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Bioremediation of electroplating industrial wastewater using bioenzymes generated from citrus

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ABSTRACT

Industries involved in electroplating have a significant potential for contamination of water sources and soil. The indiscriminate release of effluents from electroplating enterprises into natural aquatic systems poses a major hazard to the flora and fauna. Using bioenzymes in wastewater treatment is an effective and eco-friendly approach. In this work, we employed bioenzymes derived from citrus fruit peels to treat the electroplating industry effluent. The effluent was subjected to bioenzymes digestion at concentrations of 1%, 5%, 6%, and 10% at room temperature (25°C), with periodic sampling for analysis of various parameters over a 20-day treatment period. The analysis included changes in pH, electrical conductivity (EC), biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS). Additionally, the elemental profile of the bioenzymes-treated and control effluent samples was determined. The results demonstrated that bioenzymes can reduce the pH, EC, BOD, COD, and TDS of the effluent, while 10% of bioenzymes reduced ferrous (Fe) by 99.19%, phosphorous (P) by 63.02%, arsenic (As) by 98.72%, and sulfur (S) by 60.79%. The reductions were statistically significant at 6% and 10% concentrations. Following the treatment with bioenzymes, the concentration of As, Fe, and Pb in the treated effluent fell below the permissible limit for effluent discharge. This study demonstrates that bioenzymes can serve as a cost-effective and environmentally friendly solution to improve the quality of wastewater, making it suitable for safe disposal. To improve the effectiveness of bioenzymes for treating wastewater, more research should be done to find the best additives, activators, and enzyme cocktails. This should include pre-treatment strategies and an examination of how they affect different wastewater properties and metal pollutant removal.

Introduction

Background

Industrialization, subsequent urbanization, and ever-increasing population constantly contaminate the fundamental needs of existence, such as land, air, and water. Industrial activities significantly contribute to environmental pollution (Kumar *et al.,* 2020). These industrial zones primarily emit effluent, which contains heavy metals such as Zn, Ni, Cr, Pb, Cu, Cd, and Hg, along with organic compounds like phenols and formaldehyde (Meena *et al*., 2021). In ecosystems, the biomagnification of heavy metals poses a significant risk to human health. Effluents released from these industries often contain harmful heavy metals such as zinc (Zn), nickel (Ni), chromium (Cr), lead (Pb), copper (Cu), cadmium (Cd), and mercury (Hg), as well as organic compounds like phenols and formaldehyde (Meena *et al.,* 2021). The biomagnification of these heavy metals in ecosystems poses significant risks to human health and the environment, necessitating the implementation of efficient wastewater treatment processes to mitigate these impacts.

Problem Statement

Electroplating industries are among the primary contributors to water contamination due to the high concentration of toxic heavy metal ions, cyanide, organic solvents, oils, greases, and other pollutants present in their effluent. These effluents typically have high biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), and turbidity, rendering them highly corrosive and harmful to aquatic life, plants, animals, and humans (Rajoria *et al.,* 2022). Nutrients like phosphorus and

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nitrogen cause eutrophication, depleting oxygen and harming biodiversity (Bhateria and Jain, 2016). Because of the presence of these metal ions in electroplating industrial effluent, the water is poisonous and corrosive. The heavy metals found in electroplating wastewater are especially hazardous, as they accumulate in the food chain and can lead to long-term health problems. Hence, effective removal of these contaminants is crucial for meeting regulatory standards and safeguarding environmental and public health. Regulatory agencies such as the United States Environmental Protection Agency (EPA), the World Health Organization, and the European Union apply several heavy metal removal processes (adsorption of pollutants, electrochemical treatments, membrane filtration, and ion exchange) to reduce the metal concentration in industrial effluents to meet their limits.

Existing solutions and limits

Wastewater treatment employs a variety of heavy metal removal processes, including adsorption, electrochemical treatments, membrane filtration, and ion exchange, to reduce metal concentrations in industrial effluents. However, these conventional methods have significant limitations, including high costs, inefficiency at low metal concentrations, non-specificity, and the generation of secondary contaminants (Fei and Hu, 2023). When the ratio of BOD/ COD is 0.5 or above, we typically opt for biological processes using microbes (bacteria/fungi), which require a significant amount of time for treatment and cannot meet the daily effluent demand. Therefore, certain techniques are needed to accelerate the pace of response. Enzymes could potentially be the key to successful and efficient wastewater treatment through biological treatment (Tang and Tong, 2011).

Proposed Solution

Researchers have proposed different enzymes to remediate organic and inorganic pollutants (Mousavi *et al.*, 2021). One promising alternative to conventional treatment methods is the use of bioenzymes derived from the fermentation of organic waste, such as fruit and vegetable peels. The fermentation of fruits and vegetables produces bioenzymes, an organic liquid formulation that is non-poisonous and does not catch fire or corrode. Bioenzymes, also called waste enzymes, are made when organic waste like fruit and vegetable waste, jaggery (sugar), and a set amount of water are fermented without oxygen (Arun and Sivashanmugam, 2015). While one can use fruit enzymes to create edible items, bioenzymes are unsuitable for human consumption. India recognizes and implements bioenzymes at a very low level (Verma *et al.*, 2019). People prefer citrus bioenzymes due to their natural, non-toxic cleaning power and eco-friendly properties. They effectively break down organic matter, neutralize odors, and have antibacterial benefits. The combination of their natural origin, antimicrobial properties, waste utilization, and cost-effectiveness makes citrus bioenzymes a promising option for bioremediation efforts (Benny *et al.,* 2023). Rasit and Kuan's (2018) study found that pre-treating POME (Palm Oil Mill Effluent) with a 15% dilution of bioenzymes removed 90% of the oil and grease content. Applying 10% diluted bioenzymes resulted in a 50% reduction in TSS and a 25% increase in COD. The fermentation of vegetable and fruit waste produces enzymes like protease, lipase, and amylase, which not only serve as cleaning agents but also serve as excellent fertilizers, natural pesticides, and herbicides (Panicker *et al.*, 2021, Galintine *et al.*, 2021).

Given that organic waste makes up the majority of urban solid waste, using bioenzymes not only offers a different option for biological recovery from organic waste but also aids in garbage minimization and reduction. It also reduces greenhouse gas emissions and the pressure on landfills. Citrus fruit occupies 10% of India's total fruit crop area, making it the world's 5th largest citrus fruit producer (Mahawar *et al.*, 2020). The produce is mainly being used for extraction and processing of juice. Punjab is the leading producer of Kinnow, with 29% of total national production. But because of the poor post-harvest storage facilities and premature fruit drop, about 10–20% of the total production is wasted (Sharma *et al.,* 2017). There are no studies that look at how bioenzymes can be used to treat the waste water from the electroplating industry, so this one was done to see how different concentrations of citrus peel bioenzymes affected the heavy metal content and physicochemical properties of the water that was released by electroplating industries in Ludhiana.

Materials and methods

Preparation of bioenzymes

Citrus bioenzyme was prepared in Department of Renewable EnergY Engineering,PAU, Ludhiana by using 3 ingredients: citrus fruit peel, jiggery and water. Neupane and Khadka (2019) suggested mixing these ingredients in the ratio of 10:3:1 (10 parts water, 3 parts fruit peel, and 1 part jaggery). The mixing was carried out in an airtight plastic container with screw bottle tops that could expand. Gases are produced during the production of waste enzymes, making a plastic container with screw tops, like a plastic bottle, an ideal choice for releasing the gases. Then, the container was put somewhere safe so that no one could mess up the process of digestion. During this phase, gases are released as mixed acid fermentation bacteria (such as *Lactobacillus*, *Bacillus*, *Streptococcus*, *Pediococcus*, *Leuconostoc*, *Lactococcus*, etc.) break down the food waste into smaller molecules. The fermentation phase has moderate airflow, 65% humidity, and 35±2°C. After 3 months, when the peels settle at the base, the liquid bioenzymes were filtered and stored in airtight bottles for further studies. Thirumurugan (2016) and Naik (2022) have also suggested a similar methodology and tested the resultant bioenzymes for various agricultural uses.

Sample collection, physicochemical analysis, and heavy metal profiling of effluent samples

In March 2022, we collected an effluent sample under sterile conditions from an electroplating industry in Industrial Area B, Ludhiana, and allowed it to settle for 2 hours in a sterile glass bottle. The sample was tested for its pH, EC, color, BOD, COD, and TDS using standard methods after filtration through Whatmann filter No. 1 (APHA, 2005). The pH analysis was checked by using a digital pH meter (Elico LI 120) with a standard buffer solution of pH 7-9, whereas EC was determined with the help of a conductivity meter (Elico CM 180). Biochemical oxygen demand (BOD) was determined by using the Winkler method with azide modification (Winkler, 1888). The concentration of heavy metals present in the effluent sample was estimated using Inductively Coupled Argon Plasma- Optical Emission Spectroscopy (ICAP-OES). Using 5 ml of concentrated HNO_3, 100 ml of sample was digested and diluted suitably for analysis of heavy metals using ICAP-OES (APHA, 2005).

Treatment of effluent with bioenzymes

The effluent sample was treated with 1%, 5%, 6%, and 10% concentrations of bioenzymes. A total of 12 beakers were filled with effluent samples and enzyme solutions made from the fermentation of citrus fruit peels at 1%, 5%, 6%, and 10% concentrations under static conditions. The choice of bioenzymes concentrations was typically based on the balance between effectiveness, cost-efficiency, safety, and prior studies (Pawar *et al.,* 2022; Kumar *et al.,* 2020). They were then subjected to physicochemical and heavy metal analysis from the 0th day to the 20th day. A control was run simultaneously alongwith to compare the reduction in effluent with the bioenzymes treated samples.

Statistical analysis

All the experiments were carried out in triplicates, and the data were presented as mean ± standard error (SE). The different parameters were analyzed for statistical analysis by analysis of variance (ANOVA) using SPSS software (version 22.0, SPSS Inc.). The mean values were compared by using Turkey's HSD post hoc analysis at a 5% significance level ($p < 0.05$).

Results and discussion

The collected effluent sample exhibited a pH of 3.85, which renders it highly acidic with a BOD of 78.8 mg/l and a COD of about 332 mg/l. The EC and TDS of the effluent sample were found to be 1.67 mS/cm and 1068.8 mg/l. Pandian *et al.* (2014) observed the pH of electroplating industrial effluent to be 4.83. Singh *et al.* (2016) found the BOD and COD of electroplating industrial effluents of the Chandigarh and Haryana regions to be in the range of 64-102 mg/l and 371-571 mg/l, respectively. Table 1 summarizes the results of various physicochemical parameters.

The heavy metals analysis was performed using Inductively Coupled Argon Plasma-Optical Emission Spectroscopy (ICAP-OES) with pretreatment of samples. The results presented in Table 2 indicate that the dominant metal contaminant in the sample was chromium (Cr), with a concentration of 169.49 mg/l, followed by calcium (100 mg/l), magnesium (52.86 mg/l), sodium (50.55 mg/l), and sulfur (39.73 mg/l). Nguyen *et al.* (2020) also reported the highest concentration of chromium (257.76 mg/l) in the wastewater from an electroplating park. The color of the electroplating industry effluent was light greenish yellow due to the presence of a high amount of iron and chromium. Chromium concentrations in effluent samples vary from industry to industry due to differences in how chromium is used in production processes, the chemical form of chromium, the type of wastewater treatment methods employed, and operational factors such as production scale and discharge patterns. The acidic nature of effluent can disrupt ecosystems by harming aquatic life, soil health, and microbial activity, which are critical for maintaining ecological balance (Zouch *et al.,* 2018). High chromium levels, particularly in the form of Cr (VI), pose serious risks to environmental health, affecting ecosystems, agricultural productivity, and human health (respiratory problems, skin irritation, an increased risk of cancer, and cytotoxic and genotoxic effects). Sustainable remediation strategies are essential to mitigate these impacts and restore affected environments. These factors together can lead to long-term environmental degradation and reduced biodiversity (Prasad *et al.,* 2021).

Effluent sample characteristics following bioenzymes treatment

The fluctuations in pH, EC, BOD, COD, and TDS over time for various concentrations of bioenzymes solution were examined and mentioned below:

Figure 1 depicts the variations in the pH value of the effluent following treatment with bioenzymes after 5, 10, 15, and 20 days of digestion. pH was found to decrease by 5.19% over time following treatment with 1% bioenzymes from the 0th day at 3.85 to 3.65 on the 20th day, by 9.87% decrease with 5% bioenzymes, 12.99% decrease with 6%, and 16.62% decrease with 10% bioenzymes concentration. Citrus waste-derived filtered bioenzymes were found to be acidic in nature. The results of effluent treated with bioenzymes at concentrations of 1%, 5%, 6%, and 10% were found to be significant at the 1% and 5% levels of significance ($p < 0.05$). Enzymatic processes and the acidic nature of the bioenzymes cause the pH of effluent samples to gradually decrease at a steady rate over longer digestion times when com-

Table 1: Physicochemical profile of electroplating effluent sample

Parameter	Values	Permissible limits as per CPCB
pH	3.85±0.028	5.5-9.0
EC (mS/cm)	1.67±0.017	2.5
Temperature (°C)	25	40.0
Color	light greenish yellow	Clear
BOD (mg/L)	78.8±0.034	30
COD (mg/L)	332±0.288	250
TDS (mg/L)	1068.8±0.461	500

Values are mean±SE (standard error) of three replicates

Table 2: Metal profile of electroplating effluent sample

Metal	Concentration (0^{th} day)	Permissible limits as per CPCB
As	0.234± 0.001	0.2
B	0.595± 0.002	-
Ca	100.00 ±0.346	-
Cd	0.003± 0.0005	2.0
Co	0.034 ±0.004	3.0
Cr	169.49 ±0.051	2.0
Cu	0.088 ±0.002	5.0
Fe	22.11 ±0.023	3.0
K	15.83± 0.017	-
Mg	52.865± 0.002	-
Mn	0.329 ±0.005	2.0
Na	50.55± 0.011	-
Ni	0.04 ±0.005	3.0
P	0.43 ±0.046	-
Pb	0.356± 0.002	0.1
S	39.73 ±0.098	-

Values are mean±SE (standard error) of three replicates

bined with bioenzymes (Kumar *et al.*, 2020). The results are in accordance with the results of Shivalik and Goyal (2022), who observed a decrease in pH (from 8.4 to 8.16 after 8 days of digestion) in domestic wastewater treated with citrus bioenzymes. However, a decrease in pH can impair coagulation, flocculation, and chemical precipitation, reducing the removal efficiency of suspended solids and metals. It can also hinder biological treatment, disinfection, and damage equipment, increasing corrosion risks (Aragaw and Bogale, 2023). As such, monitoring

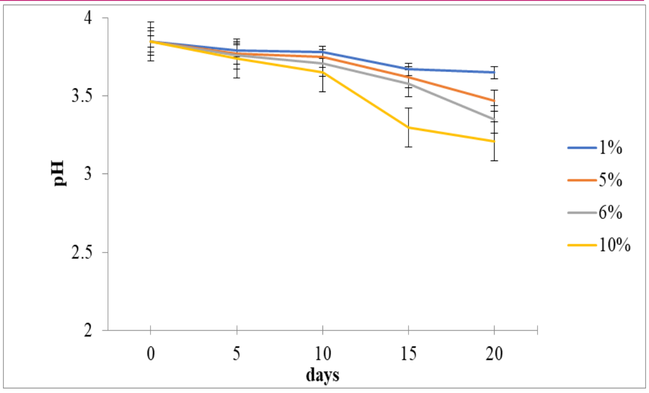

Figure 1: Reduction in pH over 20 days of treatment with various bioenzymes concentrations

and controlling pH levels is crucial to ensuring optimal treatment performance and minimizing negative impacts on both equipment and environmental compliance. Adjusting the pH of effluent to a neutral or slightly alkaline level is often crucial for ensuring the effectiveness of downstream processes.

Over the course of 20 days, we also found a decline in the electrical conductivity. Treatment with 1% bioenzymes reduced the EC by 2.99%, 5% bioenzymes by 4.79%, 6% bioenzymes decreased the EC by 7.18%, and 10% bioenzymes led to EC reduction by 11.97%. The decrease was not statistically significant in effluent samples treated with 1% and 5% bioenzymes; however, reduction was found to be significant at 6% and 10% bioenzymes concentrations ($p < 0.05$). Lower EC signifies reduced pollution, improved oxygen availability, a better balance of nutrients and minerals, and supporting aquatic life and biodiversity. Moreover, reduced EC prevents harmful effects like salinization, supports plant and animal life, and ensures that water remains safe for both environmental and human use (Yu *et al.,* 2005). Figure 2 illustrates the decrease in EC in bioenzyme-treated effluent samples over a period of 20 days.

The definition of BOD (biological oxygen demand) is a measurement of the amount of oxygen con-

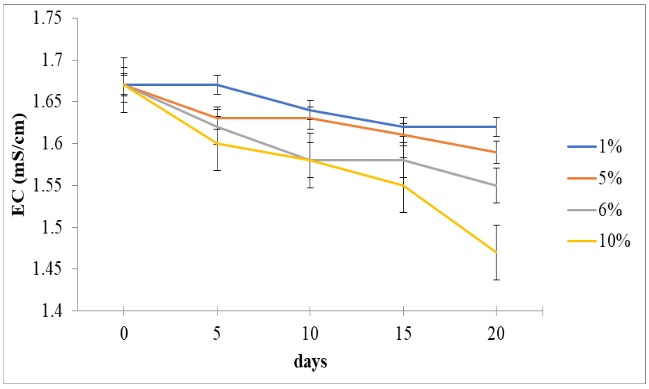

Figure 2: Reduction in EC values over 20 days of treatment with various bioenzymes concentrations

sumed by bacteria and microbes during the breakdown of organic matter in water. BOD was found to decrease by 37.81% using 1% bioenzymes, 42.89% reduction with 5% bioenzymes, 48.09% decrease using 6% bioenzymes, and 51.77% by using 10% concentration of bioenzymes. The decline was found to be statistically significant at 1%, 5%, 6%, and 10% bioenzymes concentrations ($p < 0.05$). The decrease in BOD is due to the digestion of organic pollutants by bioenzymes. Kumar *et al.* (2020) also found that the BOD of wastewater went down over 25 days when it was treated with different amounts of flower waste bioenzymes (5%, 10%, and 15%). These results support the findings. Figure 3 depicts the alterations in the BOD values of treated effluent samples after 5, 10, 15, and 20 days of digestion with bioenzymes. A big drop in BOD in treated effluent will be good for the aquatic ecosystem because it will make more oxygen available, keep aquatic life alive, and stop problems like dead zones and eutrophication (Akpor *et al.*, 2014).

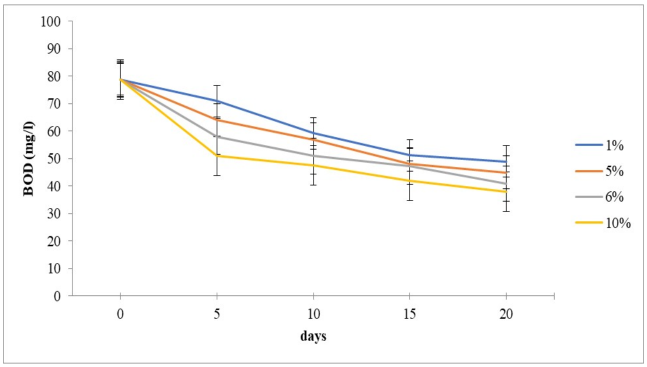

Figure 3: Decline in BOD content over 20 days of treatment with various bioenzymes concentrations

Chemical oxygen demand measures the amount of oxygen required to oxidize soluble organic compounds in water. Using 1% bioenzymes for 20 days resulted in a 17.16% decrease in the COD of the effluent sample. While 5% treatment reduced COD by 24.39%, 6% led to a 33.43% reduction, and 10% treatment reduced COD by 44.57% after 20 days. The decrease was found to be statistically significant at 1%, 5%, 6%, and 10% bioenzymes concentrations ($p < 0.05$). Shivalik and Goyal (2022) observed a 96% decrease in COD for domestic wastewater with citrus bioenzymes. Figure 4 depicts the changes in COD values of the treated effluent sample after 5, 10, 15, and 20 days of digestion with bioenzymes. The presence of citric acids and amino acids in fruit peels, which are components of the bioenzymes, may contribute to the treatment process. Through chemical reactions, they convert proteins, lipids, and carbs into CO_2 and water to provide a type of useful energy (Nazim and Meera, 2013).

Total dissolved solids determine the concentration of

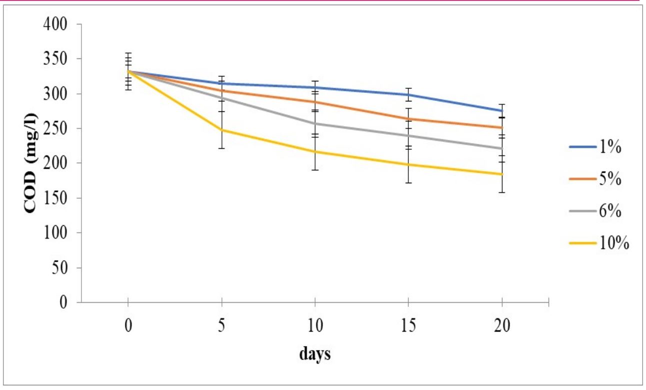

Figure 4: Reduction in COD content over 20 days of treatment with various bioenzymes concentrations

dissolved compounds in a water sample. Figure 5 shows how the TDS level of the effluent changed after bioenzymes were added. It also shows how the characteristics of treated effluent samples changed after 5, 10, 15, and 20 days of digestion. TDS was found to decrease by 5.31% using 1% bioenzymes, 6.62% with 5%, 15.60% with 6%, and 26.92% decrease by using 10% bioenzymes concentration. The reduction in TDS was found to be statistically significant at 1%, 5%, 6%, and 10% bioenzyme concentrations ($p < 0.05$). The enzymatic reactions of bioenzymes are responsible for the decline in TDS values over a period of time. Pawar *et al.* (2022) reported a 34%, 38%, and 41.6% decrease in TDS of wastewater over a period of 8 days with different citrus bioenzymes concentrations (2%, 4%, and 6%).

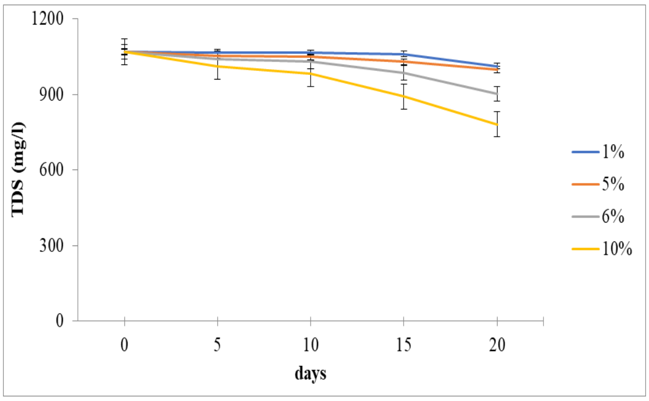

Figure 5: Decrease in TDS values over 20 days of treatment with various bioenzymes concentrations

The elemental content of the effluent sample has changed

After 20 days, we observed a decrease in various elements when we treated effluent samples with different concentrations of citrus bioenzymes (1%, 5%, 6%, and 10%). This research demonstrates that the bio-catalytic activity of bioenzymes derived from the fermentation of citrus peels performs optimally under specific conditions for metal reduction. Using bioenzymes is an effective and environmentally friendly approach to treating metal-laden wastewater. This method can address a variety of metals, such as cadmium, chromium, copper, lead, nickel, and zinc. The treatment process starts by introducing the bioenzymes into the effluent, where it reacts with the metals to form complexes. This reaction lowers the metal concentration in the effluent. After allowing the bioenzymes to settle, we facilitate the separation of these metal complexes from the effluent. We can then remove these metal complexes using various techniques such as filtration, ion exchange, or chemical precipitation. Nature contains both inorganic and organic forms of metals like arsenic (As). The inorganic forms (As^{3+} and As^{5+}) are highly toxic and may cause neurological, cardiovascular, and other health-related issues (Pratush *et al.,* 2018). While As^{3+} is more mobile and toxic, sediments can retain As^{5+} due to its immobility. Enzymes such as oxidases and reductases can interconvert both these forms. The primary cause of the release of different Pb species into the environment is the increased utilization of gasoline. Enzymes such as ureases have the ability to generate various carbonate crystalline Pb^{2+} species. Lead can mineralize into oxalate and pyromorphite forms (Rahman and Singh, 2020). A reduction of 35.23% in Fe was observed upon treatment with 1%, 81.64% with 5%, 99.03% with 6%, and 99.19% with 10% bio-enzyme treatment. Similarly, 10% bio-enzyme treatment reduced Cr concentration by 11.03%, Ca by 32.20%, Mg by 41.09%, P by 63.02%, As by 98.72%, and S by 60.79% over 20 days. A unit reduction of 0.35 was observed in the case of Pb (0.002 mg/l). Table 3 summarizes the results of elemental content reduction with bioenzyme treatment. Shivalik and Goyal (2022) reported a 35% reduction in phosphorus on the eighth day of domestic wastewater digestion with citrus bioenzymes. Table 3 summarizes the results of heavy metal reduction with bioenzyme treatment. The most toxic heavy element, Cr (VI), exerts mutagenic, carcinogenic, and teratogenic effects (Rao *et al.,* 2017). Some enzymes, like Ni-Fe dehydrogenase, chromate reductase, and cytochrome c3, are known to be able to reduce hexavalent chromium (Chardin *et al.*, 2003). Bacteria have enzymes called nitroreductase, iron reductase, flavin reductases, and quinone reductases that break down Cr^{6+} (Ackerley *et al.*, 2004). In the current study, the treatment of effluent samples with various concentrations of citrus bioenzymes led to a gradual decrease in heavy metal levels. The presence of reductase enzymes in bioenzymes, which initiate the degradation or breakdown process, could be the cause of the decline. An experiment on the ability of bioenzymes to reduce 100 mg/L Cr (VI) to Cr (III) was carried out using 1,5-diphenylcarbazide. Table 4 presents the results of this experiment. It was observed that different concentrations of bioenzymes were able to significantly reduce Cr (VI), with 10% bioenzymes exhibiting the most effective reduction (98.28%), while 1%, 5%, and 6% bioenzyme concentrations showed reductions of 62.88%, 90.31%, and 92.75%, respectively, after a span of 20 days, as compared to the control ($p < 0.05$). According to Mamma and Christakopoulos (2008) and Benny *et al.* (2023), citrus peels have enzymes like pectinase, cellulase, ligninolytic, poly-

Table 3: Percent reduction in elemental composition upon bioenzymes treatment after 20 days

Metal	Control	1%	5%	6%	10%	Max. unit reduction
As	0.23±0.006	0.12±0.001	0.05±0.13	0.006±0.001	0.003±0.0005	0.23
B	0.59±0.003	0.50±0.01	0.49±0.01	0.37±0.008	0.28±0.008	0.31
Ca	99.90±0.17	99.40±0.23	97.50±0.40	93.10±0.23	67.80±0.08	32.10
Cd	0.003±0.0005	0.003±0.001	0.003±0.001	0.002±0.0005	0.001±0.0002	0.002
Co	0.03±0.004	0.03±0.005	0.02±0.007	0.002±0.0005	0.001±0.0003	0.03
Cr	169.49±0.02	168.10±0.69	165.20±1.06	158.0±0.34	150.80±0.09	18.69
Cu	0.08±0.002	0.07±0.01	0.06±0.006	0.04±0.01	0.02±0.008	0.06
Fe	22.11±0.02	14.32±0.24	4.06±0.05	0.21±0.01	0.17±0.006	21.94
K	15.81±0.01	15.11±0.42	14.20±0.40	11.94±0.10	8.07±0.03	7.74
Mg	52.86±0.02	50.36±0.40	48.62±0.06	43.16±0.07	41.09±0.12	11.77
Mn	0.32±0.005	0.31±0.02	0.30±0.009	0.25±0.01	0.24±0.07	0.08
Na	50.55±0.01	50.10±0.40	49.68±0.07	46.94±0.08	45.26±0.21	5.29
Ni	0.04±0.00	0.04±0.005	0.03±0.003	0.03±0.005	0.03±0.008	0.01
P	0.43±0.04	0.39±0.07	0.34±0.07	0.24±0.013	0.16±0.01	0.27
Pb	0.35±0.002	0.29±0.02	0.09±0.008	0.01±0.002	0.002±0.0002	0.35
S	39.71±0.02	38.64±0.27	29.78±0.09	22.51±0.12	15.58±0.11	24.13

Values are mean±SE (standard error) of three replicates

Table 4: Cr (VI) to Cr (III) reduction ability of

Treatments	Cr (VI) concentration (mg/L)	Percent reduction (%)
10 days		
Control	99.7± 0.05[a]	0.30
1%	54.10± 0.28[b]	45.73
5%	20.62± 0.11[c]	79.31
6%	14.46 ±0.07[d]	85.49
10%	4.82± 0.09[e]	95.16
C.D. (5%)	0.452	
20 days		
Control	98.6±0.17[a]	1.40
1%	36.60± 0.79[b]	62.88
5%	9.55± 0.32[c]	90.31
6%	7.14± 0.11[d]	92.75
10%	1.69± 0.12[e]	98.28
C.D. (5%)	0.933	

Values are mean±SE (standard error) of three replicates. Values with different superscripts indicate the significant difference among the Cr (VI) concentration with respect to different bioenzymes treatments according to post- hoc Tukey's HSD (P<0.05).

phenol oxidase, and protease, as well as bioactive compounds like ascorbic acid, flavonoids, and terpenoids. These all work together to help get rid of heavy metals from wastewater. These enzymes and compounds act through mechanisms like biosorption, complexation, and reduction, making citrus peels a valuable natural resource for eco-friendly wastewater treatment.

Conclusion

Citrus fruit peels, an organic waste material, produced the bioenzymes used in this study. The results have shown that 6% and 10% bioenzyme solutions were found to reduce pH, EC, BOD, COD, and TDS in effluent. Waste production makes bioenzymes cheap and economical. Future research should explore optimal additives, activators, or enhancers for enzyme function. Therefore, the practical use of bioenzymes can enhance the qualities of effluent, enabling its recycling. Furthermore, studies can be conducted to determine the best additives, activators, or enhancers for enzyme function. Researchers can also investigate pre-treatment strategies to reduce high initial BOD and COD prior to enzyme activity. Researchers can also investigate the use of bioenzymes in the treatment of all forms of wastewater under various physicochemical conditions. Examining the impact of bioenzymes on wastewater properties beyond the parameters outlined in this study is also possible. Designing a suitable cocktail of enzymes with precise physicochemical properties can be a promising way to find efficient and cost-effective methods for the remediation of metal pollutants.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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