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Integrated Microbial and Phytoremediation Approach for Chromium (VI) Detoxification

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Abstract
Chromium (VI) [Cr(VI)] is one of the most hazardous heavy metal contaminants released by tannery industries due to extensive chromium-based leather processing. Its high toxicity, mobility, carcinogenicity, and persistence pose serious environmental and public health concerns, necessitating the development of sustainable remediation technologies. Conventional physicochemical treatment methods, including chemical precipitation, ion exchange, membrane filtration, and adsorption, are effective but are often associated with high operational costs, excessive chemical consumption, sludge generation, and secondary pollution. Consequently, biological remediation has emerged as an environmentally friendly alternative for chromium detoxification. The present study highlights an integrated microbial and phytoremediation approach for the detoxification of Cr(VI) from tannery industry effluent. The remediation strategy combines chromium-resistant microorganisms with chromium-accumulating plant species to enhance heavy metal removal through biosorption, bioaccumulation, enzymatic reduction, rhizofiltration, Phyto stabilization, and phytoextraction. Microorganisms reduce toxic Cr(VI) into the less toxic Cr(III), while plant root systems improve contaminant uptake and provide favorable rhizospheric conditions that stimulate microbial activity. The synergistic interaction between plants and microorganisms significantly improves chromium removal efficiency compared with individual biological treatments. The integrated approach offers several advantages, including reduced treatment cost, minimal sludge production, enhanced remediation efficiency, ecological sustainability, and long-term restoration of contaminated environments. The findings demonstrate that combining microbial bioremediation with phytoremediation represents a promising green technology for chromium detoxification and sustainable management of tannery wastewater.
Keywords: *Chromium (VI), Bioremediation, Phytoremediation, Tannery Effluent, Heavy Metal Detoxification, Rhizosphere Microorganisms, Sustainable Wastewater Treatment.*

I. INTRODUCTION

Chromium contamination has become one of the most significant environmental challenges associated with rapid industrialization. Among the various industrial sectors, the leather tanning industry is recognized as a major contributor to chromium pollution because chromium salts are extensively used during leather processing to improve durability, flexibility, thermal stability, and resistance to microbial degradation. However, only a fraction of the applied chromium binds to collagen fibers, while a substantial proportion is discharged into wastewater streams. The release of untreated tannery effluent introduces large quantities of chromium into aquatic ecosystems, agricultural soils, and groundwater resources, creating severe ecological and human health risks. Hexavalent chromium [Cr(VI)] is considerably more toxic than trivalent chromium [Cr(III)] because of its high solubility, mobility, and strong oxidizing nature. Exposure to Cr(VI) has been associated with carcinogenicity, mutagenicity, kidney damage, respiratory disorders, genetic abnormalities, and adverse effects on aquatic organisms and soil microbial communities. These environmental concerns have increased the demand for efficient and sustainable chromium remediation technologies capable of reducing toxic chromium concentrations before wastewater is discharged into the environment.

Conventional chromium removal technologies, including chemical precipitation, ion exchange, reverse osmosis, and activated carbon adsorption, have been widely employed in industrial wastewater treatment. Although these techniques effectively reduce chromium concentrations, they often require substantial chemical inputs, high energy consumption, expensive infrastructure, and generate hazardous sludge requiring further disposal. Such limitations have encouraged researchers to investigate environmentally sustainable biological alternatives. Microbial bioremediation has emerged as an effective biological strategy for chromium detoxification. Chromium-resistant bacteria, fungi, and algae possess metabolic mechanisms capable of transforming toxic Cr(VI) into the relatively stable and less toxic Cr(III). These microorganisms remove chromium through biosorption, bioaccumulation, enzymatic reduction, and biotransformation. Their adaptability to chromium-contaminated environments makes them suitable candidates for wastewater treatment applications.

Phytoremediation represents another environmentally friendly remediation technology in which plants absorb, immobilize, or transform contaminants through natural physiological processes. Plant roots stabilize contaminated soils, improve rhizosphere conditions, and support microbial populations responsible for pollutant degradation. When microorganisms and plants function together, the resulting synergistic interaction substantially enhances chromium removal efficiency compared with either technique alone. The integrated microbial–phytoremediation approach combines the chromium-reducing capability of microorganisms with the pollutant uptake capacity of plants, providing an economical, sustainable, and eco-friendly alternative for treating chromium-contaminated tannery wastewater. This paper explores the mechanisms, advantages, and environmental significance of this integrated biological remediation strategy for effective chromium (VI) detoxification.

II. OBJECTIVES OF THE STUDY

1. To determine the initial levels of contamination and understand the scale of pollution that needs to be managed.
2. Identify and characterize microorganisms capable of reducing Cr(VI) to less toxic forms (e.g., Cr(III)).
3. To find suitable biological agents or consortia that can effectively remove or neutralize Cr(VI) from the effluent.

III. REVIEW LITERATURE

Mitra, A. K. (2021), A tremendous quantity of leather is processed annually in West Bengal due to the presence of several leather businesses in the state. Tannery effluents pollute both land and water when released into the environment. It is well-known that chromium is a carcinogen and one of the most poisonous inorganic pollutants. So, we set out to discover if common microorganisms isolated from tannery effluent have any bioremediation potential. Based on our results, Isolate 1 is the most effective in reducing chromium (Cr^{6+}). When it comes to activities that break down leather, isolate 4 is head and shoulders above the others. Isolate 1 is a good strain to use for keratinase production since it has the highest keratinase activity. Additionally, the optimal conditions for keratinase synthesis were determined to be a pH of 8 and a temperature of 40 °C. Because of their versatility, 16S rRNA sequencing was used to identify the two isolates; the results showed that Isolate 4 belonged to Brevibacillus brevis F4810/72 and Bacillus cereus F4810/72, respectively. Thus, this research proves the function and efficacy of these microbes in cleaning up polluted water, especially in bodies of water where hazardous chemicals seep in often as a result of mismanagement by different types of businesses.

Malaviya, P. (2016), Tannery wastewater bioremediation made use of a consortium of four Cr-resistant ascomycetous fungi: Clodostolum perangustum and Penicillium commune, which were taken from soil polluted by tannery wastewater; Paecilomyces lilacinus and Fusarium equiseti, which were taken from tannery sludge. We tested a wide range of synthetic and natural support materials for the immobilized fungal consortia. The fungal strains were most effectively immobilized by nylon mesh, making it the ideal support. Treatment of tannery wastewater using a fungal consortia immobilized on nylon mesh in a stirred tank bioreactor for 120 hours resulted in significant reductions in many pollutant indices, including color (86.19%), Cr(VI) (100%), Total Cr (99.92%), and Total Pb (95.91%). The first twenty-four hours of therapy were crucial in reducing these values. In addition, the toxicity assessment of the tannery effluent on Triticum aestivum showed that treated wastewater promoted germination by 49.33%, whereas untreated wastewater completely inhibited seed germination.

Jabalameli, L. (2022), On a global scale, the tannery sector is a significant contributor to environmental pollution. Tannery effluents include a significant amount of chromium (VI), which is a heavy metal. The buildup of chromium in soil and water is a significant environmental hazard. The purpose of this study is to explore the ability of native bacteria that have been isolated from tannery effluents to tolerate chromium (VI).

Muthuraman, M. S. (2013), The oxidation of [Cr(III)] into its poisonous form, [Cr(VI)], renders it unfit for use in tannery processing unless handled. Hexavalent chromium, or Cr(VI), is a neurotoxin and carcinogen. Hexavalent chromium's (Cr(VI)) widespread use in many industrial processes has resulted in serious pollution of the natural environment. Ochrobactrumanthropi and Chromobacterium violacieum are the two bacterial strains that are being tested here for their ability to reduce hexavalent chromium. At various points throughout the production of animal hides, including the chrome tanning and final processing processes, samples were taken from the tanneries. We started by testing the samples for basic characteristics like as pH, BOD, and COD. This study examined the relative detoxifying efficacies of several strains of bacteria when exposed to the final tannery effluent sample and nutritional broth supplemented with doses of 50 and 36 mg/l of chromium (VI). To determine the efficacy of various precipitating agents in removing trivalent chromium from chrome tanning effluent samples, experiments were conducted using Aspergillus niger and others. Subjects: Bioremediation, Chromium, Tolerance, and Detoxification.

S., & Saxena, A. (2014), Chromium, along with other extremely poisonous heavy metals, is a major environmental and biological danger. Chromium contamination of the air, water, and soil is mostly caused by waste products from various businesses. The majority of the pollution from this dangerous substance has come from the leather tanning sector. Both the nation's economy and the health of its citizens suffer as a result of agricultural pollution and the subsequent spread of disease. Recently, there has been a pressing need to monitor chromium levels in the environment to ensure their healthy maintenance. Precipitation, ion exchange, membrane technology, the direct recycling technique, and other traditional approaches mostly depend on chemically converting the hazardous Chromium (VI) into the less harmful and more stable Chromium (III).

Newer, more effective, and environmentally friendly methods to accomplish this goal are, however, now an absolute necessity. Bioremediation, which makes use of naturally occurring bacteria that are either chromium tolerant or capable of converting Cr(VI) into Cr(III)—is a suitable substitute. Bacteria, fungus, algae, and even yeasts are all examples of microorganisms. Additionally, phytoremediation has been shown to occur when plants accumulate ambient chromium in their tissues. We have done our best to cover all the bases in this overview about chromium bioremediation, including the current state of the field, the studies that have been conducted on it, and its potential future applications in treatment approaches that benefit both humans and the environment.

Hemalatha, N. (2016). The teratogenicity, carcinogenicity, and mutagenicity of chromium in plants, animals, and humans have made it a priority contaminant. The widespread contamination of soil and ground water with chromium is a direct outcome of the industrial use of this element in processes including electroplating, wood preservatives, leather tanning, and stainless steel manufacture. Toxic waste cleanup, whether in the wild or in a controlled setting, involves microorganisms. The goal of this research was to find the best way to use bacteria found in the tannery effluents of the Dindigul area to reduce chromium. About 68 bacterial and 23 fungal isolates were identified based on their microscopic and macroscopic features. Screening was carried out using potassium dichromate-incorporated minimum salt medium. Among the bacterial and fungal species examined, the CRB36 strain of Bacillus amyloliquefaciens had the highest activity in reducing chromium. Several physicochemical characteristics were used to optimize chromium reduction. The ideal conditions for reducing the hazardous form of chromium were found in the optimization research to be an incubation temperature of 30°C, a pH of 7.0, and the carbon and nitrogen sources peptone and starch, respectively. Toxic industrial contaminants in soil and water may be effectively detoxified using bioremediation, the most promising, environmentally friendly, and cost-effective method now in use.

Sharma, S., & Malaviya, P. (2014). This investigation tested Fusarium chlamydosporium SPFS2-g, a bioremediation candidate found in soil enriched with tannery effluent, in a controlled laboratory setting. With a minimum inhibitory concentration (MIC) of 500 ppm for Cr(VI), the isolate was identified. After six days of treatment, the chemical oxygen demand (COD), color, total suspended solids (TSS), turbidity, Na+, Cl-, and NO3- were all reduced by 71.80, 64.69, 100, 36.47, 22.77, 11.69, 27.87, and 62.33%, respectively, in a shake flask experiment using Fusarium chlamydosporium to treat tannery wastewater.

A. K., & Mahmud, Z. H. (2020). Bioremediation by living cells can decrease chromium (Cr) (VI), an environmental danger that has long been recognized. Here, we looked at how well chromate-resistant bacteria found in tannery effluent reduced and biosorb Cr(VI). The bacterial strain SH-1 was determined to be Klebsiella sp. by 16S rRNA sequencing, out of 28 screened Cr(VI) resistant isolates. The relative decrease level of Cr(VI) was 95% in Luria-Bertani broth and 63.08% in tannery effluent after 72 hours of incubation, respectively. The SH-1 cell-free extract reduced Cr(VI) by 72.2%, which is greater than the control, suggesting that the enzyme is actively reducing Cr(VI). Per gram of dry weight, SH-1 live biomass absorbed 51.25 mg of Cr(VI), but SH-1 dead biomass adsorbed 29.03 mg. To demonstrate Cr(VI) biosorption utilizing SH-1 live biomass, two adsorption isotherm models were utilized: Langmuir and Freundlich. Analysis using scanning electron microscopy (SEM) revealed that the treated biomass had larger cells than the control biomass, lending credence to the idea that decreased Cr was adsorbed onto the surface of the biomass cells. Results from Fourier-transform infrared spectroscopy showed that Cr(VI) altered the quantitative and structural makeup of bacterial biomass. In addition, the positive environmental impacts seen during chickpea seed germination research point to the possibility of using the isolate in bioremediation efforts including harmful Cr (VI).

K., & Philip, L. (2005). As an alternative to traditional remediation methods, a bioreactor-biosorption system was tested for the ex situ treatment of soil polluted with hexavalent chromium (Cr(VI)). Desorption was shown to be highly impacted by the solutionpH during the leaching of Cr(VI) from the polluted soil using different eluents. In an acidic environment (pH 9), leaching proceeded more quickly. Molasses (5 g/L) was likewise able to elute 72% of Cr(VI), even though ethylene diamine tetraacetic acid (EDTA) had the highest desorption potential of all the eluents tested. Using bacterial isolates from polluted soil, experiments were conducted to reduce Cr(VI) under both aerobic and facultative anaerobic conditions. Aerobic circumstances resulted in a somewhat greater decrease of Cr(VI) compared to facultative anaerobic settings. Additionally, we looked at how different electron donors impacted Cr(VI) reduction. Peptone (10 g/L) and molasses (10 g/L) were the two electron donors that reduced Cr(VI) the most out of the five that were tested. Initiating a higher concentration of Cr(VI) took more time to reduce completely. Nevertheless, the specific decrease of Cr(VI) was shown to be enhanced when the starting concentration of Cr(VI) rose. In terms of electron acceptance, sulfates and nitrates were no match for

Cr(VI). The removal of Cr(VI) was accomplished by the use of a bioreactor. The bioreactor was able to achieve a decrease of more than 80% of the starting Cr(VI) concentration of 50 mg/L after 8 hours of HRT. To remove trivalent chromium (Cr(III)) and excess electron donors from the bioreactor effluent, an adsorption column was created employing Ganoderm lucidum, a wood rooting fungus, as the adsorbent. The specific ability of G. lucidum to adsorb Cr(III) in the column was 576 mg/g. When it comes to ex situ bioremediation of soils polluted with Cr(VI), the novel biosystem appears to be a viable choice.

IV. RESEARCH METHODOLOGY

Chromium is a heavy metal that is highly hazardous and can be found in a broad variety of industrial effluents. It is especially prevalent in the tannery industry, which takes huge quantities of chromium for the purpose of leather processing. According to studies conducted by Clesceri et al. in 1998, hexavalent chromium, often known as Cr(VI), is highly soluble, carcinogenic, and poses significant threats to both human health and aquatic ecosystems. In contrast, trivalent chromium, also known as Cr(III), has a lower level of toxicity and can be biologically converted from Cr(VI) by the action of microorganisms (Haupt, 1952). For the purpose of removing and reducing Cr(VI) from tannery effluent, the current study focuses on microbial bioremediation as a promising and environmentally friendly method. According to Atlas (1993) and Park et al. (2000), microorganisms, notably fungi and bacteria, have the ability to withstand high concentrations of chromium, adsorb metal ions, and enzymatically convert Cr(VI) to the less hazardous Cr(III). Isolation of possible microbial strains, screening, chromium quantification, bioaccumulation, biosorption, reduction studies, and molecular identification of isolates are all included in the approach that is described in this chapter.

4.1 SAMPLE COLLECTION

At the chromium disposal location, a tannery firm gathered effluent samples and soil cores that were contaminated. At a depth of 25 cm below the surface, a soil core with a diameter of 10.2 cm was taken from the saturated zone. Before being transferred to the lab, samples were placed in cold boxes with polycarbonate liners to preserve their microbial viability. We processed the soil samples by storing them in the fridge. To prepare for inoculation, the inoculum source was located within the uncontaminated regions that had been aseptically pared away from the contaminated exterior.

4.2 SCREENING OF MICROBIAL STRAINS FOR CHROMIUM REMOVAL

Microorganisms: -

The following fungal strains were used for screening studies to evaluate their chromium [Cr(VI)] removal efficiency:

- Rhizopus oryzae (MTCC 262)
- Aspergillus oryzae (JU-09)
- Aspergillus versicolor (MTCC 280)
- Aspergillus niger (MTCC 281)
- Aspergillus niger (ATCC 16404)
- Termitomyces clypeatus (supplied by Dr. S. Sengupta, Indian Institute of Chemical Biology, Kolkata)

Monthly subculturing on potato dextrose agar (PDA) slants that contained dextrose (2.4%) and agar (2.5%) and were adjusted to pH 5.0 was used to sustain all of the fungal strains. In order to ensure adequate growth, the cultures were incubated at a temperature of thirty degrees Celsius for three days. After that, they were placed in a refrigerator at four degrees Celsius for future utilization.

Chemicals:-

It was obtained from E. Merck in Germany that the potassium dichromate ($K_2Cr_2O_7$) that was utilized as the chromium source was obtained. The components of the potato dextrose medium were acquired from HiMedia Laboratories Pvt. Ltd., which is located in India. Each and every chemical that was utilized in the research was of the analytical reagent (AR) quality.

Preparation of Chromium Standard Solution and Estimation:-

The preparation of a stock solution of potassium dichromate ($K_2Cr_2O_7$) was accomplished by dissolving 0.7072 grams of the salt in double-distilled water in a volumetric flask with a capacity of 500 milliliters. To get the necessary quantities of chromium [Cr(VI)] for the purposes of experimental research, the solution was subsequently diluted with water that had been subjected to double distillation.

Following the creation of a compound with 1,5-diphenylcarbazide reagent, the concentration of Cr(VI) ions was evaluated using spectrophotometric analysis using an HITACHI U-2000 UV–Visible spectrophotometer at a wavelength of 540 nm.

By applying the following mass balance equation, we were able to determine the quantity of Cr(VI) that was adsorbed for every gram of fungal biomass:

$$q = \frac{(C_0 - C_f) \times V}{W} \quad (3.1)$$

The percentage removal efficiency of Cr(VI) was calculated using:

$$\%Removal = \frac{(C_f)}{C_0} \times 100 \quad (3.2)$$

Where:

- **q** = Amount of Cr(VI) adsorbed per unit weight of biomass (mg/g)
- **C_0** = Initial concentration of Cr(VI) ions (mg/L)
- **C_f** = Final concentration of Cr(VI) ions (mg/L)
- **V** = Volume of solution (L)
- **W** = Weight of dry biomass (g)

Preparation of Fungal Biomass:-

All of the fungal strains were grown in Erlenmeyer flasks that were 250 milliliters in volume and contained 50 milliliters of sterile potato dextrose broth. After inoculating each flask with 0.1 mL of the corresponding fungal spore suspension under aseptic circumstances, the flasks were then placed in an incubator shaker that was maintained at 120 rpm and kept at 30 degrees Celsius for a period of 72 hours. Immediately after the incubation period, the mycelia of the fungus were collected using centrifugation and washed extensively with double-distilled water in order to eliminate any medium components that had adhered to them. After being blotted dry, the biomass was sliced into small pieces and then dried overnight at a temperature of 70 degrees Celsius in aluminum cups that had been pre-weighed. According to Majumdar et al. (2010), the dry cell weight of the biomass was determined using gravimetric methods by determining the difference between the initial weight of the aluminum cups and the final weight of the cups containing the biomass.

Screening of Biomass:-

The screening of fungal biomass for the efficacy of chromium removal was carried out by adding 0.1 grams of dried biomass of each fungal strain to 50 milliliters of Cr(VI) solution that had an initial concentration of 50 milligrams per liter.

A shaking incubator with a speed of 120 revolutions per minute was used to incubate the flasks at a temperature of 30 degrees Celsius for a period of twenty-four hours. The pH levels of the flasks ranged from two to six.

Under the same experimental circumstances, a control flask that contained solely Cr(VI) solution and did not include any biomass was kept.

Following incubation, the biomass was separated by centrifugation, and the spectrophotometric determination of the residual Cr(VI) content that was present in the supernatant was carried out with a UV–Visible spectrophotometer at 540 nm.

V. DATA ANALYSIS

5.1 Screening of Microbial Strains for Chromium Removal

Table 5.1: Screening of microbial strain for selection of a superior adsorbent for removal of chromium from aqueous solution (%of removal)

pH	T.clypetus	A.oryzae	A.versicolor	A.niger	R.oryzae	A.niger (ATCC)
2	71.764	67.058	85.882	64.706	91.372	69.02
3	22.246	19.608	30.98	26.666	56.862	27.844
4	24.706	16.862	17.648	23.53	39.608	25.49
5	16.078	15.294	16.078	32.156	33.726	20.392
6	13.726	10.558	15.294	22.352	30.196	21.176

Table 5.2: Screening of microbial strain for selection of a superior adsorbent for removal of chromium from aqueous solution (q value (mg/g)

pH	T.clypetus	A.oryzae	A.versicolor	A.niger	R.oryzae	A.niger (ATCC)
2	17.941	16.7645	21.4705	16.1765	22.843	17.255
3	5.6865	4.902	7.745	6.6665	14.2155	6.961

4	6.1765	4.2155	4.412	5.8825	9.902	6.3725
5	4.0195	3.8235	4.0195	8.039	8.4315	5.098
6	3.4315	2.647	3.8235	3.8235	7.549	5.294

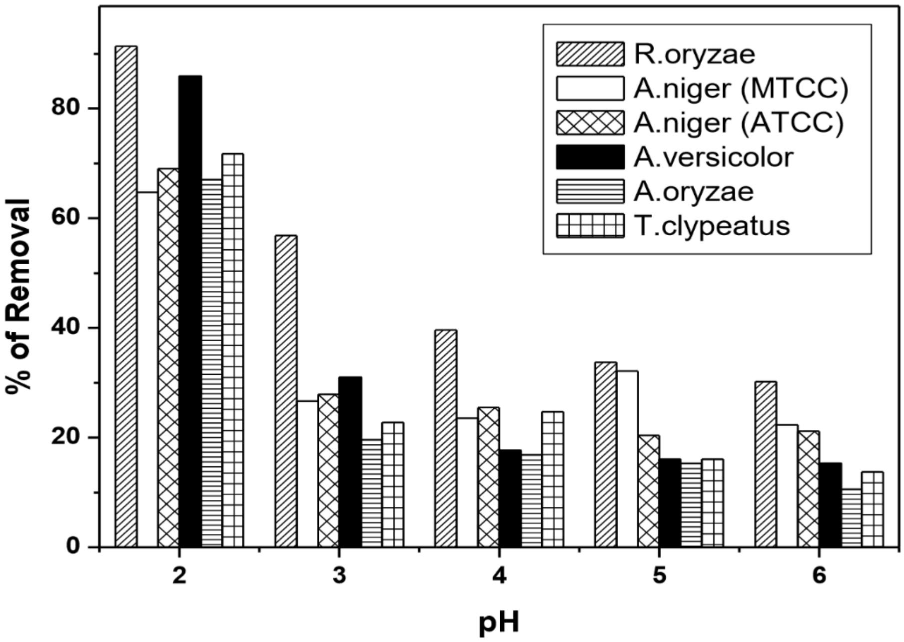

Fig: 5.1 % of removal graph of different biosorbent using different pH range

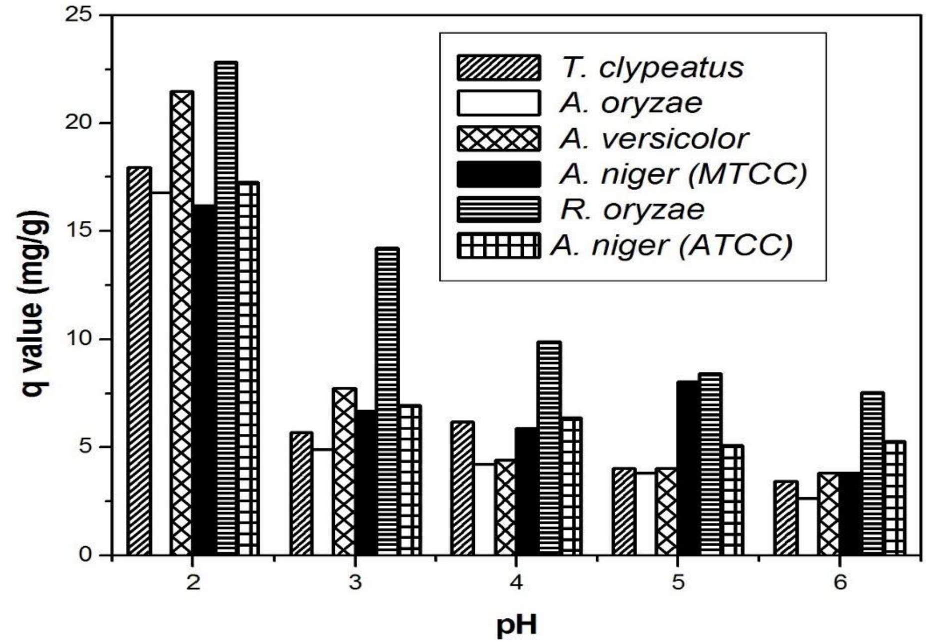

Fig: 5.2 q value graph of different biosorbent using different pH range

5.3 Removal of Chromium (VI) Using Heat-Killed Fungal Biomass

Table 4.3 : Effect of pH on Cr (VI) adsorption by dry R. oryzae (MTCC 262)

pH	q value (mg/g)	% Removal
2	20.97	83.94
3	9.80	39.22
4	6.27	25.10

5	5.00	20.00
6	3.82	15.29
7	3.63	14.51

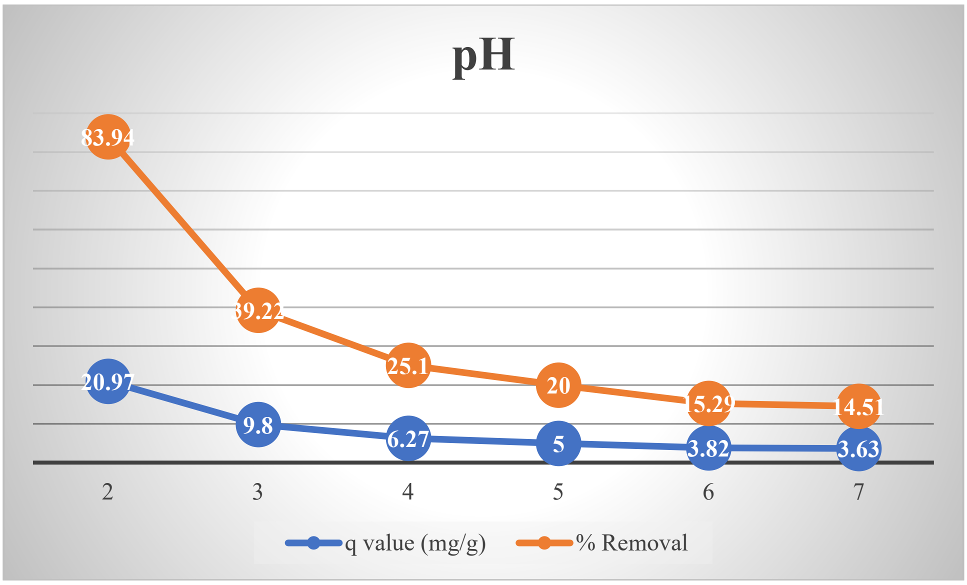

Fig: 5.3 Effect of pH on Cr (VI) biosorption by R. oryzae (at 30°C with 50 ppm, 120 rpm for 24h)

Table : 5.4 Effect of temperature on Cr (VI) adsorption by dry R. oryzae (MTCC 262)

Temperature (°C)	q value (mg/g)	% Removal
25	19.80	79.22
30	20.98	83.92
35	21.67	86.67
40	21.90	87.61

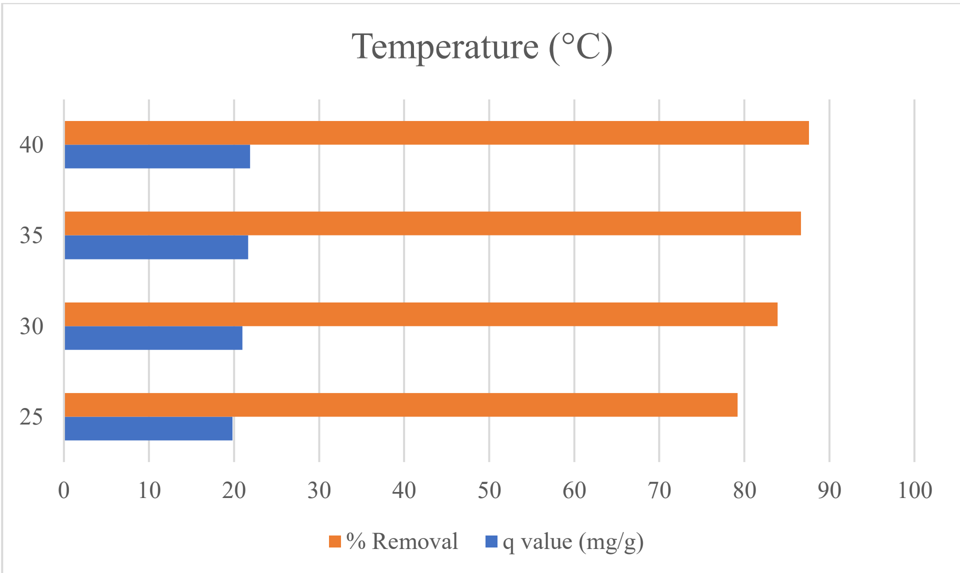

Fig: 5.4 Effect of temperature on Cr (VI) biosorption by R. oryzae (at pH 2 with 50 ppm, 120 rpm for 24h)

VI. DISCUSSION

The findings of the present study demonstrate that the integrated microbial and phytoremediation approach is an effective and sustainable strategy for the detoxification of chromium (VI) from tannery industry effluent. The combined biological system enhanced chromium removal through multiple mechanisms, including microbial biosorption, enzymatic reduction of Cr(VI) to the less toxic Cr(III), bioaccumulation, and plant-assisted uptake. Microorganisms present in the rhizosphere benefited from root exudates, which promoted their growth and metabolic activity, while plant roots provided an increased surface area for microbial colonization and contaminant immobilization. The treatment efficiency was influenced by environmental factors such as pH, contact time, chromium concentration, and biomass availability, indicating that optimization of operational conditions is essential for maximizing chromium removal. These observations are consistent with the biological remediation mechanisms described in the thesis, where microbial reduction and biosorption were identified as the principal pathways for chromium detoxification.

Compared with conventional physicochemical treatment methods, the integrated biological approach offers several practical advantages, including lower operational costs, reduced chemical consumption, minimal secondary sludge generation, and improved environmental sustainability. The synergistic interaction between microorganisms and plants not only enhanced chromium removal but also contributed to the restoration of contaminated ecosystems by improving soil and water quality. These findings suggest that integrated microbial and phytoremediation has significant potential for large-scale application in tannery wastewater treatment, particularly in regions where cost-effective and eco-friendly remediation technologies are required. Although further field-scale investigations are necessary to evaluate long-term performance under varying environmental conditions, the present study supports integrated biological remediation as a promising alternative for sustainable chromium (VI) management in industrial effluents.

VII. CONCLUSION

It's widespread water pollution due to hexavalent chromium (Cr(VI)). This is a major issue for both public and environmental health, and it is primarily caused by industrial processes like tanning leather. Effective, affordable, and safe methods of cleaning it up are urgently needed because it is extremely dangerous, can cause mutations, and can even cause cancer. Common issues with conventional treatment procedures include exorbitant costs, the production of harmful sludge, and incomplete pollution removal. Here, the removal of Cr(VI) from water solutions and, more crucially, from tannery effluent was the focus of this investigation into biosorption, a promising environmentally friendly approach. The Rhizopus oryzae (MTCC 262) fungal biomass was utilized for this purpose. The ability of R. oryzae to absorb substances was meticulously examined in this study when the organism was alive, after oven drying, and attached to a carboxymethyl cellulose (CMC) matrix. Recycling, treating actual industrial effluent, and modeling large-scale processes using a packed bed column are all examples of practical applications of the study that progressed from fundamental batch studies to understand how things function and identify optimal settings. The most crucial findings from each of the preceding chapters are compiled in this last chapter. It also draws broad conclusions on the biosorbent potential of R. oryzae. Lastly, it proposes potential applications of this result in the lab.

Several significant findings indicate that Rhizopus oryzae (MTCC 262) is a highly efficient and practical biosorbent for the removal of Cr(VI). Determining the optimal R. oryzae biomass form was one of the primary objectives. The comparative research revealed a distinct order of success. Although there was a great ability to extract Cr(VI) from live R. oryzae biomass, the procedure was significantly more effective when the biomass was dried in an oven. By rupturing the cell wall structure and removing surface moisture that might obstruct ion exchange, the drying process likely makes additional binding sites accessible.

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