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EFFICIENT WASTEWATER TREATMENT THROUGH INTEGRATED WATER HYACINTH SYSTEMS: ADVANCES AND APPLICATIONS IN CONCRETE

UČINKOVITA OBDELAVA ODPADNE VODE S POMOČJO V VODO INTEGRIRANEGA HIJACINTNEGA SISTEMA: DEJANSKI NAPREDEK IN UPORABA BETONA

Ananthakumar Ayyadurai*, **Saravanan M M, Devi M**

Vivekanandha College of Technology for Women, Tiruchengode 637205, Tamilnadu, India

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This research focuses on enhancing water quality for concrete construction by utilizing treated wastewater from wetlands. The study employs a dual-stage treatment process involving charcoal and aggregate layers for primary treatment, followed by water hyacinths for secondary treatment. Investigating water hyacinths' ability to absorb nutrients and contaminants from wastewater is a unique aspect of the study, offering a potential solution for soil and water remediation. Water hyacinths, especially stems and leaves, act as natural filters, effectively indicating heavy-metal pollution in tropical regions. The primary goal is heavy-metal removal from wastewater, allowing treated-water use in concrete production at varying proportions (20 %, 40 %, 60 %, 80 %, and 100 %). Silica fume at 15 % concentration is incorporated to enhance the concrete's durability. Concrete specimens undergo thorough preparation and mechanical property evaluations, compared to conventional M20-grade concrete. The results reveal improvements in mechanical properties, particularly with 80 % treated wastewater in the mix. The dual-stage treatment process removes heavy metals, and the inclusion of silica fume enhances the concrete's durability and resistance.

Keywords: Eichhornia Crassipes, wetland, biological treatment, charcoal, heavy metal, silicafume, compressive strength, flexural strength, split tensile strength

Avtorji opisujejo raziskavo osredotočeno na izboljšanje kakovosti vode za betonske konstrukcije z uporabo obdelane odpadne vode iz močvirij. V študiji so uporabili dvostopenjski postopek obdelave. V primarni fazi obdelave so uporabili oglje in plasti agregatov. Tej je sledila sekundarna faza obdelave vode z vodnimi hijacintami. Raziskovali so sposobnost vodnih hijacint za absorpcijo hranil in onesnaževalcev v odpadni vodi, kar je edinstvena ideja te študije. Vodne hijacinte, še posebej stebla in listi delujejo kot naravni filtri in učinkovito kažejo onesnaženost tropskih območij s težkimi kovinami. Glavni namen te študije je odstranitev težkih kovin iz odpadne vode in uporaba različnih deležev (20 %, 40 %, 60 %, 80 %, and 100 %) obdelane vode za izdelavo betona. Dodatno izboljšanje trajnosti izdelanega betoda so dosegli še z dodatkom 15 % silike v obliki zelo drobnih delcev (prahu). Izdelali so vzorce iz betona in določili njihove mehanske lastnosti v primerjavi s konvencionalnim betonom M20. Rezultati raziskave so pokazali pomembno izboljšanje mehanskih lastnosti tako obdelanega betona. Še posebej se je to pokazalo pri uporabi 80 %-nega deleža obdelane odpadne vode. Proces dvostopenjske obdelave učinkovito odstrani težke kovine, dodatek silike pa izboljša trajnost in odpornost betona.

Ključne besede: vodna hijacinta (Eichhornia Crassipes), močvirja, biološka obdelava, oglje, težke kovine, zelo drobna (fina) silika, tlačna trdnost, flexural strength, cepilna natezna trdnost

1 INTRODUCTION

Global water scarcity has emerged as a pressing challenge, necessitating the preservation of water resources amidst the development of advanced technologies for wastewater treatment and recycling. The storage and strategic use of circulating water have become essential practices to address water scarcity. Wastewater discharge poses a grave threat to ecosystems globally, with industrialization, civilization, and rapid population growth being primary contributors to environmental pollution. Recognizing the impending significance of water in future construction and building needs, this research is dedicated to mitigating society's wastewater production and water demands.

The study investigates the impact of wastewater and waste slurry on the strength and durability of concrete specimens, shedding light on specific changes in compressive strength, flexural strength, and other mechanical properties.[1] An innovative approach involves utilizing carbonized water hyacinth to enhance phase-change energy-storage materials, demonstrating its efficacy in encapsulating and improving the thermal conductivity of these materials.[2] Furthermore, the research explores sustainable practices in green concrete construction by developing biomaterial fillers using eggshells, water hyacinth fibers, and banana fibers.[3] An environmentally friendly solution is presented through the creation of thermal insulation boards from wheat bran and banana peels, showcasing the repurposing of agricultural waste into construction materials.[4]

The study also delves into a water footprint analysis, emphasizing the environmental impact of construction

*Corresponding author's e-mail:
ananthaakumar7410@gmail.com (Ananthakumar Ayyadurai)

and advocating for the incorporation of regional architectural traditions into contemporary construction for enhanced sustainability.[5] Another focus lies in the efficient separation of concrete waste through heat-mechanical synergistic treatment, offering a promising technique for recycling concrete and reducing the environmental footprint of construction materials.[6] Valuable insights into the mechanical properties of recycled aggregate concrete derived from waste concrete treated at high temperatures contribute to our understanding of sustainable construction practices.[7] Additionally, the research aligns with the trend of incorporating agricultural waste ashes, such as olive, rice husk, and sugarcane leaves, to enhance ultra-high-performance concrete, promoting eco-friendly formulations and multi-waste stream utilization.[8] The exploration of the potential use of natural materials in concrete mixtures underscores the broader commitment to sustainable construction practices.[9] The utilization of water hyacinth for wastewater treatment in residential settings is also investigated, emphasizing the environmental aspects and potential benefits of incorporating treated wastewater into concrete production.[10]

Water assumes paramount significance in construction sites, influencing the characteristics of both fresh and hardened concrete. The mineral properties of water must be scrutinized before concrete application, as this research addresses the imperative need to minimize society's wastewater generation and facilitate its treatment for diverse applications. A primary focus is on utilizing water hyacinth (Eichhornia Crassipes) as a bio-filter, assessing its potential to effectively remove pollutants from wastewater. This study delves into the influence of wastewater types on concrete properties, providing valuable insights into how wastewater composition shapes concrete characteristics.[11] Emphasizing the practical application of treated wastewater in concrete mixing, the research underscores the importance of sustainable water-management practices, particularly in arid regions.[12] Investigating the stability of cemented dried water hyacinth for the biosorption of radionuclides sheds light on potential applications in nuclear-waste management.[13] Exploring innovative methods to enhance concrete's mechanical properties, the study investigates the compressive behavior of low-strength concrete confined with water hyacinth and jute non-woven fiber-reinforced polymer (NFRP).[14] Additionally, understanding the broader context of water hyacinth invasion becomes crucial for formulating strategies to address challenges and harness potential benefits.[15] The research also delves into the phyto-accumulation of heavy metals by water hyacinth, proposing a sustainable approach for industrial wastewater treatment and highlighting its potential in phytoremediation.[16]

The treatment process involves biological treatment and heavy-metal removal from contaminated water, with charcoal playing a key role in the initial removal of impurities, addressing odor and color concerns. Wastewater-treatment findings underscore the potential utilization of treated water in concrete construction and various other applications.

1.1 Literature review

This review delves into the multifaceted applications of water hyacinth (Eichhornia crassipes) and water lettuce (Pista stratiotes) in curbing nutrient build-up in municipal wastewater, emphasizing their potential contributions to sustainable wastewater management.[17] It further explores the phytoremediation capabilities of water hyacinth in addressing industrial mine wastewater, showcasing its effectiveness in absorbing and mitigating contaminants from diverse industrial sources.[18] A crucial aspect of wastewater treatment involves the removal of organic matter and key nutrients, such as nitrogen and phosphorus. Traditional methods, utilizing activated carbon, have limitations, necessitating the exploration of alternative approaches.[19,20] Water hyacinths, with their unique ability to absorb nutrients and pollutants from water, emerge as a promising solution for wastewater treatment. Their extensive fibrous root system plays a pivotal role in pollutant extraction, primarily through the roots, preventing toxicity by efficiently absorbing and accumulating contaminants.[21] An examination of wastewater treatment by hyacinths reveals their biodegradable nature and remarkable ability to absorb heavy metals, offering an environmentally friendly and cost-effective method for wastewater treatment.[23,24] Additionally, a comprehensive investigation into the use of water hyacinth for treating industrial wastewater showcases its ability to remove coliforms, lower chemical oxygen demand (COD), and address heavy-metal contamination.[25] Beyond wastewater treatment, water hyacinths demonstrate versatile applications, ranging from aquaculture to biogas production, cow feed, waste manure, and industrial raw materials.[29]

The efficacy of water hyacinth in aquaculture wastewater filtration is explored in comparison with lettuce and parrot feathers.[30] This study confirms the potential of aquatic plants, including water hyacinth, in reducing contaminants within aquaculture effluent, supporting the applicability of wastewater recycling in aquaculture.[31] The utilization of water hyacinth waste in producing fiber-reinforced polymer composites for concrete confinement is evaluated for both mechanical performance and environmental implications.[35] Furthermore, studies on wastewater bioremediation using water hyacinth highlight its effectiveness in reducing COD levels, meeting environmental standards.[36,37] The incorporation of recycled aggregates and treated wastewater in concrete construction is explored for its potential in sustainable practices.[38,39] Understanding the impact of wastewater on concrete properties and the practical implications of incorporating treated wastewater in construction materials is essential for ensuring durability and structural integrity.[40,41] Additionally, the study investigates the performance of concrete incorporating ground-granulated blast-furnace slag (GGBS) in aggressive wastewater environments, providing insights into concrete durability under challenging conditions.[45] Finally, the incorporation of water-hyacinth ash into concrete is examined as a means of developing a sustainable building material.[46]

1.2 Review Analysis

1.2.1 Wastewater Treatment Utilizing Water Hyacinth

The exploration commences with a comparative assessment of water hyacinth and water lettuce in averting nutrient accumulation in municipal wastewater. It subsequently scrutinizes the phytoremediation of industrial mine wastewater using water hyacinth, highlighting its adeptness in absorbing and alleviating contaminants across diverse industrial contexts. The study underscores the removal of organic matter and crucial nutrients, such as nitrogen and phosphorus, from wastewater, thereby mitigating the adverse effects associated with wastewater pollution.

1.2.2 Challenges Inherent in Traditional Wastewater-Treatment Approaches

The literature articulates the drawbacks associated with traditional wastewater-treatment methodologies, citing elevated installation costs, operational intricacies, and substantial spatial demands. These challenges raise environmental concerns, necessitating the development of cost-effective alternatives.

1.2.3 Water Hyacinth's Integral Role in Wastewater Treatment

The review meticulously explores the pivotal role played by water hyacinth in wastewater remediation. Emphasis is placed on its biodegradability, intricate fibrous root system, and proficiency in absorbing heavy metals and minerals from wastewater. Studies showcased its efficacy in diminishing concentrations of contaminants like coliforms, biochemical oxygen demand (BOD), COD, dissolved oxygen (DO), total dissolved solids (TDS), total suspended solids (TSS), nitrogen, and phosphorus.

1.2.4 Diverse Applications Beyond Wastewater Treatment

Beyond its primary role in wastewater treatment, the analysis encompasses a spectrum of applications for water hyacinth. These include its potential as a raw material for aquaculture, biogas production, and fertilizer. Discussions extend to its adaptability for aquaculture, acting as a biofilter for domestic wastewater treatment, and its integration into concrete for the creation of sustainable building materials.

1.2.5 Emphasis on Eco-Friendly and Sustainable Solutions

Consistently, the review underscores the eco-friendly nature of water hyacinth-centric wastewater treatment. Its capacity to enhance water quality, address specific challenges posed by industrial pollution, and contribute to biomass production in floating systems underscores its potential for widespread adoption in sustainable and environmentally conscious wastewater-management practices.

1.2.6 Considerations in Design and Long-Term Effectiveness

The literature broaches design considerations for systems incorporating water hyacinth in constructed wetlands, accentuating their potential to augment the efficiency of such systems for environmentally friendly wastewater treatment. Long-term studies provide evidence of the effectiveness of water hyacinth beds in ameliorating water quality in urban canals.

1.2.7 Integration into Building Materials

The final segment introduces an innovative application of water-hyacinth ash in concrete, signaling its potential to influence concrete properties and contribute to the development of sustainable building materials.

2 EXPERIMENTAL SETUP

The experimental setup involves the collection of treated wastewater from wetlands following a dual-stage treatment process, which includes primary treatment with charcoal and aggregate layers and secondary treatment with water hyacinths. Ordinary Portland cement (OPC) acts as the binding agent, and fine aggregates meeting specified concrete production standards are utilized. Additionally, the concrete mix incorporates silica fume, a highly reactive pozzolanic material, at a concentration of 15 %. Various proportions of treated wastewater (20 %, 40 %, 60 %, 80 %, and 100 %) replace conventional mixing water in the concrete mix. To ensure uniformity, a concrete mixer with a known mixing capacity is employed to prepare the batches. Standard molds, such as cubes, cylinders, and prisms, are utilized to cast concrete specimens for subsequent testing. These specimens undergo controlled curing conditions, involving specific temperature and humidity settings, to simulate real-world concrete-curing scenarios. Testing apparatuses, following standard procedures, are employed to assess properties such as compressive strength (CS), tensile strength, flexural strength and density. The mechanical properties of the concrete specimens for each mix proportion are measured and recorded. Statistical analysis is then conducted to compare the mechanical properties of the concrete specimens utilizing treated wastewater at varying proportions with those of conventional M20 grade concrete. The interpretation of results aims to identify the optimal proportion of treated wastewater and evaluate the efficacy of the water-hyacinth-based secondary treatment in enhancing concrete properties.

2.1 Methods

2.1 Materials Used

Harvested (water hyacinth) from natural water bodies, water hyacinths with bluish-purple, fresh, and lush appearances are collected, ensuring they are healthy and uncontaminated. Thorough cleaning, including rinsing with clean water, precedes their use for pollutant removal in domestic wastewater. Silica fume is derived from silicon and ferrosilicon alloys; silica fume is an ultrafine concrete particle. Handled with care to prevent inhalation, it enhances concrete properties by reducing thermal cracking and increasing resistance to acid waste erosion. Charcoal produced by burning organic matter in a low-oxygen atmosphere, charcoal is collected from the south zone. It undergoes a high-temperature burning process to remove water and volatile elements. Quality charcoal, free from contaminants, is crucial for effective primary treatment. Activated charcoal, with a high adsorption surface area, may be preferred, and particle size uniformity can be ensured through sieving or screening. Coal is derived from burning wood or organic matter in a low-oxygen environment, coal is characterized by low thermal and electrical conductivity due to its amorphous structure. Depending on raw-material density, its density ranges from 0.2 t/m^3 to 0.6 t/m^3. Raw wastewater samples (**Figure 1**) are collected daily from an urban sewage-treatment plant in Tamil Nadu, India, for performance evaluation. Ten water-quality parameters (pH, COD, BOD, DO, TSS, TN, NH3-N) are assessed at 24-hour intervals. The specific gravity of cement 3.13, an initial setting time of 35 min, a total setting time of 270 min, and 33 % consistency when made using OPC grade 53. Natural crushed stone (size 20 mm) with a specific gravity of 2.56, water absorption rate of 0.45 %, and coarse aggregate fineness coefficient of 1.22, verified according to Indian Standard Specification IS 383-1970. Maximum particle size of fine aggregate (M-sand) 4.75mm, specific gravity of 2.32, water absorption rate of 1.42 %, and particle size coefficient of 2.24. Domestic wastewater collected from an urban sewage-treatment plant in 20-liter capacity containers. Collected samples follow safety protocols, including the use of personal protective equipment. Clean, sterile containers are used, and a representative sample is obtained through multiple grabs or composite sampling over a specific time interval. Metadata such as date and time are recorded, and collected samples are stored in a cool environment to slow down biological and chemical reactions before analysis. Physical properties of the materials as shown in **Table 1**.

Figure 1: Photographs of the materials

Table 1: Physical properties of raw material.

Physical Properties	Cement	Fine aggregate	Coarse aggregate	Silica fume
Specific gravity	3.13	2.32	2.56	2.24
Color	Dark grey	Light grey	Blackish	White
Loose bulk density (kg/m^3)	1332	1210	–	580
LOI (%)	3.12	0.48	–	0.51

2.2 Wastewater Treatment

Wastewater undergoes a multi-step treatment process before reaching water hyacinths. Initially, pretreatment diverts the wastewater collected from various sources, such as households, industries, and municipal sewer systems. This raw wastewater may contain a mix of organic and inorganic contaminants, suspended solids, nutrients, and other pollutants.

2.2.1 Primary Treatment

This phase focuses on physical and chemical treatments to eliminate large, suspended solids and reduce the organic load in the wastewater. The process involves the sequential flow through different layers. Charcoal serves as an adsorbent for organic compounds and certain chemicals, effectively removing odors and colors. The subsequent layer, composed of larger particles like gravel or crushed stone, acts as a physical barrier to remove substantial debris and sediments. The final primary treatment layer, using sand or similar particles, aids in trapping and settling smaller suspended solids. This layered arrangement facilitates the gradual settling of solids, organic compound adsorption, and impurity removal. Some mixing and aeration may be applied during primary treatment to enhance solid settling and separation (**Figure 2**).

2.2.2 Secondary Treatment

Following the primary treatment, the secondary stage focuses on biological treatment to further eliminate organic matter, nutrients (such as nitrogen and phosphorus), and other contaminants from the wastewater. Water hyacinth serves as the treatment agent during this phase. As a floating aquatic plant, water hyacinth excels in absorbing and metabolizing nutrients and organic pollutants from water. Its roots and foliage provide a habitat for beneficial microorganisms that contribute to organic

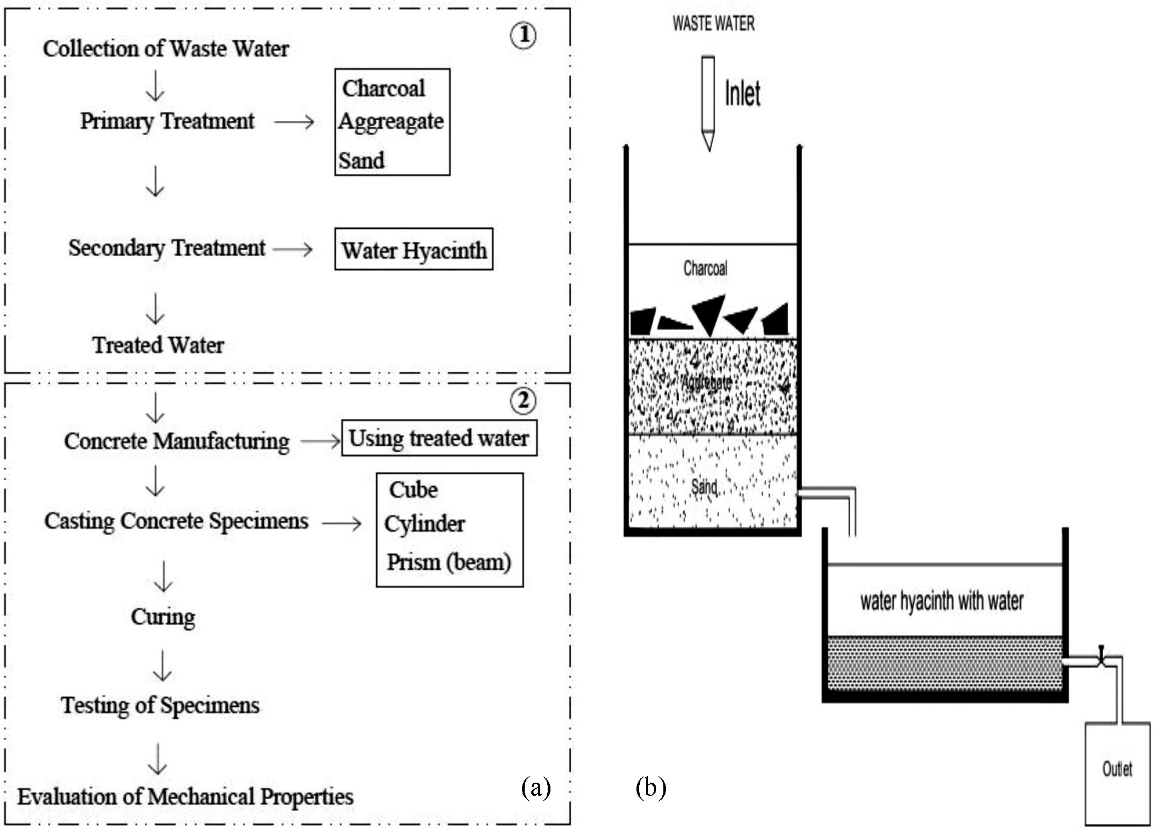

Figure 2: a) Methodology and b) wetland treatment process

Table 2: Wastewater physicochemical parameters before and after treatment with *Eichhornia Crassipes*

Parameters	pH		DO mg /L		TSS mg /L		TDS mg /L		TS mg /L		BOD mg /L		COD mg /L		NO_3 mg /L		Chlorides mg /L	
	*B.T	*A.T	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T
Waste water	8.8	7.2	0.6	6.5	1925	935	1258	636	3175	1510	220	125	335	145	9.6	1.4	45.02	33.80

* Before treatment (B.T.) and after treatment (A.T.)

matter breakdown. Treatment conditions for water hyacinth require maintaining suitable water-quality parameters, including temperature, pH, and nutrient levels, to support its growth and pollutant-removal capabilities (**Figure 2**).

2.2.3 Monitoring and Analysis

Assessing pollution levels and the efficacy of water treatment, wastewater samples are tested before and after treatment using various criteria, including physicochemical and biological parameters (**Figure 3**). Parameters such as pH, color, odor, TDS, TSS, BOD, COD, chlorides, nitrates, and heavy metals are examined (**Table 2**). Eichhornia crassipes is effective as a domestic sewage-treatment agent, with treated samples observed to be clear and odorless. The pH values before and after treatment, depending on dilution groups, approach neutrality.

The initial pH recorded before treatment was 8.8, which subsequently lowered to 7.2 at 100 percent dilution. This aligns with the wastewater guidelines of the Central Pollution Control Board of India, suggesting ef-

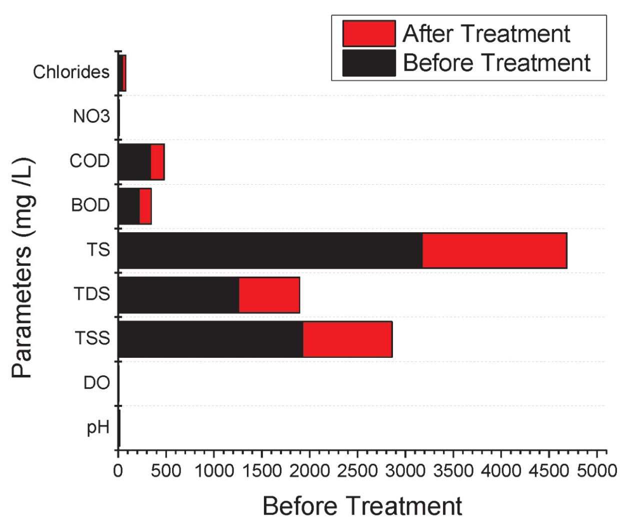

Figure 3: Physiochemical parameters of the treated wastewater

fective treatment across all tests, maintaining the pH within the recommended range of 6.5–7.5. DO levels exhibited a significant change following various hyacinth water dilutions for wastewater treatment. Untreated wastewater, rich in organic and inorganic substances, displayed low DO content and emitted a foul odor. However, post-treatment, a substantial increase in DO levels was observed. Specifically, the 100 % diluted OD increased from 0.6 before treatment to 6.5 mg/L after treatment, indicating improved water quality.

The assessment of TDS, TSS, and Total Solids indicated an overall increase, with the highest reduction in solid content observed at 100 % dilution. BOD values were calculated before and after processing, revealing a decrease from 220 mg/L to 125 mg/L at 100 percent dilution. The observed BOD reduction is influenced by the Hydraulic Retention Time (HRT), where longer retention times enhance interactions within the aquatic plant system, leading to increased organic matter processing efficiency.

Distinct levels of COD were evident across all the dilution series, with a notable decrease from 315 mg/L before treatment to 155 mg/L after treatment at 100 percent dilution. Nitrate concentrations exhibited variations based on dilution, with the most significant decrease observed at 100 percent dilution. The comprehensive study of treated wastewater suggests its suitability for various purposes, including agriculture, laundry, gardening, and planting. **Table 3** provides details on the removal of heavy metals from wastewater before and after treatment.

Table 3: Metal analysis of *Eichhornia Crassipes* plant sections

Metals	Metals Before Treatment in the plant parts (mg)	Metals After Treatment in the plant parts (mg)	Efficiency (%)
Cu	2.105	2.558	21.52
Ni	0.254	0.286	12.59
Co	0.032	0.058	81.25
Fe	0.175	0.224	28.00

The efficacy of water hyacinth in wastewater treatment has been thoroughly examined and documented. The experimental setup involved a semi-continuous wastewater drain tank, both with and without the presence of water hyacinth. **Figures 4** and **5** illustrate the substantial removal of heavy metals from the wastewater, showcasing the plant's effectiveness in enhancing water quality through the treatment process.

Utilizing the formula expressed in Equation (1), the removal efficiencies of metals in various plant parts were assessed after treatment.

$$RE(\%) = \frac{MCAT - MCBT}{MCBT} \cdot 100 \qquad (1)$$

where RE is Removal Efficiency, MCAT is Metal Concentration After Treatment and MCBT is Metal Concentration Before Treatment.

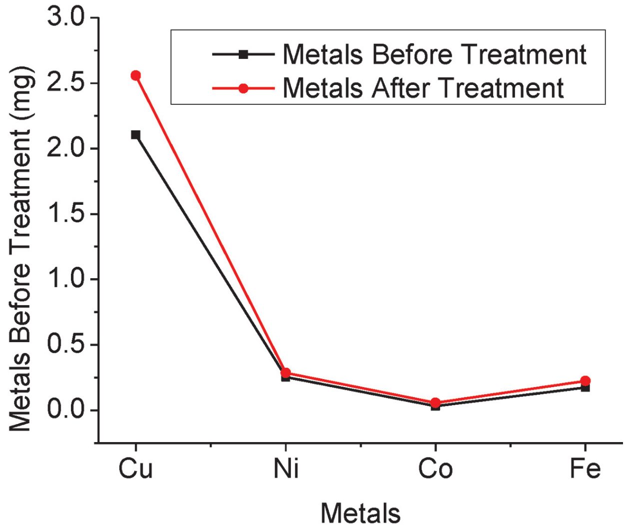

Figure 4: Before and after treatment of heavy-metal removal in waste water

The hyacinth wetlands demonstrated remarkable effectiveness in removing pollutants, with removal percentages of 73 % for BOD, 69 % for COD, 45 % for TS, 100 % for zinc, 32 % for nitrate, 41 % for chloride, and 96 % for sulfate from the wastewater. The quantification

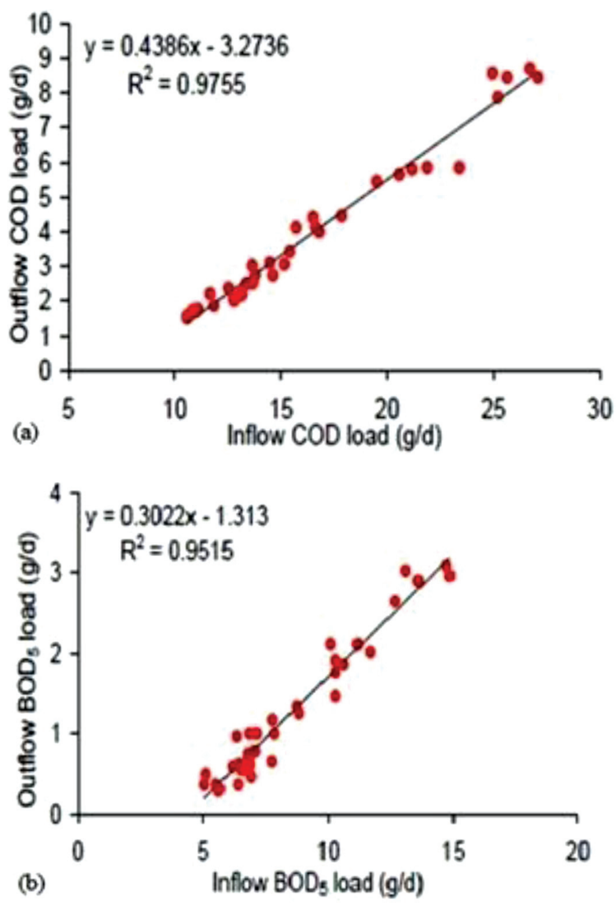

Figure 5: a) Relationship between COD and b) BOD_5 inflow and outflow

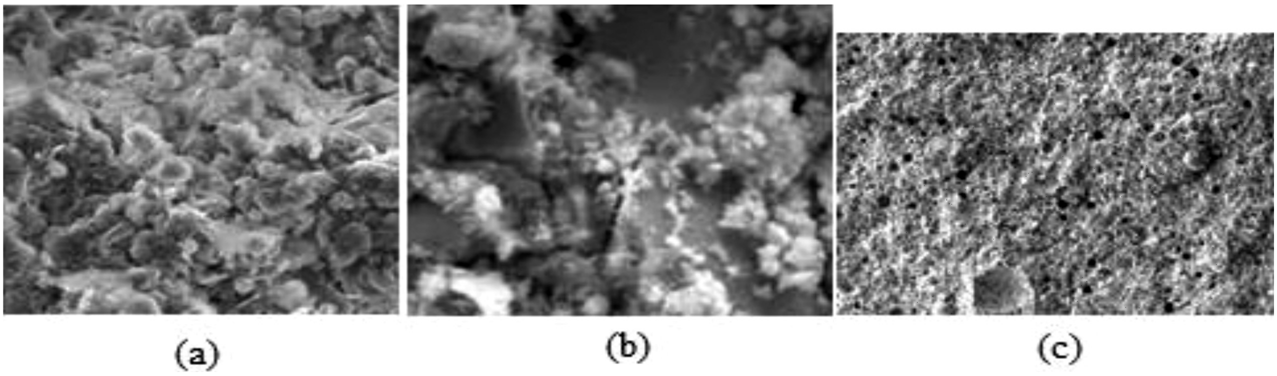

Figure 6: a) SEM image of CSH gel formation, b) SEM image of crack formation, c) SEM image of voids developed

of metal-removal efficiency is determined through the application of Equation (1).

The strength assessment of M20 grade concrete in this study adheres to IS: 456-2000 standards, achieving a compressive strength (CS) of 20 N/mm². Mix design variations using different proportions of treated water were subjected to various tests. Flow rates of 140 ± 20 mm were determined through the test method, employing treated water with a plasticizer at replacement levels of 0 %, 20 %, 40 %, 60 %, 80 %, and 100 %. Silica fume, constituting 15 %, was consistently included in all M20 concrete mixes. The quantities of materials in kilograms required to produce one cubic meter of concrete are detailed in **Table 4**.

Mix identification numbers denote the cement-replacement rate, with self-compacting concrete (SCC) undergoing testing in fresh conditions using cubes, cylinders, and prismatic specimens to regulate both the properties of fresh concrete and enforce mechanical characteristics. Mechanical properties were assessed after 7 d, 14 d, and 28 d of treatment, and the results were compared with the performance of the control concrete.

Table 4: The amount of materials required to produce 1 cubic meter of concrete (kg)

Mix ID	Normal Water (L)	Treated Water	Powder Content (kg/m^3)		Aggregate (kg/m^3)	
			Cement	Silica fume	Fine aggregate	Coarse aggregate
0TW*	146.00	0	408	0	712	1312
20TW	116.80	29.20	346.80	61.20	712	1312
40TW	87.60	58.40	346.80	61.20	712	1312
60TW	58.40	87.60	346.80	61.20	712	1312
80TW	30.00	116.00	346.80	61.20	712	1312
100TW	0	146.00	346.80	61.20	712	1312

*TW – Treated water

3 RESULTS AND DISCUSSION

Following the casting of all samples, a thorough examination of the concrete's mechanical properties was conducted – a crucial step preceding the incorporation of the sample-polymerization process. The polymerization process was conducted at a controlled temperature of 27 ± 20 °C. CS assessments were carried out in accordance with BIS 516 standards. The strengths were subjected to curing periods of 7 d, 14 d, and 28 d. The test strength was determined as the average of three specimens, encompassing CS, split tensile strength, and flexural strength evaluations. **Figure 6** presents the morphological image obtained through scanning electron microscopy of the treated concrete.

Cubes were meticulously cast and subjected to specific curing conditions (temperature and humidity) for the prescribed durations of 7 d, 14 d, and 28 d. Post-curing, the specimens underwent testing in a machine where a gradually applied axial load was administered until specimen failure. The maximum load at failure was recorded, and CS was determined by dividing the maximum load by the cross-sectional area of the specimen.

The CS tests were conducted at 7 d, 14 d, and 28 d, as depicted in **Figure 7**. For conventional concrete, the CS values were 13.65 MPa, 18.35 MPa, and 24.65 MPa on days 7, 14, and 28 for the hardened specimens, respectively. In contrast, the CS of the concrete mixture comprising 80 % treated water, 40 % plain water, and 15 % silica fume (SF) reached 15.56 MPa, 22.58 MPa, and 25.82 MPa at 7 d, 14 d, and 28 d, respectively. These values exhibited increases of 8.6 %, 4.7 %, and 4.8 % in

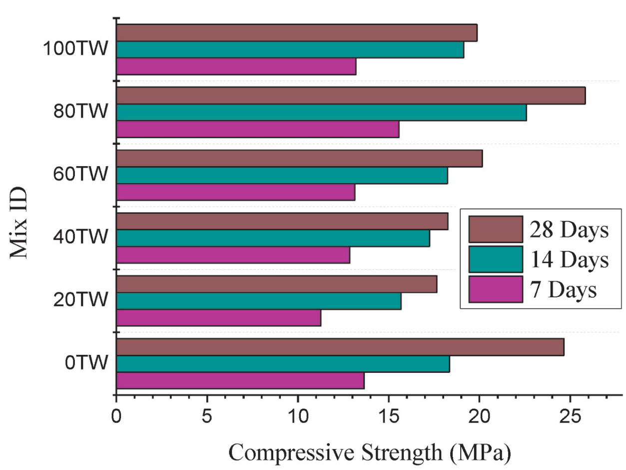

Figure 7: Variation in compressive strengths of concrete

CS compared to conventional concrete at 7 d, 14 d, and 28 d of curing, respectively. The incorporation of SF into the concrete mix contributed to the increased CS. Concrete mixtures with 20–100 % silica-fume-treated water (15 %) demonstrated a slight enhancement in CS compared to conventional concrete.

Specifically, the resistance of concrete to silica fume increased by 80 % when compared to the control concrete. Prismatic specimens, in the form of rectangular bars, were cast and cured under conditions similar to those for the CS specimens. These specimens were positioned on a testing machine with a span length, and a load was applied at the center until the specimen fractured. The maximum load at failure was recorded, and the flexural strength was calculated based on the dimensions of the specimen. Comparatively, the flexural and split tensile strengths of the 80TW concrete exhibited improvements over conventional concrete. As the flexural strength of the 60TW increased gradually, it reached the nominal flexural strength of M20 concrete (4.75 N/mm^2), and the tensile strength value of the 60TW concrete also met the standard value of concrete. **Figures 8** and **9** illustrate the flexural properties and cracking strength of water-treated concrete. The optimal ratio for the concrete mixture in M20-grade water curing is determined to be 80 TW.

The split tensile strength of concrete is a crucial indicator of its resistance to tensile stresses along a plane perpendicular to the direction of loading. This property becomes particularly significant in scenarios where concrete experiences bending or flexural stresses. Cylinders are cast and cured under identical conditions to the CS specimens. Following the designated curing period, the cylindrical specimen is positioned horizontally between two steel bearing plates within a testing machine. A compressive load is then applied along the axis of the cylinder, leading to its rupture along the horizontal plane. This applied load induces tensile stresses within the concrete specimen. The recorded maximum load at which

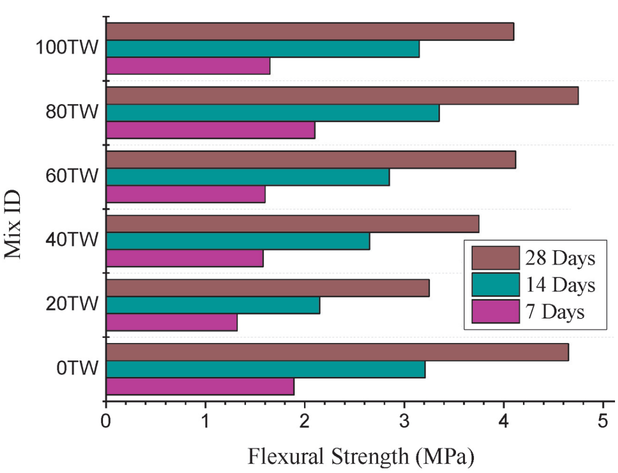

Figure 8: Variation in flexural strengths of concrete

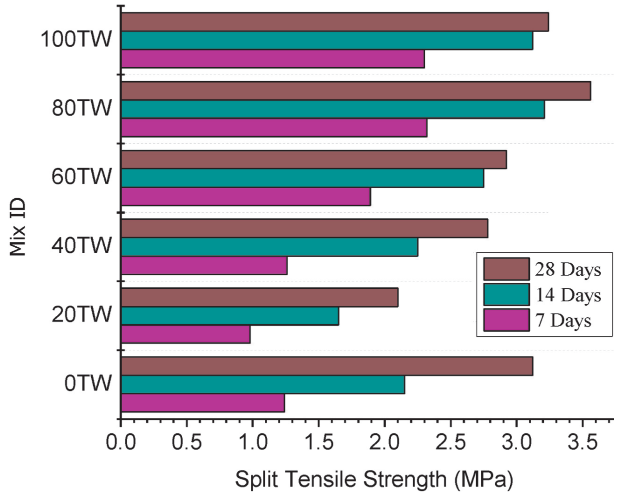

Figure 9: Variation in split tensile strengths of concrete

the cylinder fails (splits) serves as a measure of the concrete's split tensile strength.

This study introduces a novel approach by employing water hyacinth for wastewater treatment, and the treated water is subsequently utilized to enhance concrete strength, thereby reducing the overall water demand in construction. Previous publications have explored wastewater pretreatment using plants. Another study proposed the processing of wastewater as a means to enhance the mechanical properties of the concrete.

3.1 Implications and Significance of the test results

The CS is a fundamental indicator of concrete quality, crucial for assessing its load-bearing capacity. Conventional concrete exhibited the expected increase in CS over time during the curing period. However, the concrete mixture incorporating 80 % treated water, 40 % plain water, and 15 % silica fume consistently demonstrated higher CS compared to the conventional counterpart across all curing durations. The improvement was notable, with an 8.4 % increase at 7 d, 4.5 % at 14 d, and 4.8 % at 28 d, indicating the positive influence of silica fume on CS. Concrete mixtures using silica-fume-treated water displayed slightly elevated CS compared to standard concrete.

The study observed an enhancement in the flexural strength of the concrete mix with treated water, particularly noting improved flexural and tensile strengths with 80 % treated water. These results imply that incorporating treated water in the concrete mix positively affects flexural strength, making it more suitable for structural elements subjected to bending stresses. In terms of split tensile strength, which gauges a concrete's resistance to tensile stresses perpendicular to the loading direction, the study reported a slight improvement with the use of treated water. This enhancement is particularly significant in scenarios where the concrete is exposed to tensile stresses, suggesting increased resilience against cracking and tensile forces.

The study's overall findings suggest that treated water, specifically water treated with water hyacinth and combined with silica fume, can enhance the mechanical properties of concrete. The observed improvements in compressive, flexural, and tensile strength have notable implications for the construction industry, offering the potential for developing more durable and sustainable concrete mixtures. The innovative use of water hyacinth for wastewater treatment aligns with environmentally friendly practices, contributing to both improved water quality and reduced reliance on fresh water in concrete production. The study successfully addresses its research objectives in evaluating the impact of treated water on concrete properties and mechanical strengths.

3.2 Study limitations and comparison with other studies

Exploring treatment possibilities for various plant species is recommended, as the current study focused on a wetland system using one plant species. An additional limitation was the examination of only one season, while plant performance can vary seasonally. The study exclusively utilized treated water in concrete construction, necessitating a comprehensive year-long investigation.

A previous study utilized water hyacinth for wastewater remediation, and the treated wastewater found applications in agriculture. In contrast, the present study introduced both primary and secondary treatment methods, involving charcoal and aggregate layers along with water hyacinth. The process efficiently processed large quantities of wastewater, swiftly removing pollutants and heavy metals. The treated water was subsequently integrated into concrete mixtures and other construction projects. Earlier research reported a water-recovery rate of only 40–50 % during the water-hyacinth-treatment method. The utilization of water hyacinth for wastewater treatment, coupled with incorporating treated water into concrete, adheres to environmental sustainability principles.[2,3,15] An improvement in compressive strength (CS) was observed when treated water (80 % treated water, 20 % plain water, and 15 % silica fume) was integrated into the concrete mix. At 28 days, this mixture exhibited a CS of 25.82 MPa, representing an approximately 4.8 % increase compared to conventional concrete. This observed enhancement in CS aligns with the broader literature emphasizing the use of supplementary materials and treated water to enhance concrete properties. The potential of water hyacinth and its treated water to improve various mechanical properties, including flexural and split tensile strength, is underscored by these findings.[13,21]

Based on these studies, successfully collecting treated water up to 80 % of the time and incorporating it into concrete has demonstrated the potential to enhance mechanical properties compared to conventional concrete.

3.3 Summary of Key Findings

This study underscores the efficacy of water-hyacinth-based wetland treatment for household and societal wastewater. The integration of primary and secondary treatment processes, addressing color, odors, solid wastes, and heavy-metal removal through water hyacinths, demonstrates the adaptability and efficiency of this approach. Combining these methods proves to be a pragmatic strategy for comprehensive wastewater treatment. Treated water not only enhances the properties of fresh and hardened concrete, showcasing improved workability, accelerated hydration rates, and heightened compressive, flexural, and tensile strengths, but the addition of 15 % silica fume further fortifies concrete strength. The identification of the optimal mix proportion, featuring 80 % treated wastewater and 15 % silica fume, emerges as the most favorable for superior concrete performance.

3.4 Interpretations and Implications

These findings affirm the viability of water hyacinth as a sustainable wastewater-treatment solution, offering a cost-effective and environmentally friendly alternative. The dual-treatment approach ensures comprehensive pollutant removal, making the treated water suitable for diverse applications, including construction. The positive influence of treated water on concrete properties supports resource-efficient construction practices, promoting the development of innovative and eco-friendly construction materials. The research highlights the significance of wetland-based treatment systems in mitigating wastewater pollution and advancing environmental sustainability. The utilization of treated water in construction contributes to reducing the demand for freshwater resources, aligning with sustainable building practices.

3.5 Comparative Study Analysis

While the study concentrates on M20-grade concrete and specific mix proportions, extrapolating these findings to other concrete grades and mix designs may necessitate additional research and validation. Evaluating the performance of the water-hyacinth-based wastewater-treatment system across different seasons could provide a more comprehensive understanding of its effectiveness. Moreover, assessing the long-term durability and performance of concrete produced using treated water is vital for practical applications in construction. Considering potential ecological impacts and sustainability aspects of large-scale wetland systems is essential.

3.6 Overall Analysis of Results

This research contributes to sustainable water management by showcasing the potential of water-hyacinth-based treatment and its advantages for construction. It proposes a resource-efficient approach aligned with the global shift towards sustainable and eco-friendly practices. The improved concrete properties with treated water present opportunities for greener and more resilient infrastructure. The findings present an innovative solution to wastewater treatment and construction challenges, underscoring the importance of sustainable practices in urban development and construction, particularly in regions where water resources are limited. The broad applications of the study pave the way for more environmentally responsible and resource-efficient construction methods.

4 RECOMMENDATIONS

Future research endeavors should aim to evaluate the wetland system's performance across various seasons to account for potential seasonal variations. Expanding the scope of the study to encompass additional concrete grades and mix designs would enhance the applicability insights of treated water. To address practical applications, conducting long-term studies on concrete durability is imperative. In-depth cost-benefit analyses are essential to assess the economic feasibility of integrating wetland-based treatment systems and the utilization of treated water in construction projects. Additionally, comprehensive environmental impact assessments are indispensable when deploying large-scale wetland systems.

5 LIMITATIONS

Several limitations should be acknowledged, including the exclusive focus on M20-grade concrete and specific mix proportions. Generalizing the findings to encompass various concrete grades and mix designs requires additional validation. The current short-term focus on the impact of treated water on concrete properties highlights the need for investigations into the long-term durability aspects. It is crucial to consider ecological impacts and sustainability factors when contemplating the deployment of large-scale wetland systems. Further exploration into economic feasibility, including robust cost-benefit analyses, is imperative for the pragmatic implementation of these initiatives.

6 CONCLUSIONS & FUTURE WORK

The utilization of water treated with hyacinth in wetland conditions demonstrates favorable composition and achieves optimal workability for M20-grade concrete. The conclusions drawn from the results of wastewater treatment and mechanical properties are as follows:

- Wetland treatment employing hyacinths for household and societal wastewater proves to be a successful and easily implementable method. The wetland system allows for the efficient decontamination and chemical characterization of wastewater, including parameters such as pH, BOD, COD, DO, TSS, etc.
- The treatment system effectively removes contaminated minerals from wastewater using two distinct methods. The primary treatment acts efficiently to eliminate color, odors, solid wastes, etc., while the secondary treatment utilizes water hyacinth to effectively remove heavy metals from polluted water.
- The aquatic system of the water hyacinth contributes to reducing pollution loads in wastewater, enhancing water quality, and rendering the treated water suitable for concrete construction purposes.
- Treated water, when mixed with concrete treated with water hyacinth, enhances the qualities of both fresh and hardened concrete. The hydration process of concrete is increased during the utilization of wastewater after concrete treatment. Additionally, the incorporation of 15 % silica fume has been found to enhance the strength of the concrete.
- The workability of concrete mixed with treated water is 140 mm, making it recommended for concrete grade M20. The addition of silica fumes to concrete aims to increase its CS. Concrete mixtures combining treated water with varying silica fume content (15 %) exhibit superior performance compared to conventional concrete.
- In fresh concrete conditions, the performance surpasses that of control concrete. The CS of the 80 % treated water and 15 % silica fume mixture exceeds that of control concrete in terms of CS, flexural strength, and breaking strength.
- The optimal concrete proportion is achieved by using up to 80 % treated wastewater and 15 % SF. This ratio yields the optimum concrete performance.
- In future experiments, a constructed wetland featuring a variety of plant species could enhance treatment possibilities. Evaluating the performance of this combination throughout different seasons would provide a more comprehensive understanding. Furthermore, considering the technical qualities of treated water, it could find applications in various construction scenarios.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's Contributions

Conceptualization, Methodology, Investigation, and Writing - Original draft, Derive the Numerical Analysis, Writing - review & editing, A Ananthakumar; Supervision and Correction, Saravanan M.M and Devi M.

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7 REFERENCES

[1] X. Chen, J. Wu, Y. Ning, W. Zhang, Experimental study on the effect of wastewater and waste slurry of mixing plant on mechanical properties and microstructure of concrete, Journal of Building Engineering, 2022 Jul 15, 52:104307

[2] Q. He, H. Fei, J. Zhou, X. Liang, Y. Pan, Utilization of carbonized water hyacinth for effective encapsulation and thermal conductivity enhancement of phase change energy storage materials, Construction and Building Materials, 2023; 372:130841

[3] Niyasom, Samit, and Nuchnapa Tangboriboon. Development of biomaterial fillers using eggshells, water hyacinth fibers, and banana fibers for green concrete construction, Construction and Building Materials, 2021; 283:122627

[4] J. A. Di Canto, W. J. Malfait, J. Wernery, Turning waste into insulation–A new sustainable thermal insulation board based on wheat bran and banana peels, Building and Environment, 2023 Oct 1;244:110740

[5] S. M. Hosseinian, A. G. Sabouri, D. G. Carmichael, Sustainable production of buildings based on Iranian vernacular patterns: A water footprint analysis, Building and Environment, 2023 Aug 15;242:110605

[6] Z. Ma, R. Hu, P. Yao, C. Wang, Utilizing heat-mechanical synergistic treatment for separating concrete waste into high-quality recycled aggregate, active recycled powder and new concrete, Journal of Building Engineering, 2023 Jun 1;68:106161

[7] M. Zhang, L. Zhu, S. Gao, Y. Dong, H. Yuan, Mechanical properties of recycled aggregate concrete prepared from waste concrete treated at high temperature, Journal of Building Engineering, 2023 Jun 23:107045

[8] M, Alyami, I. Y. Hakeem, M. Amin, A. M. Zeyad, B. A. Tayeh, I. S. Agwa, Effect of agricultural olive, rice husk and sugarcane leaf waste ashes on sustainable ultra-high-performance concrete, Journal of Building Engineering, 2023 Aug 1;72:106689

[9] J. M. Boban, P. V. Nair, S. T. Shiji, S. E. Cherian, Incorporation of water hyacinth in concrete, International Journal of Engineering Research & Technology (IJERT), 2017 May;6(05)

[10] I. Adewumi, A. S. Ogbiy, Using water hyacinth (Eichhornia crassipes) to treat wastewater of a residential institution. Toxicological & Environmental Chemistry. 2009 Jul 1;91(5):891-903

[11] N. M. Al-Joulani, Effect of wastewater type on concrete properties. International Journal of Applied Engineering Research. 2015;10(19):39865-70

[12] I. Al-Ghusain, M. Terro, Use of treated wastewater for concrete mixing in Kuwait. Kuwait journal of science and Engineering. 2003 Jun 1;30(1):213-28

[13] H. M. Saleh, Stability of cemented dried water hyacinth used for biosorption of radionuclides under various circumstances. Journal of Nuclear Materials. 2014 Mar 1;446(1-3):124-33

[14] H. Minakawa, U. Tamon, T. Jirawattanasomkul, Compressive Behavior of Low Strength Concrete Confined with Water Hyacinth and Jute NFRP. InНовые идеи нового века: материалы международной научной конференции ФАД ТОГУ 2020 (Vol. 3, pp. 428-433). Федеральное государственное бюджетное образовательное учреждение высшего образования Тихоокеанский государственный университет

[15] I. Harun, H. Pushiri, A. J. Amirul-Aiman, Z. Zulkeflee, Invasive water hyacinth: ecology, impacts and prospects for the rural economy. Plants. 2021 Aug 6;10(8):1613

[16] M. L. Garcia, S. Rodriguez, Phytoaccumulation of Heavy Metals by Water Hyacinth: A Sustainable Approach for Industrial Wastewater Treatment, Chemosphere, 2019; 60(2):234-241

[17] Z. Ismail, S. Z. Othman, K. H. Law, A. H. Sulaiman, R. Hashim, Comparative performance of Water Hyacinth (Eichhornia crassipes) and Water Lettuce (Pista stratiotes) in preventing nutrients build-up in municipal wastewater. CLEAN–Soil, Air, Water. 2015; 43(4):521-531

[18] P. Saha, O. Shinde, S. Sarkar, Phytoremediation of industrial mines wastewater using water hyacinth, International journal of phytoremediation, 2017; 19(1):87-96

[19] S. Rezania, M. Ponraj, A. Talaiekhozani, S. E. Mohamad, M. F. M. Din, S. M. Taib, F. M. Sairan, Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater, Journal of environmental management, 2015; 163:125-133

[20] K. K.Victor, Y. Séka, K. K. Norbert, T. A. Sanogo, A. B. Celestin, Phytoremediation of wastewater toxicity using water hyacinth (Eichhornia crassipes) and water lettuce (Pistiastratiotes), International Journal of phytoremediation, 2016; 18(10):949-955

[21] P. Gupta, S.Roy, A. B. Mahindrakar, Treatment of Water Using Water Hyacinth, Water Lettuce and Vetiver Grass - A Review, Int. J. Environmental Engineering, 2015; 2(5):202-215

[22] A Khare, E. P. Lal, Waste Water Purification Potential of Eichhornia crassipes (Water Hyacinth). International Journal of Current Microbiology and Applied Sciences. 2017; 6(12):3723-3731

[23] A. Valipour, V. K. Raman, Y. H. Ahn, Effectiveness of domestic wastewater treatment using a bio-hedge water hyacinth wetland system, Water, 2015; 7(1):329-347

[24] Y. Nuraini, M. Felani, Phytoremediation of tapioca wastewater using water hyacinth plant (Eichhornia crassipes). Journal of degraded and mining lands management. 2015; 2(2):295

[25] N. Singh, C. Balomajumder, Phytoremediation potential of water hyacinth (Eichhornia crassipes) for phenol and cyanide elimination from synthetic/simulated wastewater. Applied Water Science. 2021; 11(8):1-15

[26] W. H. T. Ting, I. A. W. Tan, S. F. Salleh, N. A. Wahab, Application of water hyacinth (Eichhornia crassipes) for phytoremediation of ammoniacal nitrogen: A review. Journal of water process engineering. 2018; 22:239-249

[27] C. Anudechakul, A. S. Vangnai, N. Ariyakanon, Removal of chlorpyrifos by water hyacinth (Eichhornia crassipes) and the role of a plant-associated bacterium. International Journal of Phytoremediation. 2015; 17(7):678-685

[28] V. Kumar, J. Singh, P. Kumar, Regression models for removal of heavy metals by water hyacinth (Eichhornia crassipes) from wastewater of pulp and paper processing industry. Environmental Sustainability. 2020; 3(1):35-44

[29] E. S. Priya, P. S. Selvan, Water hyacinth (Eichhornia Crassipes) – An efficient and economic adsorbent for textile effluent treatment – A review. Arabian Journal of Chemistry. 2017; 10(2):S3548-S3558

[30] A. P. Ramkar, U. S. Ansari, Effect of Treated Waste Water on Strength of Concrete. Journal of Mechanical and Civil Engineering. 2016; 13(6):41-45

[31] A. A. Adelodun, U. O. Hassan, V. O. Nwachuckwu, Environmental, mechanical, and biochemical benefits of water hyacinth (Eichhornia crassipes). Environmental Science and Pollution Research. 2020; 27(24):30210-30221

[32] S. Mishra, A. Maiti, The efficiency of Eichhornia crassipes in the removal of organic and inorganic pollutants from wastewater: a review. Environmental science and pollution research. 2017; 24(9):7921-7937

[33] B. Panneerselvam, K. S. Priya, Phytoremediation potential of water hyacinth in heavy metal removal in chromium and lead contaminated water. International Journal of Environmental Analytical Chemistry,. 2021; 1-16

[34] U. F. Carreño-Sayago, Development of microspheres using water hyacinth (Eichhornia crassipes) for treatment of contaminated water

with Cr (VI). Environment, Development and Sustainability. 2021; 23(3):4735-4746

[35] T. Jirawattanasomkul, H. Minakawa, S. Likitlersuang, T. Ueda, J. G. Dai, N. Wuttiwannasak, Kongwang, Use of water hyacinth waste to produce fibre-reinforced polymer composites for N. concrete confinement: Mechanical performance and environmental assessment. Journal of Cleaner Production. 2021 Apr 10;292:126041

[36] L. MzukisiMadikizela, Removal of organic pollutants in water using water hyacinth (Eichhornia crassipes). Journal of Environmental Management. 2021; 295:113153

[37] F. Amalina, A. S. Abd Razak, S. Krishnan, A. W. Zularisam, M. Nasrullah, Water hyacinth (Eichhornia crassipes) for organic contaminants removal in water–A review. Journal of Hazardous Materials Advances. 2022; 1(7):100092

[38] L. M. Madikizela Removal of organic pollutants in water using water hyacinth (Eichhornia crassipes). Journal of Environmental Management. 2021 Oct 1;295:113153

[39] S. Ahmed, Y. Alhoubi, N. Elmesalami, S. Yehia, F. Abed Effect of recycled aggregates and treated wastewater on concrete subjected to different exposure conditions. Construction and Building Materials. 2021 Jan 10;266:120930

[40] H. Varshney, R. A. Khan, I. K. Khan, Sustainable use of different wastewater in concrete construction: A review. Journal of Building Engineering. 2021 Sep 1;41:102411

[41] M. F. Arooj, F. Haseeb, A. I. Butt, M. Irfan-Ul-Hassan, H. Batool, S. Kibria, Z. Javed, H Nawaz, S. Asif A sustainable approach to reuse of treated domestic wastewater in construction incorporating admixtures. Journal of Building Engineering. 2021 Jan 1;33:101616

[42] A. M. PN, G. Madhu, Removal of heavy metals from waste water using water hyacinth. International journal on transportation and Urban Development. 2011 Apr 1;1(1):48.

[43] K. Meena, S. Luhar, Effect of wastewater on properties of concrete. Journal of Building Engineering. 2019 Jan 1;21:106-12.

[44] A. T. Huynh, Y. C. Chen, B. N. Tran, A small-scale study on removal of heavy metals from contaminated water using water hyacinth. Processes. 2021 Oct 11;9(10):1802

[45] S. Rezania, M. Ponraj, A. Talaiekhozani, S. E. Mohamad, M. F. Din, S. M. Taib, F. Sabbagh, F. M. Sairan Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. Journal of environmental management. 2015 Nov 1;163:125-33

[46] K. S. Al-Jabri, A. H. Al-Saidy, R. Taha, A. J. Al-Kemyani, Effect of using wastewater on the properties of high strength concrete. Procedia Engineering. 2011 Jan 1;14:370-6