



## Regular article

# Full-scale evaluation of aerobic/extended-idle regime inducing biological phosphorus removal and its integration with intermittent sand filter to treat domestic sewage discharged from highway rest area



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## ABSTRACT

Biological phosphorus removal (BPR) has been demonstrated to be successfully achieved in the aerobic/extended-idle (AEI) wastewater treatment regime in previous bench-scale studies. To date, however, its feasibility has never been evaluated by any full-scale investigation. Here we report a first full-scale (180 m<sup>3</sup>/day) evaluation of the AEI process and its integration with intermittent sand filter to treat highway rest area sewage that is often neglected but actually brings significant impacts on receiving water bodies in China. The results showed that 70–99% of influent phosphate was removed in the AEI zone, although the sewage contained 23–37% of carbohydrate that is usually considered to be detrimental for BPR. Batch experimental investigation revealed that the presence of glucose (model compound of carbohydrate) promoted the AEI-inducing BPR efficiency, as opposed to deteriorating the conventional anaerobic/oxic regime-inducing BPR performance. Although the performance of AEI zone was affected by seasonal variation, the efficiencies of contaminant removal were stable and excellent (total nitrogen > 86%, others > 92%) in the integrated system. This study offers an attractive option for BPR from carbohydrate-rich wastewaters and also provides a prototype for wastewater treatment in remote areas.

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## 1. Introduction

Phosphorus (P) and nitrogen removal from wastewaters is one efficient method to protect freshwater environments from eutrophication. During the past few decades, numerous studies have already been performed on this topic [1–3]. However, most of these investigations to date have focused on centralised wastewaters due to their massive quantities daily treated [4–6]. Apart from centralised wastewaters, decentralised wastewaters, especially highway rest area sewages, are also significant but often overlooked. With the development of economy and increase of

population mobility, highway mileage increases year by year. The total amount of sewages discharged from highway rest areas has achieved at huge levels. For example, it was reported that more than 80 million persons were averagely transported per day via highway during the 31 day transportation for the Spring Festival in China in 2014. This indicated that wastewater treatment systems located in highway rest areas serviced more than 6% of Chinese population during this period. If highway rest area wastewater is treated inappropriately, these decentralised wastewater treatment units will become a giant network pollutant source to vulnerable water bodies.

In general, wastewater treatment technologies established for centralised wastewaters (e.g., anaerobic/anoxic/oxic (A<sup>2</sup>/O) process) are directly miniaturised for the treatment of highway rest area sewage [7]. From the technical perspective, these technologies have abilities of reducing contaminants to low levels, but problems always exist in these on-site treatment systems. According to our 3-

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year survey on 22 wastewater treatment units located in highway rest areas of Central China, 8 of them are often disturbed, and 12 of them are completely failed (Fig. S1, Supporting Information (SI), presents some failure examples). The ecological consequence of failures of these on-site treatment plants should be enlarged due to the facts that the effluent of these treatment systems is discharged directly to the vicinity environment (Fig. S2, SI), and pollution at such locations will remain unnoticed for a long period once it happens (Fig. S3, SI). Therefore, it is necessary to develop some tailored technologies for the treatment of highway rest area sewage.

Several methods, such as membrane bio-reactor [8,9], stabilization pond [10], and soil based treatment system [11,12], were employed to treat decentralised wastewaters in past years. Of these, soil based treatment technology seems to be a promising option, because it is not only simply-controlled but cost-effective. However, clogging is often observed (Fig. S4, SI). To avoid clogging, all these soil treatment systems are designed with low hydraulic (or organic) loading rates and consequently require large construction area and cost [13]. More importantly, except for the metabolic uptakes of plants and microbes, the main mechanism for P removal is adsorption and precipitation by filter media, which is widely considered as unsustainable [14]. Thus, some simple pre-treatment units with sustainable P removal are urgently required.

Our recent laboratory studies demonstrated that excellent biological phosphorus removal (BPR) would be achieved in a traditional activated sludge process without specific anaerobic zone if the idle phase was extended suitably (e.g., 210 min) [15–17]. Aeration is immediately started in this novel P removal regime when wastewaters are influent into the system. After aerobic, settling, and decanting phases, an extended-idle phase is finally followed. Thus this novel process is defined as the aerobic/extended-idle (AEI) regime [17]. Compared with the conventional aerobic activated sludge process which do not have the capability of BPR, the AEI regime extends its idle time. This difference can induce some specific metabolic reactions (e.g., a significant idle phosphate release) occurring in this new regime, which help it to establish the BPR ability [18]. Although the putative polyphosphate accumulating organisms (PAO), *Accumulibacter*, is still the main contributor in this new regime, the inducing mechanism of P removal between the AEI regime and the conventional anaerobic/oxic (A/O) regime is completely different [18,19]. Unlike the conventional one, an abundance of P release accompanied with a low polyhydroxyalkanoates (PHA) synthesis in the idle phase of AEI regime has been demonstrated to provide a selective advantage to PAO over other populations [18]. This finding may have application in new technologies for wastewater treatment. To date, however, all of these studies have been conducted in laboratories, and its feasibility has never been confirmed by any full-scale investigation. Furthermore, the AEI regime does not require any stirring and sewage backflow, but most of contaminations (especially P) are found to be biologically removed to low levels. It seems that the AEI regime may serve as a suitable pretreatment unit for the soil based systems, and the integration system of AEI-soil based treatment may be a promisingly attractive option for decentralised wastewater treatment in remote areas. However, it is also unknown whether this integration system works in a real decentralised wastewater treatment situation.

The purpose of this study was to evaluate the feasibility of BPR driven by the AEI regime in a full-scale system, and the application of AEI integrating with intermittent sand filter (ISF), which is a typical soil treatment system [13], to treat sewage discharged from a highway rest area. Firstly, P removal performance of AEI regime in a full-scale activated sludge reactor was examined from the aspects of both chemical and microbial analyses. Then, the integrated system of AEI-ISF as an effective technology to treat sewage from the highway rest area was tested for over three years. Finally, the per-

spective of AEI regime was discussed, and the techno-economic analysis of this integrated system was also performed.

## 2. Materials and methods

### 2.1. Wastewater

Experiments were carried out in a highway rest area, which is located in Hunan Province, China. The average amount of sewage is about 180 m<sup>3</sup>/d, and the characteristics of discharged wastewater are as follows: total chemical oxygen demand (COD) 142–674 mg/L, soluble COD 109–562 mg/L, total suspended solid (TSS) 123–387 mg/L, total phosphorus (TP) 5.4–11.7 mg/L, NH<sub>4</sub><sup>+</sup>-N 18.4–46.2 mg/L, total nitrogen (TN) 26.8–63.5 mg/L, pH 6.8–7.4. The top two types of organic compound in this wastewater are volatile fatty acids and carbohydrate, which account for 35–53% and 23–37% of soluble COD, respectively.

### 2.2. Full-scale AEI-ISF system

The whole full-scale system consisted of a collecting tank, an AEI reactor, an ISF, a sludge drying bed, and a programmable logic controller. Fig. 1 presents the flowchart of this full-scale system (the field photograph is presented in Fig. S5, SI), and the scale of each part is detailed in Table S1 (SI). Wastewater is first influent into the collecting tank, and then the collected wastewater is intermittently pumped to the AEI reactor for biological treatment. After that, the effluent of AEI reactor is further treated by ISF system before it is finally discharged. The surplus activated sludge generated in the AEI reactor is dewatered by two sludge drying beds before final transport and disposal.

The AEI reactor was operated with three cycles daily according to previous publications with minor revisions [16,17]. Each 8 h cycle consisted of a 1 h feeding period, a 2.5 h aerobic period, a 1 h settling period, and 2 h decanting and 1.5 h idle periods. During the feeding and aerobic periods, air was supplied into the reactor at a flowrate of 600 m<sup>3</sup>/h via two aerators. Thus, the actual aeration time for the AEI reactor was 3.5 h per cycle. During 2 h decanting period, 60 m<sup>3</sup> of supernatant was discharged into the ISF and replaced with 60 m<sup>3</sup> of wastewater in subsequent 1 h feeding period. The hydraulic retention time in the reactor was 10.7 h, while the sludge retention time was maintained at approximately 13 d by wasting 3.5 m<sup>3</sup> of settled sludge once every three days at the end of decanting period. The dewatered sludge, taken from a wastewater treatment plant (WWTP) in Changsha, China, was used as the seed sludge. It should be noted that although only 1.5 h of idle period was operated, the actual “idle rest” time for activated sludge was 4.5 h per cycle (1 h settling + 2 h decanting + 1.5 h idle), which was similar to the AEI regime reported previously.

The ISF consisted of three layers, which was respectively called as peat-sand layer (0.4 m thickness, 40% of peat soil and 60% of 0–2 mm sand by volume), sand layer (0.6 m thickness, grain size 0–2 mm), and gravel layer (0.3 m thickness, grain size 5–30 mm) from the top down. After assembling all the three filter layers, about 350 reed plants (*Phragmites australis*) were planted into the surface of ISF (i.e., the peat-sand layer). The ISF was intermittently fed with the effluent of AEI reactor (2 h of feeding and 6 h of resting) via distribution pipes, as mentioned above. When the AEI reactor was in the decanting period, the ISF was in the feeding period. In other periods of the AEI reactor, the ISF was in the resting period. The hydraulic loading rate of ISF was 1.5 m/d.

### 2.3. Effect of carbohydrate level in wastewater on biological phosphorus removal

Generally, the main carbon source in municipal wastewater is acetate, and carbohydrate is at low levels due to the fermenta-

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