T <sub>9</sub>	Irrigation of DC and DF water by charcoal

DC- dichlorination, DF- defluoridation

**Table 2.** Initial properties of soil in Chintamani taluk

pH	6.55
EC (dS m <sup>-1</sup> )	0.320
Organic carbon (%)	0.42
Available nitrogen (kg ha <sup>-1</sup> )	310.58
Available phosphorus (kg ha <sup>-1</sup> )	52.46
Available potassium (kg ha <sup>-1</sup> )	178.52
Exchangeable calcium (meq 100g)	6.34
Exchangeable magnesium	3.26
Available sulphur (mg kg <sup>-1</sup> )	18.95
DTPA extractable iron (mg kg <sup>-1</sup> )	7.13
DTPA extractable manganese (mg kg <sup>-1</sup> )	5.89
DTPA extractable copper (mg kg <sup>-1</sup> )	1.62
DTPA extractable zinc (mg kg <sup>-1</sup> )	0.65

Based on the results of the dechlorination and defluoridation studies, the 1:1 (w/v) ratio of treated sewage water with different amendments, which showed the maximum reduction of chloride and fluoride concentrations and was economically feasible, was selected for the pot culture experiment. Irrigation was carried out as per crop requirement using the respective treated water for each treatment throughout the crop growth period. The experiment was conducted under natural environmental conditions during the rabi season of 2024, with mean day temperatures of 25–30 °C, night temperatures of 18–22 °C, relative humidity of 55–60 % and a natural photoperiod of approximately 11–12 hr day<sup>-1</sup>.

## Results and Discussion

The characteristics of the treated sewage water used in this study are presented in Table 3. This provides the baseline water quality data against which the effects of dechlorination and defluoridation were assessed.

**Table 3.** Characteristics of treated sewage water of Chintamani taluk

Parameter	Value	Critical limit for evaluation of irrigation water
pH	7.50	6.50–7.50
EC (µmhos cm <sup>-1</sup> )	508	<250 – >2250
Calcium (meq L <sup>-1</sup> )	4.36	-
Magnesium (meq L <sup>-1</sup> )	2.24	-
Potassium (meq L <sup>-1</sup> )	0.16	-
Sodium (meq L <sup>-1</sup> )	0.10	-
Carbonate (meq L <sup>-1</sup> )	0.06	-
Bicarbonate (meq L <sup>-1</sup> )	2.36	-
Sulphate (meq L <sup>-1</sup> )	0.01	-
Phosphate (meq L <sup>-1</sup> )	0.61	-
Chloride (meq L <sup>-1</sup> )	11.04	2–12
Fluoride (mg L <sup>-1</sup> )	3.58	1.5

### Dechlorination of treated sewage water by using different amendments

Treated sewage water was dechlorinated using various amendments in different ratio and the data is depicted in Fig. 2.

#### Dechlorination of treated sewage water by alum

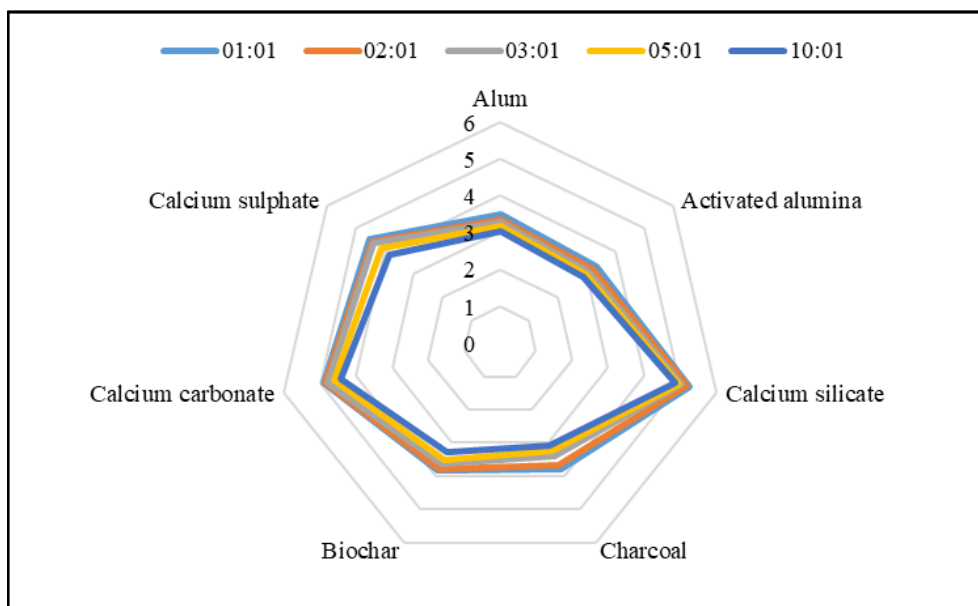
Dechlorination of treated sewage water using aluminium sulphate (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>), commonly known as alum, helps remove residual chloride. Alum forms insoluble aluminium hydroxide (Al(OH)<sub>3</sub>), which precipitates out as flocs with a large surface area. These flocs facilitate the adsorption and physical entrapment of chloride ions through sweep coagulation and sedimentation, thereby reducing chloride concentration in the treated water. In the study, chloride decreased from 11.04 meq L<sup>-1</sup> to 3.50, 3.37, 3.28, 3.16 and 3.05 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. The reduction in chloride is attributed to adsorption onto aluminium hydroxide flocs and their subsequent removal during settling. Alum flocculation significantly reduces chloride content in treated water (12).

#### Dechlorination of treated sewage water by activated alumina

Activated alumina, a highly porous material, effectively adsorbs chloride ions from treated sewage water. With a surface area of 150–380 m<sup>2</sup> g<sup>-1</sup>, it captures chloride compounds, reducing levels from 11.04 meq L<sup>-1</sup> to 3.32, 3.20, 3.08, 2.99 and 2.90 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Chloride molecules adhere to activated alumina through adsorption, reacting with aluminium ions to form aluminium chloride (AlCl<sub>3</sub>), which neutralises chloride compounds. Sol-gel-prepared mesoporous alumina (SG-Al<sub>2</sub>O<sub>3</sub>) acts as a catalyst for the complete dechlorination of carbon tetrachloride at temperatures above 350 °C (13).

#### Dechlorination of treated sewage water by calcium silicate

Calcium silicate dechlorinates treated sewage water by adsorption and chemical reaction, reducing chloride levels from 11.04 meq L<sup>-1</sup> to 5.26, 5.18, 5.05, 4.98 and 4.87 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Its high surface area adsorbs chloride, while it also reacts with free chloride (Cl<sub>2</sub>) to form calcium chloride (CaCl<sub>2</sub>) and silicon dioxide (SiO<sub>2</sub>). This process neutralises harmful chloride compounds, making water safer. Chloride uptake by calcium silicate hydrate (C-S-H) depends on sufficient Ca<sup>2+</sup> presence, with adsorption increasing at higher pH due to silanol group ionisation (14).



**Fig. 2.** Dechlorination of treated sewage water by using different amendments in different ratios.

### Dechlorination of treated sewage water by charcoal

Charcoal is an effective and cost-efficient method for dechlorination, removing chloride and chloramines due to its high surface area and porous structure. In a study, chloride content decreased from 11.04 meq L<sup>-1</sup> to 3.80, 3.66, 3.40, 3.25 and 3.10 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Dechlorination occurs through physical adsorption, where chloride molecules are trapped in charcoals' micropores. Factors like contact time, particle size, flow rate and charcoal quality influence efficiency. Over time, charcoal saturation reduces effectiveness, requiring replacement or regeneration. Activated carbon, with optimised pore structure, enhances chloride removal in water treatment (15).

### Dechlorination of treated sewage water by biochar

Biochar is effective for dechlorination, reducing chloride levels in water and soil due to its high surface area and functional groups. In a study, chloride content dropped from 11.04 meq L<sup>-1</sup> to 3.85, 3.78, 3.62, 3.50 and 3.28 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Chloride ions adsorb onto biochar via surface interactions, ionic attraction and porous adsorption. Biochar also helps buffer soil pH, reducing chloride toxicity for plants and aquatic life. High adsorption efficiency is linked to its functional groups, porosity and surface reactivity (16).

### Dechlorination of treated sewage water by calcium carbonate

Calcium carbonate (CaCO<sub>3</sub>) effectively dechlorinates water by reacting with chloride compounds, reducing chloride levels from 11.04 meq L<sup>-1</sup> to 4.90, 4.84, 4.78, 4.60 and 4.42 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. The observed reduction in chloride is attributed to adsorption on calcium carbonate surfaces and physical removal with settling solids. Calcium carbonate thus contributes to improving overall water quality by stabilising pH and facilitating indirect chloride reduction (17).

### Dechlorination of treated sewage water by calcium sulphate

Calcium sulphate (CaSO<sub>4</sub>) dechlorinates water by reacting with chloride compounds, reducing chloride levels from 11.04 meq L<sup>-1</sup> to 4.50, 4.42, 4.36, 4.10 and 3.84 meq L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. It forms calcium chloride (CaCl<sub>2</sub>) and sulphate ions, lowering chloride availability and benefiting aquatic life. This method is useful in wastewater treatment and industrial processes. Factors like chloride concentration, pH and contact time influence

efficiency. Polyvinyl chloride (PVC) was milled with hydrated or unhydrated calcium sulphates (CaSO<sub>4</sub>·2H<sub>2</sub>O or CaSO<sub>4</sub>), resulting in size reduction and in the breaking of bonds leading to mechanically induced solid state reaction, forming CaCl<sub>2</sub> and dechlorinated hydrocarbon with C=C double bonds in the product (18).

### Defluoridation of treated sewage water by using different amendments

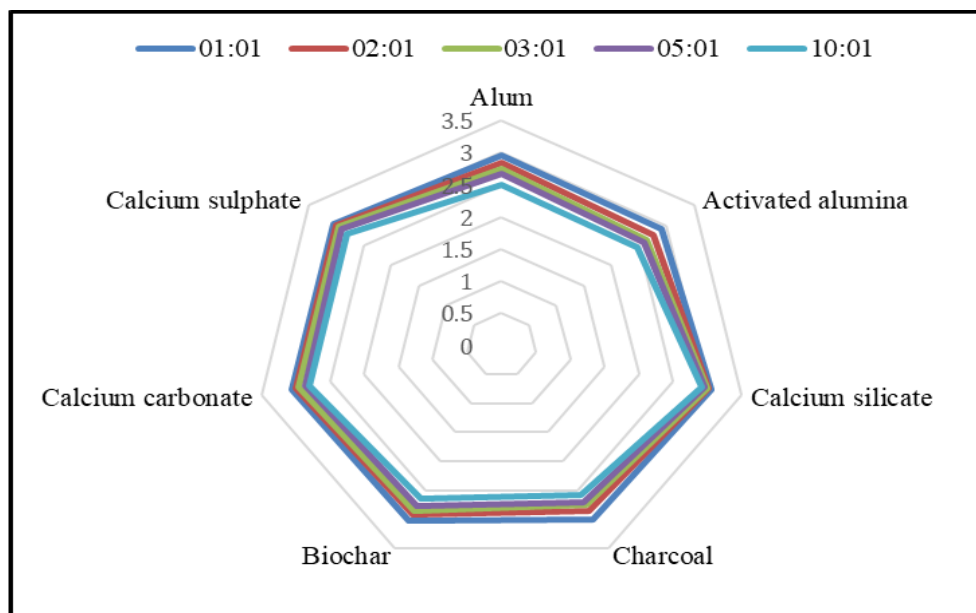
Defluoridation of treated sewage water is done by using different amendments in different ratio and the data is depicted in Fig. 3.

#### Defluoridation of treated sewage water by alum

Alum (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>) effectively reduces fluoride concentration in treated sewage water through adsorption and surface complexation mechanisms. Upon hydrolysis, alum forms amorphous aluminium hydroxide (Al(OH)<sub>3</sub>) flocs with a strong affinity for fluoride ions, which are adsorbed onto the floc surfaces and subsequently removed through sedimentation or filtration. In the present study, fluoride concentration decreased from 3.58 mg L<sup>-1</sup> to 2.95, 2.84, 2.75, 2.68 and 2.50 mg L<sup>-1</sup> at 1:1, 2:1, 3:1, 5:1 and 10:1 ratios, respectively. Alum is widely used in water treatment for effective fluoride removal while maintaining aluminium concentrations within permissible limits (19).

#### Defluoridation of treated sewage water by activated alumina

Activated alumina (Al<sub>2</sub>O<sub>3</sub>) is an effective adsorbent for water defluoridation, removing fluoride through ligand exchange reactions. When water passes through activated alumina, fluoride ions (F<sup>-</sup>) are adsorbed onto its surface via adsorption. The process follows reactions like AlOH<sub>3</sub> + F<sup>-</sup> → AlF<sub>6</sub><sup>3-</sup> + OH<sup>-</sup>, reducing fluoride concentration. Fluoride levels decreased from 3.58 mg L<sup>-1</sup> to 2.90, 2.76, 2.64, 2.58 and 2.46 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratio over time, activated alumina needs regeneration using NaOH to restore adsorption capacity. Due to its high surface area and strong fluoride affinity, it is widely used in water treatment to mitigate fluoride toxicity. The impact of major anions reduced fluoride adsorption in the order of HPO<sub>4</sub><sup>2-</sup> > HCO<sub>3</sub><sup>-</sup> > SO<sub>4</sub><sup>2-</sup> > Cl<sup>-</sup>. Other toxic elements that might coexist with fluoride in groundwater, such as arsenic and selenium, also reduced fluoride adsorption through competition for the same surface sites (20).



**Fig. 3.** Defluoridation of treated sewage water by using different amendments in different ratio.

#### Defluoridation of treated sewage water by charcoal

Activated charcoal is a porous material used for defluoridation by adsorbing fluoride ions (F<sup>-</sup>) onto its surface. It reduces fluoride concentration based on initial levels, with adsorption occurring via van der Waals forces. As water flows through, fluoride ions are retained, lowering their presence in treated water. Charcoal-based systems are cost-effective and suitable for areas with high fluoride levels. Fluoride levels decreased from 3.58 mg L<sup>-1</sup> to 3.00, 2.85, 2.76, 2.70 and 2.58 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Aluminium-amended bamboo charcoal enhances fluoride removal and higher surface area materials improve adsorption efficiency (21). The fluoride ion was adsorbed into pores in carbonaceous materials produced from wood and the larger the specific surface area, the more fluoride ions are adsorbed (22).

#### Defluoridation of treated sewage water by biochar

Biochar, produced from biomass sources, is a porous material used for fluoride removal through adsorption. Fluoride ions (F<sup>-</sup>) adhere to the surface via van der Waals forces, reducing fluoride concentration based on initial levels. As water flows through, fluoride is retained, making biochar an eco-friendly and cost-effective defluoridation method. Fluoride adsorption was reduced from 3.58 mg L<sup>-1</sup> to 3.02, 2.92, 2.85, 2.78 and 2.65 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios due to competition from phosphate, sulphate and chloride ions. Studies show biochar retains ~60 % adsorption capacity after reuse and removes fluoride through spontaneous, exothermic interactions with surface functional groups (23).

#### Defluoridation of treated sewage water by calcium silicate

Calcium silicate (Ca<sub>2</sub>SiO<sub>4</sub>) reduces fluoride in water through co-precipitation. It reacts with fluoride ions (F<sup>-</sup>) to form insoluble calcium fluoride (CaF<sub>2</sub>), which precipitates out. The precipitate is then removed by sedimentation or filtration, lowering fluoride concentration. Calcium silicate decreased the fluoride content from 3.58 mg L<sup>-1</sup> to 3.06, 3.02, 2.99, 2.95 and 2.92 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. This method is cost-effective and environmentally safe, with studies supporting its effectiveness in wastewater treatment. Chemically synthesised Ca-SiO<sub>2</sub>-TiO<sub>2</sub> could be used as an environmentally and economically safe adsorbent for defluoridation of wastewater (24).

#### Defluoridation of treated sewage water by calcium carbonate

Defluoridation by calcium carbonate (CaCO<sub>3</sub>) reduces fluoride (F<sup>-</sup>) concentration in water through chemical precipitation. Calcium carbonate decreased the fluoride content from 3.58 mg L<sup>-1</sup> to 3.05, 3.00, 2.95, 2.86 and 2.80 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Calcium ions (Ca<sup>2+</sup>) from CaCO<sub>3</sub> react with F<sup>-</sup> to form insoluble calcium fluoride (CaF<sub>2</sub>), which precipitates out and can be removed by filtration or settling. Fluoride reduction depends on initial concentration, with a greater CaCO<sub>3</sub> ratio enhancing removal. Calcium carbonate was found to have comparable F-removal abilities to the commercial ion exchange resins and possessed higher removal effectiveness compared to calcium-containing eggshells and seashells (25).

#### Defluoridation of treated sewage water by calcium sulphate

Defluoridation by calcium sulphate (CaSO<sub>4</sub>) reduces fluoride (F<sup>-</sup>) concentration through chemical precipitation. Calcium sulphate decreased the fluoride content from 3.58 mg L<sup>-1</sup> to 3.04, 3.01, 2.96, 2.90 and 2.80 mg L<sup>-1</sup> in 1:1, 2:1, 3:1, 5:1 and 10:1 ratios. Calcium ions (Ca<sup>2+</sup>) react with F<sup>-</sup> to form insoluble calcium fluoride (CaF<sub>2</sub>), which settles and can be removed by filtration. Fluoride removal efficiency depends on factors like initial concentration, pH, contact time and competitive ions. Calcined gypsum was noted to introduce Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> in the water because of its solubility and remove F<sup>-</sup> ions (26). Among the tested ratios of dechlorination and defluoridation, 1:1 was chosen for its effectiveness and economic feasibility.

Even though fluoride is more electronegative and has a smaller size, fluoride adsorption is less because adsorption of fluoride depends on factors such as the concentration of fluoride or fluoridated compounds, the pH of the water, the contact time between the water and the amendments and also the presence of competitive ions. In treated sewage water because of the presence of phosphate, sulphate and chloride, fluoride adsorption is less.

#### Effect of dechlorination and defluoridation of treated sewage water on other parameters of treated sewage water (1:1 ratio)

After the addition of different amendments, other parameters of treated sewage water like pH, EC, calcium, magnesium, carbonates, bicarbonates, sulphate, phosphate, potassium and sodium do not

significantly vary. However, a slight change can be seen and depicted in Table 4. Amendments caused minor pH variations due to their limited addition to the treated sewage water. pH changed from 7.50 to 7.15 by the addition of alum and increased from 7.50 to 7.45, 7.70 and 7.40 by the addition of calcium silicate, calcium carbonate and calcium sulphate, respectively. Adding alum to water slightly alters the pH, depending on the initial pH and buffering capacity. Alum reacts with calcium ions ( $\text{Ca}^{2+}$ ) to form insoluble calcium sulphate ( $\text{CaSO}_4$ ), which precipitates out. Alum also increases sulphate concentration and can interact with phosphate ions to form insoluble aluminium phosphate ( $\text{AlPO}_4$ ), reducing phosphate levels. These precipitates can be removed by settling or filtration.

Activated alumina and charcoal have a neutral pH, while biochar may slightly raise pH due to its alkalinity. These materials can adsorb calcium, magnesium, sulphate and phosphate ions, reducing their concentrations in water. Adsorption effectiveness depends on water hardness (27). Adsorption of ions in the order of  $\text{OH}^- > \text{H}_2\text{PO}_4^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{F}^- > \text{Cl}^-$  (28). Calcium carbonate and calcium silicate are the least soluble in water and its not having effect on pH. Calcium sulphate is soluble and it has little effect on pH. The addition of these salts increases the calcium content (29).

### Heavy metals in treated sewage water

The concentration of heavy metals, viz., nickel (Ni), lead (Pb), chromium (Cr) and cadmium (Cd) in the treated sewage water was found to be very low and well within the permissible limits for irrigation water (Table 5). Nickel concentration ranged from 124–155 ppb, lead from 95–102 ppb, chromium from 72–98 ppb and cadmium from 5.2–6.4 ppb across different amendment treatments. These values are considerably lower than the

maximum permissible limits prescribed by FAO for irrigation water, which are 200 ppb for Ni, 200 ppb for Pb, 200 ppb for Cr and 10 ppb for Cd, respectively (30). The low concentration of heavy metals may be attributed to the fact that the treated sewage water was predominantly derived from domestic wastewater sources, with no significant contribution from industrial effluents.

### Adsorption isotherm for chloride

Treated sewage water is added with different amendments to determine its adsorption behaviour of chloride, which was fitted in Freundlich adsorption equation. Freundlich adsorption equation is the most widely used empirical equation to study the adsorption isotherm. Chloride adsorption data depicted in Table 6 and  $R^2$  value in Fig. 4.

From Fig. 4, activated alumina has more  $R^2$  value ( $R^2 = 0.9076$ ), followed by activated alumina, alum, charcoal and biochar and the least has calcium silicate ( $R^2 = 0.6941$ ). The higher the  $R^2$  value more will be the adsorption of anions (31). For fluoride, little variation was observed among amendments. Hence Freundlich equation is not fitted for fluoride adsorption.

### Effect of treated sewage water on the growth and yield of French bean

#### Plant height

French bean had the highest plant height in  $T_3$  (26.52, 35.83 and 40.55 cm at 25, 50 days and harvest) in Fig. 5. This was due to reduced toxicity of treated sewage water and increased nitrate and phosphate availability. Higher nitrogen content in treated sewage promoted vegetative growth by enhancing cell enlargement and division (32).

**Table 4.** Effect of dechlorination and defluoridation of treated sewage water on other parameters in a (1:1) ratio

	pH	EC	Ca	Mg	$\text{CO}_3$	$\text{HCO}_3$	$\text{SO}_4^{2-}$	$\text{PO}_4^{3-}$	K	Na
Before treatment	7.50	508.00	4.36	2.24	0.06	2.36	0.012	0.68	0.60	0.20
	After treatment									
Alum	7.15	556.00	3.90	2.80	0.04	2.06	0.017	0.14	0.51	0.11
Activated alumina	7.20	500.00	3.72	2.58	0.01	1.98	0.005	0.15	0.52	0.12
Calcium silicate	7.45	540.00	5.50	3.80	0.09	1.96	0.007	0.15	0.51	0.12
Charcoal	7.22	520.00	3.12	2.60	0.06	1.96	0.006	0.14	0.49	0.12
Biochar	7.60	515.00	3.96	2.74	0.08	1.96	0.004	0.21	0.50	0.12
Calcium carbonate	7.70	560.00	5.72	2.19	0.05	2.19	0.009	0.23	0.50	0.12
Calcium sulphate	7.40	575.00	5.98	2.78	0.03	1.90	0.025	0.19	0.50	0.11
Min	7.15	500.00	3.12	2.19	0.01	1.90	0.00	0.14	0.49	0.11
Max	7.70	575.00	5.98	3.80	0.09	2.19	0.03	0.23	0.52	0.12
Average	7.40	538.86	4.56	2.78	0.05	2.00	0.01	0.17	0.50	0.12

$\text{Ca}^{2+}$  – Calcium ion,  $\text{Mg}^{2+}$  – Magnesium ion,  $\text{CO}_3^{2-}$  – Carbonate ion,  $\text{HCO}_3^-$  – Bicarbonate (Hydrogen carbonate) ion,  $\text{SO}_4^{2-}$  – Sulphate ion,  $\text{PO}_4^{3-}$  – Phosphate ion,  $\text{K}^+$  – Potassium ion,  $\text{Na}^+$  – Sodium ion, Min – Minimum, Max – Maximum

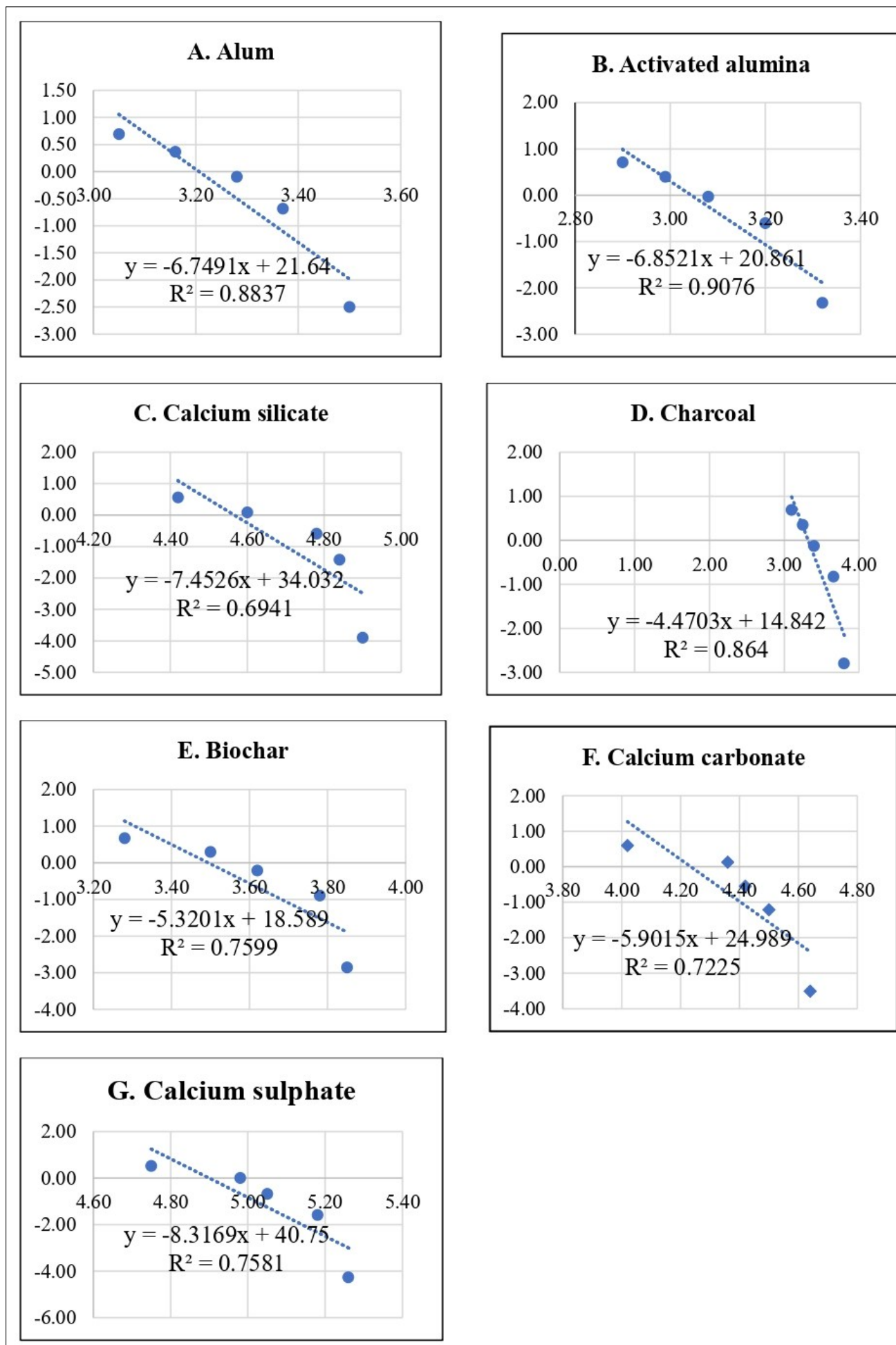
**Table 5.** Heavy metals concentration (ppb) in treated sewage water in Chintamani taluk

Treatment	Ni (ppb)	Pb (ppb)	Cr (ppb)	Cd (ppb)
Alum	0.029	0.179	0.241	0.065
Activated alumina	0.020	0.109	0.0298	0.072
Calcium silicate	0.020	0.147	0.443	0.076
Charcoal	0.017	0.188	0.113	0.082
Biochar	0.033	0.097	0.339	0.085
Calcium carbonate	0.035	0.120	0.472	0.089
Calcium sulphate	0.028	0.025	0.365	0.094

Ni – Nickel, Pb – Lead, Cr – Chromium, Cd – Cadmium, ppb – Parts per billion

**Table 6.** Freundlich adsorption equation for chloride and fluoride

Treatments	K	1/n	Regression equation	$R^2$
Alum	3.07	0.15	$y = -6.74x + 21.64$	$R^2 = 0.8837$
Activated alumina	3.04	0.15	$y = -6.85x + 20.86$	$R^2 = 0.9076$
Calcium silicate	3.53	0.13	$y = -7.45x + 34.03$	$R^2 = 0.6941$
Charcoal	2.70	0.22	$y = -4.47x + 14.84$	$R^2 = 0.8640$
Biochar	2.92	0.19	$y = -5.32x + 18.58$	$R^2 = 0.7599$
Calcium carbonate	3.22	0.17	$y = -5.90x + 24.98$	$R^2 = 0.7225$
Calcium sulphate	3.71	0.12	$y = -8.31x + 40.75$	$R^2 = 0.7581$



**Fig. 4.** Adsorption equation for chloride by different amendments- A- Alum; B- Activated alumina; C- Calcium silicate; D- Charcoal; E- Biochar; F - Calcium carbonate; G- Calcium sulphate.

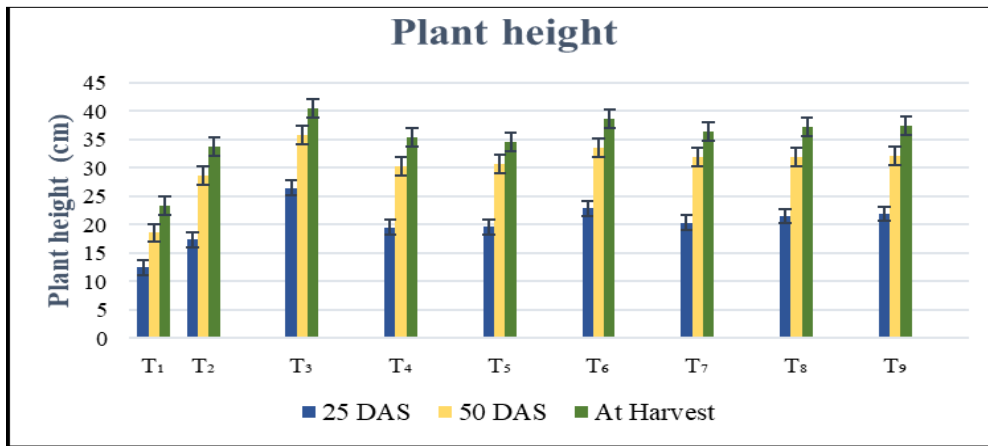


Fig. 5. Effect of dechlorinated and defluoridated water on the plant height of French bean.

**Number of branches**

French bean had the highest number of branches in T<sub>3</sub> (7.85, 13.85 and 15.68 at 25, 50 days and harvest) and the lowest in T<sub>1</sub> in Fig. 6. Increased plant height led to more branching. Irrigation with treated sewage water increased branching due to higher nutrient availability compared to groundwater irrigation (32).

**Number of leaves**

The number of leaves of French bean is more in T<sub>3</sub> (8.90, 18.56 and 24.68 in 25, 50 and at harvest) and least in T<sub>1</sub> (3.75, 9.28 and 11.20 in 25, 50 and at harvest) in Fig. 7. Increase in the plant height increased the number of leaves. It might be due to the treated sewage water more amount of nutrients. (32)

**Yield parameters**

**Pod length, Number of pods, Number of seeds per pod**

Treatment T<sub>3</sub> recorded significantly higher pod length (16.96 cm), number of pods (22.85), number of seeds per pod (19.42) and pod yield (1.65 kg pot<sup>-1</sup>) compared to groundwater-irrigated control (T<sub>1</sub>) and other treatments. Treatments T<sub>6</sub> (16.45, 22.46, 17.25 and 1.59) and T<sub>9</sub> (15.52, 21.52, 16.12 and 1.56) were statistically on par with T<sub>3</sub> for most yield attributes. The lowest values for all yield parameters were observed in T<sub>1</sub> (10.37, 17.10, 10.32 and 1.29) in Fig. 8. Yield parameters like pod length, number of pods and number of seeds per pod are higher because of more growth. Yield parameters increased because the plant uptake the dissolved nutrients

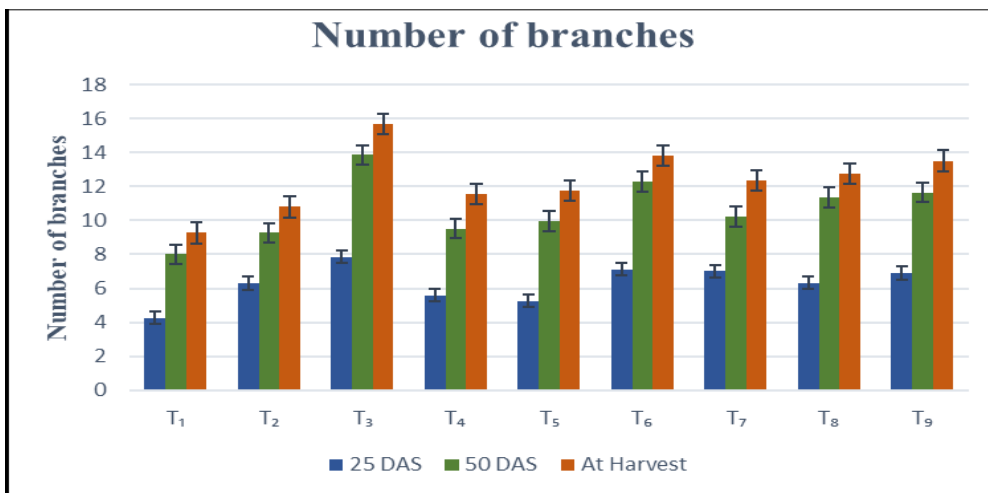


Fig. 6. Effect of dechlorinated and defluoridated water on the number of branches of French bean.

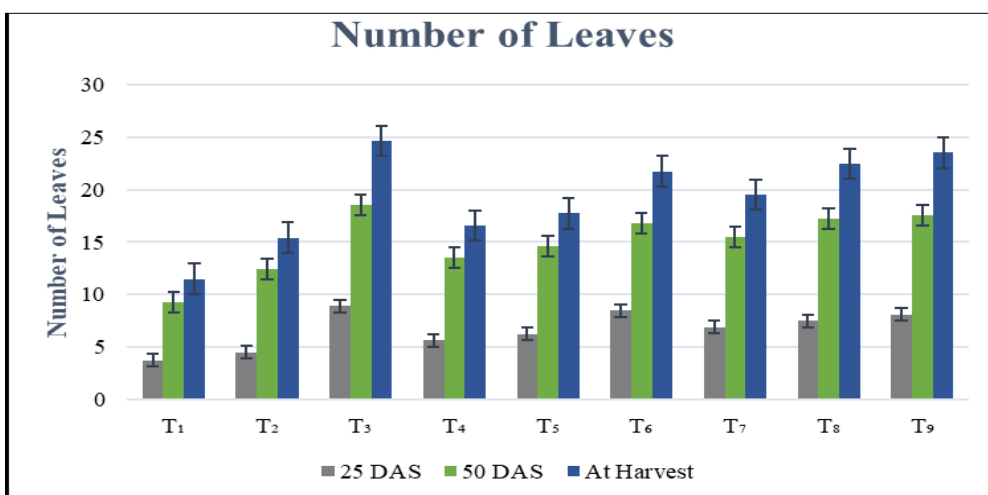
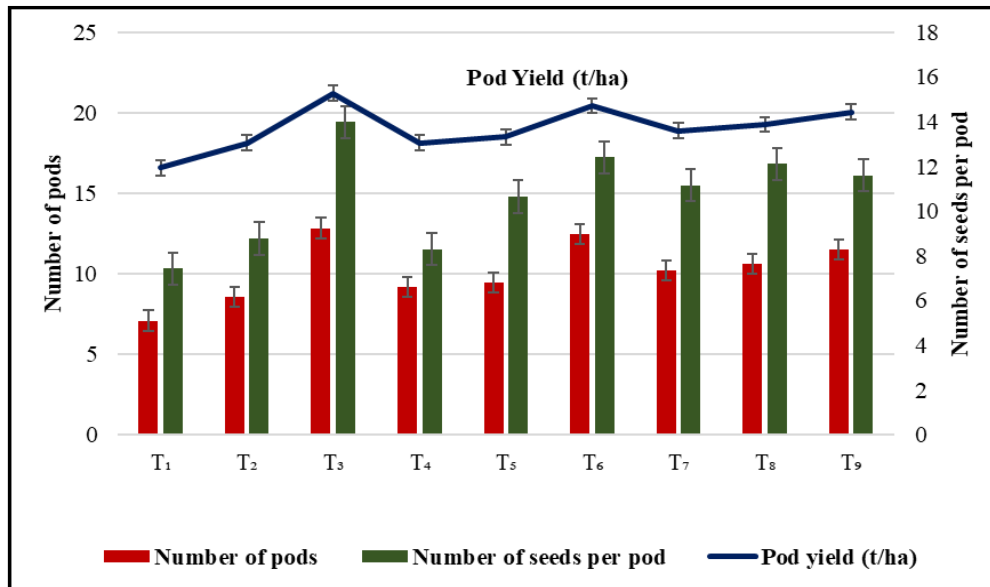


Fig. 7. Effect of dechlorinated and defluoridated water on the number of leaves of french bean.



**Fig. 8.** Effect of dechlorinated and defluoridated water on the yield parameters of french bean.

present in sewage water (32). Since French bean is sensitive to chloride and fluoride concentration, chloride and fluoride toxicity are not found in any treatment, as decreasing the concentration of chloride and fluoride leads to detoxification and no excess toxicity of ions is observed.

#### Effect of dechlorinated and defluoridated water on the economics of French bean

##### Cost of cultivation

Higher cost of cultivation was incurred in the treatments T<sub>3</sub> (DC and DF water by activated alumina) and T<sub>7</sub> (DC and DF water by alum) of about 239679 Rs. ha<sup>-1</sup> and 230279 Rs. ha<sup>-1</sup>. However, a lower cost of cultivation was incurred in the treatment T<sub>1</sub> (Irrigation with water) of 229979 Rs. ha<sup>-1</sup> over the remaining treatments under study (Table 7).

##### Gross returns

The treatment DC and DF water by biochar (T<sub>8</sub>), followed by DC and DF water by charcoal (T<sub>9</sub>), recorded the highest gross returns of 1166634 Rs. ha<sup>-1</sup> and 1155523 Rs. ha<sup>-1</sup>. Treatment T<sub>1</sub> (Irrigation with water) was noticed to record the least gross returns of about 955529 Rs. ha<sup>-1</sup> over the other treatments under study (Table 7).

##### Net returns

Higher amount of net returns of 936650 Rs. ha<sup>-1</sup> and 925534 Rs. ha<sup>-1</sup> was obtained in the treatments DC and DF water by biochar (T<sub>8</sub>), followed by treatment DC and DF water by charcoal (T<sub>9</sub>). Meanwhile, lower net returns of 725550 Rs. ha<sup>-1</sup> were registered in treatment T<sub>1</sub> (Irrigation with water) (Table 7).

##### B-C ratio

Treatment DC and DF water by biochar (T<sub>8</sub>) recorded a higher benefit to cost ratio, i.e., profit per rupee that is invested of 5.07 followed by DC and DF water by charcoal (T<sub>9</sub>) which recorded the B:C ratio of 5.02 and the lowest BC ratio was observed in treatment T<sub>1</sub> (Irrigation with water) of 4.15 (Table 7).

##### Soil properties

Initial soil properties are depicted in Table 2.

##### Soil pH

pH of soil after harvest of French bean was recorded as 6.55 (Table 8). The sewage effluent was slightly alkaline in reaction, according to the tolerance limit of pH 6–9. Similar results were obtained in the sewage irrigated soils of Gabbur village near Hubli city in Karnataka (33). The higher pH of soils could be attributed to the large number of salts present in sewage water and their deposition in the soil profile (34).

##### Soil EC

EC of irrigation with treated sewage is 0.32 dS m<sup>-1</sup> (Table 8). EC value of wastewater was higher than that of freshwater. Therefore, the application of wastewater would be expected to increase soil EC, which is confirmed by the previous studies (35). The highest value of EC was significantly observed for soil irrigated with wastewater as compared to other treatments, indicating a higher content of salts in a moderately fine soil texture. This might be ascribed to its high salt content, with a mean value of 1.46 against 0.51 dS m<sup>-1</sup> for freshwater and hence contributing more dissolved salts in the soil.

**Table 7.** Effect of dechlorinated and defluoridated water on the economics of French bean

Treatments	Cost of cultivation (Rs)	Gross returns (Rs)	Net returns (Rs)	B:C ratio
T <sub>1</sub> : Irrigation with water	229979	955529	725550	4.15
T <sub>2</sub> : Irrigation with treated sewage water	229979	1044415	814436	4.54
T <sub>3</sub> : DC and DF water by activated alumina	239679	1142788	912109	4.95
T <sub>4</sub> : DC and DF water by calcium silicate	230229	1044415	814186	4.53
T <sub>5</sub> : DC and DF water by calcium carbonate	230178	1066637	836459	4.63
T <sub>6</sub> : DC and DF water by Alum	230279	1104136	873857	4.79
T <sub>7</sub> : DC and DF water by gypsum	230254	1088858	858604	4.72
T <sub>8</sub> : DC and DF water by biochar	229984	1166634	936650	5.07
T <sub>9</sub> : DC and DF water by charcoal	229989	1155523	925534	5.02

**Table 8.** Effect of dechlorinated and defluoridated water on pH, EC and organic carbon of French bean

Treatments	pH	EC (dS m <sup>-1</sup> )	OC (%)
T <sub>1</sub> : Irrigation with water	6.70	0.33	0.42
T <sub>2</sub> : Irrigation with treated sewage water	6.80	0.32	0.42
T <sub>3</sub> : DC and DF water by activated alumina	6.52	0.31	0.45
T <sub>4</sub> : DC and DF water by calcium silicate	6.65	0.33	0.43
T <sub>5</sub> : DC and DF water by calcium carbonate	6.75	0.34	0.43
T <sub>6</sub> : DC and DF water by alum	6.50	0.30	0.45
T <sub>7</sub> : DC and DF water by gypsum	6.78	0.33	0.43
T <sub>8</sub> : DC and DF water by biochar	6.72	0.35	0.46
T <sub>9</sub> : DC and DF water by charcoal	6.52	0.31	0.46
SEm ±	0.11	0.01	0.01
CD at 5 %	NS	NS	NS

EC – Electrical conductivity, OC – Organic carbon, SEm – Standard error of mean, CD – Critical difference, NS – Not significant.

#### Organic carbon

Organic matter content increased significantly in treatments T<sub>9</sub> and T<sub>8</sub>, recording 0.46 %, respectively (Table 8). This increase is mainly due to the addition of stable, recalcitrant carbon through biochar and charcoal, which resists rapid microbial decomposition. Irrigation with treated sewage water further contributed dissolved and particulate organic carbon of domestic origin to the soil. Biochar and charcoal improved soil aggregation and pore structure, thereby protecting organic carbon from microbial oxidation. Additionally, adsorption of organic compounds from sewage water onto their porous surfaces enhanced carbon stabilisation and retention. Consequently, the combined effects of organic inputs and reduced mineralisation resulted in higher organic matter content compared to freshwater irrigation, as also reported earlier (36).

#### Available nitrogen

Available N resulted in more in T<sub>3</sub> (295.70 kg ha<sup>-1</sup>) and less in T<sub>1</sub> (232.11 kg ha<sup>-1</sup>) in Table 9. The results have indicated that application of wastewater led to a significant increase in N, P and K compared to freshwater treatment and the presence of activated alumina adsorbs the nutrient and desorbs easily in the presence of neutral pH and also with the addition of FYM. The nitrogen concentration of wastewater-treated soil at the end of the study was higher than that of freshwater treatment. Irrigation with freshwater reduced the soil nitrogen. This could be due to the nitrogen leaching and plant uptake. On the other hand, the number of soils increased by wastewater treatments because of the nitrogen profusion of urea and also the presence of nitrogen in municipal wastewater (37).

#### Available phosphorus

Available P resulted in more T<sub>3</sub> (49.25 kg ha<sup>-1</sup>) and least in T<sub>1</sub> (33.64 kg ha<sup>-1</sup>) in Table 9 because a decrease in the toxicity of chloride and fluoride increased the P content due to reduced competition of anions. The phosphorus concentration of wastewater treatment was higher than that of freshwater treatment. It is well known that soil pH plays an important role in the bioavailability of phosphorus for plants. Moderate pH change of the soil with increased wastewater irrigation might increase the availability of soil native phosphorus compared with the beginning time of treatment, as well as high concentration of phosphorus in wastewater (37).

#### Available potassium

Available K resulted in more in T<sub>3</sub> (168.06 kg ha<sup>-1</sup>) and less in T<sub>1</sub> (149.98 kg ha<sup>-1</sup>) in Table 9 because treated sewage water contains a larger amount of NPK as compared to irrigation with fresh water and also the presence of activated alumina adsorbs nutrients and desorbs easily in the presence of neutral pH and also from the addition of FYM. Available potassium levels (324–672 kg ha<sup>-1</sup>) in the sewage irrigated soils of Ahmednagar city in Maharashtra (37).

#### Available sulphur

Addition of sulphur amendment increased sulphur content in T<sub>6</sub> (16.20 mg kg<sup>-1</sup>) and T<sub>7</sub> (12.37 mg kg<sup>-1</sup>), respectively, Table 10. Irrigation with treated sewage water increased the sulphur content. Similar to the present results, an increase of sulphur content in the soils irrigated with sewage water (38).

#### Exchangeable calcium and magnesium

**Table 9.** Effect of dechlorinated and defluoridated water on available nitrogen, phosphorus and potassium of French bean

Treatments	N (kg ha <sup>-1</sup> )	P <sub>2</sub> O <sub>5</sub> (kg ha <sup>-1</sup> )	K <sub>2</sub> O (kg ha <sup>-1</sup> )
T <sub>1</sub> : Irrigation with water	232.11 <sup>c</sup>	33.64 <sup>c</sup>	149.98 <sup>b</sup>
T <sub>2</sub> : Irrigation with treated sewage water	239.55 <sup>c</sup>	35.84 <sup>c</sup>	150.65 <sup>b</sup>
T <sub>3</sub> : DC and DF water by activated alumina	295.70 <sup>a</sup>	49.25 <sup>a</sup>	168.06 <sup>a</sup>
T <sub>4</sub> : DC and DF water by calcium silicate	240.23 <sup>c</sup>	36.95 <sup>c</sup>	151.59 <sup>b</sup>
T <sub>5</sub> : DC and DF water by calcium carbonate	246.62 <sup>c</sup>	37.50 <sup>c</sup>	152.67 <sup>b</sup>
T <sub>6</sub> : DC and DF water by alum	280.24 <sup>ab</sup>	48.45 <sup>a</sup>	162.84 <sup>a</sup>
T <sub>7</sub> : DC and DF water by gypsum	264.37 <sup>b</sup>	39.04 <sup>b</sup>	154.28 <sup>b</sup>
T <sub>8</sub> : DC and DF water by biochar	269.85 <sup>b</sup>	41.62 <sup>b</sup>	156.70 <sup>b</sup>
T <sub>9</sub> : DC and DF water by charcoal	275.33 <sup>b</sup>	43.78 <sup>b</sup>	157.37 <sup>b</sup>
SEm ±	8.06	2.17	4.39
CD at 5 %	24.91	4.00	24.33

Different letters indicate statistically significant differences ( $P \leq 0.05$ ). SEm – Standard error of mean, CD – Critical difference.

Addition of calcium-based amendment increased calcium content in T<sub>4</sub> (6.10 meq 100 g<sup>-1</sup>), T<sub>5</sub> (6.30 meq 100 g<sup>-1</sup>) and T<sub>7</sub> (6.60 meq 100 g<sup>-1</sup>), respectively, Table 10. Irrigation with treated sewage water increased the magnesium content. Increase in the available calcium content in the soils irrigated with sewage water (38).

### Micronutrients

#### Iron

The addition of treated sewage water increased the iron content with the presence of activated alumina, i.e., T<sub>3</sub> (7.60 mg kg<sup>-1</sup>) in Table 11, because activated alumina adsorbs the micronutrients and desorbs easily. Application of wastewater improved the physicochemical soil properties and increased N, P and K and micronutrients (39). Higher iron content in the soils may be due to prolonged irrigation with sewage water that contains high amounts of iron.

#### Manganese

Addition of treated sewage water increased the manganese content with the presence of activated alumina, i.e., T<sub>3</sub> (4.71 mg kg<sup>-1</sup>) in Table 11. Similar DTPA extractable manganese is seen in sewage irrigated soils of Western Delhi (40).

#### Copper

Addition of treated sewage water increased the copper content with

the presence of activated alumina, i.e., T<sub>3</sub> (1.57 mg kg<sup>-1</sup>) in Table 11.

#### Zinc

Addition of treated sewage water increased the zinc content with the presence of activated alumina, i.e., T<sub>3</sub> (0.59 mg kg<sup>-1</sup>) in Table 11. Continuous irrigation with sewage water showed an increase in the zinc content of the soils (40).

### Conclusion

Quality of irrigation water is a crucial determinant of soil health, crop productivity and environmental sustainability. The present study demonstrated that dechlorination and defluoridation of treated sewage water using locally available amendments effectively reduced chloride and fluoride concentrations by converting them into less available forms. Among the tested treatments, a 1:1 ratio of amendments such as activated alumina, alum, charcoal and biochar was found to be effective, with biochar and charcoal emerging as economically viable and environmentally friendly options for improving irrigation water quality. The experiment was conducted under controlled pot culture conditions and for a relatively short duration, which may not fully represent field-scale soil-water-plant interactions. The long-term accumulation of salts, nutrients or trace elements in soil was not evaluated. Therefore, long-term field studies are required to assess the sustainability, environmental safety and

**Table 10.** Effect of dechlorinated and defluoridated water on exchangeable calcium, magnesium and available sulphur of French bean

Treatments	Ca (meq 100 g <sup>-1</sup> )	Mg (meq 100 g <sup>-1</sup> )	S (ppm)
T <sub>1</sub> : Irrigation with water	4.10 <sup>f</sup>	1.75 <sup>f</sup>	12.37 <sup>e</sup>
T <sub>2</sub> : Irrigation with treated sewage water	4.75 <sup>e</sup>	1.90 <sup>e</sup>	13.67 <sup>d</sup>
T <sub>3</sub> : DC and DF water by activated alumina	4.90 <sup>de</sup>	3.10 <sup>a</sup>	14.59 <sup>cd</sup>
T <sub>4</sub> : DC and DF water by calcium silicate	6.10 <sup>b</sup>	2.30 <sup>de</sup>	14.32 <sup>cd</sup>
T <sub>5</sub> : DC and DF water by calcium carbonate	6.30 <sup>ab</sup>	2.40 <sup>d</sup>	14.97 <sup>cd</sup>
T <sub>6</sub> : DC and DF water by alum	5.65 <sup>c</sup>	2.90 <sup>ab</sup>	16.20 <sup>ab</sup>
T <sub>7</sub> : DC and DF water by gypsum	6.60 <sup>a</sup>	2.60 <sup>c</sup>	17.58 <sup>a</sup>
T <sub>8</sub> : DC and DF water by biochar	5.00 <sup>d</sup>	2.75 <sup>bc</sup>	15.32 <sup>bc</sup>
T <sub>9</sub> : DC and DF water by charcoal	5.25 <sup>cd</sup>	2.80 <sup>b</sup>	15.62 <sup>bc</sup>
SEm ±	0.28	0.15	0.53
CD at 5 %	0.52	0.24	1.42

Different letters indicate statistically significant differences ( $P \leq 0.05$ ). Ca – Calcium, Mg – Magnesium, S – Sulphur, SEm – Standard error of mean, CD – Critical difference.

**Table 11.** Effect of dechlorinated and defluoridated water on DTPA extractable iron, manganese, copper and zinc of French bean

Treatments	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
T <sub>1</sub> : Irrigation with water	6.21 <sup>c</sup>	4.81 <sup>a</sup>	1.30 <sup>d</sup>	0.52 <sup>e</sup>
T <sub>2</sub> : Irrigation with treated sewage water	6.33 <sup>c</sup>	4.85 <sup>a</sup>	1.33 <sup>d</sup>	0.54 <sup>de</sup>
T <sub>3</sub> : DC and DF water by activated alumina	7.60 <sup>a</sup>	4.71 <sup>a</sup>	1.57 <sup>a</sup>	0.59 <sup>a</sup>
T <sub>4</sub> : DC and DF water by calcium silicate	6.45 <sup>c</sup>	4.59 <sup>ab</sup>	1.36 <sup>cd</sup>	0.55 <sup>cde</sup>
T <sub>5</sub> : DC and DF water by calcium carbonate	6.55 <sup>bc</sup>	4.52 <sup>b</sup>	1.39 <sup>cd</sup>	0.56 <sup>cd</sup>
T <sub>6</sub> : DC and DF water by alum	6.95 <sup>b</sup>	4.28 <sup>c</sup>	1.53 <sup>ab</sup>	0.59 <sup>a</sup>
T <sub>7</sub> : DC and DF water by gypsum	6.66 <sup>bc</sup>	4.25 <sup>c</sup>	1.43 <sup>bc</sup>	0.56 <sup>cd</sup>
T <sub>8</sub> : DC and DF water by biochar	6.75 <sup>b</sup>	4.25 <sup>c</sup>	1.45 <sup>bc</sup>	0.57 <sup>bc</sup>
T <sub>9</sub> : DC and DF water by charcoal	6.89 <sup>b</sup>	3.92 <sup>d</sup>	1.49 <sup>b</sup>	0.58 <sup>ab</sup>
SEm ±	0.17	0.13	0.04	0.02
CD at 5 %	0.64	0.42	0.13	0.10

Different letters indicate statistically significant differences ( $P \leq 0.05$ ). SEm – Standard error of mean, CD – Critical difference, Fe – Iron, Mn – Manganese, Cu – Copper, Zn – Zinc, ppm – Parts per million.

cumulative effects of repeated application of dechlorinated and defluoridated sewage water under diverse agro-climatic conditions.

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## Authors' contributions

NHN conducted the experiments, analysed the data, and prepared the manuscript. NDV conceptualised the study, guided the research, and reviewed the manuscript. DS assisted with experiments and data processing. RC and WV supported methodology, data interpretation, and manuscript review. CS supervised the study and critically reviewed the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, ChatGPT was used for language polishing/grammar correction/formatting of references / improving clarity of sentences. After using this tool, I thoroughly reviewed and edited the content as needed and I take full responsibility for the final version of the manuscript.

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