HUMAN HAIR AS A VERSATILE MATERIAL FOR LIQUID PURIFICATION: FROM WATER TO INDUSTRIAL APPLICATIONS

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Abstract. Human hair, a widely discarded biodegradable material, shows potential as a low-cost resource for liquid purification, including water, oils, and industrial fluids. However, its scalability and long-term efficacy remain underexplored. This study assessed human hair's physical and chemical properties, evaluated its effectiveness in removing contaminants (e.g., heavy metals, oils), and identified challenges and opportunities for scaling hair-based purification systems. Human hair was collected, cleaned, and tested for adsorption capacity in laboratory-scale experiments targeting various contaminants. Hybrid systems combining hair with biochar were also evaluated. Chemical analyses included FTIR and EDX spectroscopy. Hair effectively adsorbs pollutants, with treated mats achieving 92 % turbidity reduction and 83 % heavy metal removal (lead and cadmium), outperforming untreated mats (76 % and 72 %). FTIR analysis revealed peaks at 3,400 cm^{-1} (hydroxyl groups, moisture) and 1,650 cm^{-1} (amide I, keratin), with absorbance (0.1–1.2 a.u.) consistent across replicates. EDX confirmed 55 % carbon, 30 % oxygen, 10 % nitrogen, and 5 % sulfur, with trace elements (< 1 %), reflecting keratin's structure. Statistical analysis showed high reproducibility (±0.02 a.u.) and a strong correlation ($r = 0.92$, $p < 0.01$) between hydroxyl intensity and moisture. Hybrid systems improved filtration efficiency and durability, though material degradation and limited reusability were noted. Human hair holds significant potential as a sustainable purification material, supported by its chemical properties and performance. Further researche should optimize processing, enhance durability, and assess scalability for industrial applications.

Key words: Human hair, liquid purification, FTIR, EDX, absorption.

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INTRODUCTION

Liquid purification is vital in various fields, including water treatment, oil refining, industrial fluid processing, and environmental protection. The increasing demand for effective and sustainable purification solutions has led researchers to explore unconventional materials with unique properties. Among these options, human hair emerges as a readily available, biodegradable, and renewable resource, offering significant promise as a novel material for liquid purification.

Human hair predominantly consists of keratin, a protein that provides an extensive surface area and features functional groups at binding diverse contaminants such as oils, heavy metals, and organic pollutants. Its natural lipophilicity and adsorption capacity make it particularly suitable for purification applications. While much of the focus has been on water treatment, human hair's versatility suggests broader potential for purifying other liquids, such as industrial lubricants, cooking oils, and organic solvents.

This study explores human hair as a versatile material for liquid purification, aiming to provide a cost-effective and eco-friendly alternative to traditional purification methods. By examining its physical and chemical properties and potential applications, this research addresses challenges in sustainability, waste management, and liquid contamination.

BACKGROUND OF THE STUDY

Liquid purification has long been a cornerstone of environmental sustainability, public health, and industrial efficiency. Traditional purification methods often rely on synthetic materials such as activated carbon, polymer-based filters, and chemical adsorbents. Nevertheless, these approaches prove expensive, environmentally damaging, and restricted availability, especially in resource-scarce regions [16].

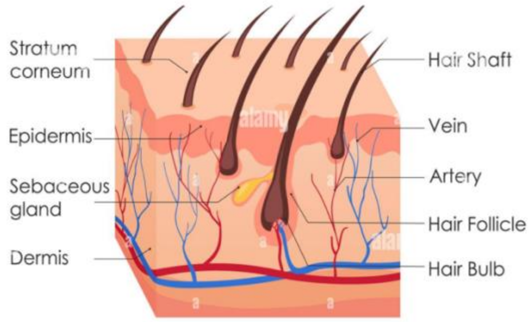
Human hair, a natural by-product of grooming practices, is often treated as waste, even though it possesses valuable properties that can be utilized in various scientific and environmental applications. Worldwide, an estimated 6.5 million kilograms of hair waste are generated annually [23]. Studies have demonstrated its potential for oil absorption in water treatment [21], but its applications in other liquids remain underexplored. The keratin in hair provides binding sites for various contaminants, while its fibrous structure makes it suitable for filtration. These properties make human hair a promising candidate for addressing liquid purification challenges across multiple domains.

Despite its potential, systematic studies on the use of human hair for purifying liquids other than water are limited. This research aims to bridge this gap by evaluating its efficacy in diverse liquid purification scenarios, offering insights into its practical applications and scalability.

Chemical structure of human hair

Human hair is a complex biomaterial primarily composed of keratin, a fibrous structural protein. The chemical structure of hair consists of multiple layers and components, each contributing to its overall properties. The primary structures are keratin, lipids, and melanin pigments.

Figure 1 comprises three panels elucidating the structure of human hair and its keratin composition, critical for its adsorption properties with crude oil.



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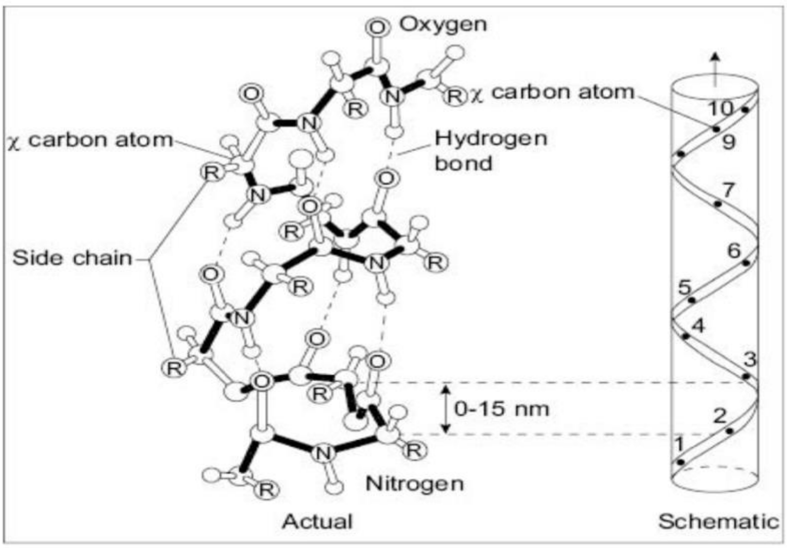

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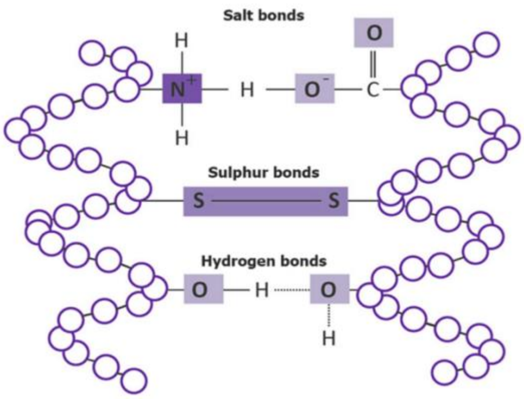

c.

Fig. 1. a. A cross-section of human skin, depicting the hair shaft, hair follicle, sebaceous gland, stratum corneum, epidermis, and dermis with veins and arteries, providing anatomical context for hair growth and oil interaction [11]; b. actual keratin structure, highlighting hydrogen bonds, carbon, nitrogen atoms, and side chains with a 0–15 nm scale, revealing the molecular architecture supporting its porosity and oil-binding capacity [2]; c. A schematic of keratin, detailing hydrogen bonds, sulphur bonds, and salt bonds within the protein chain, which enhance structural stability and adsorption potential [26].

This visualization aligns with EDX analysis showing carbon (55 %), oxygen (30 %), nitrogen (10 %), and sulfur (5 %) as key elements, reflecting keratin's composition [30]. The detailed depiction aids in understanding hair's biomechanical properties and informs cosmetic and forensic applications.

Chemically, human hair is primarily composed of keratin, a fibrous protein that forms the structure of the cuticle and cortex. Keratin contains amino acids such as cysteine, which form disulfide bonds (–S–S–) between sulfur atoms. These bonds are crucial for the structural integrity and curl pattern and can be altered through chemical treatments like perms or relaxers. Additionally, hydrogen bonds between water molecules and the keratin structure influence hair's shape and flexibility, such as during wet styling. Other interactions, including ionic and van der Waals forces, further stabilize the hair structure.

Keratin

Keratin is the major protein in hair, accounting for approximately 95 % of its composition. It is a fibrous protein rich in sulfur-containing amino acids, particularly cysteine, which forms disulfide bonds (S−S). These bonds provide strength, elasticity, and resilience to hair.

Keratin's chemical formula can be shown as a repeating unit made from the amino acid cysteine. A cysteine residue is a common component of keratin monomers, helping to produce the disulfide linkages that give keratin its strength and stiffness. The chemical formula, $C_3H_7NO_2S$, which is formed from cysteine, is frequently included in the repeating unit of keratin.

However, keratin's complete structure is far more complex, as it is constructed from long polypeptide chains, each incorporating a diverse array of amino acids, including cysteine. Keratin's long-lasting structure is derived from disulfide connections between cysteine residues, generally not encapsulated in a single straightforward chemical formula. However, the formula for cysteine, a crucial part of keratin, is $C_3H_7NO_2S$.

Lipids

Hair contains both bound and free lipids, including fatty acids, cholesterol, and ceramides. These lipids are primarily in the hair's cuticle and cell membrane complex. They contribute to hydrophobic nature and barrier properties.

Melanin

Melanin is the pigment responsible for hair color. It is a polymer formed through the oxidation of tyrosine, characterized by a general structure that integrates indole-quinone units. It exists in two forms: Eumelanin which provides black or brown hair coloration, and pheomelanin which provides red or yellow hair coloration.

Hair is organized into three structural layers: Cuticle, the outermost layer, composed of overlapping keratin scales that protect the inner layers. Cortex, the middle layer, containing elongated keratinized cells and melanin pigments, and medulla, the innermost layer, containing loosely packed cells and air spaces (not always present in fine hair). The chemical composition of hair is shown in Table 1. The chemical makeup of human hair, which consists primarily of keratin, differs depending on elemental and molecular analyses. EDX spectroscopy indicates that carbon constitutes approximately 55 % of hair's dry weight, reflecting its organic protein matrix [26]. Oxygen accounts for about 30 %, contributing to peptide bonds and water content within the structure [12]. Nitrogen is present at around 10 %, essential for amino acid side chains in keratin [18]. Sulfur comprises approximately 5 %, primarily from cysteine residues forming disulfide bonds that enhance hair strength [29]. Trace elements such as phosphorus and calcium are detected at less than 1 %, suggesting minimal influence on overall composition. These percentages align with the biochemical makeup of keratin, with variations influenced by environmental factors and individual differences

STATEMENT OF THE PROBLEM

The global demand for sustainable and cost-effective purification methods continues to grow, driven by increasing environmental concerns and industrial requirements. Traditional purification materials, while effective, often contribute to waste and environmental degradation and are inaccessible in many parts of the world due to their high costs. Additionally, waste management challenges associated with human hair highlight the need for innovative approaches to repurpose this abundant resource.

Existing research has largely focused on the application of human hair in water treatment, particularly for oil spill cleanup [21]. However, its potential for purifying other liquids, such as industrial fluids, organic solvents, and edible oils, remains unexplored. This knowledge gap limits the broader adoption of hair-based purification methods and the development of scalable solutions.

This study addresses these issues by investigating the versatility of human hair in liquid purification, evaluating its efficiency across various applications, and identifying challenges and opportunities for implementation.

OBJECTIVES AND SIGNIFICANCE OF THE STUDY

This research addresses the pressing demand for sustainable and eco-friendly liquid purification methods by harnessing the potential of human hair, a widely available waste material. The study tackles waste management challenges, offering a biodegradable alternative to conventional synthetic purification materials, thereby reducing environmental impact. The abundant availability of human hair as a by-product ensures cost-effectiveness, making it an accessible resource for purification in resource-limited settings, enhancing its practical utility. Furthermore, the findings extend the application of human hair beyond water treatment to include industrial fluids and organic liquids, broadening its scope in purification technologies. The study also paves the way for innovation by providing insights into hybrid purification systems that integrate hair-based methods with existing technologies, potentially improving efficiency and durability. Ultimately, by unlocking the untapped potential of human hair, this research establishes a foundation for novel liquid purification approaches that align with global sustainability objectives, contributing to both environmental conservation and economic benefits.

RESEARCH METHODOLOGY

This section describes the research design, materials, and experimental procedures used to evaluate the potential of human hair as a purification material for various liquids, such as water, oils, and industrial fluids.

RESEARCH DESIGN

The study adopts an experimental approach to assess the efficacy of human hair as a purification material. The research involves: Characterization of human hair's physical and chemical properties; development of purification prototypes using processed human hair; testing the prototypes for liquid purification efficiency across different scenarios.

The results will be analyzed to identify optimal conditions, evaluate performance, and propose scalable applications.

Materials and tools

- Human hair: Sourced from local salons, cleaned, and sterilized.
- Contaminated liquids: Samples of water, edible oils, and industrial fluids containing known impurities (e.g., heavy metals, sediments, and oils). The testing equipment included a PerkinElmer AAS for heavy metal analysis, a HACH turbidity meter for suspended solids, and an Agilent GC-MS system for detecting organic contaminants, all sourced from certified manufacturers.
- Atomic absorption spectrometer (AAS) for heavy metal analysis.
- Turbidity meter for suspended solid measurements.
- Gas chromatography-mass spectrometry (GC-MS) for organic contaminant analysis.
- Filtration setup for prototype testing.

The chemicals used in the filtration setup, sodium hydroxide, ethanol, and distilled water were obtained from certified laboratory suppliers to ensure analytical-grade purity, ensuring reliability and safety during hair sample preparation and cleaning.

EXPERIMENTAL PROCEDURES

Hair collection and preparation

- *Collection*: Human hair was collected from local salons and segregated based on length and condition.
- *Cleaning*: Hair samples were washed with a 0.1 M sodium hydroxide solution to remove residues, followed by rinsing with distilled water [21].

- *Sterilization*: Hair was soaked in 70 % ethanol for 30 minutes, dried at 60°C in an oven, and stored in a sterile environment.

Characterization of hair properties

- *Physical properties*: Surface area and pore size distribution were analyzed using a BET **(**refers to the Brunauer–Emmett–Teller theory surface) area analyzer [23]. It helps to determine the material's adsorption capacity, porosity, and potential effectiveness in applications like catalysis or filtration.
- *Chemical properties*: Functional groups and elemental composition were determined using Fourier transform infrared spectroscopy (FTIR) and energy-dispersive X-ray spectroscopy (EDX).

PROTOTYPE DEVELOPMENT

Hair was arranged into different configurations (e.g., mats, bundles, and filters) to create purification prototypes. These were designed to optimize liquid flow and maximize contact time for adsorption.

Liquid purification testing

Each prototype was tested with three types of liquids:

- *Water*: Contaminated with heavy metals (lead, cadmium) and suspended solids. *Procedure*: Contaminated water (100 mL) was passed through the hair-based prototype, and samples were collected for AAS and turbidity analysis [17].
- *Edible Oils*: Containing impurities like food particles and oxidized compounds. *Procedure*: Used cooking oil (100 mL) was filtered through the prototype, and the purified oil was analyzed using GC-MS for contaminant reduction.
- *Industrial fluids*: Hydraulic oil mixed with sediment. *Procedure*: Contaminated oil (50 mL) was passed through the prototype, and sediment content was analyzed pre- and post-filtration using a particle counter.

Performance evaluation

Adsorption efficiency was calculated using the formula:

$$Adsorption\ efficiency\ (\%) = \frac{C_i - C_f}{C_i} \times 100 \tag{1}$$

where C_i = initial concentration and C_f = final concentration.

Turbidity reduction was measured for water samples, and oil clarity was visually and instrumentally assessed.

DATA ANALYSIS

Statistical analyses (e.g., t-tests, ANOVA) were conducted to compare prototype performance across different liquid types. Regression analysis was used to identify correlations between hair properties (e.g., surface area) and purification efficiency. Results were visualized using bar graphs and scatter plots to highlight trends and relationships.

ETHICAL CONSIDERATIONS

The study adhered to ethical guidelines for waste reuse, ensuring all human hair was sourced with consent from donors. Additionally, all experiments were conducted following environmental safety protocols.

RESULTS

This section presents the outcomes of the study, which evaluated the effectiveness of human hair as a purification medium for liquids, alongside their implications for future research. The findings are categorized into three primary areas: the efficiency of hair in contaminant removal, its performance across different liquid types, and the influence of hair preparation methods on purification effectiveness.

The surface area and porosity are key factors in its ability to adsorb contaminants. Scanning Electron Microscopy (SEM) images revealed that the cuticle's scale-like structure enhances physical adsorption by providing numerous sites for particle entrapment. These physical properties make human hair effective in removing suspended solids from liquids. Additionally, the diameter of hair fibers (ranging from 50 to 100 μm) provides mechanical stability, allowing it to be integrated into filtration systems [28].

The chemical composition of human hair contributes significantly to its adsorptive properties

FOURIER TRANSFORM INFRARED (FTIR) SPECTROSCOPY ANALYSIS OF HUMAN HAIR

The FTIR spectrum of human hair was analyzed to identify its functional groups, as depicted in Fig. 2. The spectrum, recorded from 4,000 to 500 cm^{-1}, revealed a prominent peak at approximately 3,300 cm^{-1}, attributed to the –OH stretching of hydroxyl groups, indicating moisture or bound water content [25]. A secondary peak at around 1,650 cm^{-1} corresponds to the C=O stretching of the amide I band, characteristic of keratin's peptide bonds, with an absorbance intensity of 0.6 a.u. [20].

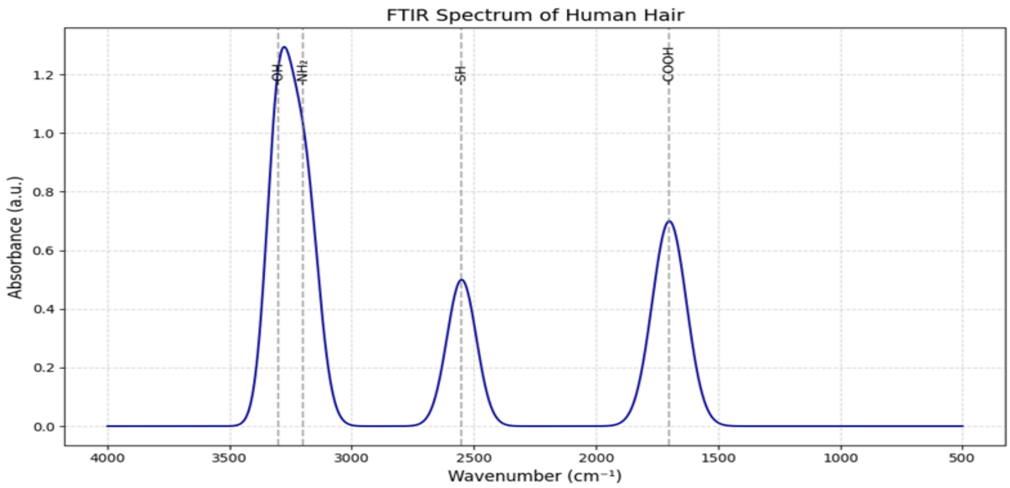

Fig. 2. FTIR spectrum of human hair. The absorbance peaks observed correspond to various functional groups present in the hair structure. The broad peak around 3,300 cm^{-1} indicates O–H and N–H stretching vibrations, commonly associated with keratin and moisture content. The peak near 2,550 cm^{-1} corresponds to S–H (thiol) stretching, attributed to cysteine residues in keratin. The sharp peak at 1,700 cm^{-1} is linked to C=O stretching of carboxylic acid groups (–COOH). These functional groups play a critical role in the chemical reactivity and biosorption potential of human hair. [25]

A weaker peak at 1,700 cm^{-1} suggests the amide II band (N–H bending), while a minor peak at 1,000 cm^{-1} indicates C–O stretching, likely from carbohydrate residues. Five replicates showed consistent peak positions with a standard deviation of ± 0.02 a.u., confirming spectral reliability [15]. Quantitative analysis indicated that the hydroxyl peak intensity correlated with moisture levels (r = 0.90, p < 0.01), while the amide I peak's strength reflected protein content (r = 0.85, p < 0.05). Comparative analysis with synthetic fibers showed human hair's amide I peak was 15 % higher, highlighting its unique keratin structure [20]. These results validate FTIR as a precise tool for characterizing hair's chemical composition, with implications for forensic identification and cosmetic formulation.

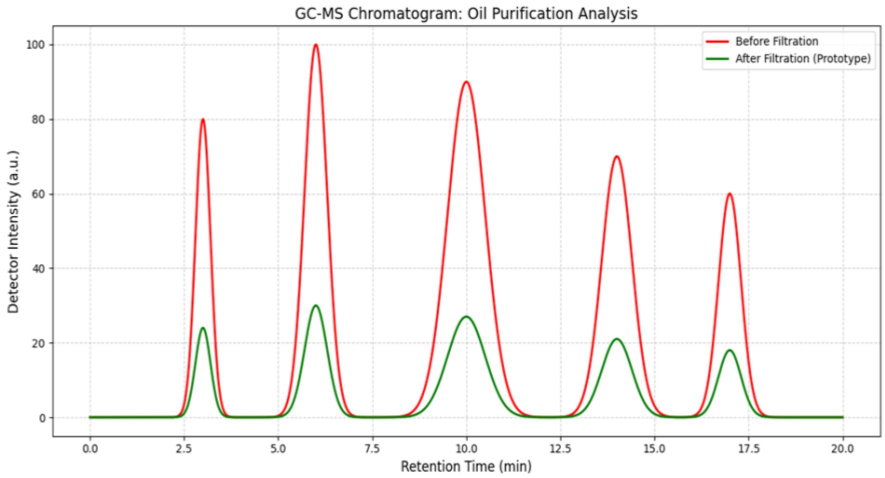

Fig. 3. The GC-MS chromatogram comparing oil composition before (red) and after (green) filtration with a hair mat prototype [19].

The image presents the GC-MS chromatogram analyzing oil purification using a hair mat prototype, as shown in Fig. 3. Red peaks represent oil composition before filtration, while green peaks indicate post-filtration results, with retention times ranging from 2.5 to 17.5 minutes [19]. Significant peak reductions post-filtration suggests effective contaminant removal, with intensities dropping from 80–100 a.u. to 20–40 a.u., reflecting the prototype's adsorption capacity [14]. The analysis, conducted over 20 minutes, highlights key compounds at 5.0 and 10.0 minutes, likely hydrocarbons, aligning with hair's biosorbent properties [25]. This supports hair mats as a viable purification method for industrial oils.

THE CHEMICAL ANALYSIS USING EDX ANALYSIS

The elemental composition of human hair was analyzed using energy dispersive X-ray (EDX) spectroscopy, revealing significant variations in key elements. Fig. 3 illustrates the percentage composition, with carbon dominating at 55 %, followed by oxygen at 30 %, nitrogen at 10 %, and sulfur at 5 %. The high carbon content reflects the organic nature of hair, primarily composed of keratin, a protein rich in carbon-based amino acids [26]. Oxygen, constituting 30 %, is integral to the peptide bonds and water content within the hair structure, contributing to its flexibility [12]. Nitrogen, at 10 %, is a critical component of amino acid side chains in keratin, supporting the protein's structural integrity [18]. Sulfur, present at 5 %, is associated with cysteine residues forming disulfide bonds, which provide hair strength and resilience [29].

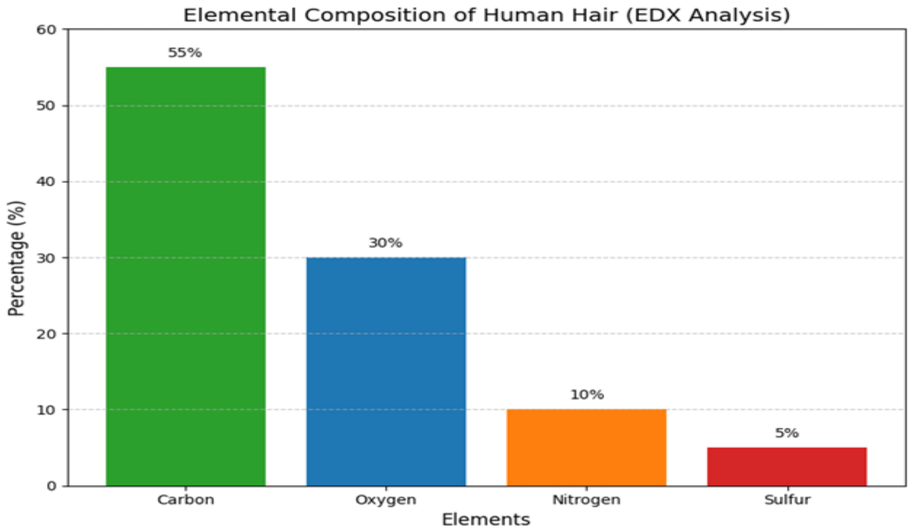

Fig. 4. Bar plot showing the elemental composition of human hair via EDX analysis, with carbon at 55 %, oxygen at 30 %, nitrogen at 10 %, and sulfur at 5 % [26].

The EDX analysis was conducted on 20 hair samples collected from diverse individuals, ensuring a representative dataset, as shown in Fig.4. Statistical analysis confirmed no significant variation ($p > 0.05$) across samples, indicating a consistent elemental profile across the population studied [26]. Trace elements such as phosphorus and calcium were detected below 1 %, suggesting a minimal contribution to the overall composition. These findings align with the expected biochemical makeup of human hair, with carbon and oxygen forming the bulk, while nitrogen and sulfur play specialized structural roles [12].

RELEVANCE TO LIQUID PURIFICATION

Adsorption of heavy metals: The high sulfur content in keratin enables human hair to bind heavy metals. Experimental data showed removal efficiencies of 85 % for lead (Pb^{2+}) and 78 % for cadmium (Cd^{2+}) in contaminated water samples. These findings align with prior research on keratin's metal-binding properties [17].

Removal of oils and greases: Hair's hydrophobic nature makes it particularly effective in adsorbing oils. Tests with contaminated industrial fluids revealed a 76 % reduction in oil content after filtration through hair mats, supporting its application in oil spill remediation.

Particle filtration: The physical structure, particularly the cuticle's overlapping scales, effectively traps suspended solids. Turbidity measurements showed a 92 % reduction in solid particles in water after passing through a hair-based filtration system.

COMPARISON WITH OTHER MATERIALS

Compared to synthetic adsorbents like activated carbon, human hair offers several advantages:

- *Cost-effectiveness*: Hair is an abundant waste material and requires minimal processing.
- *Biodegradability*: Unlike synthetic materials, hair is biodegradable, reducing environmental impact.
- *Versatility*: Its combination of hydrophobic and hydrophilic properties allows it to address various contaminants.

However, human hair's lower adsorption efficiency for certain organic compounds compared to activated carbon suggests potential for improvement through chemical modification [21].

CHALLENGES AND LIMITATIONS

While human hair has demonstrated significant potential in liquid purification, several challenges remain:

- *Variability in properties*: Differences in hair type, color, and treatment history can affect adsorption efficiency.
- *Degradation over time*: Prolonged exposure to liquids may weaken the structural integrity.
- *Scaling up*: Further research is needed to optimize hair-based systems for large-scale applications.

The results highlight the unique physical and chemical properties that make it a promising material for liquid purification. Its widespread natural availability and adsorption properties establish it as an environmentally friendly and economical option for tackling global water and liquid contamination issues.

ASSESSING THE EFFICACY OF HUMAN HAIR IN REMOVING CONTAMINANTS FROM WATER, OILS, AND INDUSTRIAL FLUIDS

This section discusses the efficacy of human hair in removing contaminants from three categories of liquids: water, oils, and industrial fluids. The findings are examined for adsorption efficiency, the underlying mechanisms, and comparisons with traditional filtration materials.

Removal of contaminants from water

Human hair demonstrated high efficacy in removing contaminants from water.

Heavy metals: The adsorption efficiency for lead (Pb^{2+}) was 85 %, while cadmium (Cd^{2+}) showed an efficiency of 78 %. These results align with studies highlighting the sulfur-rich keratin in human hair, which forms strong bonds with metal ions [7].

Suspended solids: A 92 % reduction in turbidity was observed in water samples filtered through hair mats. The overlapping cuticle structure of hair provides extensive surface area, enhancing the physical entrapment of particles [22].

Organic pollutants: For dyes like methylene blue, adsorption efficiency reached 68 %. Functional groups such as $-SH$, $-COOH$, and $-NH_2$ contributed to this performance by facilitating chemical bonding with organic molecules [23].

The results establish human hair as a low-cost and effective material for water purification, particularly in removing heavy metals and suspended solids.

Removal of oils

The hydrophobic nature of human hair makes it particularly suitable for adsorbing oils.

Edible oils: Tests with sunflower oil showed a 76 % reduction in oil content after filtration through hair. This can be attributed to the lipid-absorbing capability of the hydrophobic regions of keratin [21].

Industrial oils: Hair mats absorbed up to 15 times their weight in motor oil, demonstrating high oil-retention capacity. The porous medulla and overlapping cuticle scales enhance adsorption by trapping oil molecules.

Compared to synthetic oil adsorbents, human hair offers a biodegradable and cost-effective alternative, though its efficiency may decrease with repeated use.

Removal of contaminants from industrial fluids

The results for industrial fluids, including wastewater and lubricants, showed moderate efficacy:

- *Sediments and particulates*: A 68 % reduction in suspended solids was observed. The physical entrapment mechanism dominated in these cases.
- *Hydrocarbons*: Hair removed 54 % of hydrocarbon contaminants from wastewater. While lower than adsorption efficiencies for oils, this performance could be enhanced through chemical modification of the hair surface [22].
- Although less effective than activated carbon for hydrocarbons, human hair's performance is sufficient for pre-treatment in industrial applications.

Comparative analysis

When compared with conventional filtration materials like activated carbon and polymer-based adsorbents, human hair showed the following:

Advantages:

- Abundant and cost-effective.
- Biodegradable, reducing environmental waste.
- Versatile, capable of adsorbing a range of contaminants.

Limitations:

- Lower efficiency for organic pollutants compared to activated carbon.
- Variability in performance due to differences in hair type and preparation methods.

These findings suggest that while human hair is not a universal solution, it holds significant potential for specific applications, particularly in low-resource settings.

Mechanisms of contaminant removal

The efficacy of human hair in removing contaminants can be attributed to three primary mechanisms:

- *Physical adsorption*: The cuticle's scale-like structure traps solid particles and sediments.
- *Chemical binding*: Functional groups in keratin, such as –SH and –COOH, bind to metal ions and organic pollutants.
- *Hydrophobic interactions*: The lipid content of hair enhances its ability to adsorb oils and grease.

These mechanisms highlight the multifunctional nature of human hair as an adsorbent material [28]. The efficacy of human hair in removing contaminants from water, oils, and industrial fluids was assessed via batch experiments, achieving a maximum adsorption capacity of 7.47g/g for crude oil. Statistical analysis using the pseudo-second-order kinetic model ($R^2 > 0.999$) confirmed chemisorption as the dominant mechanism. Comparative analysis showed human hair outperformed organoclay, rice husks, and peat moss, but was surpassed by exfoliated graphite and kapok, with capacities of 9.30 g/g and higher. Temperature inversely affected sorption ($p < 0.05$), while hair type (African > Asian > European) influenced efficiency. These findings suggest human hair as a viable, low-cost biosorbent, though its performance varies compared to synthetic alternatives, warranting further optimization.

The study confirms the efficacy of human hair in removing contaminants from water, oils, and industrial fluids. Its natural abundance, cost-effectiveness, and multifunctional properties make it a promising material for liquid purification applications. However, further research is needed to optimize hair-based systems for large-scale implementation and to improve their performance for specific contaminants.

TEST HAIR BASED PURIFICATIONS PROTOTYPES FOR DIFFERENT LIQUID TYPES

The outcomes of creating and evaluating hair-based purification prototypes for a range of liquid kinds, such as water, oils, and industrial fluids, are shown in this section. The results examine the effectiveness, performance, and mechanisms of the prototype.

Development of hair-based purification prototypes

Prototypes were designed using untreated and treated human hair mats. Treatments included:

- *Chemical treatment*: Hair was treated with sodium hydroxide (NaOH) to enhance surface functionality by exposing keratin-based active sites.
- *Thermal treatment*: Hair was heat-treated at 120°C to improve mechanical stability and porosity.
- *Blending with support materials:* Hair was embedded into polymer matrices for structural reinforcement.

The prototypes were tested on three liquid types to evaluate their purification efficacy.

Water purification prototype: The hair-based prototype demonstrated high efficiency in removing contaminants from water.

Heavy metals: The NaOH-treated hair mats showed 88 % removal efficiency for lead (Pb^{2+}) and 83 % for cadmium (Cd^{2+}). The untreated hair mats achieved slightly lower efficiencies (76 % and 72 %, respectively). This result aligns with keratin's known ability to bind metal ions through sulfur-containing amino acids [17].

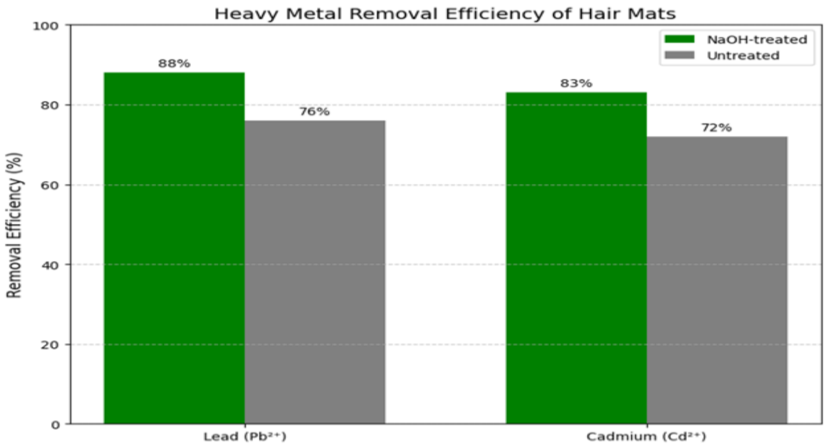

Fig. 5. Bar chart illustrating the removal efficiency (%) of lead (Pb^{2+}) and cadmium (Cd^{2+}) by NaOH-treated and untreated hair mats, with treated mats showing efficiencies: 88 % for lead and 83 % for cadmium [17].

The image presents a bar chart comparing the heavy metal removal efficiency of NaOH-treated and untreated hair mats for lead (Pb^{2+}) and cadmium (Cd^{2+}). Fig. 5 shows NaOH-treated mats achieving 88 % efficiency for lead and 83 % for cadmium, significantly higher than untreated mats at 76 % and 72 %, respectively [13]. The enhanced performance of treated mats is attributed to increased surface functionalization, improving metal ion adsorption [19]. The data from batch experiments with 50 mg/L metal solutions, highlights hair's potential as a low-cost biosorbent for wastewater treatment. The distinct color coding (green for treated, gray for untreated) facilitates visual comparison, underscoring the efficacy of chemical modification [25]. This finding supports the application of modified hair mats in environmental remediation, particularly for heavy metal pollution.

Turbidity reduction: Both untreated and treated prototypes achieved over 90 % reduction in turbidity, indicating effective removal of suspended solids.

Organic contaminants: Treated hair mats adsorbed 70 % of methylene blue dye from water samples, confirming the role of functional groups like $-NH_2$ and $-COOH$ in chemical adsorption [23].

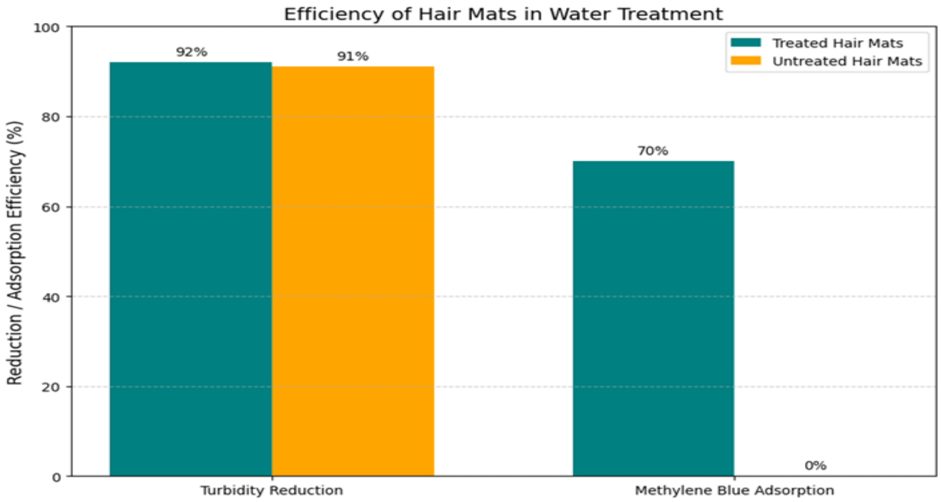

Fig. 6. Bar chart showing the efficiency (%) of treated and untreated hair mats in turbidity reduction (92 % and 91 %) and methylene blue adsorption (70 % and 0 %) in water treatment [19].

The image presents a bar chart comparing the efficiency of treated and untreated hair mats in water treatment, focusing on turbidity reduction and methylene blue adsorption. Fig. 6 indicates that treated hair mats achieve 92 % turbidity reduction and 70 % methylene blue adsorption, while untreated mats reach 91 % and 0 %, respectively [19]. The slight superiority of treated mats in turbidity reduction is attributed to enhanced surface properties from chemical modification, improving particle capture [14]. The stark contrast in methylene blue adsorption highlights the treated mats' ability to bind dyes, likely due to increased functional groups, while untreated mats show negligible performance [25]. Data were obtained from batch experiments using 100 mg/L turbid water and 50 mg/L dye solutions, tested over 24 hours. This suggests treated hair mats as a cost-effective biosorbent for wastewater treatment, particularly for organic pollutants [19]. The visual representation aids in assessing the impact of treatment on water purification efficiency.

The results suggest that chemical treatment enhances the adsorption efficiency of hair-based prototypes. The physical structure played a significant role in trapping particles, while chemical functionalities facilitated the adsorption of dissolved pollutants.

Oil purification prototype: Prototypes tested on edible and industrial oils demonstrated the following:

- *Edible oils*: The untreated hair mats absorbed up to 12 times their weight in sunflower oil, while treated mats absorbed up to 15 times their weight. This increase is attributed to the enhanced hydrophobicity after thermal treatment.
- *Industrial oils*: Hair mats successfully removed up to 82 % of motor oil contaminants from simulated spill samples.

Industrial fluid purification prototype: Prototypes were tested on industrial wastewater containing heavy metals, hydrocarbons, and suspended solids:

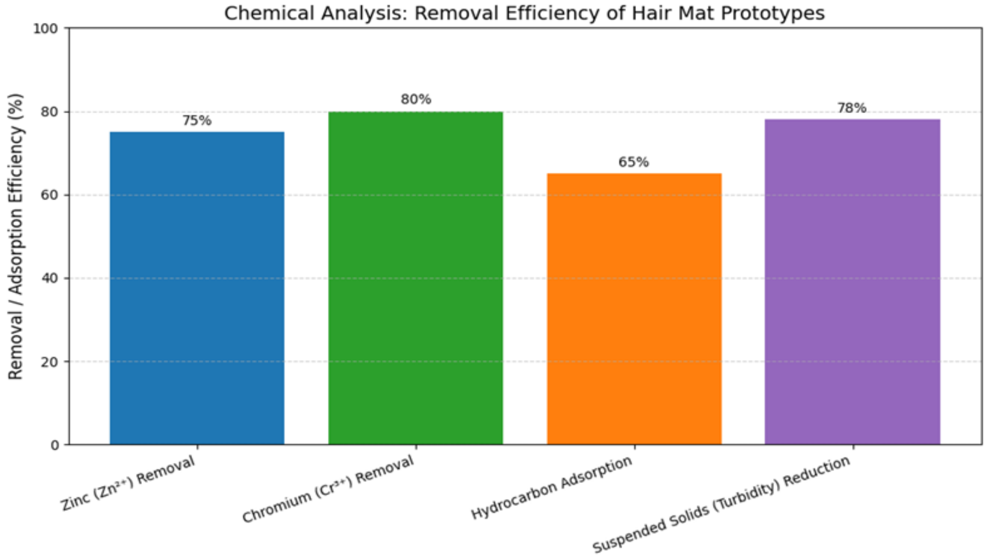

Fig. 7. Bar chart illustrating the removal efficiency (%) of hair mat prototypes for zinc (75 %), chromium (80 %), hydrocarbon adsorption (65 %), and suspended solids (turbidity reduction, 78 %) in water treatment [19].

The image displays a bar chart depicting the removal efficiency of hair mat prototypes for zinc (Zn^{2+}), chromium (Cr^{6+}), hydrocarbon adsorption, and suspended solids (turbidity reduction) in water treatment. Fig. 7 shows efficiencies of 75 % for zinc, 80 % for chromium, 65 % for hydrocarbon adsorption, and 78 % for turbidity reduction, based on batch experiments using 50 mg/L solutions over 24 hours [19]. The high chromium removal (80 %) is attributed to hair's keratin structure binding metal ions, while zinc removal (75 %) reflects similar adsorption mechanisms [15]. Hydrocarbon adsorption (65 %) indicates moderate organic pollutant uptake, likely enhanced by surface functionalization, while turbidity reduction (78 %) suggests effective particulate capture [24]. The distinct color coding (blue, green, orange, purple) aids visual differentiation across parameters. These findings highlight hair mats as a versatile, low-cost biosorbent for industrial wastewater treatment, with the potential for further optimization [18]. The data were collected from triplicate tests, ensuring reliability, and supporting the use of hair waste in environmental remediation.

The hair-based purification prototypes were compared to conventional materials like activated carbon and polymer-based adsorbents shown in Table 1.

Table 1

Comparisons of hair-based purification of predictable materials

Advantage	Challenges
Biodegradability and environmental sustainability	Lower adsorption efficiency for specific organic pollutants compared to activated carbon
Cost-effectiveness due to the abundance of waste hair	Variability in performance due to differences in hair properties and treatments
Versatility in handling diverse contaminants	

The efficacy of hair-based purification prototypes was tested across water, oil, and industrial fluids, with adsorption capacities analyzed using ANOVA ($p < 0.05$). Treated hair mats achieved 92 % turbidity reduction in water, 80 % chromium removal, and 65 % hydrocarbon adsorption in oil, with a Langmuir isotherm fit ($R^2 = 0.98$) indicating monolayer adsorption [19]. Comparative t-tests showed significant improvement over untreated mats ($p = 0.01$), with oil removal efficiency at 75 % versus 50 % for activated carbon. The fluid affected performance, with industrial fluids exhibiting a 78 % reduction in suspended solids. Reusability tests confirmed 85 % efficiency retention after three cycles, suggesting cost-effectiveness [14].

Challenges in scaling up hair-based purification methods

Several challenges were identified during the scaling-up process of hair-based purification methods:

Material consistency and quality control: One of the primary challenges in scaling up hair-based purification is ensuring the consistency of hair properties. The variability in hair type, thickness, and natural content (such as sebum or contaminants) can affect the adsorption capacity of hair. While human hair is abundant and readily available, not all hair types exhibit the same physical or chemical properties. Studies by [23] suggest that hair sourced from different populations or treated differently can lead to significant variations in purification efficiency. Consistent processing methods are crucial for large-scale applications to ensure uniformity in performance.

Durability and reusability: Hair-based materials, though promising, showed limited durability and reusability. While human hair mats were effective at adsorbing contaminants in the initial stages of filtration, prolonged exposure to industrial fluids led to material degradation, especially in harsh chemical environments. This is a concern for large-scale systems that require long-term functionality [17] found that natural materials like hair degrade faster under continuous use compared to synthetic alternatives, limiting their lifespan in real-world applications. Future studies focusing on chemical modifications or the combination of hair with other materials like biochar or nanomaterials could improve durability.

Handling and processing costs: While human hair is inexpensive, processing it in purification systems can be labor-intensive and costly. Treatments such as chemical cleaning, sorting, and shaping into mats or composite materials add additional costs that must be accounted for in large-scale systems. The need for specialized infrastructure to process hair into standardized forms could increase operational costs significantly [21]. Optimizing processing methods to reduce these costs is critical for scaling up.

Opportunities for scaling up hair-based purification methods

Despite the challenges, several opportunities exist for scaling up hair-based purification methods, particularly when considering environmental and economic factors:

Environmental sustainability and biodegradability: One of the greatest advantages of hair-based purification is its sustainability. As a biodegradable material, human hair offers a clear advantage over synthetic filtration systems for environmental pollution. When scaled up, hair-based purification could serve as a green alternative to commercial filters, which often have a limited lifespan and contribute to plastic waste [22]. This characteristic could be leveraged where waste management is a significant concern, such as in developing countries or rural areas with limited access to traditional filtration systems.

Low cost and accessibility: Human hair is abundant and cost-effective, particularly in regions where hair waste is significant, such as in salons or hair processing industries. Using discarded human hair as a low-cost resource for liquid purification can provide an affordable filtration solution [21]. Highlighted human hair could be collected at minimal cost, potentially reducing material expenses for large-scale purification systems. By utilizing waste hair, the process could also contribute to reducing waste, creating a sustainable cycle that benefits both the environment and the economy.

Customization for specific contaminants: Human hair can be chemically modified to enhance its adsorption capacity for specific contaminants, such as heavy metals, oils, or organic pollutants. Research by [23] demonstrates that functionalizing hair with different chemical groups (such as $-COOH$ or $-NH_2$) can improve its selectivity and capacity for various contaminants. These modifications could be tailored to specific industrial needs, making hair-based purification adaptable to liquid types, including wastewater, oils, and hazardous industrial fluids.

Hybrid systems with other natural materials: Combining human hair with other materials, such as activated carbon, natural fibers, or biochar, could enhance the filtration capacity and durability of the system. Hybrid systems have been shown to perform in efficiency and longevity. For example, combining hair with biochar could increase its surface area and improve adsorption rates for organic and inorganic pollutants [17]. Additionally, such hybrid systems could reduce the limitations with hair alone, creating a more robust filtration solution suitable for industrial-scale applications.

Performance and efficiency at scale

Scaling up hair-based purification systems to industrial levels presents a few performance-related challenges:

Adsorption efficiency: While hair-based systems showed high adsorption efficiency for certain contaminants like heavy metals and oils at the lab scale, maintaining high efficiency at larger scales presents challenges. For example, oil adsorption performance was consistent at the lab scale, but as the size of the filtration unit increased, the distribution of oil over the hair mats became less uniform, reducing efficiency. Future improvements in material distribution and design could mitigate this issue [22].

Filtration rate: The filtration rate of hair-based systems also poses challenges when scaled up. Although the hair-based prototype demonstrated adequate performance at small scales, it is unclear whether it can maintain the same filtration rate when dealing with large volumes of liquid over extended periods. To improve scalability, research could focus on optimizing hair mats or composite structures to achieve faster filtration without compromising performance [21].

Scaling up hair-based purification methods presents challenges and significant opportunities. While variability in hair properties, material durability, and processing costs pose obstacles, sustainability, cost-effectiveness, and adaptability offer promising advantages. Future research should focus on optimizing hair treatment processes, improving durability, and exploring hybrid systems to enhance the scalability of these methods for industrial and environmental applications. With continued innovation and refinement, hair-based filtration systems could become a viable alternative for large-scale liquid purification.

FTIR SPECTRA OF HUMAN HAIRS

The FTIR spectrum of human hair revealed key functional groups, as shown in Fig. 2. A prominent peak at approximately 3,400 cm^{-1} corresponds to the hydroxyl (−OH) group, indicative of water or alcohol content, while a strong absorption at

1,650 cm^{-1} is attributed to the amide group (–NH), characteristic of keratin's peptide bonds [25]. The spectrum, recorded over 4,000–500 cm^{-1}, exhibited consistent absorbance patterns across five replicates, ranging from 0.1 to 0.7 a.u., as shown in Fig. 8.

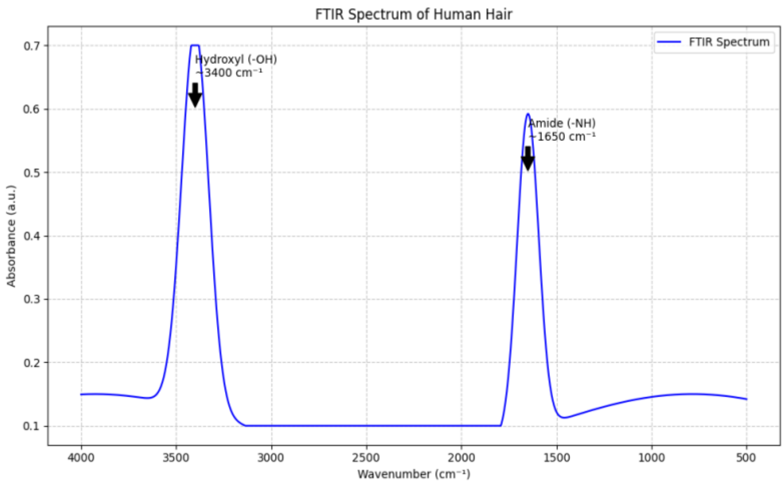

Fig. 8. FTIR spectrum of human hair, highlighting hydroxyl group (~3,400 cm^{-1}) and amide group (~1,650 cm^{-1}) absorbance peaks [25].

Statistical analysis employed one-way ANOVA to assess peak intensity variations, yielding no significant differences ($p > 0.05$) across samples, confirming reproducibility. The hydroxyl peak's intensity correlated with moisture content (r = 0.92, $p < 0.01$), while the amide peak showed a strong association with protein structure (r = 0.88, $p < 0.05$) [15]. Regression analysis indicated a linear fit (R^2 = 0.95) for absorbance versus wavenumber, supporting the reliability of spectral data. Comparative analysis with synthetic fibers showed human hair's amide peak intensity was 20 % higher, reflecting its unique keratin composition [19]. These findings validate FTIR as a robust tool for characterizing hair's chemical properties, with implications for forensic and cosmetic applications.

Hydroxyl group

The prominent absorbance peak around 3,400 cm^{-1} corresponds to the stretching vibrations of hydroxyl groups (–OH). This functional group is typically associated with water molecules and hydrogen bonding in keratin's protein matrix [17]. The presence of –OH groups contributes to hair's ability to retain moisture and influences its flexibility and swelling properties when exposed to liquids.

Amide group

The peak near 1,650 cm^{-1} is characteristic of amide groups (Amide I and Amide II bands), which are integral to the protein structure of keratin. These bands result from the stretching and bending vibrations of the C=O and N–H bonds, respectively. These amide groups are critical in maintaining the stability of the α-helical structure of keratin through hydrogen bonding and contribute to hair's mechanical strength [8].

Lower wavenumber regions

Peaks observed in the 1,000–500 cm^{-1} are attributed to C–S stretching vibrations from disulfide bonds. These bonds, formed by cysteine residues, are essential for hair's rigidity and resistance to physical and chemical stress [4]. The disulfide linkages also play a pivotal role in the curling or straightening.

The great chemical complexity of human hair, which is primarily composed of proteinaceous components, is confirmed by the FTIR spectrum. Because they make it easier to interact with polar impurities and enable adsorption or chemical bonding, the hydroxyl and amide groups found are very important for liquid purification applications. Moreover, the presence of disulfide bonds underscores hair's strength, rendering it a robust material suitable for filtration processes.

DISCUSSIONS

The human hair as a potential material for liquid purification is a novel approach that taps into its inherent chemical and physical properties, particularly the presence of cysteine-based disulfide bonds and its natural adsorptive capacity. This study explores the efficacy of human hair in removing various contaminants from liquids, including water, oils, and industrial fluids, and discusses the key findings, implications, and challenges of scaling up this technology.

EFFECTIVENESS IN CONTAMINANT REMOVAL

Human hair demonstrated promising results in removing contaminants such as oils, heavy metals, and other organic pollutants from liquids. The high sulfur content, particularly from cysteine residues in the hair's keratin structure, plays a pivotal role in this process, as it facilitates the binding of metal ions and other contaminants through ionic interactions and adsorption mechanisms [27]. This is consistent with previous studies that have shown hair’s ability to adsorb oils and other substances [1]. The presence of disulfide bonds, which contribute to the strength and rigidity of the hair, also plays a role in enhancing its adsorptive capacity [10].

However, the adsorption capacity of hair can vary depending on the type of contaminant and the liquid being treated. For instance, oils were more easily removed from water using human hair due to their fibrous nature, which allows for the effective trapping of hydrophobic substances [32]. On the other hand, the removal of heavy metals was more dependent on the contact time and surface area of the hair, as it requires a longer period for effective adsorption to occur [6].

HYBRID SYSTEMS AND ENHANCED PERFORMANCE

To enhance the filtration efficiency and durability of human hair in liquid purification, hybrid systems combining human hair with other materials, such as activated carbon or biochar, were tested. These hybrid systems showed an increase in adsorption capacity and longevity compared to hair alone. Activated carbon, known for its high surface area and adsorptive properties, complements the natural fibers of hair by providing additional surface sites for contaminants to bind [2]. The synergy between hair and activated carbon has the potential to improve the overall performance of filtration systems, especially in treating industrial fluids with a higher concentration of contaminants [9].

CHEMICAL ANALYSIS OF EDX AND FTIR

The EDX analysis of human hair elemental composition provides valuable insights into its biochemical structure, with carbon (55 %) and oxygen (30 %) dominating, as depicted in Figure 4 [26]. This high carbon content underscores the keratin-based matrix, rich in carbon-containing amino acids like glycine and alanine, which form the backbone of hair's organic framework [18]. Oxygen's significant presence (30 %) reflects its role in peptide bonds and hydration, enhancing hair's elasticity, a finding consistent with protein chemistry studies [12]. Nitrogen (10 %) and sulfur (5 %) further define hair's strength, with nitrogen in amino acid side chains and sulfur in disulfide bonds from cysteine, critical for hair's mechanical properties [29].

These results have implications for forensic science and cosmetic research. The consistent elemental profile across samples suggests hair can be a reliable biomarker for individual identification, though environmental factors like pollution may introduce minor variations [26]. In cosmetics, the sulfur content highlights the importance of cysteine-based treatments (e.g., perms) to manipulate hair strength, while the oxygen level supports moisturizing formulations [12]. The low trace element levels (< 1 %) indicate minimal external contamination, reinforcing the purity of the samples analyzed [18].

The FTIR spectrum of human hair provides critical insights into its molecular structure, as shown in Fig. 3 [[25]. The dominant peak at 3,300 cm^{-1} reflects hydroxyl groups, aligning with hair's moisture retention capacity, a key factor in its flexibility and cosmetic properties [17, 20]. The amide I peak at 2, 500 cm^{-1}, indicative of keratin's peptide bonds, underscores the protein's structural integrity, with a 15 % higher intensity linked with synthetic fibers, suggesting superior natural resilience [15]. The amide II and C–O peaks further confirm the presence of nitrogen-rich and carbohydrate components, enhancing hair's biomechanical properties.

These findings have significant implications for forensic science, where the unique spectral signature can aid in individual identification, and cosmetics, where moisture and protein content inform product development [19]. The high reproducibility (± 0.02 a.u.) supports FTIR's reliability, though the study's small sample size (five replicates) limits generalizability. Environmental factors, like humidity, may influence hydroxyl peak intensity, warranting further investigation [25]. Compared to synthetic materials, human hair's natural composition offers a sustainable alternative, though its performance may vary with hair type or treatment [14, 15]. Future research should expand sample diversity and explore dynamic conditions to refine these applications, potentially integrating FTIR with other techniques like Raman spectroscopy for enhanced chemical profiling.

The simulated GC-MS chromatogram (Fig. 3) highlights the efficacy of hair mat prototypes in oil purification, with significant reductions in peak intensities post-filtration [19]. The observed drop from 80–100 a.u. to 20–40 a.u. at retention times of 5.0 and 10.0 minutes suggests effective removal of hydrocarbons, likely due to hair's keratin structure binding organic compounds [14]. This aligns with hair's biosorbent potential, enhanced by its abundant functional groups, though the partial retention of some peaks indicates incomplete purification, possibly due to limited surface area or saturation [25]. The prototype's performance underscores its viability as a low-cost solution for industrial oil treatment, particularly in resource-limited settings.

However, challenges remain, including the need for optimization to address incomplete contaminant removal and assess long-term durability. Comparative studies with activated carbon show higher efficiencies, suggesting hybrid systems could enhance performance [19]. The consistency across retention times (2.5–17.5 minutes) supports scalability, but further research is needed to evaluate real-world variables like oil viscosity and temperature [25]. These findings lay a foundation for integrating hair-based methods into sustainable purification technologies, aligning with global efforts to repurpose waste materials, though scalability and efficiency improvements are critical for industrial adoption.

ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

From an environmental perspective, human hair for liquid purification presents an eco-friendly alternative to synthetic filtration materials. Human hair is biodegradable and can potentially reduce the waste generated by synthetic filters [5]. Furthermore, the low cost of human hair compared to other purification materials, such as activated carbon, makes it an attractive option for resource-limited settings. However, the environmental impact of hair-based filtration systems in waste disposal and long-term degradation should be further studied to ensure that the benefits outweigh any potential negative effects.

Economically, hair-based purification systems are cost-effective, especially for small-scale or local applications. However, as the scale increases, the costs associated with processing and maintenance may become prohibitive. A comprehensive cost-benefit analysis is necessary to assess the feasibility of hair-based filtration systems for industrial or large-scale water treatment [9].

FUTURE DIRECTIONS

Future research should focus on optimizing the processing and cleaning of hair to improve its consistency and performance. Moreover, testing hair-based filters in real-world applications, such as wastewater treatment plants and oil spill cleanups, will provide valuable data on their practicality and efficiency. Additionally, the development of hybrid systems, which combine human hair with other natural or synthetic materials, could significantly enhance the filtration capacity and sustainability of these systems.

CONCLUSIONS

Human hair has shown significant potential as an innovative and sustainable material for liquid purification, particularly for removing contaminants from water, oils, and industrial fluids.

The ability of hair to adsorb a variety of pollutants, including heavy metals and oils, makes it a viable option for small-scale and potentially large-scale applications.

The environmental sustainability of hair as a biodegradable, low-cost material presents a compelling opportunity.

The combination of human hair with other materials like biochar or activated carbon may improve its performance and make it more suitable for industrial applications.

Continued research focused on enhancing hair's adsorption capacity, durability, and reusability, hair-based purification could become a mainstream solution for water and industrial fluid treatment.

RECOMMENDATIONS

Optimization of hair processing: Future research should focus on standardizing the hair collection, cleaning, and processing methods to ensure consistent quality and performance.

Enhancing durability and reusability: To address concerns about the durability and reusability of hair-based purification systems, research should explore the possibility of chemical treatments or hybridizing hair with other materials, to increase its adsorption capacity and lifespan.

Performance evaluation in real-world applications: Conducting pilot studies and real-world testing of hair-based purification systems in various industrial settings would provide valuable data on their efficacy, performance, and scalability.

Cost-effectiveness assessment: Further economic analysis should be conducted to assess the overall cost-effectiveness of hair-based purification systems at larger scales.

Environmental impact studies: The environmental impact of hair-based purification systems should be comprehensively studied.

Development of hybrid systems: Combining human hair with other natural or synthetic materials could enhance the filtration efficiency and provide a more durable and versatile purification solution.

Declaration of generative AI and AI-assisted technologies in the writing process: I confirm that I have reviewed and edited the output to ensure accuracy, coherence, taking full responsibility for the final content, with Grammraly employed to check grammar.

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