Environmental Impact Assessment of Wastewater Discharge with Multi-Pollutants from Iron and Steel Industry

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Abstract: The iron and steel industry discharges large quantities of wastewater. The environmental impact of the wastewater is traditionally assessed from the quantitative aspect. However, the water quality of discharged wastewater plays a more significant role in damaging the natural environment. Moreover, comprehensive assessment of multi-pollutants in wastewater from both quality and quantity is still a gap. In this work, a total environmental impact score (TEIS) is defined to assess the environmental impact of wastewater discharge, by considering the volume of wastewater and the quality of main processes. To implement the comprehensively qualitative and quantitative assessment, a field monitoring and measurement of wastewater discharge volume and the quality is conducted to acquire pH, suspend solids (SS), chemical oxygen demand (COD), total nitrogen (TN), total iron (TFe), and hexavalent chromium (Cr(VI)). The sequence of TEIS values is obtained as steelmaking > ironmaking > sintering > hot rolling > coking > cold rolling and TN > COD > SS > pH > Cr(VI) > TFe. The TEIS of the investigated steel plant is 26.27. The leading process lies in steelmaking with a TEIS of 19.98. The dominant pollutant is TN with a TEIS of 15.00. Finally, a sensitivity analysis is performed to validate the feasibility and generalisability of the TEIS.

Keywords: environmental impact assessment; iron and steel industry; wastewater pollutant; water quality; total environmental impact score (TEIS)

1 Introduction

The iron and steel industry receives urgent attention due to its high intensity of material consumption (Dai, 2015), energy consumption (Sun et al., 2018a), CO_2 emission and particulate matter emission (Li et al., 2019). The iron and steel industry is also a water-intensive sector (Wang et al., 2017a) and a major wastewater discharger (Sun et al., 2018b). World Steel Association (2018a) reported that the average water intake per tonne of crude steel for an integrated plant was 28.6 m^3, with an average fresh water consumption of 3.3 m^3; whereas the average energy consumption per tonne of crude steel is only 20 GJ with an average CO_2 emission of 1.9 tonnes (World Steel Associate, 2018b). The calculation of Wang et al. (Wang et al., 2017b) indicated that 4.1 m^3 of the water use was related with the water-energy-emission network per tonne of crude steel production, accounting for around 66% of the total water consumption in the steel production processes. Therefore, it is of great importance to reduce the fresh water consumption and wastewater discharge from the iron and steel industry.

Many papers on water consumption and wastewater discharge have been published. Mahjouri et al. (2017) developed an integrated methodology for determining the most appropriate wastewater treatment technology for Iran's steel industry. Colla et al. (2017) evaluated the implementation of ultrafiltration and reverse osmosis by modelling and simulation. Lv et al. (2018) introduced a concept of cycles of temperature to evaluate the quality of the open circulating cooling water system. Alcamisi et al. (2015) and Torkfar and Avami (2016) optimised the water system from the perspective of pipeline network, by integrating wastewater treatment models into traditional water pinch technology (Porzio et al., 2014). Nevertheless, less attention was paid to the assessment of wastewater discharge. Water consumption per tonne of crude steel and fresh water consumption per tonne of crude steel (Tian et al., 2008; Strezov et al., 2013) are two indices used to evaluate the water use in the iron and steel industry. Fresh water consumption refers to the water intake from the surface and underground water. Water consumption is the sum of fresh water and circulating water. Statistically, the iron and steel industry contributes 14% of the national total wastewater of China (Guo and Fu, 2010). Although these two indices can quantitatively evaluate the water consumption status, few studies on water quality have been devoted to the environmental impact assessment of wastewater discharge (Burchart-korol and Kruczek, 2015).

Regarding water quality, Kanu and Achi (2011) pointed out that high suspended solids (SS) were generated in the iron and steelmaking processes, which is relative to their water use characteristics. Pallabi et al. (2018) analysed the effluents from the iron and steel industry loaded with toxic, hazardous pollutants, such as chemical oxygen demand (COD), and unutilized components which necessitates mitigation. Wang et al. (2018) qualified the content of COD, SS, electrical conductivity (EC), and pH of converter dust removal sewage.

To evaluate the environmental impact of the pollutants, water footprint (Ma et al., 2018) is the main method for the assessment of water use in the iron and steel industry. Water footprint includes green (Zhuo et al., 2016), blue (Boyacıoğlu, 2018), and grey water footprint (Gu et al., 2014). Gerbens-Leenes et al. (2018) calculated the blue and grey water footprint of steel products. Gu et al. (2015) calculated the grey water footprint of iron and steel industry with Eastern China as a case study. Yet, the value of water footprint may be the same for different components in wastewater with the same maximum volume of diluting water to meet the environmental standard.

In addition, although the pollutants discharge data were published in many studies, the results on simultaneous monitoring of multi-wastewater-related pollutants from the iron and steel industry are rarely reported. The lack of simultaneous data may be the difficulty to conduct the comprehensive assessment of multi-pollutants in wastewater from the iron and steel industry. Thus, the environmental impact assessment of wastewater discharge with multi-pollutants is still a gap and requires more attention.

This work proposes an environmental impact assessment approach for evaluating the wastewater discharge with multi-pollutants. The volume of wastewater discharge and the quality of water are considered as a whole, which is rarely seen before. A field measurement is conducted to acquire the content of multiple pollutants and the volume of wastewater. In addition, an environmental impact assessment of the wastewater discharge from the main process of an integrated iron and steel industry and a corresponding sensitivity analysis are implemented.

2 Methodology

In this work, the total environmental impact score (TEIS) of a production process is proposed to quantify the environmental impact of wastewater discharge with multiple pollutants. The TEIS is expressed as

$$TEIS = \frac{q}{q_0} \cdot \sum_{i=1}^{I} \left(\omega_i \cdot \frac{c_i}{c_{0i}} \right). \tag{1}$$

where q and q_0 are volumes of actual and benchmark wastewater discharge of the process, respectively; ω_i denotes the weight of pollutant i; c_i and c_{0i} are the actual and permissible discharge index of pollutant i, respectively; and I is the number of pollutants.

In Eq. (1), the index c for the pollutants, except for pH, is the concentration of pollutant in the discharged wastewater measured in mg/L. As for pH, the permissible value is regarded as 7, and the partial TEIS is calculated by:

$$TEIS_{\text{pH}} = \frac{q}{q_0} \cdot \omega_{\text{pH}} \cdot \frac{|\text{pH} - 7|}{7}. \tag{2}$$

The benchmark volume and permissible water quality of the discharged wastewater are stimulated by local or national government. However, it is difficult to directly determine the weight of every single pollutant. In this work, an equivalent weight 1, which is widely used in the air quality assessment, is assigned to each pollutant.

To compare the difference between the TEIS based approach and existing methods, a widely used indicator, grey water footprint (GWF) (Franke et al., 2013), is selected. The TEIS is defined as the theoretical amount of water required to dilute pollutants discharged into the natural water system, which is used for maintaining the quality of ambient water above the objectives. The GWF of each process is obtained according to its definition (Gu et al., 2015) and expressed as:

$$GWF = \max\left\{q \cdot \frac{c_i}{c_{0i}}\right\}. \tag{3}$$

According to Eqs. (1) and (3), the GWF is the maximum volume of water for diluting every single wastewater-related pollutant, whereas the TEIS evaluates the accumulative impact of multi-pollutants in the discharged wastewater. In the TEIS, both the wastewater discharge volume and the concentration of each pollutant are considered.

3 Experimental

The investigated area is one of the largest integrated steel plants in China. The steel plant is located in the northeast of China and is a complex process mixture, mainly including coking, sintering, ironmaking, steelmaking, hot rolling, and cold rolling processes.

To measure different pollutants in the discharged wastewater, a field measurement of wastewater discharged from above-mentioned processes was conducted. The volume of wastewater was recorded by the flowmeters installed on wastewater pipelines. The water quality parameters investigated in this work include pH and the concentrations of SS, COD, total nitrogen (TN), total iron (TFe), and hexavalent chromium (Cr(VI)). pH was monitored by a SevenGo Duo™ pH meter (Mettler-Toledo AG, Switzerland). The concentration of the SS was determined by the gravimetric method according to China National Standard GB/T 11901-1989. The concentration of the COD was determined by the dichromate method according to HJ 828-2017. The determination of the TN was conducted by the gas-phase molecular absorption spectrometer method according to HJ/T 199-2005. The determination of the TFe was executed by the phenanthroline spectrometer method according to HJ/T 345-2007. The concentration of Cr(VI) is determined by the 1,5 diphenylcarbohydrazide spectrophotometric method according to GB/T 7467-1987.

4 Results and Discussion

4.1 Volume and Quality of the Wastewater

Fig. 1 shows the volumes of wastewater from coking, sintering, ironmaking, steelmaking, hot rolling, and cold rolling processes. It can be seen that ironmaking process, the main discharger of wastewater in the steel plant, accounts for 47.14% of the total wastewater discharge. The volume of wastewater is lower than the benchmark volume, 0.75 m^3/t, set by GB 13456-2012. The steelmaking process accounts for 34.30% of the total wastewater, which is higher than the benchmark volume, 0.10 m^3/t. The contributions of coking, sintering, hot rolling and cold rolling processes to the total wastewater are 5.03%, 4.77%, 6.55% and 2.43%, respectively, The corresponding benchmark volumes are 0.40, 0.05, 0.25 and 0.25 m^3/t, respectively. Note that the benchmark volume of the coking process, different from other processes, is issued in GB 16171-2012.

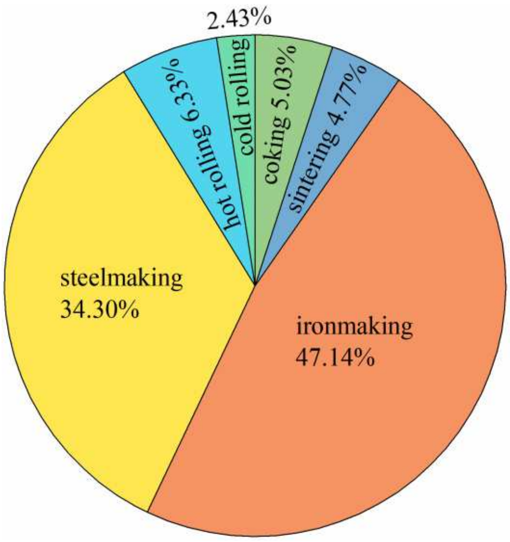

Fig. 1 Volume of discharged wastewater per tonne of crude steel [m^3/t]

Fig. 2 compares the monitored water quality of the six main processes and the corresponding permissible limits. It can be found that the permissible range of pH for all processes is 6-9. Most of the processes meet the pH standard, except the steelmaking process with a pH of 9.37. In this work, a reference permissible limit of 7 is used to calculate the TEIS. The wastewater of the sintering process is slightly alkaline, because of the widely-used spraying alkali technology in the sintering process; while other processes are acidic due to the acid radical in the wastewater. The SS concentration of each process is within the permissible limit. Steelmaking process has the highest SS concentration of 18.95 mg/L, followed by the ironmaking process of 16.05 mg/L due to its wet dedusting systems. The SS is also the major component of hot and cold rolling processes for the existence of iron scale. Coking process has the highest COD concentration at 4.07 mg/L, which is higher than the permissible limit 80 mg/L. This is led by the heavy chemical units in the coking process. The COD concentrations of steelmaking and hot rolling processes are 8.20 and 3.30 mg/L, respectively, higher than the permissible limit 50 mg/L. The TN pollution is the worst regarding the concentration of the investigated plant. Except for the cold rolling, no process is within the corresponding permissible limit. The highest one, 43.65 mg/L of steelmaking process, has nearly tripled its permissible limit. Hot rolling holds the second position of TN concentration, with the value of

35.77 mg/L. The concentrations of TFe and Cr(VI) are both perfectly acceptable. Note that the processes with the iron element have lower TFe concentrations, because the iron content is paid attention to in these processes. In addition, no Cr(VI) is detected in the coking process.

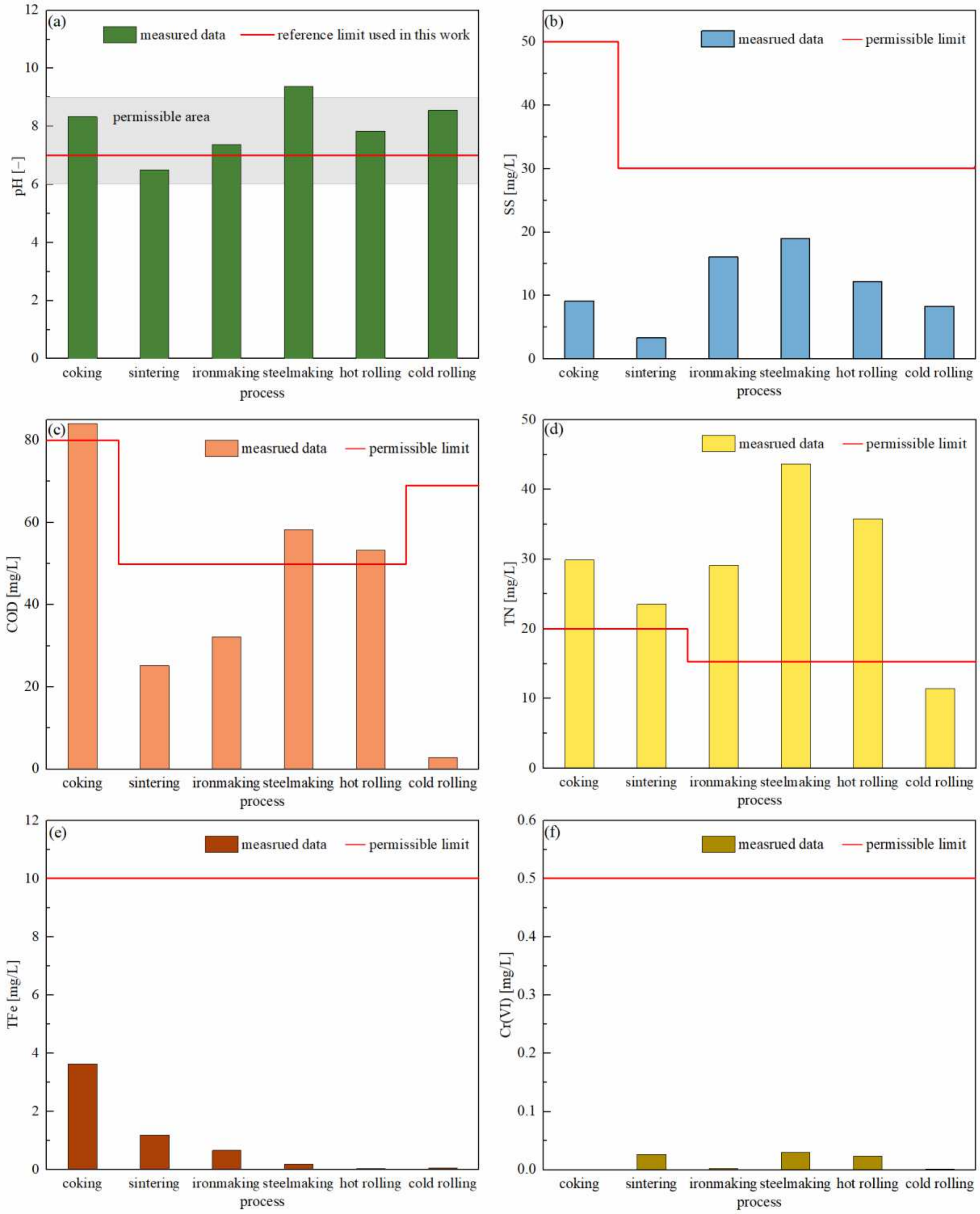

Fig. 2 Measured and permissible wastewater quality of main processes of the integrated steel plant: (a) pH; (b) SS; (c) COD; (d) TN; (e) TFe; and (f) Cr(VI).

4.2 The TEIS

The TEISs of coking, sintering, ironmaking, steelmaking, hot rolling, and cold rolling processes are analysed in this section. According to Eqs. (1) and (2), the partial TEIS of every single process or pollutant can be calculated. Fig. 3 depicts the partial TEIS of each process. The sequence of TEIS values in different processes is as follow: steelmaking > ironmaking > sintering > hot rolling > coking > cold rolling. Steelmaking process ranks first in the process TEISs with a value of 19.98. It is much greater than the following ironmaking process, with a TEIS of 2.31. This is because: 1) the volume of wastewater in the steelmaking process is 2.9 times higher than the benchmark volume; 2) the values of pH, SS, TN and Cr(VI) are all the highest among the six main processes. The TEISs of sintering, hot rolling, coking and cold rolling processes are 2.21, 1.16, 0.47 and 0.14, respectively. And the TEIS of the whole plant is the sum of every single process partial TEIS, which is 26.27.

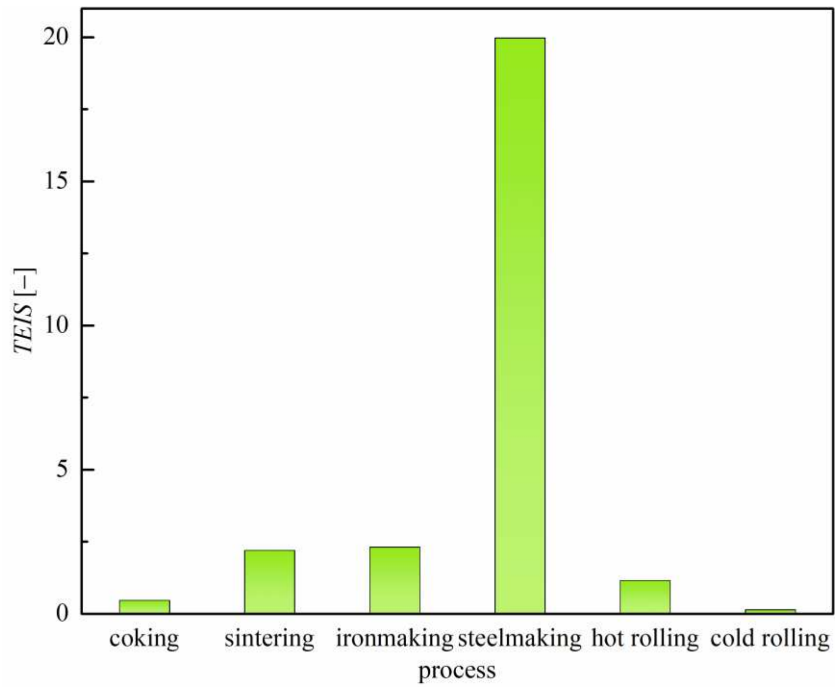

Fig. 3 Contribution of main processes to TEIS

Fig. 4 performs the partial TEIS of each pollutant. It is obvious that the TEIS of the whole plant is also 26.27. The amount of pollutant satisfies TN > COD > SS > pH > Cr(VI) > TFe. TN contributes the most to the TEIS, with the value of 15.00, because five of six processes' TN concentration exceeds the permissible limit. COD ranks the second in the TEIS with a value of 6.01, followed by SS and pH, with the values of 3.14 and 1.52, respectively. TFe and Cr(VI) have the smallest two TEISs of 0.299 and 0.308, respectively. This is because the treatment of Cr(VI) and TFe of the integrated steel plant is satisfied; and thus, the discharge quality index is markedly lower than their permissible limits.

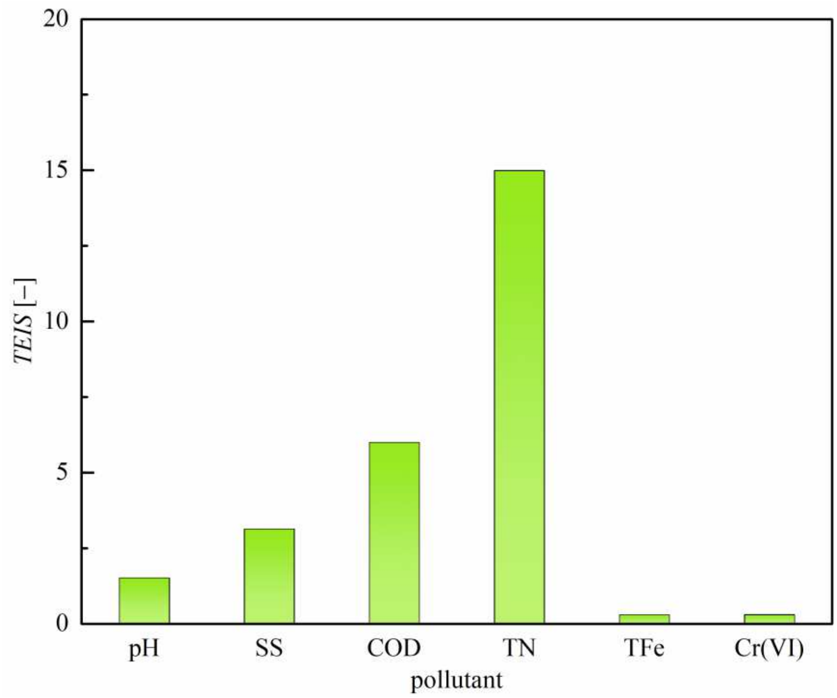

Fig. 4 Contribution of investigated pollutants to TEIS

Fig. 5 compare the results obtained from the TEIS with the GWF respect to all main processes. Steelmaking process is still a leading process in the GWF because its discharge volume remarkably exceeds the benchmark volume, and the TN concentration also significantly exceeds its permissible limit. Ironmaking has the largest wastewater discharge volume in all processes, accounting for 47.14% of the total wastewater discharge of the integrated steel plant; and thus, it has the second highest GWF. The relationship of the GWF is: steelmaking > ironmaking > hot rolling > coking > sintering > cold rolling. It differs from the relationship of the TEIS shown in Fig. 3 because the actual and benchmark wastewater volumes are not considered in the GWF assessment. The wastewater discharge volume is far smaller than the benchmark volume because of the application of water-saving and wastewater-reduction technologies. Thus, the TEIS is more comprehensive for the assessment of multiple pollutants involved wastewater discharge in the iron and steel manufacturing process.

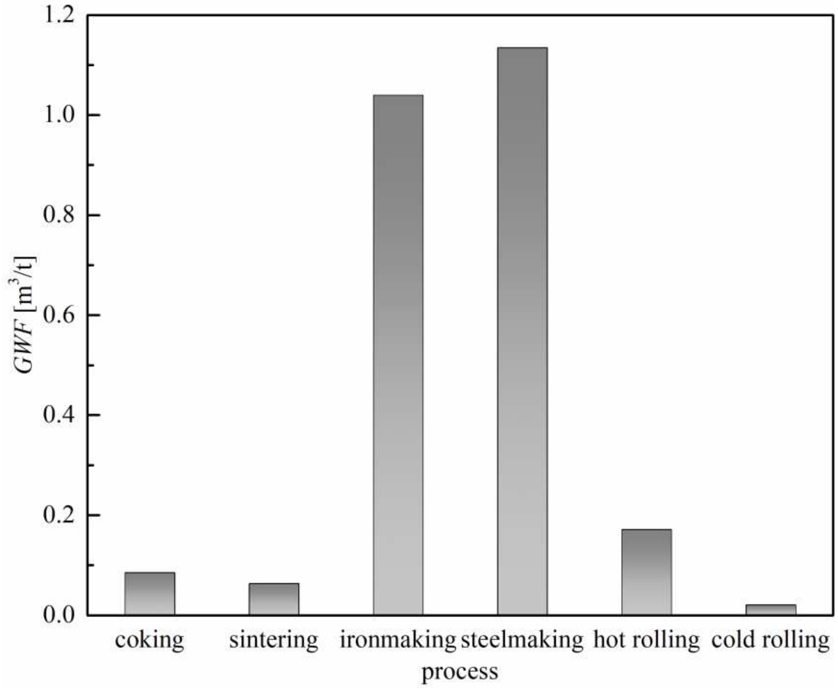

Fig. 5 GWF of main processes

Fig. 6 further examines the detailed decomposition of the TEIS for each process. The partial TEIS proportions are 45.54%, 57.88%, 59.91%, 56.80%, 59.23% and 58.26% for coking, sintering, ironmaking, steelmaking, hot rolling and cold rolling processes, respectively. The TN is the most significant contributor to all processes.

The second dominant pollutant in the TEIS of the coking process is COD, which accounts for 32.05% of the TEIS of the coking process. The proportions of TFe, pH and SS in the coking process are 11.06%, 5.81% and 5.04%, respectively. The second largest contributor to the sintering process is also COD, accounting for 24.79% of the TEIS of the sintering process. The proportions of TFe, SS, pH and Cr(VI) in the sintering process are 5.80%, 5.43%, 3.51% and 2.59%, respectively. For the ironmaking process, the proportions of COD and SS are19.85% and 16.52%, respectively. Cr(VI) accounts for only 0.12% of the TEIS. The second, third and fourth pollutants of steelmaking and hot rolling processes are COD, SS and pH, with the proportions of 22.72%, 12.33%, 6.62% and 26.48%, 10.11%, 2.97%, respectively. The proportions of SS and pH in the cold rolling process are 21.18% and 16.95%, respectively. The proportions of COD, TFe and Cr(VI) in the cold rolling processes are 3.02%, 0.38% and 0.20%, respectively.

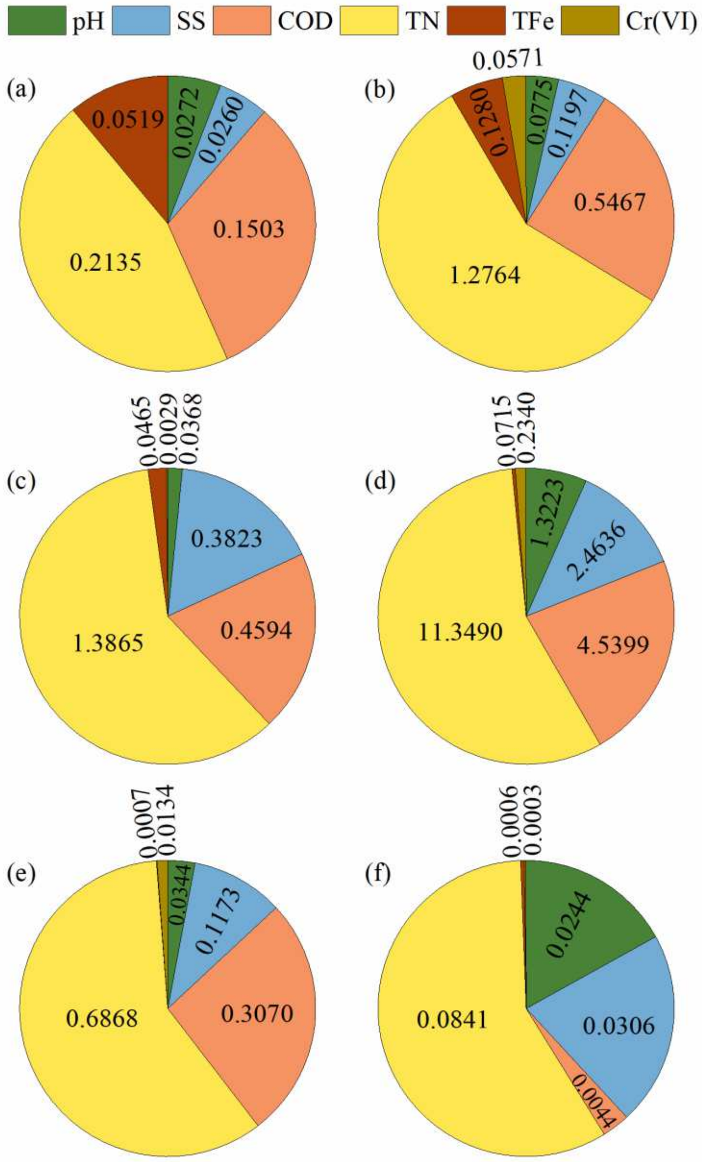

Fig. 6 Contribution of pollutants to process TEISs: (a) coking; (b) sintering; (c) ironmaking; (d) steelmaking; (e) hot rolling; and (f) cold rolling.

4.3 Sensitivity Analysis

The variation in the weight will cause a change in the TEIS. To quantify the effect of pollutant weight on the TEIS, a sensitivity analysis was conducted, as shown in Fig. 7.

Compared with other pollutants, the variation of TN weight changes the TEISs of all processes most. If the weight of the TN increases by 20%, the partial TEIS of coking, sintering, ironmaking, steelmaking, hot rolling and cold rolling processes will increase by 9.11%, 11.58%, 11.98%, 11.36%, 11.85% and 11.65%, respectively. When the increment of TN weight is 100%, the partial TEISs of these processes will have an increase of 45.54%, 57.88%, 59.91%, 56.80%, 59.23% and 58.26%, correspondingly. Other pollutants' weight has weaker impact on the TEIS than the TN. If the weight of pH, SS, COD, TN, TFe and Cr(VI) increases by 20%, the TEIS of the whole plant will have an increase of 1.16%, 2.39%, 4.57%, 11.42%, 0.23% and 0.23%. If the weight increment is 100%, the increase in the TEIS of the whole plant will be 5.80%, 11.95%, 22.87%, 57.08%, 1.14% and 1.17%, respectively. The order of the TEIS still remain as follow: steelmaking > ironmaking > sintering > hot rolling > coking > cold rolling, at all sensitivity analysis cases. This unchanged order proves that the TEIS approach is stable and robust for the environmental impact assessment of wastewater discharge.

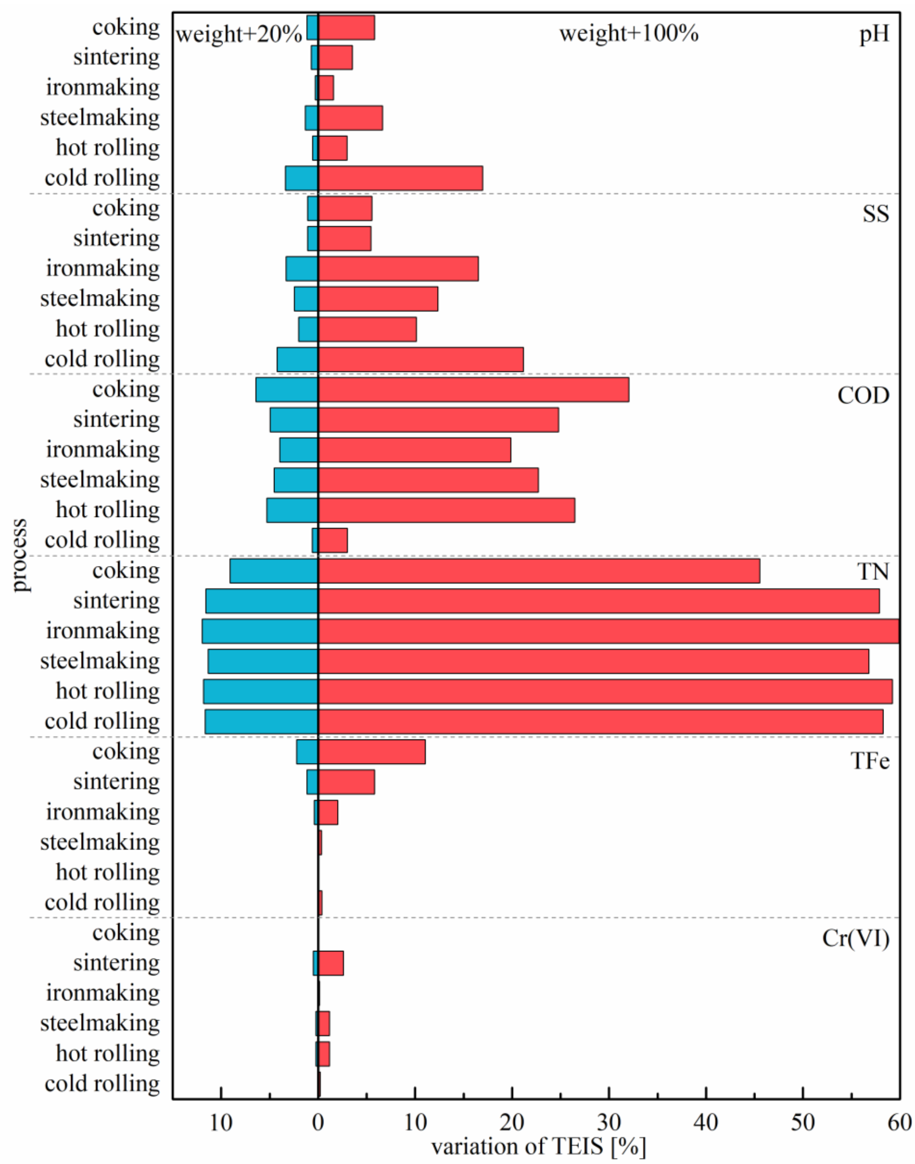

Fig.7 Sensitivity analysis of pollutant weights

5 Conclusions

In this work, a total environmental impact score (TEIS) approach is proposed to assess the environmental impact of wastewater discharge for the iron and steel industry. This approach makes it possible to examine multi-pollutants in the wastewater comprehensively. In addition, the volume of discharged wastewater is considered along with the concentrations of multi-pollutants in discharged wastewater, which increase the effectiveness of the TEIS.

To validate the TEIS approach, a simultaneous monitoring of wastewater discharge from coking, sintering, ironmaking, steelmaking, hot rolling and cold rolling processes was implemented. The ironmaking process accounts for 47.14% of wastewater discharge, followed by steelmaking process with the level of 34.30%. Steelmaking has the highest pH value and SS concentration, which reaches 9.37 and 18.95 mg/L, respectively. Coking process has the highest COD concentration of 84.07 mg/L. The highest TN concentration (43.65 mg/L) occurs at the steelmaking process. The concentrations of TFe and Cr(VI) are both small in all the main processes.

Based on the proposed approach, the whole and partial TEISs of the investigated steel plant were calculated. The whole TEIS is 26.27 with partial TEIS relationship as steelmaking > ironmaking > sintering > hot rolling > coking > cold rolling. The leading TEIS-contributed steelmaking process has the process partial TEIS of 19.98. For pollutants, the order of the TEIS is as follow: TN > COD > SS > pH > Cr(VI)> TFe. The TN contributes most to the TEIS, with a value of 15.00. Also, the TN is the major contributor to all processes. The proportions of the TN for coking, sintering, ironmaking, steelmaking, hot rolling and cold rolling processes are 45.54%, 57.88%, 59.91%, 56.80%, 59.23% and 58.26%, respectively.

Finally, the sensitivity of pollutants' weight was analysed with variations of 20% and 100%. If the weight of pH, SS, COD, TN, TFe and Cr(VI) has an increase of 20%, the whole TEIS will increase by 1.16%, 2.39%, 4.57%, 11.42%, 0.23% and 0.23%. If the weight increment is 100%, the increase in the TEIS will be 5.80%, 11.95%, 22.87%, 57.08%, 1.14% and 1.17%, respectively. Besides, the TEIS sequence remains unchanged when adjusting the pollutant weight.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (51734004), and the China State Scholarship Fund – International Clean Energy Talent Program (CSC-iCET-201802180028).

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