Supporting Information

Magneto-bio-production of extracellular polymeric substances from starch wastewater: mechanistic insights into green valorization

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1.1. Carbon and cost calculation

To improve the transparency of the carbon and economic assessment, the system boundary and comparison routes are illustrated in Figure S1. The functional unit was defined as 1 m^3 of treated starch wastewater. Three routes were compared, including conventional flocculant production/use, traditional UASB-SBR starch wastewater treatment, and the MF-assisted SW treatment process proposed in this study. The accounting boundary included indirect emissions from electricity, materials, and chemical consumption, direct emissions from CH_4 and CO_2 generated during wastewater treatment, and carbon reduction associated with avoided chemical use and recoverable EPS production.

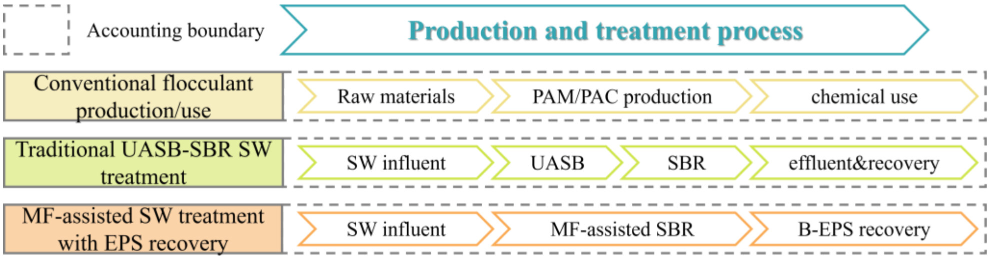

Figure S1. Carbon accounting boundary and cost-assessment framework for the compared systems.

The direct and indirect greenhouse gas emissions of compared systems were calculated (Zawartka et al., 2020). Operational data with identical time periods and annual average data from conventional plants were selected to achieve the comparability of results. Although numerous studies have proposed carbon accounting for municipal wastewater treatment plants (Allami et al., 2023), formulas in this study were refined by integrating plant-specific water quality characteristics and operational conditions with a more practical framework. The detailed calculation is presented in Table S1, with key parameters listed in Table S2. The carbon accounting boundary in this study was defined within the enterprise scope of wastewater treatment process, considering both carbon emissions and carbon reduction (Hua et al., 2022). Emissions included indirect emissions from material, chemical, and electricity consumption during wastewater treatment, as well as direct emissions of greenhouse gases methane (CH_4) and carbon dioxide (CO_2) generated in the process (Zhang et al., 2022). Major boundary routes for consideration include the conventional flocculant production process, the traditional biological treatment process and the MF-assisted process. The emission factors were selected based on updated standards to ensure both accuracy and comparability of the accounting results, and their detailed values are presented in Table S3.

To assess the feasibility of MF-assisted sludge treatment, a simplified cost–benefit analysis was conducted (Liu et al., 2023). The annual net benefit (ANB) was estimated as:

$$ANB=(S_e+S_c+S_s+V)-C_{O\&M}$$

Where S_e: savings in aeration/pumping energy, S_c: reduced flocculant or nutrient addition costs, S_s: avoided sludge handling and disposal costs, V: potential value of byproducts (e.g., recovered biogas or EPS), $C_{O\&M}$: annual operation and maintenance costs of MF equipment (power input, magnet replacement, maintenance).

The payback period (PBP) was calculated as:

$$PBP=\frac{C_c}{ANB}$$

where C_c is the initial investment for MF installation (per reactor volume basis). If PBP<5 years, the technology is generally considered economically attractive for full-scale application (Li et al., 2022).

Net Present Value (NPV) was applied to measure the difference between the present value of future cash inflows and outflows during the project lifetime (n years), expressed as:

$$NPV=\sum_{t=1}^{n}\frac{B_t-C_t}{(1+i)^t}-I_0$$

where B_t is the annual benefit in year t, C_t is the annual operating cost, i is the discount rate, and I_0 is the initial capital investment.

Table S1. Carbon accounting methodology

Category		Formula
Indirect carbon emissions		$C_g=M_if_i$
Direct carbon emissions	Methane	$C_{CH_4}=10^{-6}\times G_{CH_4}Q\times(B_I-B_O+B_E)\times f_{CH_4}$
Total carbon emissions		$C=C_g+C_{CH_4}$
Carbon reduction		$J=M_jf_j$
Net carbon emissions		$C_{\triangle}=C-J$

Table S2. Carbon emission accounting parameters

Parameters	Definitions	Units
E, E_{Δ}	Carbon emission intensity, net carbon emission intensity	t CO_2/m^3
C, J, C_g, C_{Δ}	Carbon emissions, carbon reduction, indirect carbon emissions, net carbon emissions	t CO_2/a
C_{CH_4}	Methane-related carbon emissions from wastewater treatment	t CO_2/a
Q	Annual treated water volume	m^3/a
f_{CH_4}	CH_4 conversion factor for wastewater treatment	t CH_4/(t BOD_5)
M_i	Annual consumption of the i-th chemical or energy source	t/a or kW·h/a
f_i	Emission factor of the i-th chemical or energy source	t CO_2/t or t CO_2/(kW·h)
B_I, B_O	Annual average influent and effluent BOD_5 concentrations	mg/L
B_E	Annual average concentration of external carbon source addition	mg BOD_5/L
M_j	Electricity generation, reuse volume, or other reduction measures of the j-th category	m^3/a
f_j	Emission factor of the j-th reduction measure	t CO_2/m^3
G_{CH_4}	Global warming potential (GWP) of methane	t CO_2/(t CH_4)

Table S3. Values of carbon emission accounting factors

Category	Parameter	Value	Unit
Chemicals	Polyacrylamide (PAM) dosing	1.50	t CO_2/t
	Polyaluminum chloride (PAC) dosing	1.62	t CO_2/t
	PAM production	3.25	t CO_2/t
	PAC production	1.30	t CO_2/t
Electricity	Electricity	5.257×10^{-4}	t CO_2/(kW·h)
Conversion factor	f_{CH_4}	0.003 6	t CH_4/(t BOD_5)
Reduction factor	f_{eps}	0.61	kg CO_2/kg
GWP	G_{CH_4}	28	t CO_2/(t CH_4)

1.2. MLSS concentrations in MF and NF reactors

To support the interpretation of MLSS-normalized EPS contents, the average MLSS concentrations of the MF and NF reactors under the six OL/DO scenarios are shown in Figure S2. The MF reactor did not show systematically higher MLSS than the NF reactor. Specifically, MLSS in the MF reactor was lower than that in the NF reactor in Scenarios I, II, III, and VI, with values of 1.29 versus 1.41 g/L, 0.97 versus 1.74 g/L, 4.43 versus 4.75 g/L, and 1.37 versus 1.44 g/L, respectively. In Scenario V, MLSS was nearly identical between the MF and NF reactors, with values of 1.85 and 1.85g/L, respectively. Only Scenario IV showed a slight increase in the MF reactor, with 1.74 g/L compared with 1.71 g/L in the NF reactor. These results indicate that the MF-associated increase in B-EPS was not simply attributable to higher suspended-solid accumulation.

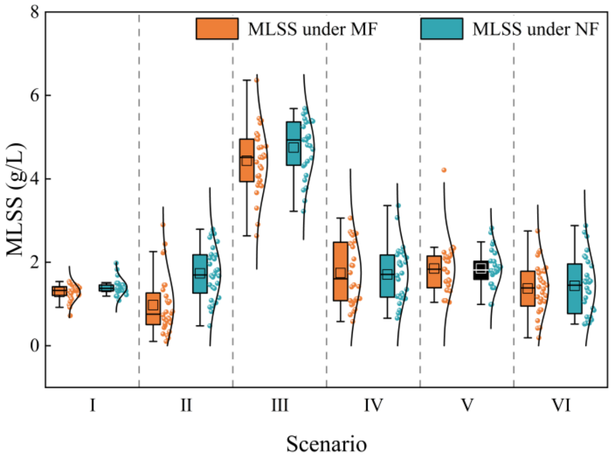

Figure S2. Average MLSS concentrations in MF and NF reactors under different OL/DO scenarios.

1.3. PCA Loading Values and m/z Assignments for TB-EPS TOF-SIMS Analysis

PCA was performed on the positive and negative ion TOF-SIMS spectra of TB-EPS samples under different operational conditions to identify the key organic species contributing to compositional changes induced by MF (Zimmermann et al., 2023). The principal component analysis revealed the ions with the largest contributions to differences among scenarios (Yu et al., 2023), with their loading values and corresponding m/z assignments presented in Tables S4.

Table S4. PCA loading values and m/z of key TB-EPS ions under different operational conditions

Rank				1	2	3	4	5	6
I	MF	Pos	loading	0.78	0.40	0.24	0.20	0.18	0.15
			m/z	39	81	139	40	141	41
		Neg	loading	0.73	0.58	0.28	0.14	0.09	0.09
			m/z	35	37	1	93	151	95
	NF	Pos	loading	0.82	0.34	0.21	0.17	0.17	0.15
			m/z	39	23	139	97	141	81
		Neg	loading	0.75	0.58	0.18	0.15	0.08	0.07
			m/z	35	37	93	151	97	95
II	MF	Pos	loading	0.49	0.42	0.40	0.36	0.29	0.26
			m/z	97	16	80	64	96	17
		Neg	loading	0.37	0.35	0.34	0.32	0.30	0.25
			m/z	164	38	61	23	62	148
	NF	Pos	loading	0.53	0.39	0.37	0.32	0.32	0.23
			m/z	61	148	84	164	63	112
		Neg	loading	0.51	0.33	0.32	0.30	0.28	0.24
			m/z	1	16	80	64	17	97
III	MF	Pos	loading	0.74	0.51	0.27	0.24	0.17	0.12
			m/z	23	80	138	82	39	140
		Neg	loading	0.74	0.39	0.26	0.26	0.21	0.17
			m/z	35	1	93	151	37	16
	NF	Pos	loading	0.73	0.67	0.08	0.06	0.04	0.02
			m/z	23	80	138	140	82	39
		Neg	loading	0.74	0.51	0.34	0.17	0.12	0.10
			m/z	35	1	37	16	93	17
IV	MF	Pos	loading	0.92	0.28	0.16	0.14	0.10	0.10
			m/z	23	81	83	139	141	39
		Neg	loading	0.78	0.61	0.10	0.08	0.06	0.05
			m/z	35	37	93	95	151	1
	NF	Pos	loading	0.69	0.49	0.31	0.29	0.20	0.17
			m/z	81	23	139	83	141	39
		Neg	loading	0.74	0.58	0.23	0.17	0.09	0.08
			m/z	35	37	1	16	93	17
V	MF	Pos	loading	0.86	0.28	0.24	0.23	0.20	0.08
			m/z	23	81	139	83	141	46
		Neg	loading	0.96	0.17	0.15	0.10	0.05	0.05
			m/z	35	37	93	151	95	1
	NF	Pos	loading	0.95	0.26	0.09	0.07	0.07	0.05
			m/z	23	39	139	83	141	40
		Neg	loading	0.59	0.59	0.31	0.21	0.15	0.11
			m/z	35	37	1	95	16	17
VI	MF	Pos	loading	0.96	0.25	0.07	0.06	0.05	0.04

Rank			1	2	3	4	5	6
		m/z	23	81	141	139	46	83
	Neg	loading	0.75	0.62	0.19	0.08	0.06	0.05
		m/z	35	37	1	93	95	16
NF	Pos	loading	0.68	0.43	0.37	0.29	0.25	0.13
		m/z	81	23	139	83	141	46
	Neg	loading	0.78	0.50	0.19	0.11	0.10	0.07
		m/z	35	37	1	93	26	16

1.4. Carbon emission and cost-effectiveness

1.4.1. Carbon emission accounting

Carbon emission of the optimized scenario in this study was calculated and compared with the conventional flocculant production and traditional UASB-SBR EPS production, as shown in Table S5. Direct methane emissions were also markedly decreased by 68.0% under MF exposure, and the power consumption was simultaneously lowered. Moreover, elimination of PAM and PAC dosing could avoid emissions associated with chemical production and application, and EPS generated during treatment were retained within the system, thereby achieving an additional indirect reduction of 5.70 kg CO_2 per cubic meter of treated SW. Compared to the traditional UASB-SBR system, a reduction of 90.5% in carbon emission was achieved under MF exposure, equivalent to 13.59 kg CO_2 per cubic meter of treated SW. Compared to the conventional flocculant production system, carbon emission were reduced by 27.2% under MF exposure, while enabling in-situ generation of bio-flocculants without external chemicals. Overall, the system under MF exposure succeeded to offer a sustainable alternative for low-carbon SW treatment, aligning with national "dual carbon" goals, and hold considerable potential for practical application.

Table S5. Carbon emission comparison

Category			Conventional flocculant production system (Du et al., 2018)	Traditional UASB-SBR SW treatment system (Wu et al., 2020)		SW treatment process under MF exposure (this study)
Carbon Emission (kg CO_2 m^{-3})	Direct emissions		0.61	13.77		4.41
	Indirect emissions	Electricity	1.01	2.57		2.71
		Chemicals	0.33	1.94	0.18	0
	Carbon reduction		0	3.45		5.70
	Total emissions		1.95	15.01		1.42

1.4.2. Cost-effectiveness analysis

As shown in Table S6, substantial financial benefits were delivered under MF exposure compared with the other two systems. Specifically, operating costs under MF exposure were reduced by 64.7% to 1.78 CNY m^{-3}, due to elimination of the UASB unit and chemical dosing, and the moderate increase in equipment investment could shorten the payback period to 1.3 years and markedly improve its capital efficiency. High-value EPS recovery of 235.5 CNY m^{-3} was identified as the dominant economic driver, compared to 150.16 CNY m^{-3} derived from methane and PN recovery in conventional systems. The equivalent revenue increment reached 65.55 CNY m^{-3} after performance adjustment and achieved a net present value (NPV) of 9.94 billion CNY, which was 32 times higher than that of the traditional process. Sensitivity analysis confirmed the robustness of this advantage through the fact that the NPV remained at 7.1 billion CNY even with a 33.3% reduction in EPS price to 50 CNY kg^{-1} (Fitriani et al., 2019). Moreover, a 30% reduction in sludge volume and elimination of external chemical inputs further lowered environmental treatment costs and mitigated supply chain risks. On the contrary, PAC and PAM production and application could account for up to 38.2% of the total operating cost in conventional systems and underscore their lower sustainability. Generally, the process under MF exposure simultaneously reduced operational and environmental costs while creating substantial revenue through EPS recovery, thereby demonstrating strong economic resilience and superior sustainability relative to conventional wastewater treatment technologies.

Table S6. Economic benefit analysis

Category		Sub-item	Conventional flocculant production (Du et al., 2018)	Traditional UASB-SBR sweet potato wastewater treatment (Wu et al., 2020)	SW treatment process under MF exposure (this study)
Resource input (CNY m^{-3})	Direct cost	Electricity	-	2.05	0.78
		Chemicals	1.93	2.40	0
		Equipment investment	-	0.11	0.47
	Indirect cost	Environmental treatment	0.08	0.15	0.03
	Total operating cost		2.01	5.05	1.78
Resource recovery (CNY m^{-3})	Product revenue	CH_4	-	1.68	-
		Protein feed	-	5.75	-
		EPS	-	142.73	235.50
		PAM	0.60	-	-
		PAC	1.80	-	-
	Total revenue		2.40	150.16	235.50

Category	Sub-item	Conventional flocculant production (Du et al., 2018)	Traditional UASB-SBR sweet potato wastewater treatment (Wu et al., 2020)	SW treatment process under MF exposure (this study)
Net economic benefit		0.47	145.11	233.72
Annual revenue (10,000 CNY)		256	5477	8713
Long-term economic indicators	PBP (years)	5.9	2.4	1.3
	NPV (6% discount, billion CNY)	0.25	0.53	9.94
	NPV (8% discount, billion CNY)	0.22	0.45	8.56
	NPV (10% discount, billion CNY)	0.19	0.37	7.41

Notes:

a) Environmental cost of traditional flocculant production: disposal of PAC residue (80 CNY t^{-1}), allocated per cubic meter of wastewater.

b) Sludge landfill/incineration cost in conventional processes: 0.15 CNY m^{-3}.

c) The process under MF exposure reduced sludge production by 30.0% and enabled EPS recovery, thereby lowering environmental treatment costs.

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