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Effect of Meteorological Conditions on Pollutants Removal and Enhancing Approaches During Photovoltaic Energy Direct Application: Electrokinetic Remediation of Soil Containing Cr(VI) as an Example

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To explore the effect of meteorological conditions on pollutants removal and enhancing removal efficiency approaches in weak solar irradiation intensity during photovoltaic energy direct application, electrokinetic remediation of soil containing Cr(VI) was investigated as an example. The results show that meteorological conditions have a significant effect on pollutants removal, and Cr(VI) removal efficiency for a sunny day is the highest. Cr(VI) concentration and total Cr concentration in the different layer suggest that chromium in soil is electromigrated and accumulated near the anodic region. Total Fe concentration implies that the anodic product Fe^{2+} is migrated into the cathode. Energy conversion efficiency for a sunny day is the highest and is 10.4%. However, energy utilization efficiency for an overcast day is the highest, and E_m and E_v are 24.1kWh/kg and 38.3kWh/m^3, respectively. In weak solar irradiation intensity of 37±3.5W/m^2, the parallel connection of photovoltaic panels is a feasible approach to enhance pollutants removal, and in 30min Cr(VI) removal efficiency for four panels can rise to 79.8% from 64.3% for only one panel. The extending reactive time is also a feasible way, and removal efficiency for one panel can increase from 64.3% to 80.7% as time prolonging from 30 min to 60 min.

Keywords: Meteorological conditions, Photovoltaic energy, Pollutants removal, Enhancing approaches, Soil containing Cr(VI)

1. INTRODUCTION

The photovoltaic solar panel is a very important renewable energy, and it can directly convert abundant sunlight into DC power without need of any fossil fuel resources. Its advantages are nonpolluting, silent, abundant, decentralized, free, long-life and low maintenance cost [1-2]. In addition, to attain higher current and/or voltage, the photovoltaic panels are usually connected in series and/or in parallel mode. Furthermore, the photovoltaic panels can be also used in remote or absent power zones, as brings the users great convenience. More importantly, the photovoltaic panels can directly supply electric energy to reactors without requirement of some classical devices such as transformers, rectifiers, filters and storage batteries. Based on the above facts, the photovoltaic energy is being used widely in wastewater treatment and soil remediation, which is getting a popular trend in the environmental protection field [1-16]. However, meteorological conditions have predominant effect on the performance of photovoltaic panels. For example, in an overcast day the photovoltaic panel's output voltage and current are very small because of low solar irradiation intensity. Additionally, in a cloudy day output voltage and current are also changeable with solar irradiation intensity varying. All these impede the photovoltaic panels from extensively spreading. In particular, how to improve removal efficiency is an urgent problem to be solved when the photovoltaic panel is used to treat pollutants in weak solar irradiation intensity. For that, in this study electrokinetic remediation of soil containing Cr(VI) is used as an example to explore the effect of meteorological conditions on pollutants removal and enhancing removal efficiency approaches in weak solar irradiation intensity when the photovoltaic energy is adopted directly. During experiments, firstly the effect of meteorological conditions on Cr(VI) removal was investigated. Next, energy conversion efficiency of photovoltaic panels and energy consumption during soil treatment were analyzed. Finally, approaches to enhance Cr(VI) removal in weak solar irradiation intensity were suggested. The aims of this paper are: (1) to use electrokinetic remediation of soil as an example to illustrate the effect of meteorological conditions on pollutants removal, energy conversion and energy consumption when the photovoltaic panels are directly used. (2) to suggest feasible approaches to enhance pollutants removal efficiency in weak solar irradiation intensity.

2. MATERIALS AND METHODS

2.1 Pretreatment and analytical methods

The soil was dug from a farmland formerly used for cultivation in the Jinyinhu campus of Wuhan Polytechnic University in Hubei Province, China. The soil containing Cr(VI) was prepared according to the literature[13]. The sample was pretreated and Cr(VI), total Cr and total Fe concentrations in soil were monitored in accordance with the literatures[13,17-19]. pH value of soil, organic matter content and cation exchange capacity were determined in the light of the documents [20-24].

For a better application, all the trials were performed at room temperature and original pH value. The main physic-chemical properties of soil containing Cr(VI) before treatment were listed in Table 1.

Table 1. Physic-chemical properties of soil containing Cr(VI) before treatment.

Parameters	Content
Cr(VI) (mg kg^{-1})	200
Total Cr (mg kg^{-1})	202.2
Total Fe (g kg^{-1})	24.4
Water content (%)	21
pH	7.6
Organic matter content (g kg^{-1})	10.3
Cation exchange capacity (cmol kg^{-1})	6.5

2.2 Experimental setup and procedure

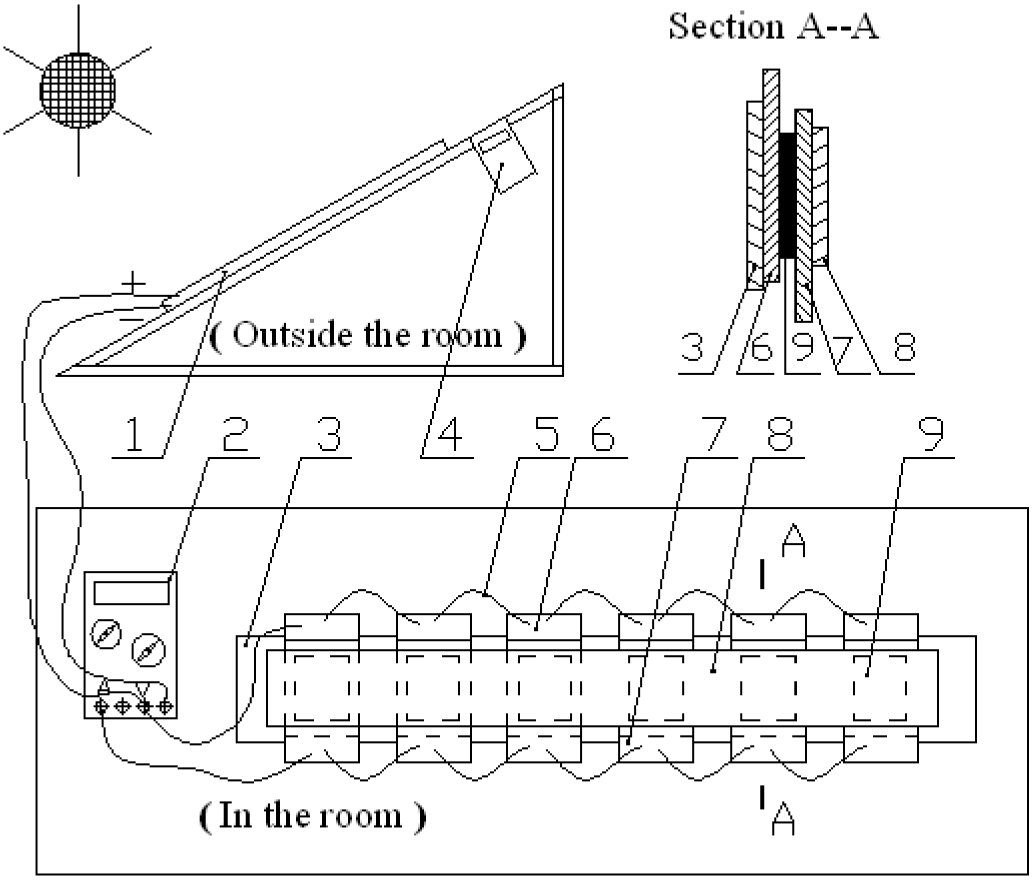

Figure 1. Diagram of the experimental setup: 1. Photovoltaic solar panels 2. Digital multi-meter 3. Insulating board 4. Digital solar power meter 5.Electric wire 6. Iron anodic boards 7. Iron cathodic boards 8. Insulating press board 9. Soil bricks

The experimental setup is schematically demonstrated in Figure 1. The photovoltaic solar panel (30 watts, Model XLY30M) bought from Wuhan Solar Technology Co., Ltd (Hubei, China) was directly connected to the anodic plates and the cathodic plates, and it made up of 36 monocrystalline silicon cells, each of which was 70 mm long and 80 mm wide. Its characteristic parameters, such as short circuit current, optimum operating current, open circuit voltage and optimum operating voltage, were 1.93A, 1.74A, 21.6V and 17.2V, respectively. During tests, the photovoltaic solar panels were located on the roof of the biochemistry lab building in Wuhan Polytechnic University and were tilted at 30°.

Before each experiment, surface oxide layer of iron electrode, the dimension of which was 110 mm × 70 mm × 2 mm (length × width × height), was smoothed away by an angle grinder, and then the electrode was washed by distilled water to remove surface powder of oxide layer. After that, the electrode was dried in a loft drier at 40℃. Soil containing Cr(VI) was pressed into some small bricks under the pressure of 0.2MPa, and the dimension of each brick was 60 mm × 50 mm × 4 mm. During each trial, six soil bricks were laid between six pairs of electrodes, respectively, and then they together were placed between an insulating board and a 5 kg insulating press board. During experiments, all the iron anodic boards and the iron cathodic boards were connected with the photovoltaic solar panel in parallel mode. At an expected experimental time, a pair of electrodes was disconnected to the photovoltaic panel, and then soil brick clamped in the electrodes was dried in the loft drier at 40℃ for the subsequent analysis.

During each run, potential difference and electronic current between electrodes were measured by a digital multi-meter (Model PROVA 803, made in Taiwan), and the solar irradiation intensity was monitored using a digital solar power meter (Model TES-1333R, made in Taiwan).

3. RESULTS AND DISCUSSION

3.1 Effect of meteorological conditions

3.1.1 Cr(VI) removal efficiency

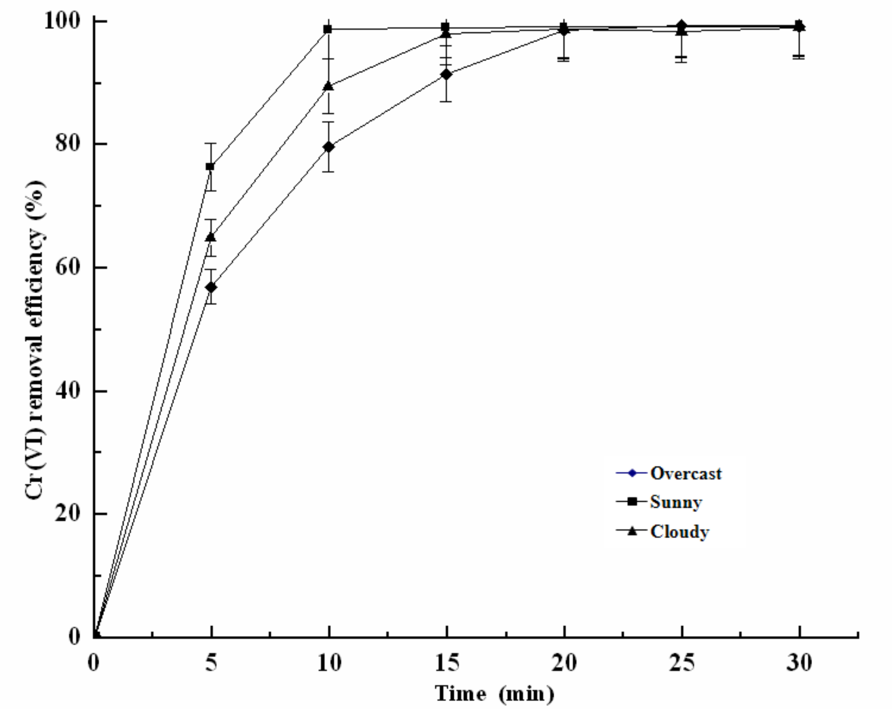

Figure 2. Cr(VI) removal efficiency for meteorological conditions versus reactive time.

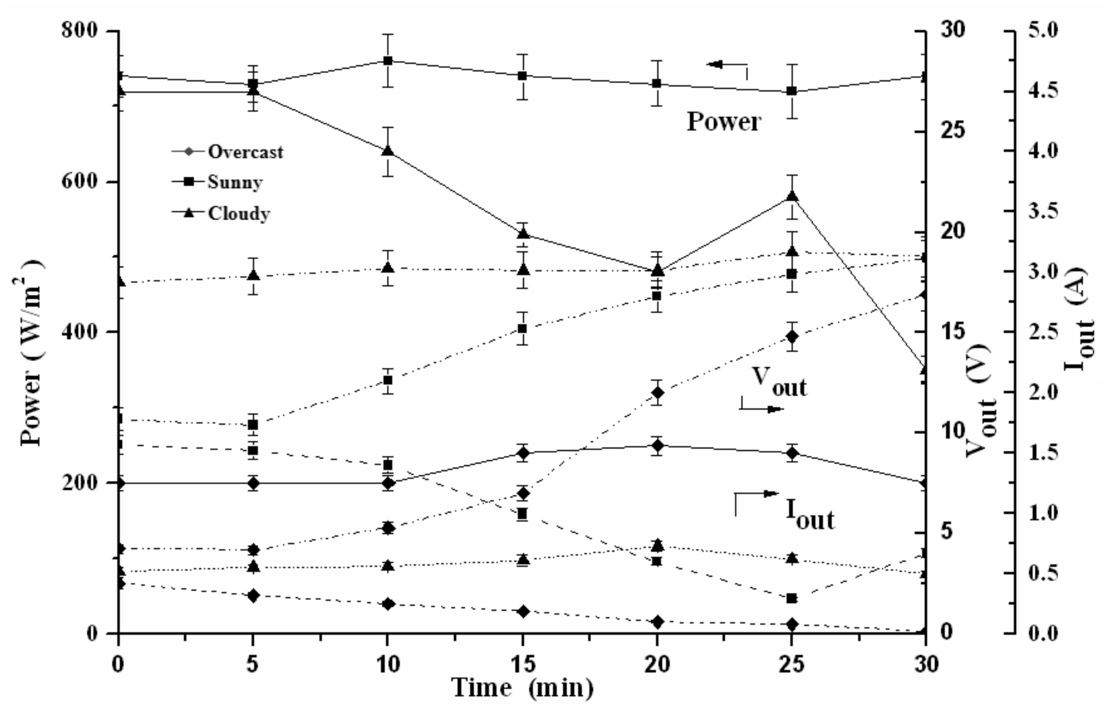

Figure 3. The solar irradiation intensity, voltage and current parameters for meteorological conditions versus reactive time.

Solar irradiation intensity varies with meteorological conditions, and so meteorological conditions not only influence the photovoltaic panels' output voltage and current, but also do the performance of electrokinetic remediation. Figure 2 illustrates the effect of meteorological conditions on Cr(VI) removal efficiency versus reactive time. Additionally, during experiments the solar irradiation intensity, voltage and current between electrodes can be seen from Figure 3.

It can be seen from Figure 2 that in a sunny day of 740±20 W/m^2 solar irradiation intensity, Cr(VI) removal efficiency is the highest in the first 15 min. As for a cloudy day, Cr(VI) removal efficiency is also higher than that in an overcast day. For instance, at the time of 5 min and 10 min, Cr(VI) removal efficiency are 77.0% and 99.3% for a sunny day, 65.5% and 90.1% for a cloudy day and 57.5% and 80.3% for an overcast day, respectively. Consequently, meteorological conditions have a significant effect on pollutants removal efficiency. However, 20 min later, Cr(VI) removal efficiency under different meteorological conditions are all much high and above 99.0%. Meantime, it can be seen from Figure 3 that output voltage in a sunny day is lower than that in a cloudy day while output current is on the contrary, which suggests that the optimum conditions, such as a suitable migration rate of Cr(VI) ion and a large number of Fe^{2+} from the anode , have been built up[25-26]. And this is perhaps a reason that Cr(VI) removal efficiency for a sunny day is the highest in the first 15 min. Nevertheless, due to weak solar irradiation intensity, output voltage and current in an overcast day are all the lowest, and so the above optimum conditions have not appeared, which is a possible reason that Cr(VI) removal efficiency is the lowest. In addition, Cr(VI) removal rates are all faster than ones in the literatures [19,21,27]. For instance, in a sunny day, 99.3% of Cr removal efficiency can be attained in ten minutes. The analysis on Figure 3 reveals that in ten minutes applied voltage and current for a sunny day are above12.4V and 1.3A, respectively. The calculation shows that during experiments electric field strength is above 30.1V/cm and current density is more than 43.3mA/cm^2, and these are all far greater than ones in the literatures [19,21,27]. Moreover, Cr(VI) concentration in used soil is smaller than ones in the literatures [19,21,27]. Higher electric field strength suggests that ions bear a much greater static electric force and bigger current density infers that more ions are passing through soil, which are the possible reason that Cr(VI) removal rates are all faster than ones in the literatures.

In order to understand the migration of Cr(VI) in soil, some other soil bricks are treated in the aforementioned sunny day, too. As Cr(VI) remove rate is very fast, the soil is sampled at the 3rd minute, 7th minute and 15th minute, respectively. In addition, each treated brick is, from the cathode to the anode, cut into the cathodic layer, the middle layer and the anodic layer, and then concentrations of Cr(VI), total Cr and total Fe in each layer are measured.

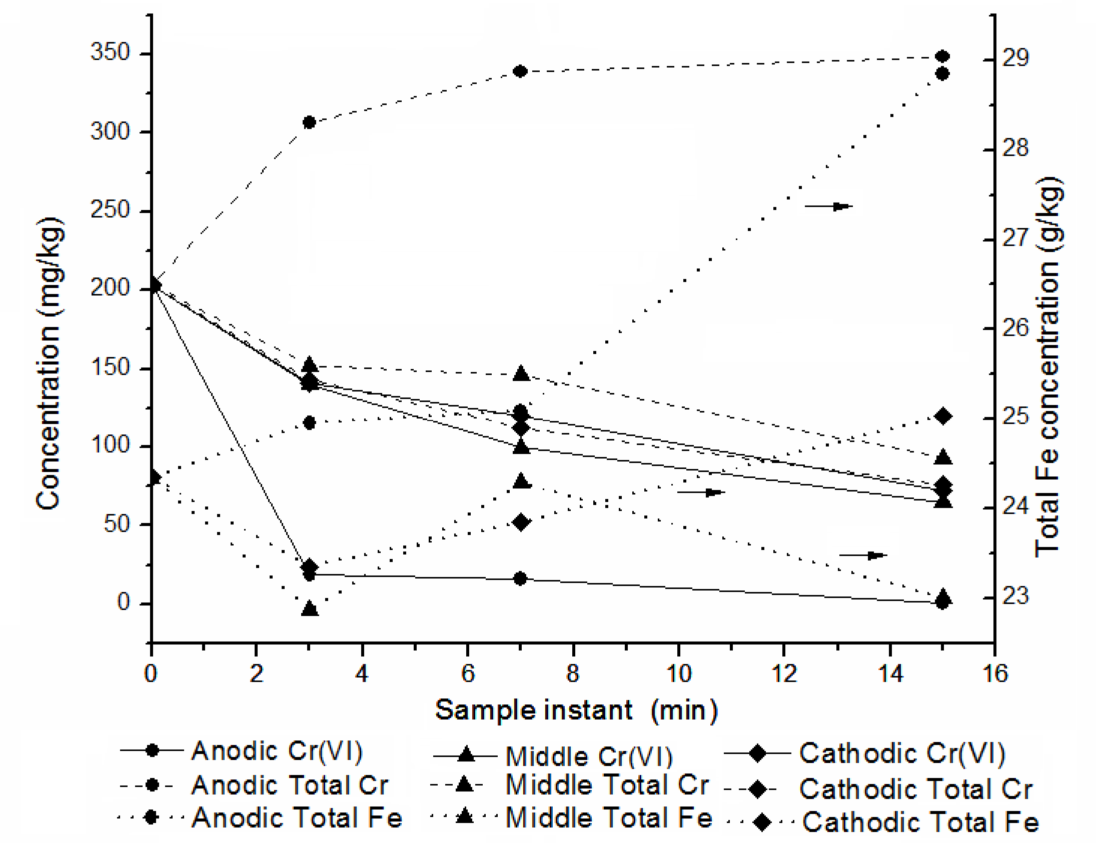

Figure 4. Cr(VI), total Cr concentrations and total Fe concentrations in the different layer at 0 minute, 3 minute, 7 minute and 15minute.

Figure 4 indicates that Cr(VI) concentrations in the same layer all decrease with time increasing. Moreover, at the same sampling instant, Cr(VI) concentrations in soil are getting lower and lower in the following sequence: the cathodic layer, the middle layer and the anodic layer. At the meantime, it is worthwhile to note that total Cr concentration in the anodic layer becomes higher and higher with the extension of time whereas those in the cathodic layer and in the middle layer grow lower and lower. In addition, total Cr concentrations in the anodic layer are all above 300 mg/kg and much bigger than the initial 202.2 mg/kg. The above results infer that chromium in soil is electromigrated into the anode from the cathode and is accumulated near the anodic region. Moreover, total Fe concentrations in the anodic layer are all bigger than the initial 24.4g/kg and are getting higher and higher with time prolonging, which mainly attributes to the anodic electrode dissolution according to the Eqs.(1). Under the action of the anodic product Fe^{2+}, Cr(VI) in soil is reduced into Cr(III) according to the Eqs.(2) , which is the main reason that a high Cr(VI) removal rate in the anodic layer is obtained. Nevertheless, total Fe concentrations in the middle layer are all lower than the initial 24.4g/kg and show a tendency of first decreasing, next ascending and then decreasing again. In addition, total Fe concentrations in the cathodic layer decrease firstly, and then keep on increasing. Surprisingly, total Fe concentration is 25.04g/kg at 15 minute and even goes beyond the initial 24.4g/kg, which implies that the anodic reaction product Fe^{2+} is migrated into the cathode from the anode.

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

$$Cr^{6+} + Fe^{2+} \rightarrow Cr^{3+} + Fe^{3+} \quad (2)$$

3.1.2 Analysis on energy conversion efficiency and energy consumption

To examine the photovoltaic panel's light-to-electric energy conversion efficiency and energy consumption while Cr(VI) is removed from soil during electrokinetic remediation, energy conversion efficiency and energy consumption for the above meteorological conditions are analyzed. During analysis, light-to-electric energy conversion efficiency (η) is carried out by the Eqs. (3).

$$\eta = \frac{\int_0^t IVdt}{\int_0^t PSdt} \quad (3)$$

Where P is the solar irradiation power (W/m^2), S is the effective area (m^2) of the used photovoltaic panel, I is the current (A) passing through the electrodes, V is the potential difference (V) applied to the electrodes and t is the reactive time (Second).

In addition, energy (E_m) used to remove a unit mass of Cr(VI) and energy (E_v) used to process a unit volume of soil are calculated by the Eqs.(4) and the Eqs.(5), respectively.

$$E_m = \frac{\int_0^t IVdt}{M(C_t - C_0)} \quad (4)$$

$$E_v = \frac{\int_0^t IVdt}{V_s} \quad (5)$$

Where the mass (kg) of soil processed is represented as M, the Cr(VI) concentration (mg/kg) at t moment is expressed as C_t, the initial Cr(VI) concentration (mg/kg) is expressed as C_0 and the volume (m^3) of treated soil is V_s.

During the calculation of the above values, solar irradiation intensity, voltage and current parameters are seen in Figure 3. Additionally, as a higher Cr(VI) remove efficiency in 20 min can be obtained under different meteorological conditions, 20 min is regarded as effectively calculating time.

According to the Eqs. (3)~(5), energy conversion efficiency and energy consumption for different meteorological conditions are listed in Table 2.

Table 2. Energy conversion efficiency and energy consumption for different meteorological conditions.

Weather conditions	Sunny	Cloudy	Overcast
η (%)	10.4	8.4	3.2
E_m ($kWh\ kg^{-1}$)	269.7	183.5	24.1
E_v ($kWh\ m^{-3}$)	430.0	293.3	38.3

It can be seen from Table 2 that for a sunny day the highest energy conversion efficiency can be gotten and can reach10.4%, which is slightly low in contrast to the typical value of 15% for current monocrystalline silicon photovoltaic panels [12]. However, unfortunately, for an overcast day the lowest energy conversion efficiency shows out and is 3.2%, as is in conflict with results in the literature [4]. Due to solar irradiation power changing with meteorological conditions, the above results suggest that when Cr(VI) removed from soil higher solar irradiation power is favorable to the photovoltaic panel's energy conversion efficiency. Moreover, Table 2 also presents that E_m and E_v for an overcast day are all the lowest and its values are 24.1kWh/kg and 38.3kWh/m^3, respectively. This infers that energy utilization efficiency for an overcast day is the highest during electrokinetic remediation. It is noticeable that although for a sunny day energy conversion efficiency is highest, its E_m and E_v are 269.7kWh/kg and 430.0kWh/m^3, respectively, and energy utilization efficiency is the lowest. The values of energy consumption are similar to the results in the literature [28]. During experiments, we notice that the phenomenon of the Joule heat is obvious in a sunny day, which is a main reason that for a sunny day the energy utilization efficiency is the lowest.

3.2 Effect of photovoltaic panels' connection mode

According to the results from Section 3.1, "due to weak solar irradiation intensity, output voltage and current in an overcast day are all the lowest, Cr(VI) removal efficiency is the lowest. " In order to improve removal efficiency for an overcast day, it is necessary to enhance output voltage and current of the photovoltaic solar panel. However, in an overcast day, enhancing output voltage and current are seemingly conflicted with weak solar irradiation intensity when the photovoltaic panel is used. Luckily, during photovoltaic solar panels application they are usually connected in series and/or in parallel mode to get a higher current and/or voltage, which makes it possible to improve removal efficiency for an overcast day. Consequently, the connection mode of photovoltaic panels, which directly influence voltage and current applied to the reactor and pollutants removal efficiency, is investigated. The effect of photovoltaic panels' connection mode on Cr(VI) removal efficiency versus reactive time is shown in Figure 5. At the same time, the solar irradiation intensity, voltage and current during experiments are also demonstrated in Figure 6.

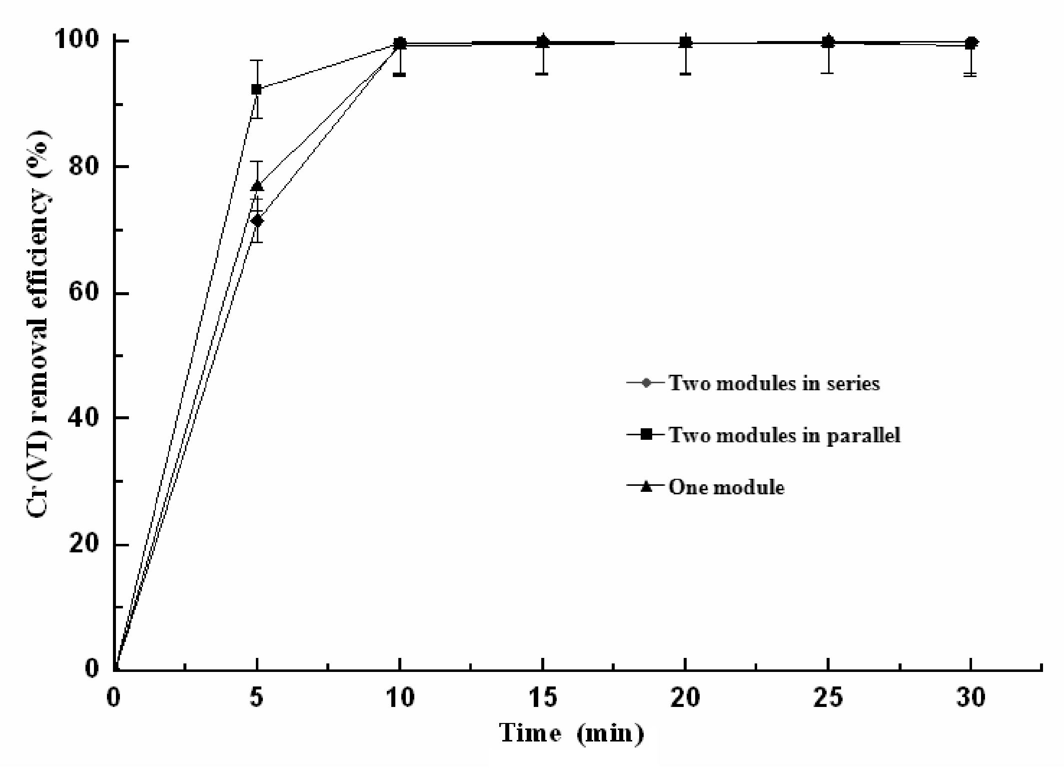

Figure 5. Cr(VI) removal efficiency for photovoltaic panels' connection mode versus reactive time.

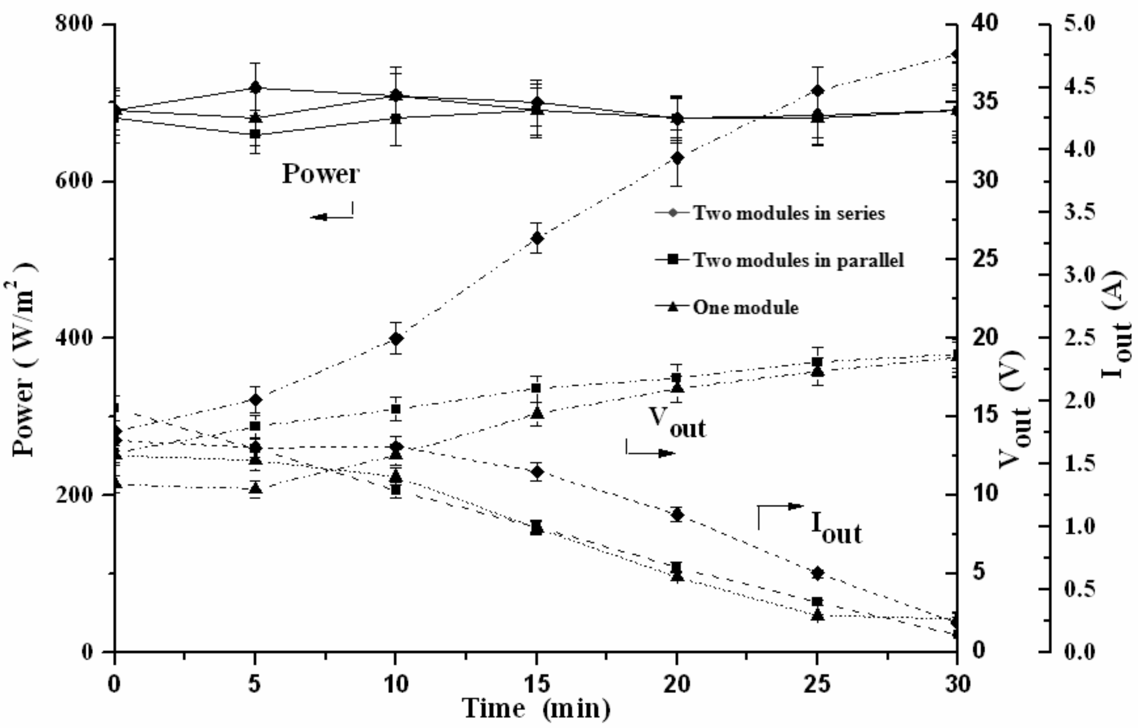

Figure 6. The solar irradiation intensity, voltage and current parameters for photovoltaic panels' connection mode versus reactive time.

As is shown in Figure 5 that under the solar irradiation intensity of 680±20W/m^2, Cr(VI) removal efficiency in 10 min is the highest for two panels in parallel, the second for only one panel and the least for two panels in series. For example, Cr(VI) removal efficiency at 5 min is 92.4%, 77.1% and 71.6%, respectively. After 10 min, Cr(VI) removal efficiency is all close to each other. At the same time, it can be seen from Figure 6 that during electrokinetic remediation, the output voltage order of the photovoltaic panels from bigness to smallness is two panels in series, two panels in parallel and only one panel. Nevertheless, in 5 min current passed through soil is the biggest for two panels in parallel while that is the smallest for only one panel. A bigger current implies that a larger amount of the anodic product Fe^{2+} is diffused into soil and more Cr(VI) in soil is reduced to Cr(III) according to the Eqs. (2), which is the main reason that Cr(VI) removal efficiency for two panels in parallel in 10 min is the highest [19]. However, for two panels in series, output voltage is the highest during experiments and according to the electrostatic force mechanics Cr(VI) ion in soil bears the biggest force under a given distance. As a result, migration rate of Cr(VI) ion is so fast that in a short time a higher Cr(VI) concentration thin layer occurs near the anode. Namely, the phenomenon of concentration polarization produces. Subsequently, it influences the reaction between Cr(VI) and Fe^{2+} [25,29-30], which is perhaps the reason that in the first 10 min Cr(VI) removal efficiency for two panels in series is lower than that for only one panel. Therefore, the parallel connection mode of photovoltaic solar panels is advantageous to pollutants removal.

3.3 Approaches to enhance Cr(VI) removal in weak solar irradiation intensity

How to enhance removal efficiency in weak solar irradiation intensity is a problem that must be encountered and be solved during application of the photovoltaic solar panels in pollutants treatment. For that, on the basis of the results of Section 3.2, the parallel connection of photovoltaic solar panels is used. In addition, another approach is investigated by an extending reactive time. Simultaneously, in order to confirm the feasibility of the approaches, very low solar irradiation intensity is adopted. Figure 7 represents Cr(VI) removal efficiency for the two approaches versus reactive time. Similarly, Figure 8 shows the solar irradiation intensity, voltage and current parameters versus reactive time during experiments.

It is seen from Figure 7 that in 30 min Cr(VI) removal efficiencies for the parallel connection of photovoltaic panels are all higher than that for only one panel. Moreover, the number of photovoltaic panels in parallel is more, and Cr(VI) removal efficiency is higher. For instance, at the time of 15 min and 30 min, Cr(VI) removal efficiency in weak solar irradiation intensity of 37±3.5 W/m^2 are 36.9% and 64.3% for only one panel, 50.5% and 70.7% for two panels, 59.8% and 77.1% for three panels and 64.7% and 79.8% for four panels, respectively.

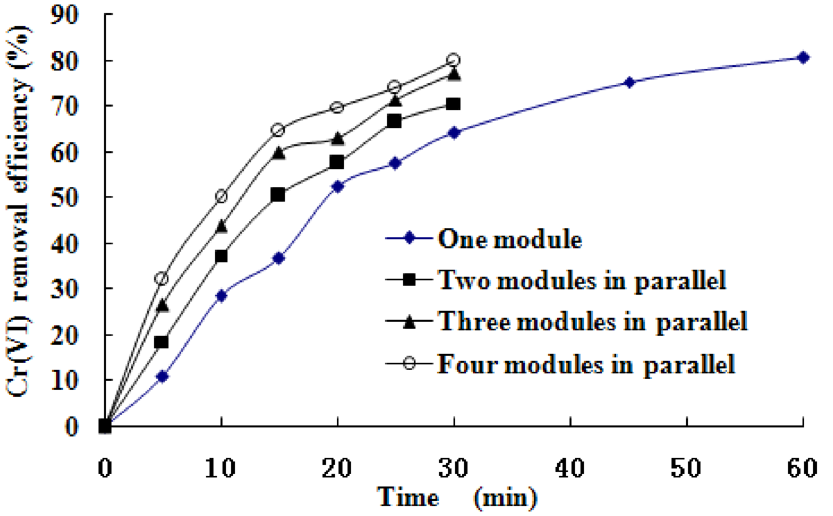

Figure 7. Cr(VI) removal efficiency for approaches used in weak solar irradiation intensity versus reactive time.

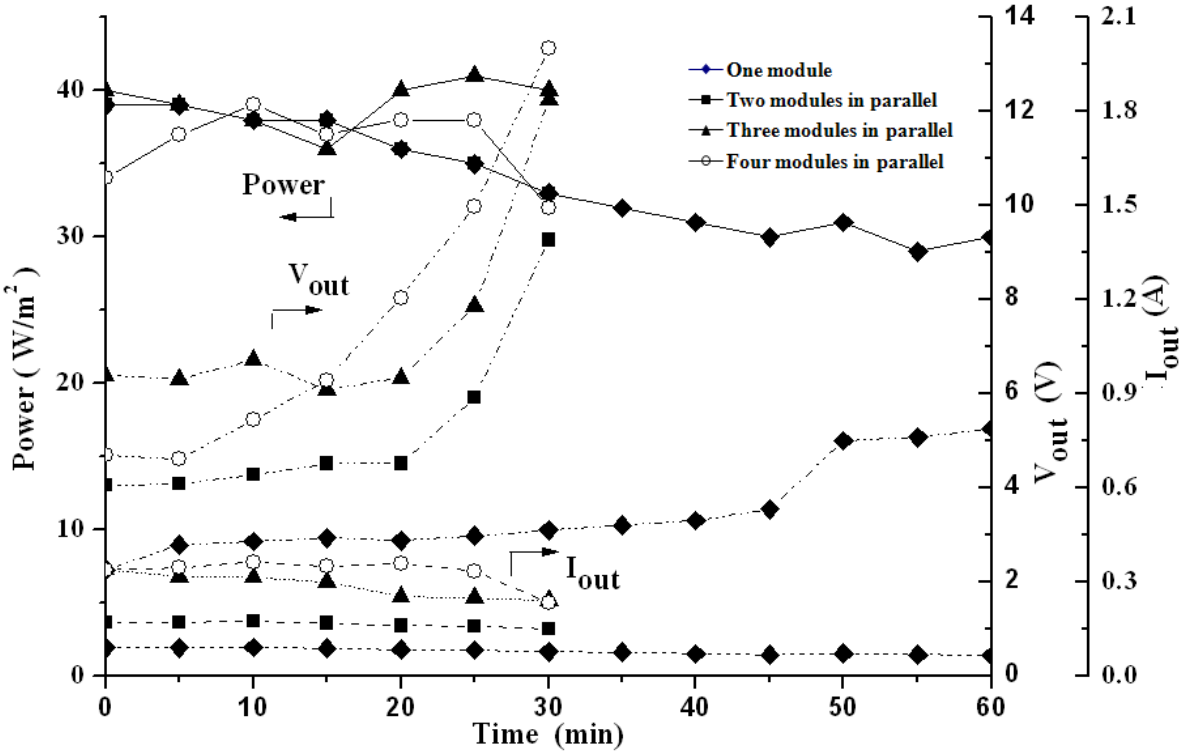

Figure 8. The solar irradiation intensity, voltage and current parameters for approaches used in weak solar irradiation intensity versus reactive time.

Consequently, the parallel connection of photovoltaic solar panels is a feasible approach to enhance Cr(VI) removal in weak solar irradiation intensity. Meanwhile, it is worth noting that Cr(VI) removal efficiency for only one panel is also becoming higher and higher with the extension of reactive time. For example, Cr(VI) removal efficiency increases from 64.3% to 80.7% as the reactive time is extended from 30 min to 60 min, which implies that the extending reactive time is also a feasible way to enhance Cr(VI) removal. As is seen from Figure 8 that for only one panel, output voltage and current are all the lowest in 30 min, which is maybe a main reason that Cr(VI) removal efficiency is the lowest than those for the parallel connection of photovoltaic solar panels. Due to time prolonging, the number of Fe^{2+} from the anode is becoming more and more. As a result, more Cr(VI) in soil is reduced to Cr(III) under the action of Fe^{2+}, which is a reason that Cr(VI) removal efficiency is enhanced by an extending reactive time.

3. CONCLUSIONS

In this study, electrokinetic remediation of soil containing Cr(VI) is used as an example, the effect of meteorological conditions on pollutants removal was investigated and approaches to enhance removal efficiency approaches in weak solar irradiation intensity were suggested when the photovoltaic energy was used directly. Some conclusions can be drawn as follows:

Meteorological conditions have a significant effect on pollutants removal efficiency and in a sunny day of 740±20 W/m^2 Cr(VI) removal efficiency is the highest in the first 15 min and is above 99.0%. In addition, Cr(VI) concentrations and total Cr concentrations in the cathodic layer, the middle layer and the anodic layer suggest that chromium in soil is electromigrated into the anode from the cathode and is accumulated near the anodic region. Simultaneously, total Fe concentration in the different layer implies that the anodic product Fe^{2+} is migrated into the cathode from the anode. Analysis on energy conversion efficiency shows that conversion efficiency for a sunny day is the highest and is 10.4%. However, analysis on energy consumption demonstrates that energy utilization efficiency for an overcast day is the highest, and E_m and E_v are 24.1kWh/kg and 38.3kWh/m^3, respectively.

Under the solar irradiation intensity of 680±20 W/m^2, Cr(VI) removal efficiency in 10 min is the highest for two panels in parallel, the second for only one panel and the least for two panels in series. The parallel connection of photovoltaic solar panels is advantageous to pollutants removal.

In weak solar irradiation intensity of 37±3.5 W/m^2, the parallel connection of photovoltaic solar panels is a feasible approach to enhance pollutants removal, and in 30 min Cr(VI) removal efficiency for four panels can rise to 79.8% from 64.3% for only one panel. The extending reactive time is also a feasible way, and Cr(VI) removal efficiency for only one panel can increase from 64.3% to 80.7% as time is extended from 30 min to 60 min. The suggested approaches to enhance removal efficiency are feasible in weak solar irradiation intensity.

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