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Chemical oxygen demand degradation of the wastewater from photovoltaic cell plants: a case study on an actual plant in Taiwan

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ABSTRACT

Following the recent rise of high technology industries, mixtures of polyethylene glycols (PEGs), silicon, concentrated acid, and lactic acid have been frequently identified in the polishing wastewater generated by photovoltaic cell plants. After the sedimentation of silicon and the recycling of PEGs, this type of wastewater still contains leftover PEGs, lactic acid, and other salt mixtures, as well as a chemical oxygen demand (COD) concentration of 2,000–3,100 mg/L. Therefore, a biological anaerobic digestion system is required to process this type of wastewater. This type of wastewater primarily consists of PEGs ($HO(CH_2CH_2O)_nH$), which are nonionic synthetic water-soluble polymers (ethylene oxides) that have been disposed into conventional wastewater treatment systems after their application in manufacturing processes. Up to now, few studies have been conducted on the biological treatment of the wastewater generated from the photovoltaic cell industry. Most of these studies have examined the treatment of a single substance. Relatively little research has been published on the fully biological treatment of PEGs, and no studies have examined the treatment of mixtures of multiple toxic substances, such as PEGs, lactic acid, and phosphates. A bench-scale experiment preceding this study, in which an up-flow anaerobic biological treatment method was combined with an aerobic treatment involving high-density biological carriers, yielded notable results. This study empirically analyzed an onsite application of this treatment method. The results confirmed that this biological treatment system can effectively process high-COD-concentration wastewater containing PEGs, lactic acid, and other types of salts with little sludge production, low operating costs, and economic land use. The wastewater treatment model, associated data, and onsite operation records in this study provided a feasible reference for planning operational procedures for wastewater treatment plants for the photovoltaic cell industries.

Keywords: Anaerobic digestion system; Biological treatment; Chemical oxygen demand degradation; Polyethylene glycols; Photovoltaic cell

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1. Introduction

Following the recent booming in high technology industries, mixtures of substances, such as polyethylene glycols (PEGs), lactic acids, and other salts, have been identified in the polishing wastewater generated by photovoltaic cell plants [1]. Studies have indicated that the wastewater generated from food, textile, and alcohol industries can be readily processed through aerobic biological treatment. Following the rising in high technology industries, alternative energy industries such as solar energy have emerged. However, the wastewater generated from the production processes in this industry contains numerous types of chemical contaminants, the most common of which are PEGs ($HO(CH_2CH_2)_nOH$). PEGs are nonionic synthetic water-soluble polymers (ethylene oxide) and are difficult to process through conventional biological treatment methods after their application in manufacturing processes.

Huang et al. [2] as well as Kawai and Enokibara [3] conducted experiments to process this type of wastewater through the isolation of the PEG strains, revealing that degrading the PEGs with this method required a minimum of 6–7 d [2,3]. Bernhard et al. [4] reported that inoculating the sludge produced from daily living to degrade PEGs required as long as 65 d. Regarding the extent of degradation in these aforementioned experiments, unlike that of Huang et al. [2], the reports of Kawai and Enokibara [3] and Bernhard et al. [4] revealed that the carbon U2-units were not comprehensively decomposed. The difficulty of decomposing these units has caused a considerable influence on the natural environment.

The wastewater from photovoltaic cell plants is prevailingly generated from wafer cutting and grinding that mainly contains PEGs. These long-chain polymers change to acetic acid through anaerobic decomposition by microorganisms [5] and can form methane [6]. However, PEGs exhibit low bioavailability and are difficult to degrade biologically [7]; they inhibit the activities of anaerobic microorganisms, particularly methanogens [5,8]. Studies on bacterial inhibition have reported that each type of polymer in wastewater features a different degradation rate [9] and impairs the microbial activities in fermentation tanks to a further extent when its concentration is excessive [10]. The accumulation of acid reduces the pH value of the liquid in a treatment tank, destroys cell membranes, and causes homogeneous damage, thereby slowing or halting the hydrolysis process. Consequently, acetic acid bacteria and acetic methanogens have their activities inhibited and undergo long periods of hysteresis in batch anaerobic dark fermentation [2,11].

Bernhard et al. [3] and Huang et al. [4] indicated that the microorganisms domesticated in an anaerobic environment still underwent a period of hysteresis after they were inoculated for biological degradation. No linear relationship existed between the degradation capability of the microorganisms and the PEG concentration; each type of microorganisms led to a unique curve relationship for PEG degradation. Therefore, when microorganisms are inoculated, the time taken for their environmental adaptation and activation should be noted; the application of microorganisms for biodegradation should not be relinquished because of the hysteresis. However, methanogens can adapt to inhibition by ammonia and can form floras or undergo internal changes. This reveals the strong environmental adaptation capabilities of methanogens. Table 1 lists the ranges of the concentrations of various inhibitory substances which are toxic to anaerobic microorganisms [12]. The interactions among the substances and the changes in the data should be noted. Anaerobic bacteria are domesticated through the gradual increase in the concentrations of inhibitory substances to strengthen their resistance against the substances in wastewater. Angelidaki et al. [13] and Sosnowaki et al. [14] addressed the following advantages of processing wastewater through anaerobic microbial digestion: (1) A balance of nutrient salts can be attained without adding any chemical substances. (2) Organic load can be increased. (3) Latent toxins can be diluted. (4) Anaerobic microbial digestion generates little sludge, can be conducted in large volumes, enables easy facility maintenance, is one of the most economic wastewater treatment methods, requires simple facility structures, and features, less land, facilities, and operating costs. Therefore, this method was employed to process the wastewater from photovoltaic cell plants in this study.

Inoculation substantially affects the outcome of biodegradation; the types of microorganisms inoculated affect biodegradation systems considerably. Inoculating cultured microorganisms at specific concentrations enables the rapid activation of an anaerobic digestion system, a high chemical oxygen demand (COD) degradation rate, large and stable gas production. However, there are numerous factors that affect the biodegradation processes. Each type of substrate differs in its biodegradability and the biodegradation processes should be promptly adjusted according to feedback from the examination data in actual operations [15]. Imbalance in nutrient salts (low carbon-to-nitrogen ratio) is a major limiting factor to biodegradation. Glucose is a type of substrate commonly applied to fermentation [16,17]. Accordingly, although the PEG-contaminated water from photovoltaic cell plants contains high-carbon-to-nitrogen-ratio substances ($HO(CH_2CH_2)_nOH$), during laboratory domestication and onsite inoculation, microorganisms should be supplemented with glucose to maintain their carbon nutrients, which are vital for their survival. During the two aforementioned

Table 1
Substances that inhibit anaerobic bacteria and the ranges of their toxic concentrations [12]

Substance	Moderately inhibitory (ppm)	Strongly inhibitory (ppm)
Na^+	3,500–5,500	8,000
K^+	2,500–4,500	12,000
Ca^{2+}	2,500–4,500	8,000
Mg^{2+}	1,000–1,500	3,000
Ammonia–nitrogen	2,500–3,000	3,000
Free ammonia	–	650
Sulfide	–	200
Copper (Cu)	–	50–70
Chromium VI (Cr)	–	200–260
Chromium VIII (Cr)	–	180–420
Nickel (Ni)	–	30
Zinc (Zn)	–	1.0 (Soluble)

phases, the long-chain molecules have not been decomposed, and the nutrient salts are insufficient. Therefore, microorganisms should be provided with glucose during the operation of the biological treatment system.

The composite wastewater from beer plants typically contains 1,500–3,000 mg/L of COD. Aerobically treating this wastewater requires substantial operating costs and power usage and generates a considerable amount of sludge. Furthermore, the efficiency of the processes varies considerably. Kuang et al. [18] verified through an empirical analysis that simultaneously applying an inner-loop up-flow anaerobic sludge blanket (UASB) reactor and the aerobic treatment method in the wastewater generated by large beer plants stabilized the pollutant concentration in the wastewater to the regulatory standard. Compared with the other known anaerobic biological treatment methods, UASBs feature lower operating and construction costs, as well as stronger adaptability with various types of wastewater; additionally, applying UASBs leads to substantial economic benefit. Refuse and wastewater with rich carbohydrates produce high amounts of hydrogen in their fermentation [19]; the hydrogen or biogas energy [13,14] and water produced from the fermentation can be reused. The results of the anaerobic biological treatment process in this study can be linked to fuel usage; the water disposed of the process can be reused, thereby satisfying environmental sustainability and simultaneously achieving energy and environmental benefits.

Few studies have examined the biological treatment of the wastewater from photovoltaic cell plants. Most of these studies have involved treating a single type of substance but not mixtures of multiple types of toxic substances, such as PEGs, lactic acid, and phosphates. Moreover, few studies have employed fully biological approaches to eliminate PEGs [2]. Currently, no comprehensive treatment system has been formulated to verify the feasibility of the microbial degradation of COD in PEG-contaminated water from photovoltaic cell plants through laboratory simulations and actual applications. Therefore, the goal of this study was to construct an effective and fully biological treatment method to degrade wastewater mixtures containing multiple types of pollutants. The results of this study provided a reference for industrial applications and further research.

In a bench-scale experiment, Lai et al. [20] obtained noteworthy results by combining an up-flow anaerobic biological treatment process with an aerobic water treatment involving high-density biological carriers . This study focused on practical applications of this combined method. The results confirmed that the treatment system formulated in the previous study can effectively process high-COD-concentration wastewater mixed with PEGs, lactic acid, and other types of salts; the proposed treatment had low sludge production, low operating costs, and economic land use; it can improve the quality of the water discharged from the emerging solar energy industry.

2. Materials and methods

2.1. Laboratory environment

The materials and methods of the laboratory work in this study including sample source, laboratory facilities, bacterium source, hydraulic retention time, recycling flow rate, pH value, temperature, water quality analysis methods, and operating parameters are described as follows:

- Sample source: The wastewater from a solar wafer plant in Taiwan, which had been generated from the silicon material cleaning and wafer grinding processes, was tested. The wastewater contained abrasive grains and slurry, organic substances from the cleaning solvents, such as lactic and citric acids, and high-strength nitrate. Table 2 lists the substances contained in the wastewater.
- Pre-experiment: To ensure the parameters of wastewater treatment system, the authors followed the precedent of the bench-scale experiment. An AnBio-Cube® biological treatment system with a 10-L UASB tank as its main body was employed for experiments on the high-polymer PEGs and PEGs in the wastewater from the photovoltaic wafer plant. Fig. 1 illustrates the processes carried out in this AnBio-Cube® system.
- Bacterium source: Approximately 8 L of granular sediment was taken from the wastewater treatment plant of a pig farm in Yunlin County, Taiwan.
- Flow rate: 2–10 mL/min.
- Recycling flow rate: 60 mL/min.
- pH value: 6.8–7.2.
- Temperature: The microorganisms were domesticated for the onsite application in the actual wastewater treatment plant. Therefore, the temperature in the laboratory was not controlled in the experiment (25°C–33°C).
- Water quality analysis methods: As listed in Table 3, the primary items of analysis were the COD concentration

Table 2
Parameters and scopes of water quality of PEGs wastewater

Substance	Scopes
pH	6–8
SS (ppm)	<100
COD (mg/L)	2,000–3,100
NO_3–N (ppm)	<350

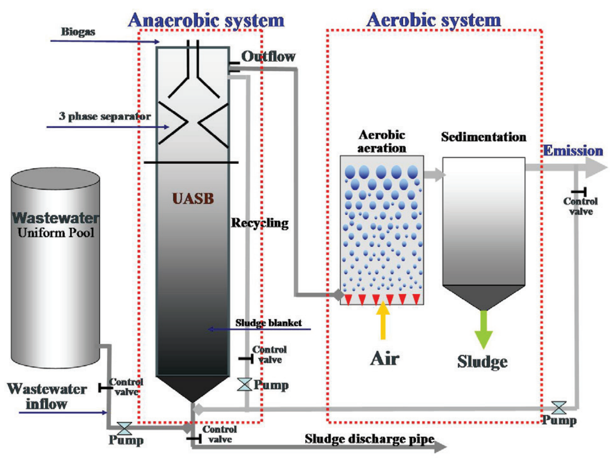

Fig. 1. Schematic of the processes in the AnBio-Cube® system.

Table 3
Items and methods of the analysis

Item	Unit	Analysis methods
pH	–	NIEA W424.52A
SS	ppm	NIEA W210.57A
VSS	ppm	APHA2540E
COD	mg/L	NIEA W510.54A
NO_3–N	ppm	NIEA W419.51A

and the pH values. All the items were analyzed according to the standard methods certified by the Environmental Analysis Laboratory, under EIA Taiwan.

- Operating parameters: Through the use of the AnBio-Cube® system, the COD concentration of the wastewater was reduced to 500 mg/L. The wastewater was then inducted into the aforementioned anaerobic system through a peristaltic pump to domesticate the microorganisms. The inner-loop recycling system was activated and maintained at a recycling flow rate of 60 mL/min. When the effluent COD concentration dropped to no higher than 200 mg/L. It indicated that the microorganisms had successfully adapted to the wastewater environment and had initiated their biodegradation activity. Subsequently, the influent COD concentration was raised for the next domestication process. The domestication and testing processes were repeated to raise the COD concentration tolerable for the microorganisms to 3,000 mg/L, and the rate of inflow was promoted from 2 to 7 mL/min. These steps constituted the domestication phase of the anaerobic system, the outflow of which was connected to the aerobic system. These were the operating parameters of the AnBio-Cube® system.

2.2. Practical wastewater treatment plant (processing capacity: 2,000 m^3/d)

The materials and operating process of the practical case in this study are described as follows:

- Bacterium source: Granular sediment was taken from the wastewater treatment plant on a pig farm with >12,000 ppm of volatile suspended solids (VSS) and a high level of activity (Q_{max} > 150 mL CH_4/g VSS d).
- Hydraulic retention time (HRT): 24–36 h on the basis of the parameters measured in the laboratory experiment. In the actual operation of the plant, the experimental data were used to calculate the standard HRT, and the optimal HRT was determined through trial and error.
- Recycling flow rate: Approximately 8–12 times the amount of the influent wastewater. To reflect the influent rate of 5–7 mL/min in the laboratory, the recycling flow rate was maintained at 60 mL/min.
- pH value: 6.5–7.2.
- Temperature: The onsite water temperature was 23°C–35°C ± 2°C (noncontrolled).
- Water quality analysis methods: As listed in Table 3, the primary items of analysis were the COD concentrations and the pH values. All the items were analyzed according to the standard methods certified by the Environmental Analysis Laboratory under EIA Taiwan.
- The actual wastewater treatment plant and the laboratory differed the most drastically in the changes of their influent COD concentrations. The influent COD concentration in the laboratory was fixed at 3,000 mg/L, but that of the plant was 1,064–13,130 mg/L with a fluctuation rate of nearly 12 times. Although the microorganisms had undergone domestication in the laboratory system at 3,000 mg/L, they were substantially challenged by a wastewater environment with a COD concentration higher than 3,000 mg/L. Therefore, the negative effect of the changes in the influent COD concentration on the microorganism should be highlighted.

3. Results and discussion

To enable the microorganisms to adapt naturally to the characteristics of PEGs in the biological treatment process in the laboratory, no nutrients such as carbon and nitrogen were added. This was a qualitative procedure. The microorganisms adapted to the substance characteristics first (qualitative) and to the substance concentrations subsequently (quantitative). This two-phase approach is applicable for domesticating microorganisms. Notably, methanogens originate from an archaea family and exhibit a considerable environmental endurance capability. The purpose of the domestication process was simply to activate this characteristic of the methanogens and thereby cleanse the environment.

Applying the treatment method developed from the laboratory experiment in the actual wastewater treatment plant (processing capacity: 2,000 m^3/d) required facing numerous challenges. According to the inflow conditions, the results of the onsite application of the method, which was performed for more than 1 y, can be divided into the following five phases: (1) The 66th–95th d after the inoculation constituted the initial phase of normal operation. (2) The influent COD concentration spiked, and the first anomaly occurred in the effluent COD concentration. (3) The influent COD concentration spiked, but no anomaly occurred in the effluent COD concentration. (4) The treatment system became unstable, and anomalies frequently occurred in the effluent COD concentration for a total of 125 d. (5) During the 323rd–410th d (the final days of observation), the system remained stable; the influent COD concentrations were 1,600–4,300 mg/L; and the effluent COD concentrations were no higher than 500 mg/L; the COD efficiency rate was higher than 80%. The details of each phase are illustrated as follows:

- The biological treatment system underwent 30 d of domestication after the inoculation, during which the influent COD concentration was raised no more than 20% each time. On the 31st d, a test run was conducted on the system; on the 66th d, the system began its normal operation. As shown in Fig. 2, the effluent COD concentration was stable in the initial phase of the operation; with the exception of the 68th (583 mg/L) and 89th (560 mg/L) d, the effluent COD concentration was no higher than the acceptable 500 mg/L on all the other days.
    - The 30-d domestication after the inoculation was the qualitative phase in which the microorganisms in the treatment system adapted to the environment of the PEG-contaminated water. This was consistent

with the results of the laboratory experiments, in which the influent COD concentration was fixed at 3,000 mg/L (the effluent COD concentration was no higher than 500 mg/L on the 32nd–33rd d). Fig. 3 illustrates the status of the COD elimination in the aerobic system in the laboratory experiment.

  ○ The 31st–66th d were the quantitative phase, in which the microorganisms adapted to the changes in the onsite COD concentration.
  ○ After the 66th d, the microorganisms became capable of thoroughly processing the PEG-contaminated water. This indicated that the microorganisms were capable of surviving the environment and reproducing smoothly. As revealed in the experimental results, the time required for the microorganisms to adapt to the fluctuating onsite influent COD concentration was twice as long as the time required to adapt to the fixed laboratory influent COD concentration.
  ○ The influent COD concentration in the initial operation phase should be rigorously controlled.
- The influent COD concentration spiked from 4,740 to 9,900 mg/L on the 93rd d, to 6,060 mg/L on the 94th d, and to 8,050 mg/L on the 95th d, respectively. On the 96th d (the 3rd d after the spike in the influent COD concentration), the effluent COD concentration exceeded 500 mg/L (from 450 mg/L on the 95th d to 780 mg/L on the 96th d). The excessive effluent COD concentration persisted until the 110th d when it dropped to 458 mg/L (lower than 500 mg/L). Fig. 4 depicts the aforementioned results.
  ○ On the 93rd–96th d, the growth of the microorganisms was not fully optimized because the microorganisms were at the initial adaptation phase to the PEG-contaminated water. The height of the anaerobic sludge blanket was 13% of the height of the layer below the partition and did not fulfill its height requirement, indicating that the microorganisms were still incapable of responding to any sharp changes in the influent COD concentration. The excessive impact profoundly affected the survival of the microorganisms.
  ○ On the 96th d, an anomaly occurred in the effluent COD concentration. In response to this anomaly, the influent COD concentration was controlled at approximately 3,000 mg/L, and the pH value was adjusted to 6.8–7.2 through the use of $NaHCO_3$ according to the pH values measured in the laboratory. The recycling flow rate was increased. The COD concentration was reduced. The HRT was extended. Consequently, the effluent COD concentration dropped to lower than 500 mg/L on the 110th d. The anomaly lasted for a total of 14 d.
  ○ An anomaly in the influent COD concentration occurred on the 93rd d, and an anomaly in the effluent occurred on the 96th d. A 3-d time interval was observed between the two anomalies. Accordingly, when the influent COD concentration was not properly controlled on any day, the effluent water quality became abnormal after 3 d. The microorganisms sustained subsequent damage without facing extinction. No further increase in the influent COD concentration occurred subsequently. A total of approximately 2 weeks were required for the microorganisms to readapt to the environment and return to their normal growth. This provides a reference for future onsite operations.
- On the 120th d, the influent COD concentration spiked from 2,790 to 8,230 mg/L and remained higher than 5,000 mg/L for six consecutive days. However, the effluent COD concentration on the 120th–122nd d did not exceed 500 mg/L even though it was higher than the 5-d average of 80–100 mg/L, and it stabilized on the 124th d. On the 162nd d, the influent concentration spiked from 2,034 to 7,500 mg/L with a substantial fluctuation difference, but the reaction of the effluent concentration was similar to that of the 120th d; the effluent concentration stabilized after the 2-d reaction to the influent concentration spike (Fig. 5).
  ○ From the 120th–162nd d, the influent COD concentration became 3 to 3.5 times higher, and the effluent COD

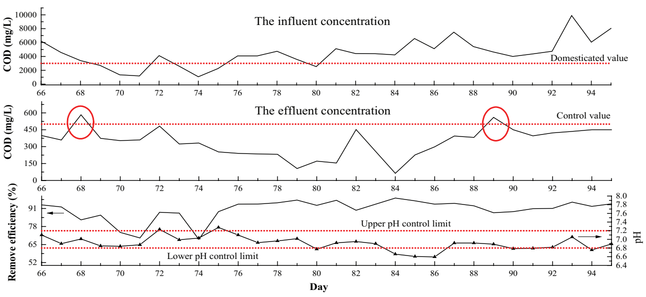

Fig. 2. Concentrations of the 66th–95th d.

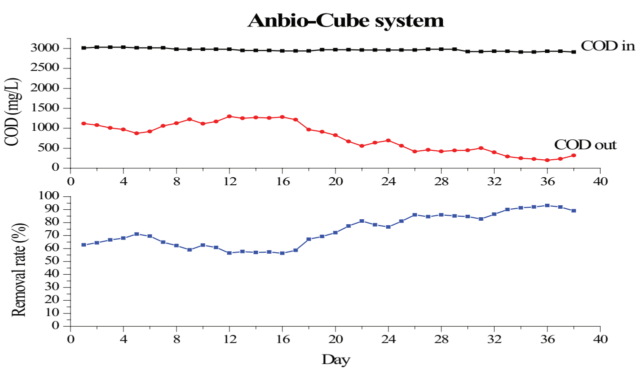

Fig. 3. Status of the COD removal in the AnBio-Cube® system during the laboratory experiment (32nd–33rd d).

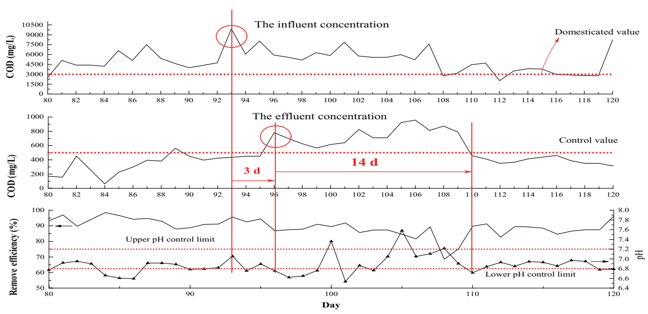

Fig. 4. Concentrations of the 80th–120th d.

concentration reacted to the change. By this point, however, the microorganisms had developed an improved tolerance to the unstable COD concentration compared with their tolerance on the 93rd–96th d; furthermore, they had developed a satisfactory PEG degradation capability. Moreover, this research observed that the reaction time to the influent concentration anomaly by the effluent concentration was also 3 d. The height of the anaerobic sludge blanket was 23% of the distance below the partition according to the nonwater 12 h measurement and reached the required height. Therefore, the flourishing microorganisms exhibited an improved buffering capacity against the target substrates.

- ○ According to Fig. 5, when the influent concentration spiked on the 120th–162nd d, the effluent concentration reacted without exceeding 500 mg/L. This indicated that the microorganisms that were healthy had improved their endurance against the target substances. Basically, the height of the anaerobic sludge blanket should be maintained at a minimal 25% of the distance below the partition. To respond to abnormal changes in the COD concentration, the microorganisms must be satisfactorily cared for and maintained at their optimal status (as defined in this study).

- In the 136 d interval from the 186th–321st d, the treatment system was unstable. The effluent COD concentration exceeded 500 mg/L for a total of 82 d; furthermore, the concentration exceeded the value for 19th consecutive days and for 28th consecutive day (Fig. 6).
  - ○ During this phase, because the system was unstable for more than 14 d, and the anaerobic sludge was unsatisfactorily developed, the height of the sludge blanket was only 8% the distance below the partition and could not be effectively increased through any means of adjustment, and the flora of the aerobic bacteria was weakened. This was attributed to the following causes: (1) the plant employed a new prescription; (2) the split flow of wastewater was unsatisfactorily managed; (3) some of the substances were not contained by the system microorganisms; (4) toxic fluorides were present in the substrates. These caused the bacteriostasis of the microorganisms, thus preventing their cellular growth. Prolonged bacteriostasis would destroy all the microorganisms and restrain the recovery of the biological treatment system.
  - ○ The cause of the prolonged instability in the treatment system was identified as the incomprehensive wastewater distribution in the plant, which caused the inflow of acid wash liquid. Although the microorganisms were able to process the existing substrates, they had not adapted to the appearance of the new substrates. After the instability problem was solved, the system returned to its normal operation on the 322nd d. In future operations, the status of the microorganisms should be optimized during the system operation according to the model in this study, thereby improving the treatment capacity of the system.

- From the 320th–410th d (the final day of observation), the entire biological treatment system was stable (Fig. 7). The influent COD concentration was maintained at 1,600–4,300 mg/L, and the effluent concentration was maintained at no higher than 500 mg/L. The COD removal rate was maintained at no lower than 80%. The spike in the influent COD concentration (11,970 mg/L) on the 240th d was caused by the inflow of a massive amount of high COD substance (lactic acid).
  - ○ Through reinoculation, domestication, and test runs of the granular anaerobic and aerobic sludge, the treatment system was reset. Moreover, because the remaining microorganisms had adapted to the wastewater environment and survived the activity inhibition, the system rapidly recovered.

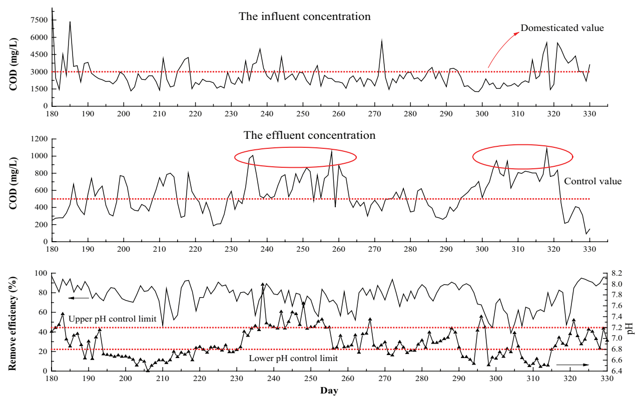

Fig. 6. Concentrations of the 180th–330th d.

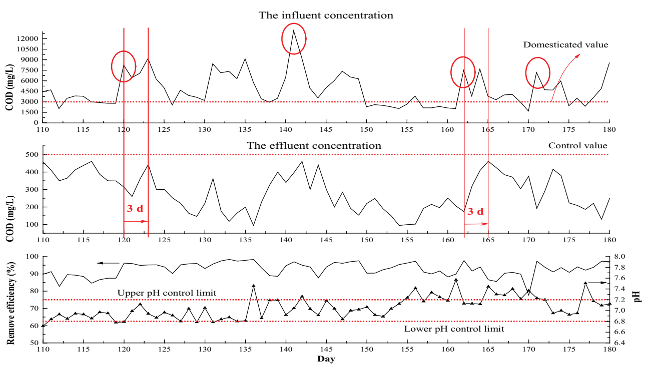

Fig. 5. Concentrations of the 110th–180th d.

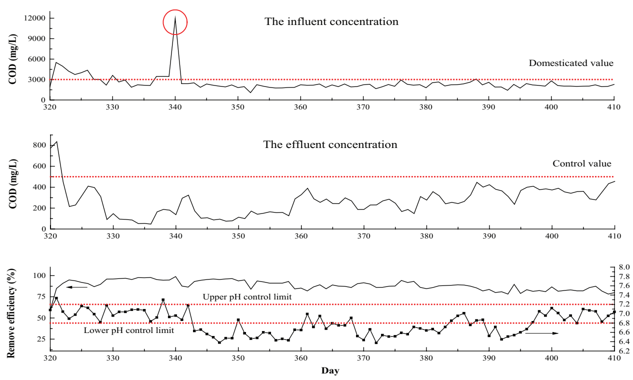

Fig. 7. Concentrations of the 320th–410th d.

- In plants of this type, the operational status of the biological treatment system must be watched closely at all times, and its stability should be preserved according to the parameter control procedures detailed in this paper, thus maintaining the effluent COD concentration at no higher than 500 mg/L and improving the COD removal efficiency rate.
- As revealed in this phase, when the treatment system became unstable for more than 14 d, and the anaerobic sludge underwent inhibited growth, the height of the sludge blanket could not be increased, and the flora of the aerobic microorganisms became weakened. At that point, it was necessary for the sludge to be reinoculated to rapidly and effectively recover the biological treatment system.
- For the task of pH controlling: There was no salient influence on removal efficiency even when the pH value is under 6.8 in 84th–86th d (shown in Fig. 2), 96th–100th d, and 104th d (shown in Fig. 3). Moreover, the treatment demonstrated high stability when the pH value is higher than the upper control limit (pH = 7.2) in 104th and 155th–171th. The results were interpreted as the fact that even though the pH value was roughly maintained between 6.5 and 7.2, the treatment continued to present well efficiency. The coincident result was asserted by Fang's [21] research in 2007 [21].

4. Conclusions

According to the results of the laboratory examination and the practical case, this study introduces the following conclusions:

- In the initial stage of the systems, the influent for COD concentration should be rigorously governed. The buffer pool control should be increased in frequency coordinating the tolerance of the system microbial when the COD concentration is unstable.
- When the system became unstable for more than 14 d, the growth of the anaerobic microorganisms was inhibited, reinoculating the sludge source rapidly and effectively recovered the treatment system.
- For the onsite operation, according to the parameters measured from this research results, the pH value should be maintained at 6.5–7.2; the HRT should be longer than 20 h (24 h in design); the recycling flow rate should not be lower than 0.5. Thus, the COD removal rate can be optimized.
- The AnBio-Cube® biological treatment system was validated to be an effective process for the COD in the PEG-contaminated water from photovoltaic cell plants. The consistent correlations from laboratory to an actual wastewater treatment plant in this study provide a feasible reference for the photovoltaic cell industry.

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