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(Research Article)

Utilizing a modified down-flow sponge reactor for the treatment of industrial sewage sludge, offering a solution to the fertilizer crisis through agricultural applications

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Abstract

Untreated sewage poses severe threats to ecosystems, public health, and economies, particularly in developing nations where treatment facilities often fail due to poor maintenance. Concurrently, rising natural gas prices have escalated chemical fertilizer costs. This study evaluates an eco-friendly biological and chemical sewage sludge treatment using a modified Down-flow Hanging Sponge (DHS) reactor with organic additives at hydraulic retention times of 3 and 6 hours. The modified DHS system demonstrated high removal efficiency for organic pollutants, suspended solids (COD, BOD, TSS, VSS), oil/grease, nitrogenous compounds (NH3, NO3−), total coliforms, and toxic heavy metals (Pb,Ni,Cu,Zn,Cr,Cd,Fe). Agricultural trials on radish plants (Raphanus sativus) under identical cultivation conditions revealed significantly lower heavy metal accumulation in plants fertilized with DHS-treated sludge compared to untreated sludge. These findings confirm that modified DHS reactors offer an effective, sustainable, and cost-efficient solution to treat sewage sludge while producing a safe, nitrogen-rich alternative to synthetic fertilizers.

Keywords: Wastewater treatment; Down-flow Hanging Sponge (DHS) reactor; Sewage sludge; Heavy metal removal; Biofertilizers

1. Introduction

Sewage treatment typically encompasses four main stages: preliminary, primary, secondary, and tertiary. The preliminary and primary stages primarily aim to eliminate gross debris and suspended solids, yielding clarified wastewater alongside solid byproducts known as sewage sludge. The overall quality of these byproducts is dictated by local operational conditions, with landfill disposal remaining the predominant management pathway for sludge [1].

To enhance effluent quality for potential reuse, recent research titled "Down-flow Hanging Sponge (DHS) Reactor in the Presence of Chelating Ligand as a Novel Post-Treatment System for Municipal Wastewater" investigated the deployment of the Down-flow Hanging Sponge (DHS) system for treating primary and secondary activated sludge effluents. This system incorporates ethylenediaminetetraacetic acid (EDTA) derivatives (ligands) and their corresponding metal complexes to facilitate heavy metal chelation and removal [2]. The experimental pilot system was constructed and evaluated at the El-Kharry Sewage Treatment Plant in Damanhour, Beheira Governorate, Egypt. The reactor was fed with primary sedimentation effluent across two operational phases: Phase 1 at a hydraulic retention time (HRT) of 6 hours, and Phase 2 at a reduced HRT of 3 hours. Subsequent laboratory analyses confirmed the central role of EDTA derivatives in achieving cost-effective wastewater purification with minimal heavy metal contamination [3].Advanced

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sewage treatment remains imperative for safeguarding public health and securing sustainable water reuse options [4–8]. Operational configurations vary based on influent characterization and local discharge standards, driving interest toward cost-effective technologies that minimize environmental footprints [9]. Among these, the DHS reactor has emerged as a high-performance post-treatment option. Utilizing polyurethane sponge modules suspended in an aerobic filtration matrix, the system treats primary and secondary effluents [10–12] in conjunction with synthetic chelating agents, including hydrazide and Schiff-base derivatives, to enhance heavy metal removal. Evaluated across the 6-hour (Phase 1) and 3-hour (Phase 2) HRT conditions at the El-Kharry facility [13, 14], the system was monitored for its overall removal efficiency regarding organic matter, suspended solids, nitrogen species, heavy metals, and pathogenic indicators such as coliform bacteria. The primary objective was to demonstrate the technical viability and operational suitability of the modified DHS reactor for municipal wastewater reclamation and sustainable agricultural reuse [15].

2. Experimental Method

2.1. Materials

The starting chemicals used in this study were of analytical grade and were utilized without any further purification.

2.2. Physical and Spectroscopic Techniques

The synthesized hydrazide derivatives, Schiff-base ligands, and their corresponding metal complexes were systematically characterized using a comprehensive suite of physical and spectroscopic techniques. Elemental microanalyses (C, H, N) and metal content (M) determinations were conducted at the Microanalytical Center of Cairo University, Egypt. To evaluate the electrolytic nature of the complexes, molar conductivity measurements (Λm) were carried out in 10−3 M dimethylformamide (DMF) solutions at room temperature using a Bibby Conductimeter Model MCl [16]. Molecular weight profiles and fragmentation pathways were verified by electron ionization mass spectra (EI-MS) recorded on a JEOL JMS-AX-500 mass spectrometer. Solid-state Fourier-transform infrared (FT-IR) spectra were acquired over the range 4000–400 cm−1 on a Perkin-Elmer 683 spectrophotometer using KBr or CeBr pellet techniques, while electronic absorption spectra in DMF were measured using a Perkin-Elmer 550 spectrophotometer. Room-temperature magnetic susceptibility measurements were obtained via the Gouy balance method calibrated against Hg[Co(NCS)4] [17]. Furthermore, solid-state X-band electron spin resonance (ESR) spectra were recorded at room temperature using a Bruker ELEXSYS E500 spectrometer with 2,2-diphenyl-1-picrylhydrazyl (DPPH) as the standard marker [18]. Finally, thermal stability and degradation pathways (TGA and DTA) were investigated using a Shimadzu DT-30 thermal analyzer from ambient temperature up to 600 ∘C at a dynamic heating rate of 10∘C·min−1 under a dynamic nitrogen atmosphere [19].

2.3. Preparation of Ligand [HL]

The ligand was synthesized by refluxing tartaric acid (15 g, 0.072 moles) in ethanol (75 cm^3) with the addition of 0.5 mL concentrated H_2SO_4 at 100°C and stirring at 1.5 rpm for 2 hours. After cooling the reaction mixture in an ice bath, 7.5 mL of 2-methyl ethylene diamine was added. The resulting white precipitate was filtered, washed multiple times with ethanol, and dried under vacuum over P_4O_{10}.

2.4. Preparation of Schiff Base Ligand

The Schiff base ligand was prepared by refluxing a mixture of the ligand [HL] (4 g, 0.022 moles) and salicylaldehyde (4.8 mL) in ethanol for 5 hours. A yellow precipitate was formed, which was filtered, washed several times with ethanol, and dried under vacuum over P_4O10

2.5. Metal complexes were prepared as follows

The metal complexes were synthesized via a (1:2 M) molar reaction of ligands (hydrazide and Schiff base) with metal salts (chlorides, acetates, or nitrates) dissolved in ethanol (30 mL for ligands and 25 mL for salts), followed by refluxing under stirring for 1–3 hours, cooling, and filtration. Comprehensive chemical and physical characterizations confirmed the structural integrity, stoichiometry, and coordination environments of the synthesized compounds [20, 21]. Elemental analysis verified elemental composition [22], while FT-IR, NMR, and UV-Vis spectroscopies elucidated functional group coordination, structural profiles, and electronic transitions, respectively [23]. Thermal (TGA/DSC) and magnetic analyses confirmed the thermal stability, magnetic properties, chemical formulas, and structural integrity of the synthesized complexes [24].

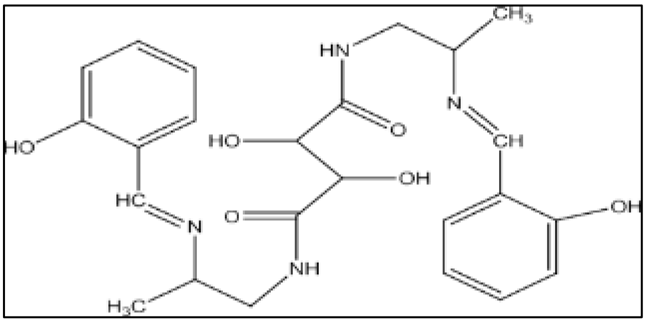

Figure 1 Schiff-base structure Chemical Formula and Structure

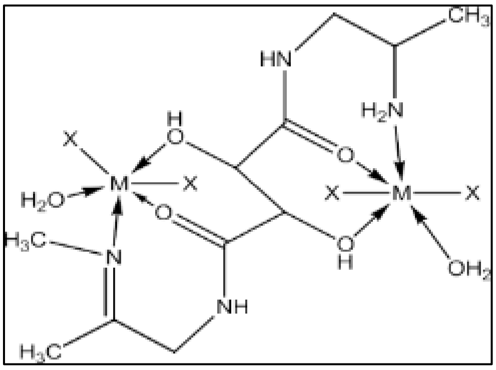

Figure 2 The metal- Hydrazide complexes Chemical Formula and Structure M= Pb, Cd, Cu, Ni, Fe, Cr, Zn, X= OAc, NO3, Cl

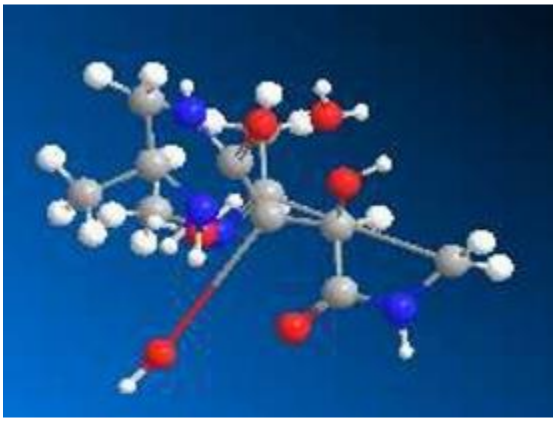

Figure 3 The metal- Hydrazide complexes 3D Chemical Structure

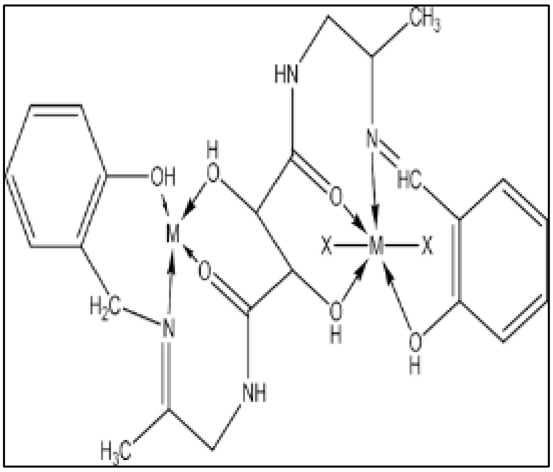

Figure 4 The Chemical Formula and Structure of metal- Schiff-base complexes

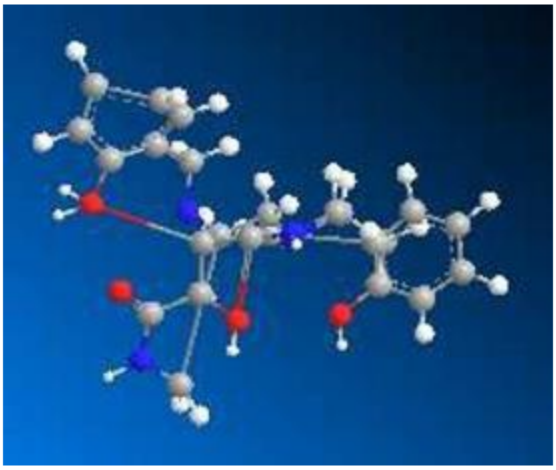

Figure 5 The 3D Structure of metal- Schiff-base complexes

M= Pb, Cd, Cu, Ni, Fe, Cr, Zn,   X= OAc, NO_3, Cl

2.6. Down-Flow Hanging Sponge (DHS) Reactor

This study evaluated a Down-Flow Hanging Sponge (DHS) reactor incorporating novel hydrazide and Schiff-base ligands and their metal complexes as a cost-effective post-treatment for primary and secondary municipal effluents, where operating under hydraulic retention times of 6 h (Phase-1) and 3 h (Phase-2) significantly enhanced heavy metal removal and produced high-quality water suitable for reuse [25].

2.7. Assessment the efficiency of raw and treated sludge inplanted radish plant and fertilizer by them

The study assessed the concentrations of heavy metals (Zn, Ni, Cr, and Cu) in radish plants grown with different fertilizers: raw sludge, sludge treated with a ligand, and sludge treated with a Schiff base. Results showed that heavy metal concentrations were highest in radishes fertilized with raw sludge, followed by those with ligand-treated sludge, and lowest with Schiff base-treated sludge. Zinc had the highest concentration, followed by chromium, copper, and nickel. Heavy metals primarily accumulated in the soil's top 15 cm, with only soluble and chelated forms being plant-available [26]. The treatment methods significantly reduced heavy metal uptake in radishes.

3. Results and discussion

Sewage sludge from the El-Beheira station (Northern Egypt) contains hazardous heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Fe^{3+}, Cr^{3+}, Zn^{2+}) alongside anions (acetate, Cl^{-}, NO^{3-}). To evaluate their remediation, novel hydrazide and Schiff-base ligands and their metal complexes (1:2 ligand-to-metal ratio) were synthesized at room temperature (Figures 1 and 2). Comprehensive characterizations including elemental analysis, FT-IR, UV-Vis, EI-MS, 1H-NMR, molar conductivity, magnetic susceptibility, and ESR confirmed the proposed structures [3–5]. Under identical refluxing conditions (2 h, ethanol), the hydrazide ligand exhibited superior overall removal efficiencies compared to the Schiff-base ligand: Pb^{2+} (41.1–46.1% vs. 35–38.7%), Ni^{2+} (27.5–31.7% vs. 13.2–15%), Cd^{2+} (27.5–31.7% vs. 22.8–25.5%), Cu^{2+} (17.8–21% vs. 14.3–16.4%), Zn^{2+} (17.9–21% vs. 14.4–16.5%), Fe^{3+} (17.8% vs. 14.4%), and Cr^{3+} (16.6% vs. 13.5%). These findings demonstrate the promising potential of both ligands particularly hydrazide for heavy metal extraction from contaminated sewage sludge, highlighting the need for further parameter optimization [30].

3.1. The Research scheme depending Retention time, (six hours Retention time Research scheme):

The results of the study are summarized in Figures (6-11) and presented in Tables (1-3), covering various parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand over five days (BOD5), Total Suspended Solids (TSS), nitrogen groups, heavy metals, and coliform bacteria removal efficiencies.

3.1.1. COD and BOD5 Removal

The study demonstrated exceptional removal efficiencies for chemical oxygen demand (COD) and five day biochemical oxygen demand (BOD5) across the evaluated systems, emphasizing that particle capture is prerequisite for effective digestion and biodegradation [31]. Raw municipal wastewater exhibited initial COD concentrations of 630±410 mg/L. While the conventional primary activated sludge treatment at the El-Kharry plant achieved modest removal efficiencies of 30±11% for COD (reducing concentrations from 290 mg/L to 200 mg/L) and 32±11% for BOD5 (from an initial 213±50 mg/L), the Down-flow Hanging Sponge (DHS) system outperformed traditional methods significantly. The DHS reactor achieved superior overall removal efficiencies of 95±3% for COD and 96±4% for BOD5, markedly lowering effluent concentrations to 11.4±7 mg/L and 13±5 mg/L, respectively, even under operational conditions of 20∘C and a 6.0-hour hydraulic retention time (HRT).

3.1.2. Total Suspended Solids (TSS) Removal

The removal of Total Suspended Solids (TSS) was also assessed. In the treated primary effluent of the El-Kharry wastewater treatment plant, the TSS removal efficiency was 58 ± 12%, reducing the TSS concentration to 180 ± 25 mg/L. In contrast, the DHS system achieved a much higher removal efficiency of 94 ± 8%, bringing TSS levels down to 13 ± 9.4 mg/L. The higher efficiency in the DHS system can be attributed to the longer Sludge Retention Time (SRT), which allows for better entrapment and degradation of suspended solids in the sponge material of the system [32].

3.1.3. Nitrogen Group Removal

Nitrogen removal in the DHS system was carried out through the nitrification and denitrification processes [33]. Nitrification primarily occurs in the lower portion of the reactor, where the organic loading is lower, and the dominance of autotrophic bacteria for oxygen utilization is less intense. The results showed a 79% removal of Total Kjeldahl Nitrogen (TKN) and a 94 ± 4% removal of ammonia nitrogen (NH4-N). The average concentrations of TKN and NH4-N in the final effluent were 1.76 mg/L and 0.95 mg/L, respectively. Additionally, the concentrations of nitrate and nitrite in the DHS effluent ranged from 0.86 to 5.1 mg/L and from 2.6 to 15 mg/L, respectively, indicating that the DHS system was effective in reducing nitrogenous compounds.

3.1.4. Heavy Metal Removal

The removal of heavy metals was also studied, particularly focusing on manganese (Mn) and iron (Fe). The study utilized a polymer called hydrazide, which was added at a dose of 3 mg per 50L to facilitate the chelation or capture of heavy metals. The results indicated good performance in terms of heavy metal removal. The removal efficiencies of manganese (Mn) and iron (Fe) in the DHS system were 94 ± 18% and 74 ± 20%, respectively, when treating primary effluent from the El- Kharry wastewater treatment plant [34].

3.1.5. Coliform Bacteria Removal

Microbiological analysis revealed exceptional pathogen log-reductions within the Down-flow Hanging Sponge (DHS) system, achieving overall removal efficiencies of 99.9% (37°C) and 99.8% (22°C). Specific log-removals reached 99.8% for total coliforms (TC; 95% reduction efficiency), 99.6% for fecal coliforms (FC; 93% reduction efficiency), and 99.0% for fecal streptococci (FS). Effluent bacterial counts at 37∘C and 22∘C ranged between 6×104–9.2×106 CFU/mL (mean: 1.7×106 CFU/mL) and 3.7×104–5.6×106 CFU/mL (mean: 1.0×106 CFU/mL), respectively, yielding Most Probable Number (MPN) values of 1500 MPN/100 mL for TC and 750 MPN/100 mL for both FC and FS. Overall, the DHS reactor significantly outperformed conventional activated sludge systems across core pollution parameters including COD, BOD5, TSS, nitrogen species, and microbial indicators—while the integration of chelating ligands efficiently enhanced heavy metal removal (notably Fe and Mn), confirming its high potential as a reliable, low-cost wastewater reclamation technology [15, 35].

Table 1 Summery of the data of Raw Sewage sludge Characteristics

Parameters		**Unit**	**Min**	**Max**	**Average**
Heavy metals	Pb	mgL^{-1}	0.41	0.56	0.49
	Cd	mgL^{-1}	0.042	0.064	0.054
	Cu	mgL^{-1}	1.39	1.60	1.50
	Fe	mgL^{-1}	150.2	828	451.06
	Ni	mgL^{-1}	0.54	0.64	0.597
	Zn	mgL^{-1}	4.94	7.91	6.49
	Cr	mgL^{-1}	1.31	3.832	2.26
Parasites	Salmonella	unit/l00ml	$2.8x10^3$	$2.6x10^4$	$1.44\ x10^4$
Sv30		Cm^3/l	300	950	625

Table 2 Summery of the performance data of the treatment system at 6 hours as retention time

Parameters	**Unit**	**Raw Sewage**			**Primary effluent**			**Finial effluent**			**DHS effluent**		
		Average	**Max**	**Min**	**Average**	**Max**	**Min**	**Average Max**		**Min**	**Average Max**		**Min**
COD tot	mg O_2/ l	400	630	310	233	290	200	27.3	41	15	11.40	30	3.6
BOD5	mg/l	200	256	115	146	213	105	15	27	8	5	16	2.11
TSS (105 ^{0}C)	mg/l	253.20	280	210	146	67	82	18.13	28	12	9.18	13	4.3
VSS (105 ^{0}C)	mg /l	134.18	204	93.50	79.49	144	40.20	14.55	23.80	6.80	8.80	17	2.89
TKN	mg N / l	5.30	7	3.50	3.8 0	5.03	1.5 0	1.2 0	3.7 0	0.45	2.02	3.50	0.94
Ammonia	mg N / l	38.13	50	27.80	30.36	43	19	7.97	12.80	4.20	4.50	23.50	1
Nitrate	mg/l	1.12	2.90	0.32	1.49	3.06	0.85	3.14	6.02	0.88	3.06	5.58	0.75
Total Phosphate	mg P/ l	15.20	33	6.72	13	30	8.60	9.80	24	5.02	9.50	16.60	2.82
Oil and Grease	mg / l	10.8	13	8	7.39	8.7	6	4.30	5.40	2.30	3.44	5.80	2.02

Table 3 Performance results of heavy metal in the primary of activated sludge and effluent of DHS system treating domestic waste water at a total HRT of 6 h

Heavy metal	**Raw**	**Ligand (mg L^{-1})**	**Schiff base (mg L^{-1})**	**Percentage %**		**Raw sludge(mg/kg)**			**Heavy metals which treated with**	
				ligand	**Schiff base**	**limit EG**	**EPA limit**	**Raw calculated**	**Ligand (mg/ kg)**	**Schiff base(mg /kg**
Pb	0.5	0.4	0.29	20	42	300	840	637	500	362.5
Cd	0.064	0.04	0.012	35.9	81.25	39	85	80	51.25	15
Cu	1.39	1.01	0.91	26.8	34.53	1500	4300	1737.5	1271.25	1137.5
Fe	375	277	182	26.13	51.46	------	------	468750	346250	277500
Ni	0.641	0.31	0.216	51.1	66.3	240	420	801.25	391.25	270
Zn	6.62	4.01	3.406	39.3	48.54	2800	7500	8275	391.25	4257.5
Cr	1.31	0.82	0.61	37.4	53.4	1200	------	1637.5	1025	762.5

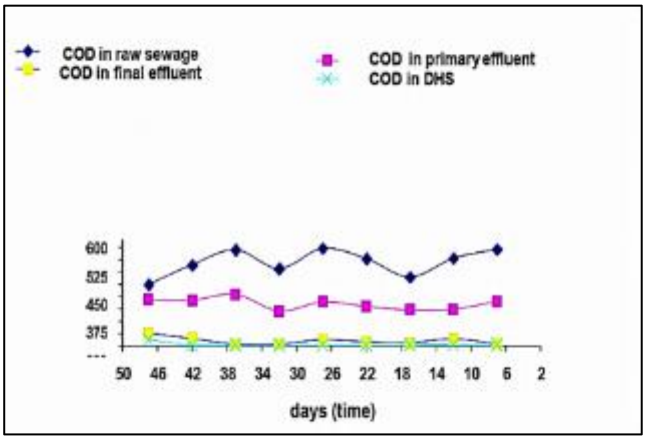

Figure 6 Variation in total COD along AS plant and the DHS treatment system

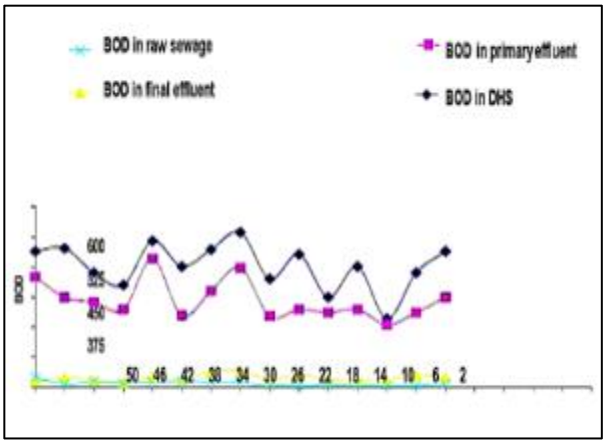

Figure 7 BOD total variation along AS plant and the DHS treatment system

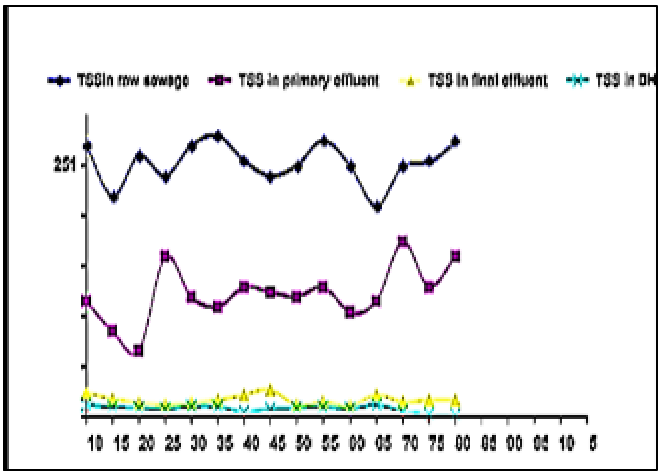

Figure 8 Variation in total TSS along treatment system

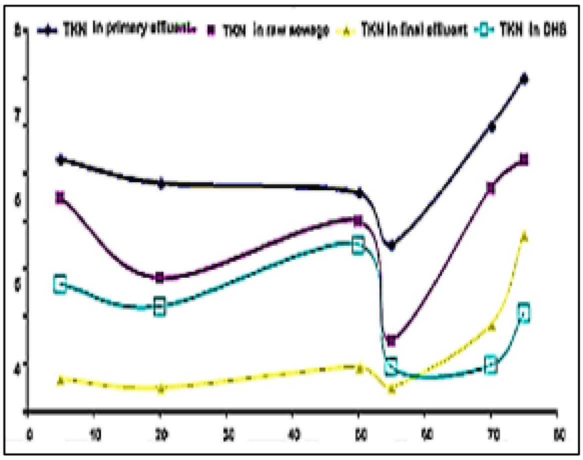

Figure 9 Variations in TKN concentrations along AS plant and the DHS treatment system

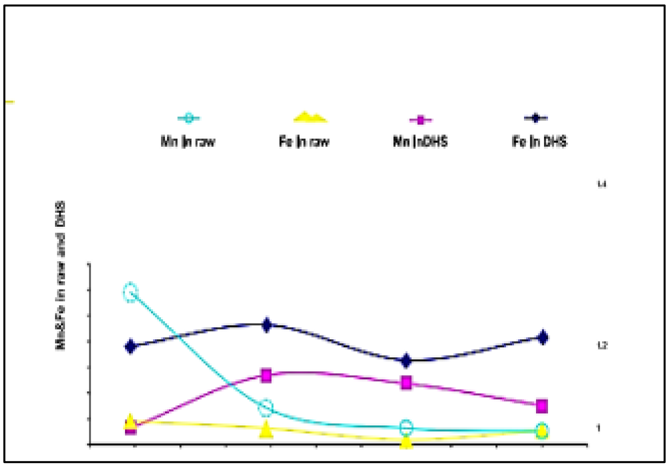

Figure 10 Variations in Heavy metal concentrations along the treatment system

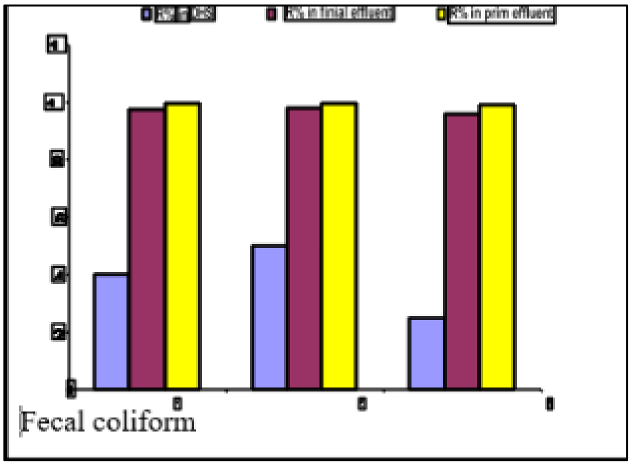

Figure 11 Removal efficiency of FC along the treatment system

3.2. Three hours Retention time Research scheme:

The results of the study are summarized in Figures (12-17) and presented in Tables (4-5). The efficiency of the Down Flow Hanging Sponge (DHS) system was assessed in this study, specifically focusing on its performance at a retention time of 3 hours, using effluent from the primary sedimentation tank of the El-Kharry wastewater treatment plant. The study aimed to evaluate the system's capacity to remove various contaminants, including Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD5), Total Suspended Solids (TSS), heavy metals, and pathogens, from municipal wastewater.

3.2.1. COD Removal

Operating at a 3-h HRT, the DHS reactor achieved 93±6% COD removal from raw wastewater (444–594 mg/L) via physical entrapment and biodegradation [15]. The upper sponge matrix removed 75% of suspended COD, outperforming the primary activated sludge process at the El-Kharry plant (28–30% reduction; 212–314 mg/L). Subsequent DHS post-treatment increased overall efficiency to 94±1% (9±4 mg/L effluent) [36], driven by an extended solids retention time (SRT) and high bio-retention capacity.

3.2.2. BOD5 Removal

The DHS system achieved exceptional BOD5 removal efficiency (96±1%), lowering concentrations from 180–251 mg/L in raw wastewater to just 13±5 mg/L (12–48 mg/L) in the final effluent. This performance significantly outperformed the El-Kharry primary treatment, which achieved only 28–30% removal (120–180 mg/L). The substantial reduction is driven by effective particulate entrapment within the sponge matrix and an extended solids retention time (SRT), which promotes complete microbial degradation of organic matter [37].

3.2.3. Total Suspended Solids (TSS) Removal

The removal of Total Suspended Solids (TSS) was another key parameter evaluated in this study. Operating at a long solids retention time (SRT), the DHS system achieved 90±7% Total Suspended Solids (TSS) removal, lowering concentrations from 170±30 mg/L in the El-Kharry primary effluent to 5±2 mg/L (8–11 mg/L) in the final discharge [37]. This significantly outperformed the primary plant's modest removal efficiency (45±10%), driven by physical entrapment and bio-degradation within the sponge matrix [37].

3.2.4. Heavy Metal Removal

Heavy metal removal in the DHS system focused on manganese and iron. This was facilitated by adding a hydrazide polymer (3 mg/50L) to chelate the metals, causing them to precipitate onto the sponge material. The system demonstrated good performance, achieving removal efficiencies of 88 ± 10% for manganese and 85 ± 6% for iron, thereby significantly enhancing the treated water quality.

3.2.5. Pathogen Removal

Pathogen removal evaluation revealed exceptional disinfection efficiency across all microbial indicators, achieving 99% reduction for Total Coliform (TC), 99.4% for Fecal Coliform (FC), and 99% for Fecal Streptococcus (FS) [38]. Post-treatment bacterial counts in the DHS effluent were significantly reduced to averages of 2×103 CFU/mL at 22∘C and 2×106 CFU/mL at 37∘C (corresponding to overall removal efficiencies of 99.8% and 99.9%, respectively). Final indicator densities dropped to 1300 MPN/100 mL for TC and 500 MPN/100 mL for FC. In summary, the modified DHS system demonstrated superior multi-pollutant removal capabilities at a remarkably short 3-hour HRT, successfully eliminating organic loads (BOD5: 96±1%, COD: 94±1%), suspended solids, heavy metals, and pathogenic indicators. These comprehensive findings confirm the technical efficacy and viability of the DHS reactor for producing high-quality effluent suitable for sustainable environmental discharge and agricultural reuse [39].

Table 4 Summery of the performance data of the treatment system at 3 hours (as retention time)

Parameters	Unit	Raw Sewage			primary effluent			%R	finial effluent			DHS effluent			%R
		Average	Max	Min	Average	Max	Min		Average	Max	Min	Average	Max	Min	
COD tot	Mg O_2/ l	444	594	290	256	314	212	54(±12)	26	77	9	6	36	2	98(±5)
BOD5	mg/l	251	350	150	145	180	105	56(±8)	14	48	5	6	36	1.7	97(±4)
TSS(105 C0)	mg/l	340	662	246	211	236	160	50(±7)	17	32	13	7	32	3	96(±3)
VSS(105 C0)	mg/l	131	250	85	73	220	32	62(±5)	14	26	10	6	25	2.6	98(±2)
TKN	mg N/l	26	30	23	20	23	19	19(±2)	9	12	7	9	11	6	60(±7)
Ammonia	mg N/l	32	38	28	26	35	19	40(±5)	8	16	5	3	6	1.9	98(±4)
Nitrate	mg/l	1.9	4	1	2	3	1	-	4	10	1.98	18	26	8	-
Total Phosphate	mg P/l	19	25	9	15	20	8	22(±6)	12	24	5	10	16	7	59(±10)
Oil and Grease	mg/l	10	13	2	6	9	3	44(±9)	4	6	3	3	10	2	56(±7)

Table 5 Performance results of heavy metal in the primary of activated sludge and effluent of DHS system treating domestic waste water at a total HRT of 3 hrs

Heavy metal	Raw	Ligand (mg L-1)	Schiff base (mg L^{-1})	Percentage %		Raw sludge(mg/kg)			Heavy metals which treated with)	
				ligand	Schiff base	limit EG	EPA limit	Raw calculated	Ligand (mg/ kg)	Schiff base(mg/kg)
Pb	0.41	0.27	0.13	34.1	68.2	300	840	512	337.5	162.2
Cd	0.057	0.03	0.011	47.3	80.7	39	85	71.25	37.5	13.75
Cu	1.6	0.704	0.527	56	67.06	1500	4300	2000	880	658.75
Fe	150.2	76.9	68.9	48.8	54.12	-----	-----	187750	96125	86125
Ni	0.61	0.235	0.11	61.4	81.9	240	420	762.5	293.75	137.5

Zn	7.91	3.15	2.12	60.17	73.19	2800	7500	9887.5	3937	2650
Cr	1.64	0.857	0.385	47.7	76.5	1200	-----	2000	1071.25	481.25

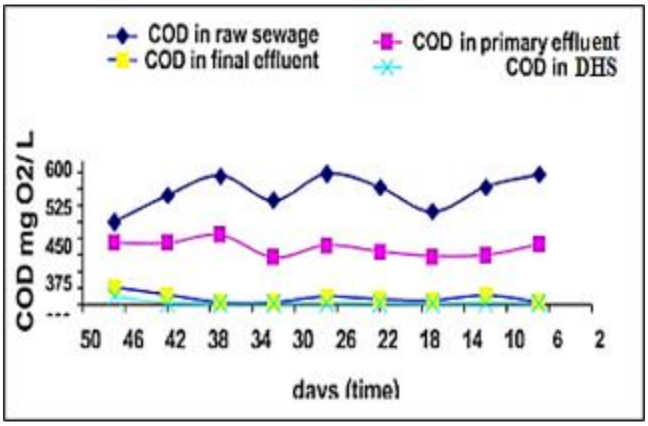

Figure 12 Variation in total COD along AS plant and the DHS treatment system

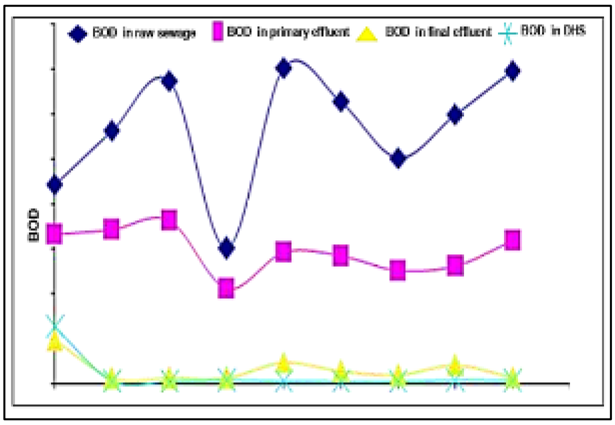

Figure 13 Variation in total BOD along AS plant and the DHS treatment system

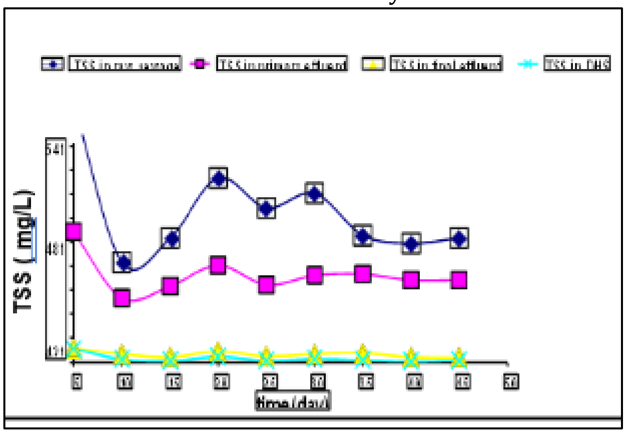

Figure 14 Variation in TSS concentrations along AS plant and DHS the treatment system

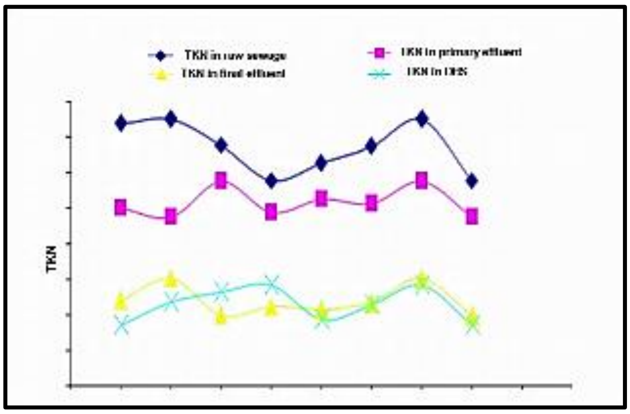

Figure 15 Variations in TKN concentrations along AS plant and the DHS treatment system

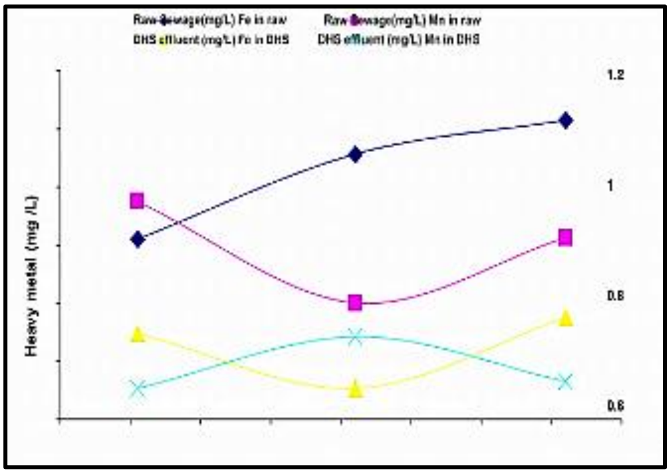

Figure 16 Variations in Heavy metal concentrations in along as plant and the DHS the system

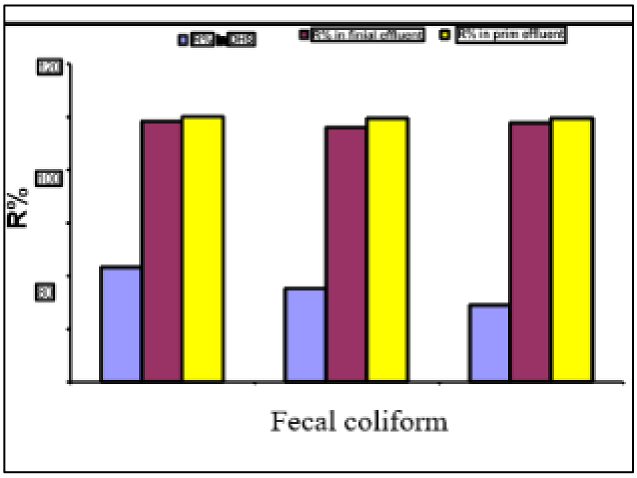

Figure 17 Removal efficiency

4. Conclusion

In conclusion, this study demonstrates the successful synthesis, comprehensive characterization, and environmental application of novel hydrazide and Schiff-base ligands for targeted wastewater remediation. Analytical characterization via FTIR, NMR, UV-Vis spectroscopy, and thermal analysis verified the structural integrity and functional efficacy of the synthesized compounds. Performance evaluation revealed that while both ligand types hold significant promise for pollution abatement, the hydrazide derivatives exhibited superior chelation efficiency toward heavy metals, specifically Pb(II), Ni(II), and Cd(II).Furthermore, this work establishes the operational superiority of the Down flow Hanging Sponge (DHS) system over conventional wastewater treatment modalities. Operating at an optimized hydraulic retention time (HRT) of six hours, the DHS configuration achieved exceptional contaminant removal efficiencies, specifically for COD (95%), BOD5 (96%), and TSS (94%), alongside substantial reductions in nitrogenous compounds and bacterial pathogens, thereby outperforming traditional activated sludge processes. Notably, the integration of chelating agents synergistically enhanced heavy metal immobilization; yielding pronounced concentration reductions for manganese and iron. Overall, these findings underscore the transformative potential of coupling innovative coordination chemistry with advanced bioreactor engineering to combat environmental pollution. This research provides a robust framework for future process optimization and scales up the deployment of sustainable water treatment technologies.

Compliance with ethical standards

Disclosure of conflict of interest

The authors have declared no conflict of interest.

Author's Contributions

A.S. El-Tabl designed the study and performed the complexes synthesis. A.M. Ashour, S.Z. Mohamed and A.A. Alhalib performed most of the experiments. A.M. Ashour and S.M. Faheem analyzed and interpreted the data. A.M. Ashour and A.A. Alhalib wrote the first version of the manuscript. All authors reviewed and approved the final version of the manuscript.

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