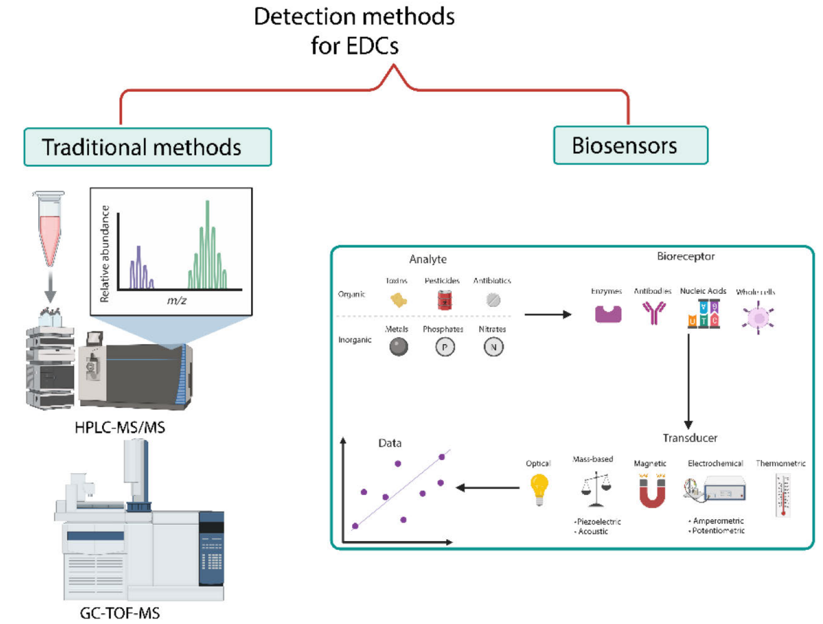

- Pros
    - High sensitivity
    - High reproducibility
- Cons
    - Expensive
    - Long time of analysis
    - More complex operations
    - Large sample volumes

- Pros
    - High sensitivity
    - Low cost of production
    - Fast analysis
- Cons
    - High costs of noble metals
    - Low stability
    - Low reproducibility

Fig. S1　A comparison of endocrine-disrupting chemical（EDC）detection methods and a schematic illustrating the operation of biosensors (Created with BioRender.com)

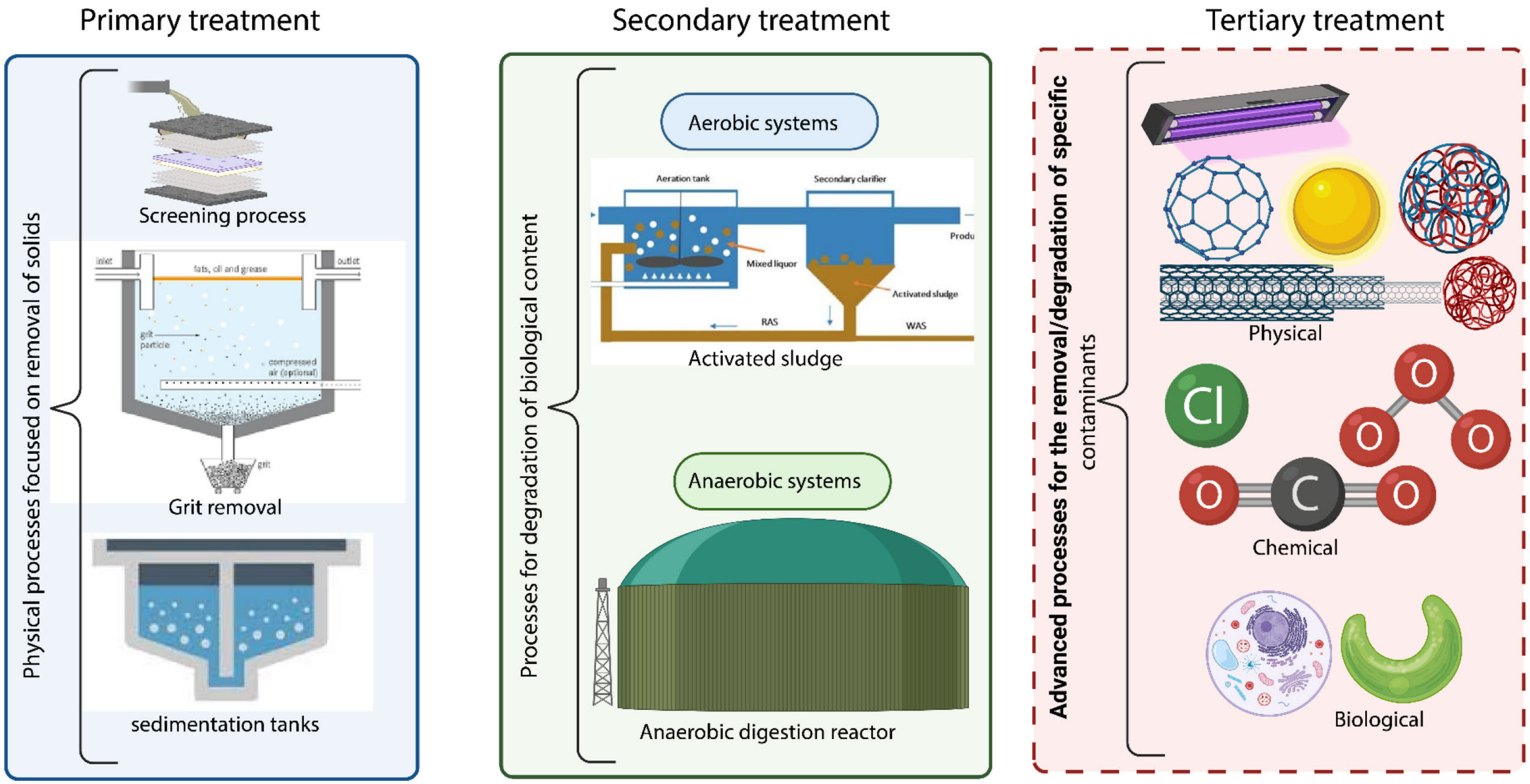

Fig. S2 Schematic presentation of wastewater treatment plant stages and their role in decontamination of water (Created with BioRender.com)

Fig. S3 Schematic representation of challenges and alternate solutions of endocrine-disrupting chemicals (EDCs) in aquatic ecosystems (Created with BioRender.com)

Table S1 Concentrations of endocrine-disrupting compounds in surface water (ng/L) and sediments (ng/g) of various aquatic environments

Location	Compound	Ecosystem type	Concentration	References
Ebro River, Spain	BPS	Surface water	0.007–0.0204	(Gil-Solsona et al., 2022)
Dongjiang River basin	BPA	Surface water	1.81	(Yang et al., 2024)
Ganga River	BPA	Surface water	2.0	(Chakraborty et al., 2019)
East China Sea	BPS	Surface water	2.2	(Xie et al., 2022)
Beibu Gulf, South China Sea	BPA	Surface water	5.26–12.04	(Gao et al., 2023)
Rhone River	BPA	Surface water	21	(Schmidt et al., 2020)
East China Sea	BPS	Surface water	23	(Xie et al., 2022)
Major Rivers of Mega Manila	BPA	Surface water	54	(Sta Ana et al., 2024)
Yangtze River	DEP, DiBP	Surface water	93.3, 174.2	(Miao et al., 2025)
Dongjiang River basin	Monobutyl phthalate (MPE)	Surface water	266	(Li et al., 2024)
Yangtze River	BPA	Surface water	613	(Zheng et al., 2019)
Pearl River	BPA	Surface water	7480	(Huang et al., 2018)
Persian Gulf	DiBP, DEHP	Surface water	1150, 11300	(Khishdost et al., 2023)
Dongjiang River basin	BPA	Sediment	3.1	(Yang et al., 2024)
Dongjiang River basin	MPE	Sediment	10.6	(Li et al., 2024)
East China Sea	BPA	Sediment	13	(Xie et al., 2022)
Yangtze River	BPAF	Sediment	46.7	(Zheng et al., 2019)
Ganga River	BPA	Sediment	199	(Chakraborty et al., 2019)
Yangtze River	BPS	Sediment	46.7, 353	(Zheng et al., 2019)
Korean Coasts	DEHP	Sediments	380	(Lee et al., 2020)
Laizhou Bay, China	DEHP, DBP	Sediments	813.1, 975.6	(Zhang BT et al., 2020)

Table S2 Toxic effects of endocrine-disrupting chemicals (EDCs) on aquatic organisms under various exposures

Organism	Compound	Organ	Exposure duration	Concentration	Phenomenon	References
Xenopus laevis	DBP, BBP, DPHP	Embryo	96 h	Varying	Induced developmental toxicity, endoplasmic reticulum stress, and apoptosis	(Xu et al., 2022)
Denio rerio	DBP, DBP+DiBP	Embryo, larvae	30 d	Varying	Parental exposure to DBP and DiBP, whether administered individually or in combination, led to an increase in hatch rates at 48 h post-fertilization (hpf) and elevated heart rates at 96 hpf in F_1 larvae. Additionally, there was a rise in the incidence of malformations and mortality among the offspring.	(Chen et al., 2021)
Oryzias latipes	DEHP	Whole organs	21 d	20, 100, 200 μg/L	Reduced body weight and length through a combined impact of oxidative stress, neurotoxicity, and apoptosis pathways	(Yang et al., 2018)
Pelteobagrus fulvidraco	DEHP	Head, kidney, liver	56 d	100, 500 μg/L	Reduced phagocytic index, lowest expression of myeloid differentiation factor 88 in fish exposed to 0.5 mg/L DEHP. Induced ROS generation, malondialdehyde accumulation, and immunosuppression, leading to blood deterioration and compromised immune responses	(Yuan et al., 2017)
Mytilus galloprovincialis	BPA	Tissue samples	28 d	0.461 μg/g	Increased tissue concentration over 28 d of exposure	(Gatidou et al., 2010)
Procambarus clarkii	BPA	Hepatopancreas	7 d	225 μg/L	Induced oxidative stress by inhibiting antioxidant enzyme activities of SOD and CAT. Furthermore, suppressed expression of immune related genes	(Zhang YY et al., 2020)
Tegillarca granosa	BPA	Hemocytes	14 d	0.1, 1 μg/L	Significantly decreased the expression of four immune-related genes from the NF-κB signaling pathway	(Tang et al., 2020)
Ruditapes philippinarum	BPS, BPF, BPAF, BPA analog mixture (BPS, BPF, BPAF)	Hemolymph	7 and 14 d	0.3 μg/L	BPS induced genotoxicity and oxidative stress, BPF and BPAF impacted antioxidant systems and cellular parameters	(Fabrello et al., 2023)
Aristicthys nobilis	BPA	Gill, liver, kidney, brain	60 d	500, 1000, 1500 μg/L	increased frequency of morphological and nuclear changes in red blood cells, and increased DNA damage potential in multiple tissues	(Akram et al., 2021)
Dicentrarchus labrax	DEHP	Embryonic cell	24 h	Varying	Significant decrease in cell viability, increase in apoptosis and necrosis, morphological changes, cell detachment, moderate increase in DNA strand breaks, dose-dependent increase in micronucleus frequency	(Molino et al., 2019)

					and inhibition of cell proliferation.	
Denio rerio	BPA	Whole body tissues	24 h, 120 h, and 21 d	90, 900 µg/L	Increased BPA levels in tissue after exposure at 90 µg/L, whereas induced potential endocrine disruption at 900 µg/L	(Eser et al., 2022)
Channa punctatus	NP	Blood cells	90 d	70, 100, 150 µg/L	Time and dose-dependent increase in DNA damage, as revealed by comet and micronucleus assays	(Sharma and Chadha, 2017)
Daphnia magna	BBP	Embryo	21 d	100, 600, 1200 µg/L	Reduction of embryonic development cycle and an induction of abnormal infants	(Li et al., 2021)
Litopenaeus vannamei	BPA	Gonads	14 d	2 µg/L	Delayed gonad development by disrupting endocrine regulation and metabolism	(Han et al., 2022)
Clarias gariepinus	NP	Gonads	15 d	100, 200, 300 µg/L	Decreased testosterone and estradiol levels, with no significant changes in follicle stimulating and luteinizing hormone	(Sayed et al., 2022)
Tegillarca granosa	DOP		14 d	2600, 7200 µg/L	increased SOD and metallothionein gene expression in response to various concentrations of DOP, with the potency of the response reducing with increased concentrations	(Wang et al., 2016)
Haliotis diversicolor supertexta	DAP BPA	Hepatopancreas	Three months	50, 100 µg/L	Altered the expression of detoxification-related proteins	(Zhou et al., 2010)

Table S3 Comparative evaluation of SERS and NMR for endocrine-disrupting chemical (EDC) detection under realistic field conditions (Deriu et al., 2023; Mitschke et al., 2023; Usman et al., 2023; Sloan-Dennison et al., 2024; Balasubramani et al., 2025)

Feature	SERS	NMR
Sensitivity	High sensitivity, ideal for trace detection	Limited sensitivity for low-abundance metabolites compared to SERS
Real-time monitoring	Ideal for monitoring dynamic processes in real time	Long acquisition time, making it less suitable for high-throughput or real-time monitoring
Spatial resolution	High spatial resolution for localized detection, ideal for imaging biological molecules and structures	Limited spatial resolution compared to SERS for nanoscale imaging
Structural information	Provides limited structural information, primarily through vibrational modes	Provides detailed molecular and structural information
Reproducibility	Reproducibility issues due to nanoparticle-based enhancement, dependent on substrate quality	Highly reproducible once set up, with fewer variables affecting the result
Complexity in data analysis	SERS spectra can be complex and require advanced data analysis methods	NMR spectra are also complex and require skilled interpretation
Pathway analysis	Allows multiplexing and enables analysis of complex mixtures in real-time, identifying multiple compounds simultaneously	Ideal for studying metabolic pathways in detail, particularly with the use of tools like Metabo analyst
Sample volume requirement	Requires minimal sample volume, but the technique can still face issues with low-abundance samples	Requires relatively large sample volumes, which may be a limitation with precious biological samples
Multiplexing	Can identify multiple analytes in a single experiment	Cannot achieve multiplexing to the same degree; typically focuses on a single target at a time
Analysis speed	Provides rapid analysis, with the potential for quick identification of target compounds	Relatively slower, especially for complex samples requiring high-resolution 2D/3D experiments
Application flexibility	Wide-ranging applications in food safety, drug monitoring, microbial analysis, and environmental monitoring	Primarily used for metabolomics, structural analysis, and pathway analysis

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