Supporting Information

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SI Text

Treatment Systems for Wastewater Treatment Plants

The most common form of energy production from wastewater is generation and collection of CH_4-containing biogas during anaerobic digestion of waste-activated sludge (WAS) (1). Anaerobic systems are used globally, and the produced CH_4 can be combusted onsite to generate heat or electricity or cleaned and sold to a local natural gas provider or used as fuel for vehicles. Recycling of WAS on agricultural fields is a well-documented application for both waste disposal and plant nutrient recycling that is becoming increasingly common in both developed and developing countries (2). In addition, there have been new developments in capturing fertilizers, e.g., struvite ($NH_4MgPO_4{\cdot}6H_2O$), from WAS (3). The resource recovery practices included in this study were selected based on these available options. Six typical wastewater treatment alternatives (Table S2) were selected as the control and alternative WWTP approaches for treating 2×10^5 m^3/d of raw municipal wastewater having 500 mg/L chemical oxygen demand (COD), 50 mg N/L, and 12 mg P/L. Detailed information on the six alternative wastewater treatment systems and resource recovery practices can be found in the previous literature (4, 5).

Calculation of *PF* and *NF* in the Net Environmental Benefit Method

In the net environmental benefit (NEB) method (Eq. **1**), three simplified indicators were used as environmental cost metrics (*NF*, dimensionless), defined as shown below:

$$NF_j(a) = \frac{\sum_{k=1}^{n} NF_{j,k}}{n}, \quad \textbf{[S1]}$$

where a represents the scenario, j represents the environmental cost metric (i.e., energy consumption, GHG emissions, or chemical use), and the operator $NF_{j,k}$ was estimated as follows:

$$NF_{j,k} = \frac{p_{j,k} - min\left(p_{j,1}, p_{j,2}, \cdots, p_{j,n}\right)}{max\left(p_{j,1}, p_{j,2}, \cdots, p_{j,n}\right) - min\left(p_{j,1}, p_{j,2}, \cdots, p_{j,n}\right)}, \quad \textbf{[S2]}$$

where $p_{j,k}$ is the raw value of alternative wastewater treatment system k for the environmental cost categories (energy consumption, kilowatt-hours per cubic meter of treated water; GHG emissions, kilograms of carbon dioxide equivalent per cubic meter of treated water; chemical use, kilograms per cubic meter of treated water).

The additional indices used to estimate the environmental benefits generated by the resource recovery practices (*PF*, dimensionless) were defined as shown below:

$$PF_i(a) = \frac{\sum_{k=1}^{n} PF_{i,k}}{n}, \quad \textbf{[S3]}$$

where the subscript i specifies the environmental gain metric (i.e., bioenergy recovery performance, recycling of sludge on agricultural fields, or struvite capture potential), and the operator $PF_{i,k}$ was estimated as follows:

$$PF_{i,k} = \frac{q_{j,k} - \min\left(q_{i,1}, q_{i,2}, \cdots, q_{i,n}\right)}{\max\left(q_{i,1}, q_{i,2}, \cdots, q_{i,n}\right) - \min\left(q_{i,1}, q_{i,2}, \cdots, q_{i,n}\right)}, \quad \textbf{[S4]}$$

where $q_{i,k}$ is the raw value of alternative wastewater treatment system k for the environmental gain categories [bioenergy recovery, kilowatt-hours per cubic meter of treated water; recycling of sludge on agricultural fields, kilograms of N and P per cubic meter of treated water; struvite capture, kilograms of inorganic suspended solids (ISS) per cubic meter of treated water].

Additionally, the subscript k in the above equations specifies the serial number of the wastewater treatment alternative, whereas the subscript n specifies the total number of wastewater treatment systems assessed (n = 6). Table S3 presents the calculated values for all assessment metrics for each scenario (scenarios 1, 2, 3, and 4).

Data Sources for Determining Metric Interactions

For some environmental performance metrics (EPMs), there was a directly available dataset. For instance, national energy consumption data (MkWh/cap·y) obtained from the US Energy Information Administration (USEIA) database (6) were used to weight the impact of the NF_{ener} metric. For the NF_{chem} metric, chemical import data ($1,000/cap·y) were obtained from the database (7) of the Organisation for Economic Co-operation and Development (OECD) and used in the weighting estimates. Another set of USIEA data (8), bioenergy production using wastes as feedstock (kWh/cap·y), was used to weight the impact of the PF_{bioe} metric.

The relationship of the other EPMs with the available data were more indirect. To weight the role of the PF_{slud} metric, municipal waste generation (t/cap·y) extracted from the OECD database (7) was used, because recycling nutrients from WAS on agricultural fields is regarded as an appropriate means of waste disposal. For the PF_{stru} metric, a dataset for phosphate exploitation (t/cap·y) obtained from the British Geological Survey (9) was applied for weighting, because the remaining accessible reserves of phosphate rock are estimated to be depleted in 50 y if the growth of demand for fertilizers remains at 3% per year (10, 11); struvite is generally viewed as the optimal phosphate mineral for recovery as it contains 51.8% P_2O_5 (10, 11). Additionally, for the NF_{gree} metric, the inventory data used for weighting would ideally represent total GHG emissions (e.g., CO_2, N_2O, CH_4, etc.); however, the required data at a national level for the studied time period are scarce and frequently proprietary. Thus, as an alternative, data on CO_2 emissions from power consumption (t CO_2/cap·y) derived from the USEIA database (12) were used to weight the role of the NF_{gree} metric, because CO_2 releases from energy consumption are generally considered to be a large proportion (>80%) of total GHG emissions (13).

Forecasting Model for Metric Interactions

For the modeling approach presented in the text, the algorithm of the autoregressive integrated moving average (ARIMA) (p, d, q) model provided in IBM SPSS Statistics 21.0 (SPSS) was used to fit the historic trends for each weighted set for developed and developing countries during the study period of 1991–2009, and subsequently to search for the best-fitting model parameters for each weighting coefficient (Table S4). Model validation was performed to evaluate the generated models using observed data for 2010. Comparisons between the observed and predicted results are presented in Fig. S2. There were small relative differences between the observed and predicted values (within 5% and 10% for developed and developing countries, respectively), demonstrating that the generated models provided good time-series descriptions for each weighting coefficient.

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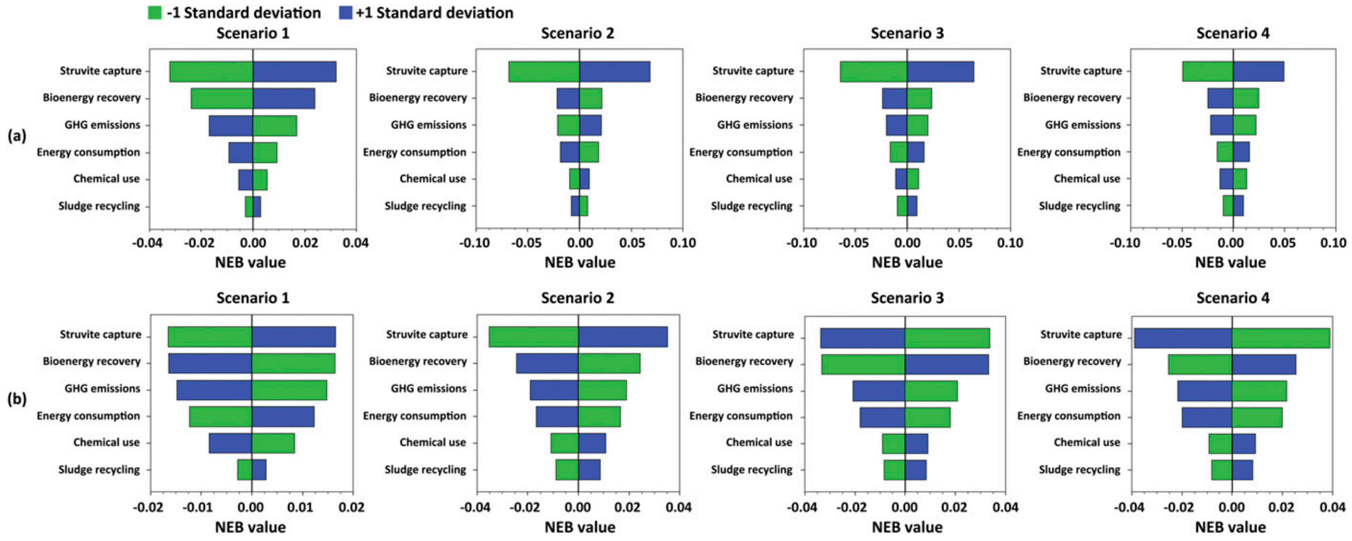

Fig. S1. Sensitivity test of the weighting coefficients for the NEBs associated with each scenario for the emerging WWTP approach for (*A*) developed countries and (*B*) developing countries.

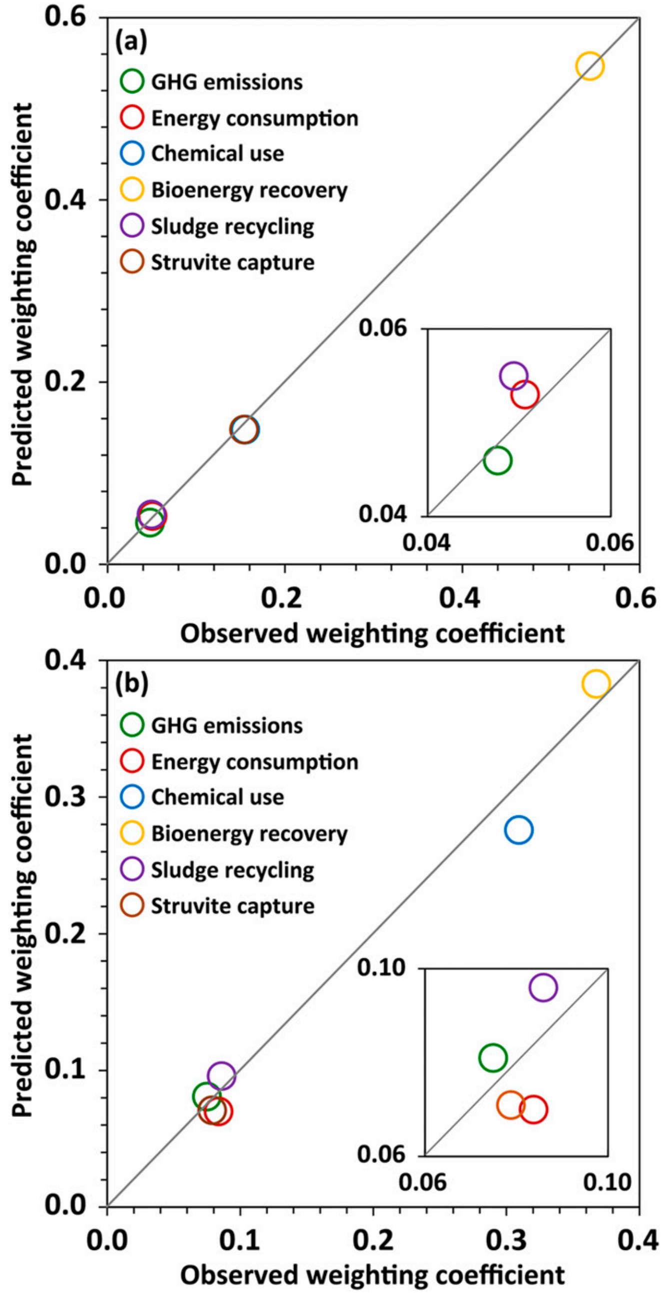

Fig. S2. Observed and predicted values for the weighting coefficients for 2010 for (*A*) developed countries and (*B*) developing countries.

Table S1. Summary statistics for the sample-out NEBs associated with each scenario for the emerging WWTP approach

	Developed countries					Developing countries				
		Distribution parameters*		95% Confidence interval			Distribution parameters*		95% Confidence interval	
Scenario	Mean	μ	σ	Lower	Upper	Mean	μ	σ	Lower	Upper
Scenario 1	0.095	0.093	0.053	0.012	0.185	−0.048	−0.048	0.033	−0.102	0.005
Scenario 2	0.101	0.091	0.097	−0.038	0.276	−0.032	−0.033	0.057	−0.123	0.059
Scenario 3	0.021	0.010	0.095	−0.117	0.192	−0.118	−0.118	0.058	−0.210	−0.024
Scenario 4	−0.055	−0.063	0.082	−0.177	0.091	−0.201	−0.202	0.054	−0.289	−0.113

*The distribution parameters μ and σ are the median and the SD, respectively.

Table S2. Simplified description of the wastewater treatment alternatives

Treatment system	Simplified description
Alternative 1 (A1)	A1 presents the conventional anaerobic/anoxic/oxic (A^2/O) process.
Alternative 2 (A2)	A2 portrays one optimization of the conventional A^2/O process that cancels the mixed liquor recirculation (MLR). One obvious feature of this system is that its return activated sludge (RAS) rate is higher than that of the conventional A^2/O process.
Alternative 3 (A3)	A3 presents another modification of the conventional A^2/O process, with a focus on RAS distribution. In this system, RAS is returned not only to the anaerobic zone (20% of the total RAS) but also to the anoxic zone (80% of the total RAS).
Alternative 4 (A4)	A4 describes another optimization of the conventional A^2/O process, the University of Cape Town (UCT) process, which provides an adjustment for MLR and RAS.
Alternative 5 (A5)	A5 presents the most common conventional reversed A^2/O process.
Alternative 6 (A6)	A6 employs a step-feed mode based on A5. In this system, 80% of the influent flows to the anoxic zone, whereas the rest is distributed in the anaerobic zone.

Table S3. Mean values of the assessment metrics associated with each scenario for the conventional and emerging WWTP approaches

	Emerging WWTP approach				Conventional WWTP approach			
Assessment metric	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
GHG emissions (NF_{gree})	0.588	0.755	0.822	0.862	0.590	0.775	0.833	0.912
Energy consumption (NF_{ener})	0.341	0.674	0.732	0.813	0.097	0.299	0.351	0.430
Chemical use (NF_{chem})	0.383	0.569	0.784	0.907	0.050	0.235	0.451	0.598
Bioenergy recovery (PF_{bioe})	0.217	0.621	0.587	0.446	—	—	—	—
Sludge recycling (PF_{slud})	0.111	0.347	0.362	0.371	—	—	—	—
Struvite capture (PF_{stru})	0.747	0.492	0.379	0.366	—	—	—	—

Table S4. Parameters in the ARIMA (*p*, *d*, *q*) model for the weighting coefficients

	Developed countries			Developing countries		
Weighting coefficient	*p*	*d*	*q*	*p*	*d*	*q*
Energy consumption (w_{ener})	0	1	0	0	2	2
GHG emissions (w_{gree})	0	1	0	0	1	0
Chemical use (w_{chem})	0	0	1	0	1	1
Bioenergy recovery (w_{bioe})	0	1	0	0	1	0
Sludge recycling (w_{slud})	0	1	0	0	1	0
Struvite capture (w_{stru})	0	1	1	0	1	0