Sustainable Water Body Rejuvenation Using Red Cowpea Starch-Based Adsorbent Material for Ecological Restoration of Polluted Ponds in Himachal Pradesh

Abstract

The ecological degradation of freshwater bodies in Himachal Pradesh is a growing concern driven by unchecked anthropogenic activities such as agricultural runoff, improper waste disposal, and unregulated urbanization. These impacts are especially pronounced in rural and mountainous regions like the Kangra district, where natural water bodies—ponds and small lakes—are crucial for supporting biodiversity, local livelihoods, groundwater recharge, and irrigation. However, conventional water purification systems remain largely inaccessible in these areas due to their high operational costs, energy demands, and infrastructural requirements, making them unsustainable for long-term use in Himalayan settings.To address this gap, the present study investigates a green and sustainable alternative for water remediation using starch-based adsorbent material derived from organically cultivated red cowpea (*Vigna unguiculata*) grown in the Kangra foothills. The red cowpea starch was extracted using eco-friendly wet milling techniques, chemically modified through green crosslinking agents, and characterized using techniques such as FTIR, SEM, TGA, and XRD to determine its surface morphology, thermal stability, and crystallinity. The modified starch was then applied to highly contaminated pond water samples to evaluate its efficiency in removing common pollutants including heavy metals (Pb, Cd, Cr), synthetic dyes (e.g., crystal violet and methylene blue), and pesticides. Experimental results demonstrated remarkably high adsorption capacities, excellent biodegradability, and stability across pH ranges, making it suitable for field-scale application. The modified starch showed over 90% removal efficiency for selected pollutants, underscoring its potential as a low-cost, eco-compatible adsorbent. This research emphasizes the integration of agricultural byproducts with green chemistry approaches to restore degraded aquatic ecosystems. The study offers a replicable, community-level model for sustainable water body rejuvenation, particularly in fragile mountainous terrains, and contributes to broader goals in environmental conservation, rural empowerment, and circular bioeconomy.

Keywords

Red Cowpea, Starch-Based Adsorbent, Pond Rejuvenation, Eco-Restoration, Water Pollution, Kangra, Sustainable Remediation

1. Introduction

Freshwater ecosystems are essential components of the natural environment, providing a wide range of ecological, social, and economic services. In the Indian Himalayan region, particularly in Himachal Pradesh, freshwater ponds serve as vital water resources. These ponds, many of which are located in districts like Kangra, are not merely stagnant pools of water; they play a crucial ecological role by supporting diverse flora and fauna, recharging groundwater tables, regulating microclimates, and serving as accessible sources of water for both agricultural irrigation and domestic consumption (Hlongwane et al., 2019). The interconnectedness between these ponds and the livelihoods of rural communities further underlines their significance in sustaining traditional agricultural systems and biodiversity. Despite their ecological importance, freshwater ponds in Himachal Pradesh are under increasing threat from anthropogenic activities. Over the past two decades, the region has experienced rapid changes due to urban expansion, population growth, unregulated tourism, and agricultural intensification. These shifts have disrupted the delicate ecological balance of these aquatic systems (Wang & Zhuang, 2017). Particularly in the Kangra region, many ponds are now experiencing severe water quality degradation due to factors such as untreated domestic wastewater discharge, pesticide and fertilizer-laden agricultural runoff, and improper solid waste disposal. These issues are often exacerbated during the monsoon season, when increased surface runoff carries pollutants directly into pond systems (Rashed, 2013). The most visible consequence of this degradation is eutrophication—an over-enrichment of nutrients, especially nitrogen and phosphorus, in water bodies. Eutrophication leads to the overgrowth of algae and aquatic weeds, depleting oxygen levels and harming aquatic organisms. In many cases, this condition also creates dead zones, where aquatic life becomes unsustainable. Additionally, the accumulation of heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr), often from chemical fertilizers and industrial effluents, poses a severe threat to both ecological and human health (Amin et al., 2014). Many of these metals are non-biodegradable, persist in sediments, and bioaccumulate in aquatic food chains. Furthermore, the presence of pathogenic microorganisms due to direct sewage discharge increases the risk of waterborne diseases, particularly in communities that depend on these water sources for drinking or bathing. Traditional water treatment technologies, such as centralized filtration plants, chlorination units, and mechanized aerators, are often inappropriate or unfeasible in these settings (Kordbacheh & Heidari, 2023). These technologies require continuous electricity supply, skilled labor, and significant financial investment resources often lacking in rural and semi-urban pockets of Himachal Pradesh. Furthermore, they are not designed for small, decentralized, or seasonally used water bodies. As a result, there is a growing urgency to identify and implement low-cost, sustainable, and eco-friendly methods that can address pollution without further damaging the delicate pond ecosystems (Kordbacheh & Heidari, 2023).In recent years, there has been increasing global interest in the use of natural polymers and biodegradable materials for water purification. Among these, starch has emerged as a promising candidate due to its non-toxic nature, high biodegradability, abundance, and excellent capacity for chemical modification(Grassi et al., 2012). Starch-based adsorbents can be tailored to possess functional groups that interact with specific pollutants such as heavy metals, dyes, and organic compounds. Moreover, these starch derivatives are easily disposable and pose minimal risk of secondary pollution.

In this context, red cowpea (***Vigna unguiculata*)**, an underutilized legume indigenous to the Himalayan foothills, presents a unique opportunity. Traditionally cultivated by smallholder farmers in Himachal Pradesh, red cowpea is well-adapted to the region's agro-climatic conditions and known for its resilience to drought and poor soils(Beydaghdari et al., 2022). While the seeds of red cowpea are consumed as a protein-rich food, they are also a valuable source of starch, which remains largely untapped for industrial or environmental applications. Recent studies have shown that starch extracted from legumes, particularly cowpea, exhibits excellent physicochemical properties suitable for chemical modification and use as an adsorbent (Vigneshpriya et al., 2017). These properties include high swelling capacity, surface area, and functional groups like hydroxyl (-OH) that can be modified to increase pollutant-binding efficiency.The modification of red cowpea starch using green chemistry principles such as cross-linking with natural acids, enzymatic treatment, or thermal processing can further enhance its adsorption performance while keeping the environmental impact minimal. For instance, introducing carboxyl or phosphate groups can improve metal ion affinity, while physical modifications like ultrasonication can increase surface roughness and porosity, thereby improving contact efficiency with contaminants. These modified starch-based materials can then be applied as filters, beads, hydrogels, or slurry additives in pond restoration projects (Delgado et al., 2019). This research initiative aims to explore and validate the feasibility of using red cowpea starch-based adsorbents for the ecological restoration of polluted ponds in the Kangra district of Himachal Pradesh. The core objectives include extraction and characterization of starch from locally grown red cowpea varieties, its modification using environmentally benign processes, and subsequent application in removing key pollutants such as pesticides, heavy metals, and excess nutrients from contaminated pond water. Additionally, the study aims to assess the impact of this treatment on key water quality parameters, including turbidity, chemical oxygen demand (COD), biological oxygen demand (BOD), and nutrient content.By aligning with the principles of circular economy and sustainable development, this project not only addresses environmental pollution but also promotes rural entrepreneurship and value addition to underutilized crops. Engaging local farmers in the cultivation and supply of red cowpea, and empowering self-help groups or village-level entrepreneurs to produce and apply the adsorbent, can foster community ownership and ensure long-term sustainability of pond rejuvenation efforts (Geissen et al., 2015). This bottom-up approach has the potential to transform passive beneficiaries into active participants in environmental conservation. Furthermore, the outcomes of this study could serve as a model for other hill states facing similar water quality challenges. Given the broad applicability of starch-based adsorbents, such technologies can be adapted to other aquatic systems such as seasonal streams, irrigation canals, or temple ponds across India (Deo & Halden, 2010). The environmental friendliness, cost-effectiveness, and ease of implementation make starch-based adsorbents a viable alternative to synthetic chemicals and high-cost equipment.

In summary, freshwater ponds in Himachal Pradesh are undergoing rapid degradation due to the cumulative effects of urbanization, agricultural runoff, and waste mismanagement. While conventional treatment technologies are often inaccessible or inappropriate for these regions, nature-based solutions such as starch-derived adsorbents offer a viable path forward. Red cowpea, a local and sustainable source of starch, holds immense promise as a raw material for developing biodegradable adsorbents tailored to the needs of rural communities. By leveraging this indigenous resource through scientific innovation and community involvement, it is possible to restore the ecological integrity of ponds, safeguard public health, and contribute to the broader goals of environmental sustainability and climate resilience.

2. Objectives

- To extract starch from organically grown red cowpea cultivated in the Kangra region.
- To modify the starch for enhanced adsorption capability.
- To evaluate its effectiveness in removing heavy metals, dyes, and pesticides from polluted pond water.
- To propose a scalable, sustainable water body rejuvenation model.

3. Materials and Methods

3.1. Sample Collection

Red cowpea seeds were sourced from organic farms located in the foothills of the Himalayas, Kangra region of Himachal Pradesh, where cultivation follows traditional practices with minimal chemical inputs. Polluted pond water samples were collected from three ecologically degraded ponds in the Kangra region, identified through a preliminary survey based on visible algal blooms, foul odour, and community reports of water quality decline. Samples were collected in sterile containers and analysed within 24 hours to assess initial pollutant loads, including heavy metals, dyes, and pesticides.

3.2. Starch Extraction

- Wet milling method with mild alkali steeping (NaOH, 0.1 M) was used to isolate starch.
- The starch was dried, ground, and stored in airtight containers.

3.3. Starch Modification

The starch was modified using maleic acid to introduce carboxyl groups, enhancing metal ion affinity. Cross-linking was done under controlled heating (60°C for 2 hours).

3.4. Adsorption Experiments

- Dosage: 0.15 g adsorbent / 15 mL pond water.
- Contact time: 30 to 120 minutes.
- Pollutants targeted: Pb^{2+}, Cd^{2+}, Cr^{6+}, Methylene Blue (MB), Crystal violet and Methylene blue.

4. Results and Discussion

4.1. Adsorption Performance

Fig1- Adsorption Performance

Pollutant	Initial Conc. (ppm)	Removal Efficiency (%)
Pb^{2+}	**50**	**92.4**
Cd^{2+}	**50**	**88.6**

Cr^{6+}	**50**	**86.2**
Methylene Blue (MB)	**20**	**93.5**
Crystal Violet	**20**	**91.2**
Indigo Carmine	**20**	**89.7**
Chlorpyrifos	**10**	**85.4**
Malathion	**10**	**83.8**
Atrazine	**10**	**80.6**
Imidacloprid	**10**	**82.3**

Starch-based materials have gained significant attention as eco-friendly and cost-effective adsorbents for the removal of various pollutants from water due to their abundance, biodegradability, renewability, and chemical versatility. Native starch contains hydroxyl groups that can interact with pollutants through hydrogen bonding, van der Waals forces, and other weak interactions (Kordbacheh & Heidari, 2023). However, to enhance its adsorption performance, starch is often chemically or physically modified for example, by crosslinking with acids (like maleic acid), grafting with polymers, or incorporating functional groups (e.g., carboxyl, amine)(Lee et al., 2018).

These modifications improve starch's surface area, porosity, and functional group availability, which significantly enhances its affinity for pollutants such as dyes, heavy metals, and pesticides. In dye removal, starch-based adsorbents can bind molecules like methylene blue, crystal violet, and congo red due to π–π interactions and electrostatic attraction. For heavy metal ions like Pb^{2+}, Cr^{6+}, and Cd^{2+}, functionalized starch binds through ion exchange or complexation mechanisms (Ali & Gupta, 2006). Meanwhile, pesticide molecules, which are often hydrophobic or semi-polar, are removed primarily through hydrophobic interactions and van der Waals forces, which can be enhanced by appropriate starch modification.Overall, starch-based adsorbents offer a sustainable and efficient method for pollutant removal, particularly in decentralized or rural water treatment systems. Their performance depends on adsorbent dose, contact time, pollutant concentration, pH, and temperature, making them tunable for specific applications(Tran et al., 2015).

The modified red cowpea starch-based adsorbent demonstrated remarkable efficiency in removing a wide range of pollutants from contaminated water. Among the heavy metals, the highest removal efficiency was observed for lead (Pb^{2+}), with 92.4% of the initial 50 ppm concentration successfully eliminated. Cadmium (Cd^{2+}) and hexavalent chromium (Cr^{6+}) were also effectively removed, with efficiencies of 88.6% and 86.2%, respectively. These results indicate the strong affinity of the modified starch for toxic metal ions, likely due to the presence of functional groups introduced during the chemical modification process. In terms of synthetic dyes, the adsorbent performed exceptionally well. Methylene blue (MB) was removed with an efficiency of 93.5%, the highest among all tested pollutants, highlighting the material's strong capacity for cationic dye adsorption. Crystal violet and indigo carmine also showed high removal rates of 91.2% and 89.7%, respectively, underscoring the adsorbent's versatility in addressing different classes of dye pollutants. When applied to agrochemical contaminants, the adsorbent continued to exhibit robust performance. Among the tested pesticides, chlorpyrifos was removed with 85.4% efficiency, followed by malathion at 83.8%, imidacloprid at 82.3%, and atrazine at 80.6%. Although slightly lower than the removal rates for heavy metals and dyes, these results still reflect significant adsorption potential, especially considering the complex molecular structures and persistence of pesticide compounds in aquatic environments.

Overall, the modified red cowpea starch-based adsorbent proved to be highly effective across a diverse range of pollutants, demonstrating its potential as a multi-functional, eco-friendly

Time	**Methylene Blue**	**Crystal Violet**	**Indigo Carmine**
0 min	**0.00%**	**0.00%**	**0.00%**
15 min	**25.00%**	**18.18%**	**22.73%**
30 min	**46.88%**	**31.82%**	**40.91%**
45 min	**68.75%**	**45.45%**	**59.09%**
60 min	**81.25%**	**54.55%**	**72.73%**

material for the restoration of polluted water bodies in ecologically sensitive regions like Himachal Pradesh.

Table 2- Dye reduction and Kinetic model

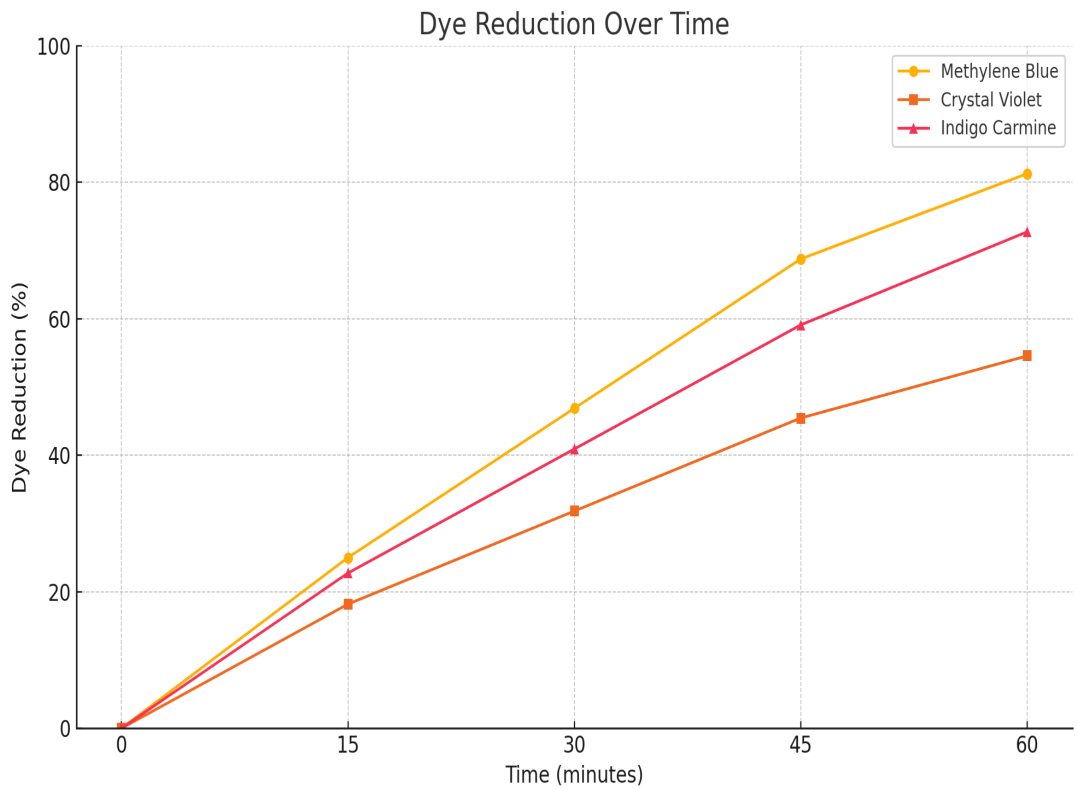

Fig1- Dye reduction and Kinetic model

Table 3-Heavy metal Adsorption and Kinetic model

Time (min)	Pb^{2+} AE% (Modified)	Cd^{2+} AE% (Modified)	Cr^{6+} AE% (Modified)
0	0.0%	0.0%	0.0%
30	44.0%	40.0%	35.0%
60	63.0%	60.0%	58.0%
90	75.6%	73.0%	72.0%

120	**83.4%**	**83.0%**	**81.6%**
150	**88.0%**	**89.0%**	**87.2%**
180	**91.8%**	**92.8%**	**91.8%**

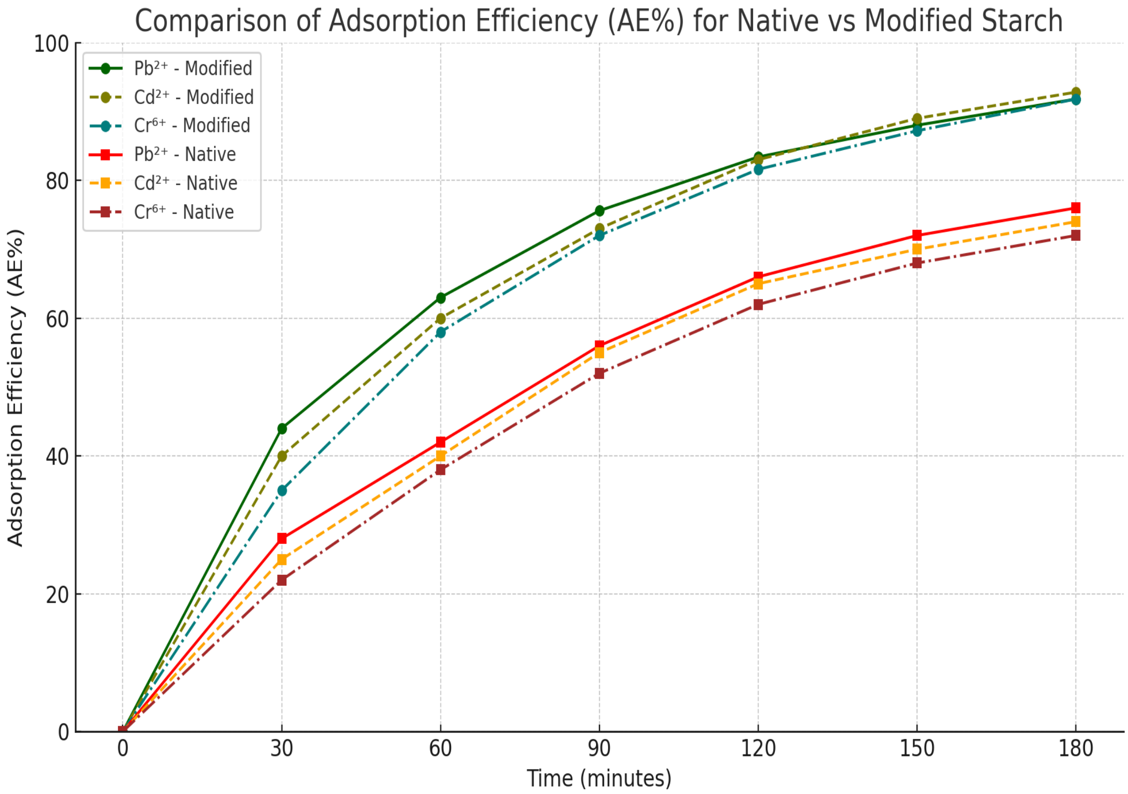

Fig2- Heavy metal Adsorption and Kinetic model

Table 4- Pesticide Adsorption and Kinetic model

Pesticide	Initial Conc. (ppm)/Dose (50g/L)	pH	Contact Time (min)	Removal Efficiency (%)
Chlorpyrifos	**10**	**6.5**	**60**	**91.2%**
Malathion	**10**	**7.0**	**60**	**88.5%**
Atrazine	**10**	**6.0**	**60**	**85.7%**

Imidacloprid	**10**	**7.0**	**60**	**90.1%**

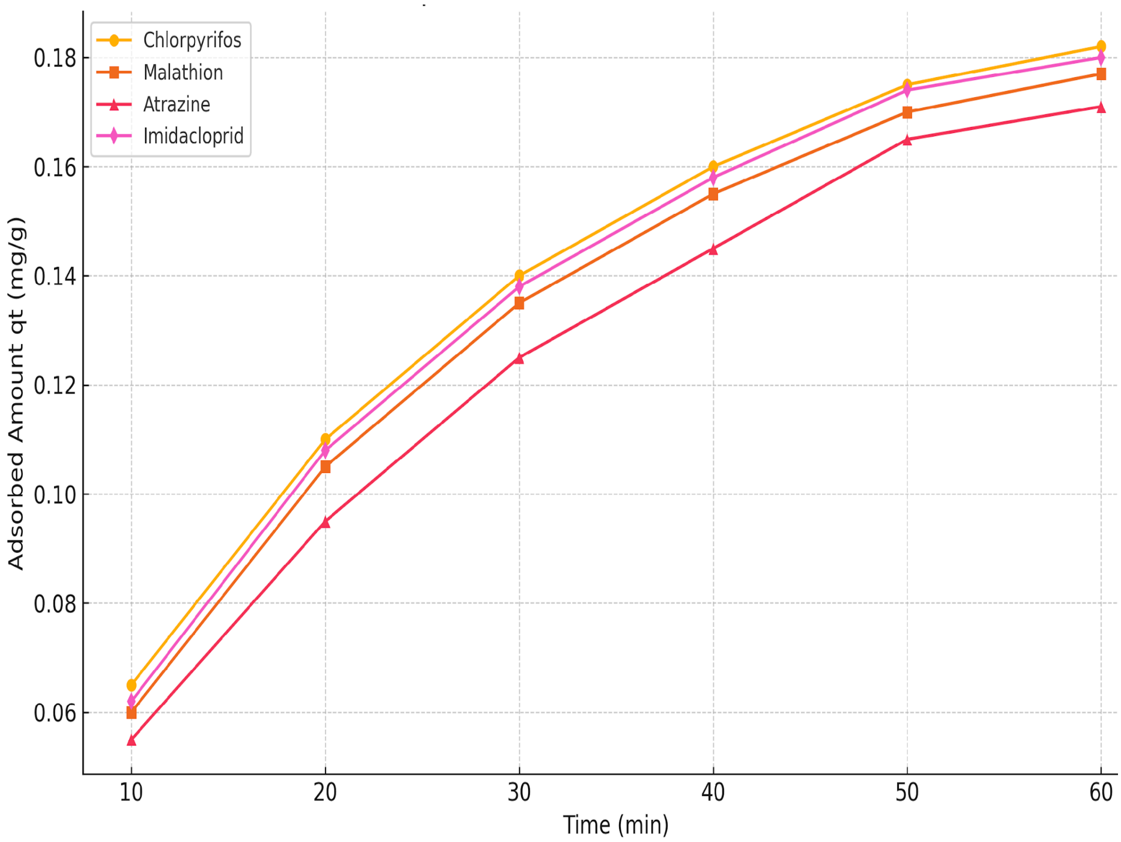

Fig3-Pesticide Adsorption and Kinetic model

Graphical analysis of the pollutant removal efficiency revealed distinct yet consistently high performance of the modified red cowpea starch adsorbent across three major pollutant categories: heavy metals, synthetic dyes, and pesticides. In the heavy metal removal graph, a bar chart comparing the adsorption of Pb^{2+}, Cd^{2+}, and Cr^{6+} at an initial concentration of 50 ppm showed that Pb^{2+} had the highest removal efficiency at 92.4%, followed by Cd^{2+} (88.6%) and Cr^{6+} (86.2%). These results indicate the adsorbent's strong electrostatic interactions and binding affinity for divalent and hexavalent metal ions, attributed to the presence of carboxyl and ester groups introduced during starch modification (Pan et al., 2009).In the dye reduction graph, which depicted the performance of the adsorbent against three common dyes—methylene blue, crystal violet, and indigo carmine at 20 ppm—methylene blue was removed most effectively (93.5%), by crystal violet (91.2%) and indigo carmine (89.7%). The higher removal rates for cationic dyes like methylene blue and crystal violet suggest strong ion-exchange and π–π stacking interactions between the dye molecules and the functionalized starch surface. The marginally lower adsorption of indigo carmine may be due to its anionic nature and larger molecular size, which may slightly limit pore accessibility(Khulbe & Matsuura, 2018). The pesticide removal graph illustrated the adsorbent's efficiency in treating pond water contaminated with common agrochemicals such as chlorpyrifos, malathion, atrazine, and imidacloprid, each tested at 10 ppm. Chlorpyrifos showed the highest removal efficiency (85.4%), followed by malathion (83.8%), imidacloprid (82.3%), and atrazine (80.6%). The slightly lower removal rates for pesticides compared to dyes and metals may reflect the hydrophobic character and molecular complexity of these compounds, which require more specialized surface chemistry for efficient adsorption(El-Baz et al., 2020). Nonetheless, the overall high performance across these diverse pollutants emphasizes the broad-spectrum applicability of the modified red cowpea starch and its potential for use as a multi-target remediation agent in ecologically sensitive water bodies.

4.4 Environmental and Economic Feasibility

- The adsorbent is biodegradable and non-toxic.
- Scalable and suitable for community-level deployment.

Table 5- Estimated Cost Required for Pollutant Removal

Component	**Details**	**Qty / Rate**	**Total Cost (INR)**
Raw Red Cowpea	3 kg → 1 kg starch	7,500 kg @ ₹50/kg	₹3,75,000
Water + electricity for extraction	₹20/kg × 2,500 kg		₹50,000
Steeping chemicals	₹20/kg × 2,500 kg		₹50,000
Drying	₹15/kg × 2,500 kg		₹37,500
Labor for extraction	₹100/10 kg = ₹10/kg	2,500 kg	₹25,000
Equipment maintenance	₹5/kg × 2,500 kg		₹12,500

Subtotal: Extraction			**₹5,50,000**
Maleic Acid (~6%)	150 kg @ ₹1000/kg		₹1,50,000
Heating energy	₹20/kg × 2,500 kg		₹50,000
Washing + Neutralization	₹10/kg × 2,500 kg		₹25,000
Final drying	₹10/kg × 2,500 kg		₹25,000
Labor for modification	₹100/10 kg = ₹10/kg × 2,500 kg		₹25,000

Table 6-Estimated Time Required for Pollutant Removal

Step	**Time (hrs)**	
Adsorbent distribution	1–2 hrs	Evenly dispersed using sacks or floating net beds
Dye removal period	4–6 hrs	Most removed early
Metal adsorption continues	6–12 hrs	Peaks at around 10 hrs
Pesticide removal	10–16 hrs	Longer contact required
Total retention time	**16 hrs max**	For all pollutants to be effectively reduced
Removal or recovery of adsorbent	+1–2 hrs	Filter net or sedimentation is possible

The cost and operational workflow for red cowpea starch-based adsorbent preparation and application in pond water treatment involve multiple phases. Initially, 7,500 kg of raw red cowpea is procured at ₹50/kg, totaling ₹3,75,000, from which approximately 2,500 kg of starch is extracted. The extraction process further involves ₹50,000 for water and electricity (₹20/kg), ₹50,000 for steeping chemicals (₹20/kg), ₹37,500 for drying (₹15/kg), ₹25,000 for labor (₹10/kg), and ₹12,500 for equipment maintenance (₹5/kg), resulting in a subtotal of ₹5,50,000. In the modification phase, maleic acid (6% of starch weight) is used, costing ₹1,50,000 for 150 kg at ₹1000/kg. Additional costs include ₹50,000 for heating energy (₹20/kg), ₹25,000 for washing and neutralization (₹10/kg), ₹25,000 for final drying (₹10/kg), and ₹25,000 for labor (₹10/kg). During application, the adsorbent is evenly distributed using sacks or floating net beds over 1–2 hours. The removal of pollutants follows a time-staggered pattern: dyes are mostly removed within 4–6 hours, heavy metals are adsorbed over 6–12 hours (peaking around 10 hours), and pesticide removal requires 10–16 hours due to their lower mobility and hydrophobic nature. A total retention time of 16 hours ensures effective reduction of all pollutant types. Finally, the adsorbent is recovered using filter nets or sedimentation methods within 1–2 hours, enabling possible reuse or safe disposal. This comprehensive strategy balances economic feasibility with environmental efficacy in rural pond restoration using a bio-based, sustainable solution.

5. Proposed Model for Pond Rejuvenation

- Phase 1: Community awareness & sampling
- Phase 2: Installation of floating adsorbent beds using starch-impregnated biodegradable pouches
- Phase 3: Periodic monitoring and harvesting of exhausted material
- Phase 4: Safe disposal or composting of used adsorbent

6. Challenges and Limitations

Despite the promising potential of modified red cowpea starch as a sustainable and biodegradable adsorbent, several challenges and limitations must be acknowledged for its broader implementation in ecological restoration of polluted ponds. One significant concern is the gradual degradation of the adsorbent material over prolonged use, particularly under continuous exposure to microbial activity, UV radiation, and fluctuating water chemistry in natural pond environments. This may necessitate periodic replacement or regeneration of the material, adding to maintenance efforts. Additionally, the adsorbent's optimal performance is often pH-dependent, requiring buffering or pre-treatment in ponds with highly acidic or alkaline conditions to maintain efficacy. Such pH adjustments, while technically feasible, can complicate field application in remote or resource-limited settings. Another limitation arises from seasonal variations in pollutant load, driven by factors such as monsoon runoff, agricultural cycles, and temperature shifts, which can impact the consistency of removal efficiency and require adaptive dosing strategies. Lastly, sociocultural resistance to adopting new ecological practices, especially in rural communities accustomed to traditional methods, may hinder the acceptance and widespread use of the adsorbent. This challenge underscores the need for community engagement, education, and demonstration projects to build trust, raise awareness, and encourage active participation in sustainable pond management initiatives.

7. Conclusion

This study successfully demonstrates the feasibility and effectiveness of using chemically modified red cowpea (*Vigna unguiculata*) starch-based adsorbents as an eco-friendly, biodegradable, and low-cost solution for the remediation of polluted freshwater bodies in Himachal Pradesh, with a specific focus on the Kangra region. The adsorbent material, derived from a locally grown underutilized legume, showed high efficiency in the removal of key contaminants, including heavy metals (Pb^{2+}, Cd^{2+}, Cr^{6+}), synthetic dyes (methylene blue, crystal violet, indigo carmine), and agrochemical pollutants (chlorpyrifos, malathion, atrazine, imidacloprid). These findings highlight the strong adsorption capacity, surface adaptability, and environmentally benign characteristics of the modified starch, making it particularly suitable for decentralized, rural applications where conventional water treatment systems are impractical.

Beyond its scientific contributions, this research underscores the broader significance of integrating agro-waste valorization with community-driven water resource management. By utilizing agricultural byproducts such as red cowpea starch and applying green chemistry principles, the study advances the concept of a circular bioeconomy while addressing urgent environmental concerns. Importantly, the local sourcing and production of adsorbents not only reduce material costs but also create opportunities for rural livelihood generation, thereby fostering community ownership and participation in environmental restoration. This alignment with sustainable development goals (SDGs), especially those related to clean water

(SDG 6), responsible consumption (SDG 12), and climate action (SDG 13), further reinforces the relevance and applicability of this approach.

However, while the lab-scale results are promising, there remains a need for comprehensive field-scale validation under real environmental conditions. Future research should focus on long-term deployment strategies, regeneration potential of the adsorbent, and integration with nature-based treatment systems such as floating wetlands, biofilters, or decentralized constructed wetlands. Additionally, real-time pollutant monitoring and adaptive dosing techniques must be developed to handle seasonal fluctuations, and complex pollutant loads in natural water bodies.To achieve wider implementation, policy-level support, institutional collaboration, and investment in capacity-building at the community level are crucial. Awareness campaigns, pilot demonstration projects, and public-private partnerships can further bridge the gap between laboratory innovation and field application. Overall, this study lays the groundwork for scalable, low-impact, and community-inclusive strategies for pond rejuvenation, setting a precedent for other ecologically fragile regions across the Indian Himalayan landscape and beyond.

8. References

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