Heliyon 10 (2024) e25308

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Novel pollution prevention process for regulating industrial wastewater for better protection of the environment and public health

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ARTICLE INFO

Keywords:
Environmental protection
Environmental damage
Wastewater effluent
Regulatory effluent limit
Polluttion load
Environmental science
Environmental regulations
Waste disposal
Compliance
Wastewater treatment

ABSTRACT

Regulating the concentrations of pollutants in industrial wastewater through wastewater treatment as practiced worldwide without regulating their pollution loads and wastewater discharge rate alongside, is not enough for protection of the environment and public health. This work investigated why some companies in the Niger Delta do not treat their wastewater; with the aim of providing a solution. The aforesaid prompted this work to invent the "Novel Pollution Prevention Process for Regulating Industrial Wastewater" introducing additional controls namely pollution load and wastewater discharge rate controls for better protection of the environment and public health. Questionnaire survey, wastewater analysis, discharge rate measurement, mathematical modeling and design were the methods adopted. Results revealed that pollution load and wastewater discharge rate should be regulated alongside concentrations of pollutants. Results showed that cost is the major factor responsible for the inability of some companies to treat their wastewater in the Niger Delta. Results revealed that pollution load is a qualitative measure of environmental damage caused by a pollutant and that the larger the pollution load, the larger the environmental damage and vice versa. Results showed that industry can apply the novel pollution prevention process to determine the environmentally-friendly wastewater discharge rate, environmentally-friendly pollution load of pollutants and the corresponding production rate of finished goods. Results revealed that when the concentration of a pollutant in industrial wastewater is not compliant and discharge rate is excessive, pollution load control can protect the environment and public health while regulatory agencies take appropriate measures to make the company comply with the allowable concentration limits of the pollutant. The "novel pollution prevention process for regulating industrial wastewater" has global applicability. It can be applied in every country.

1. Introduction

Wastewater treatment as practiced worldwide is designed to reduce the concentrations of targeted pollutants only, without controlling pollution load and wastewater discharge rate alongside. Non-targeted pollutants in wastewater treatment are released untreated into the environment. Furthermore, the concentrations of targeted pollutants in wastewater treatment are not always reduced to compliant levels. Hence, wastewater treatment does not always ensure compliance to environmental regulations. Ref. [1] reported that the quality of surface water is a function of the efficiency of wastewater treatment and there are difficulties evaluating the

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https://doi.org/10.1016/j.heliyon.2024.e25308
Received 24 August 2023; Received in revised form 18 January 2024; Accepted 24 January 2024
Available online 1 February 2024

effectiveness of wastewater treatment because research has revealed unexpected discharges of untreated or poorly treated wastewater into receiving water bodies. Ref. [2] stated that wastewater treatment plants deplete available freshwater resources by polluting them with their discharges.

Wastewater treatment is based on the allowable concentration limits of pollutants in the effluent regulations of a country but the concentration limits vary from country to country. Environmental regulatory agencies are not effective in every country especially in developing countries. Therefore, untreated wastewater or poorly treated wastewater discharged into surface water in country-A can also pollute the surface water in neighboring country-B and inflict health problems on the people of that country especially coastal communities without potable drinking water. If the source of the pollution is a company that continually discharges untreated wastewater into the flowing surface water, the cumulative effect over time could be enormous. This implies that, lack of wastewater treatment or presence of ineffective regulatory agencies in one country can pose health risks to the people of other countries. Therefore, the fact that wastewater treatment is practiced in a country and its environmental regulatory agencies are effective do not guarantee that the surface water of that country will be safe or suitable for drinking, economic or recreational activities.

Point-source pollution reduction is based on effluent standards that discharges must comply with to be authorized e.g. the US Clean Water Act was designed to control point-source discharge of effluents into surface water [3]. Ref. [4] stated that pollutants are discharged into the environment in various ways threatening the quality of air, land and sea but the presence of pollutants in wastewater is critical because it introduces pollutants into the food chain where biochemical processes rapidly increase their concentrations to toxic levels. Ref. [5] reported that untreated industrial wastewater is being discharged into surface water causing diseases, loss of aquatic life and reduction in life expectancy.

Based on the regulatory options available, regulatory agencies may impose penalties or prosecute a company whose wastewater is not compliant. Furthermore, in countries where regulatory agencies are effective, prosecution takes some time. Meanwhile, there would be ongoing natural transport of pollutants between water, land and air as the polluted surface water flows from place to place. It is worthy to note that apart from the legal punitive measures, there are no technical measures for protecting the environment and public health against non-compliant wastewater pending when a defaulting company is able to reduce effluent concentrations of pollutants to within allowable limits. This reality makes it more compelling that, in addition to controlling concentrations of pollutants via wastewater treatment, a complementary process based on other technical parameters is required to regulate industrial wastewater for better protection of the environment and public health.

The environmental damage (e.g., poor water quality) caused by a pollutant in wastewater or the potential environmental damage due to a pollutant in wastewater is a function of its pollution load. The larger the pollution load of the pollutant, the larger the environmental damage. The pollution load of a pollutant in wastewater discharged into the environment is the product of its concentration and the wastewater discharge rate. The numerical magnitude of the wastewater discharge rate is the major factor that determines the magnitude of the pollution load because it is always much larger than the numerical magnitude of the concentration of a pollutant. Consequently, it will be expedient that as concentrations of pollutants are regulated through wastewater treatment, wastewater discharge rate and pollution load of pollutants should be regulated alongside. Therefore, as pollution prevention is better than pollution control, it will be much better for the environment and humanity, that industry should reduce at source, the pollution load of pollutants and wastewater discharge rate during production of finished goods. This implies that controlling pollution load of pollutants and wastewater discharge rate at source will also help industry to control energy consumption and its associated cost during wastewater treatment. Ref. [6] wrote that within the scope of water-energy nexus, industrial wastewater treatment is energy-intensive because of its high organic content, treatment standards and associated pumping processes. Ref. [7] stated that pollution prevention is any practice that reduces pollution at source or prevents creation of pollution at source and it is better than pollution control.

With the aim of providing a solution, this research work conducted a questionnaire survey on why some companies in the Niger Delta do not treat their wastewater and also examined the regulations in the Nigerian Federal Environmental Protection Agency (FEPA) Act [8] to determine if the regulations are in anyway responsible for the inability of those companies to treat their wastewater. Questionnaire survey, wastewater analysis, discharge rate measurement, mathematical modelling and design were the research methods adopted. The desire to make every country benefit from this work prompted online search of the industrial effluent regulations of other countries (developed and developing countries) to know if the additional regulation parameters determined from the mathematical modelling aspect of this work; were already stipulated but they were not stipulated as was the case with the Nigerian FEPA Act [8], thus indicating a global trend.

The aforesaid prompted this work to invent the "Novel Pollution Prevention Process for Regulating Industrial Wastewater" for better protection of the environment and public health in every country. The novel pollution prevention process for regulating industrial wastewater, reduces at source, the pollution load of pollutants in wastewater and the wastewater discharge rate based on the concept of maximum allowable pollution load per pollutant. Therefore, when industry combines wastewater treatment to reduce concentrations of pollutants and the novel pollution prevention process for regulating industrial wastewater, to reduce at source, the pollution load of pollutants and wastewater discharge rate, there will be better protection for the environment and humanity. The novel pollution prevention process for regulating industrial wastewater, does not require alteration of the standard chemical reactions of industrial production processes because it hinges on the quantity of finished goods produced by industry, thus eliminating any concern about the quality of industrial products.

The novel pollution prevention process for regulating industrial wastewater, applies to every pollutant in wastewater provided that its regulatory effluent limit and the regulatory wastewater discharge rate are stipulated in the industrial effluent regulations of the country of interest. It has been demonstrated with heavy metals in this research work. The novel pollution prevention process for regulating industrial wastewater, has global applicability. It can be applied in every country.

2. Materials & methods

Questionnaire survey, industrial wastewater analysis, wastewater discharge rate measurement, mathematical modeling and design were the research methods adopted in this work. Anonymous questionnaires were prepared, enveloped, addressed and distributed to a total of twenty two companies in the Niger Delta to know why they do not treat their wastewater. After securing appointment for the visit, the questionnaires were hand-delivered during the visit to each of the companies. The thirteen companies that participated in the survey answered the questions during the visits after clarifying the purpose of the survey. Nine companies declined participation in the survey.

Two key rules that were applied in the survey are: (i) A company that has a functional wastewater treatment plant is accepted as a company that treats its wastewater and (ii) A company that has only oil-water separator is not accepted as a company that treats its wastewater. The wastewater discharge rate of each of the thirteen companies that participated in the questionnaire survey were separately measured using a flow meter; for a period of one hour and converted to wastewater discharged in nine working hours per day. Equations were developed to establish the theoretical framework for the novel pollution prevention process for regulating industrial wastewater, based on the concept of maximum allowable pollution load per pollutant. The equations were applied to design pollution load control for wastewater containing a single pollutant and wastewater containing multiple pollutants using the industrial effluent regulations stipulated in the Nigerian Federal Environmental Protection Agency Act [8]. Wastewater samples of the thirteen companies were analyzed for selected heavy metals using Atomic Absorption Spectrophotometer. Start-up cost estimates were also obtained online for wastewater treatment plant and the pollution load control unit of the novel pollution prevention process for regulating industrial wastewater.

2.1. The concept of pollution load and wastewater discharge rate controls

Environmental damage is any harmful or undesirable change or disturbance to the environment [9]. Environmental damage is the deterioration of the environment (e.g. reduction in the quality of air, water and soil) caused by pollution, depletion of resources, destruction of ecosystems, habitat destruction and extinction of wildlife [10]. Environmental damage caused by pollutants discharged via industrial wastewater into the environment is the focus of this work.

The principle of control concept in environmental management states that environmental damage can be avoided by controlling the manner, time and rate at which pollutants are released into the environment [11]. Mathematically:

$$E_d = f(\textit{manner of pollutant release}, t, r) \tag{1}$$

where, E_d = environmental damage due to the pollutant and r = rate of discharge of the pollutant into the environment.

Therefore, considering a particular manner of discharge of pollutants into the environment i.e., keeping manner of discharge of pollutants into the environment constant e.g., discharging pollutants via wastewater into the environment; then the potential environmental damage due to a pollutant becomes a function of time, t and the rate of discharge of the pollutant, r:

$$E_d = f(t, r) \tag{2}$$

Considering a fixed period of time, t (i.e., keeping time constant e.g., daily), the potential environmental damage due to the pollutant becomes a function of the rate (r) of discharge of the pollutant.

$$E_d = f(r) \tag{3}$$

But

$$r = \left(\frac{\textit{amount of pollutant discharged}}{\textit{time}}\right) \tag{4}$$

Therefore,

$$E_d = f\left(\frac{\textit{amount of pollutant discharged}}{\textit{day}}\right) \tag{5}$$

Ref. [7] wrote that pollution load is the amount of a pollutant discharged into a receiving water body per time and it is usually expressed in Ib/day or kg/day. Mathematically:

$$\textit{Pollution load} = \frac{\textit{Amount of pollutant discharged}}{\textit{day}} \tag{6}$$

Substituting in Equation (5):

$$E_d = f(\textit{Pollution load}) \tag{7}$$

Therefore, environmental damage due to a pollutant or caused by a pollutant is a function of its pollution load discharged into the environment as evidenced by Equation (7). In other words, the pollution load of a pollutant can be used as a qualitative measure of the environmental damage caused by the pollutant or as a qualitative measure of the potential environmental damage due to that pollutant.

If a company in a city discharged into a lake a given volume, V (m^3) of wastewater containing a pollutant of concentration c, (kg/m^3) in a given time, t (day), pollution load discharged can be expressed as:

$$P_l = c\frac{V}{t} \tag{8}$$

But

$$q = \frac{V}{t} \tag{9}$$

Therefore,

$$P_l = cq \tag{10}$$

where:
P_l = Pollution load in kg/day;
c = concentration of the pollutant in kg/m^3;
q = wastewater discharge rate in m^3/day;
t = time, day;
V = volume of wastewater discharged in m^3.

Considering Equation (10) in relation to Equation (7), it is evident that the environmental damage due to a pollutant can be controlled by regulating the pollution load, discharge rate and the concentration of the pollutant. Equation (10) in relation to Equation (7) also asserts that the larger the pollution load of a pollutant, the larger (or worse) the environmental damage caused by the pollutant or the larger the potential environmental damage due to the pollutant and vice versa. Ref. [12] reported that lead pollution of soil, water and air is dangerous as low-level lead exposures cause neurological effects and intellectual disability in children; high levels of lead exposure cause anemia, weakness, kidney damage, miscarriage, stillbirth and infertility in adults while very high levels of lead exposure can cause death.

As stipulated in the industrial effluent regulations of a country, the concentration of a pollutant in wastewater should not exceed its regulatory effluent limit (maximum allowable concentration).

Rearranging Equation (10):

$$c = \frac{P_L}{q} \tag{11}$$

It can be deduced from Equation (11) that in order not to exceed the regulatory effluent limit of a pollutant, a regulatory wastewater discharge rate must be stipulated in the industrial effluent regulations of a country. This will automatically fix the maximum allowable pollution load per pollutant in industrial wastewater, in that country, as expressed by Equations (12) and (13).

$$C_{max} = \frac{P_{Lmax}}{q_r} \tag{12}$$

$$P_{lmax} = c_{max} q_r \tag{13}$$

where:
q_r = regulatory wastewater discharge rate
P_{Lmax} = maximum allowable pollution load of a pollutant in wastewater
c = concentration of the pollutant in wastewater in kg/m^3 and
c_{max} = regulatory effluent limit (maximum allowable concentration) of the pollutant in kg/m^3.

Therefore, the maximum allowable pollution load of a pollutant is calculated from its maximum allowable concentration (regulatory effluent limit) and the reference (regulatory) wastewater discharge rate as expressed by Equation (13). In other words, the maximum allowable pollution load of a pollutant is the pollution load corresponding to its regulatory effluent limit and the regulatory wastewater discharge rate.

The concept of maximum allowable pollution load states that the pollution load of a pollutant discharged into the environment should not exceed its maximum allowable pollution load. This is the fulcrum of the novel pollution prevention process for regulating industrial wastewater. It reduces pollution load of pollutants and wastewater discharge rate at source. The aforesaid implies that when the novel pollution prevention process for regulating industrial wastewater, becomes enforceable by legislation in a country, compliance with the industrial effluent regulations of the country would be in three modes: (i) the concentration control mode which is usually accomplished through wastewater treatment, (ii) the pollution load control mode and (iii) wastewater discharge rate control mode to be accomplished through the novel pollution prevention process for regulating industrial wastewater. The three modes of control are further explained as follows:

i) Concentration control mode: The concentration of a pollutant in the treated wastewater of a company must be less than or equal to its regulatory effluent limit (maximum allowable concentration) of the pollutant.

(ii) Pollution load control mode: The pollution load of a pollutant in the treated wastewater of a company should not exceed its maximum allowable pollution load. In other words, it must be less than or equal to the maximum allowable pollution load of the pollutant.

(iii) Wastewater discharge rate mode: The treated wastewater discharge rate of a company should not exceed the regulatory wastewater discharge rate unless the concentration of the pollutant in the treated wastewater is less than its regulatory effluent limit (maximum allowable concentration), provided that the maximum allowable pollution load of the pollutant is not exceeded.

Hence; to be compliant on the basis of maximum allowable pollution load:

$$cq \leq C_{max}q_r \tag{14}$$

This implies that, in order not to exceed the maximum allowable pollution load, if the concentration of a pollutant in a treated wastewater is c, kg/m^3 and its maximum allowable pollution load is P_{lmax}, kg/day; then the nominal wastewater discharge rate q_n can be derived from

$$cq_n = c_{max}q_r \tag{15}$$

Therefore,

$$q_n = \frac{C_{max}q_r}{c} \tag{16}$$

$$\text{Nominal wastewater discharge rate, } q_n = \frac{P_{lmax}}{C} \tag{17}$$

Based on the concept of maximum allowable pollution load, the following can be deduced from Equation (17), assuming a single pollutant in the wastewater:

i) Equation (17) implies that in order not to exceed the maximum allowable pollution load of a pollutant at a particular concentration of the pollutant, the treated wastewater discharge rate of a company must be less than or equal to the nominal wastewater discharge rate. When the nominal wastewater discharge rate at a particular concentration of a pollutant is exceeded the maximum allowable pollution load of the pollutant will be exceeded.

ii) When the concentration of a pollutant in the treated wastewater of a company is equal to its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be equal to the regulatory wastewater discharge rate. Therefore, the wastewater discharge rate of the company should not exceed the regulatory wastewater discharge rate to avoid exceeding the maximum allowable pollution load of the pollutant.

iii) When the concentration of a pollutant in the treated wastewater of a company is higher than its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be less than the regulatory wastewater discharge rate.

iv) When the concentration of a pollutant in the treated wastewater of a company is less than its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be higher than the regulatory wastewater discharge rate.

It is worthy to note that the regulatory wastewater discharge rate is not a maximum allowable discharge rate or regulatory discharge rate limit that must not be exceeded. It is titled regulatory wastewater discharge rate because it is the standard or reference wastewater discharge rate used to define the maximum allowable pollution load of a pollutant as represented by Equation (13). It is the wastewater discharge rate corresponding to the regulatory effluent limit (maximum allowable concentration) of a pollutant and its maximum allowable pollution load.

The regulatory wastewater discharge rate and the maximum allowable pollution load constitute the game-changer in the novel pollution prevention process for regulating industrial wastewater, that will give the environmental regulatory agencies of a country the technical leverage to make companies comply with the regulatory effluent limits of pollutants. The regulatory wastewater discharge rate can only be exceeded with the written official approval of the relevant environmental regulatory agency of a country based on a written application from the company concerned. This written official permit is issued only when the concentration of the pollutant in the treated wastewater of the company has been verified and confirmed to be consistently less than the regulatory effluent limit of the pollutant, provided that the maximum allowable pollution load of the pollutant is not exceeded. Furthermore, the higher wastewater discharge rate granted must be determined based on the novel pollution prevention process design for regulating industrial wastewater.

It can be deduced from the foregoing, that when flow meters are installed upstream, the exit points of wastewater in every company, environmental regulatory agencies can monitor the wastewater discharge rate per company and compute the corresponding pollution load per pollutant discharged into the environment, when the concentrations of the pollutants in the wastewater are given.

The environmentally-friendly pollution load of a pollutant is given by:

$$P_{lef} = cq_{ef} \tag{18}$$

where, P_{lef} = environmentally-friendly pollution load, q_{ef} = environmentally-friendly wastewater discharge rate, c = actual concentration of the pollutant in the treated wastewater. The environmentally-friendly wastewater discharge rate is 10 % less (or more depending on the accuracy of the flow meter for recording the discharge rate of the treated wastewater) than the nominal wastewater discharge rate corresponding to the actual concentration of the pollutant. Therefore,

$$q_{ef} = 0.9q_n \quad (19)$$

Substituting for q_{ef} in Equation (18):

$$P_{lef} = 0.9cq_n \quad (20)$$

Re-arranging Equation (17):

$$P_{lmax} = cq_n \quad (21)$$

Comparing Equation (21) with Equation (20), the environmentally-friendly pollution load of a pollutant is 10 % less than its maximum allowable pollution load. The environmentally-friendly wastewater discharge rate and the environmentally-friendly pollution load are safety windows provided in this novel process for protection of the environment and public health.

Therefore, to combine wastewater treatment with the novel pollution prevention process for regulating industrial wastewater, the minimum requirement for a company *that already has a wastewater treatment plant, is* a flow meter installed upstream the wastewater exit point to record wastewater discharge rate. The cost estimate of a digital flow meter is $12000/unit [13]. Fig. 1 depicts a wastewater treatment plant and the pollution load control unit of the novel pollution prevention process for regulating industrial wastewater.

A company that has no wastewater treatment plant has to acquire a wastewater treatment plant and the pollution load control unit (flow meter) of the novel pollution prevention process for regulating industrial wastewater. Start-up cost estimates are presented in Table 1.

2.2. Novel pollution prevention process design for regulating industrial wastewater

The novel pollution prevention process for regulating industrial wastewater involves matching the production rates of finished goods of a company with the environmentally-friendly pollution loads of pollutants to ensure that the maximum allowable pollution load of each pollutant in the treated wastewater is not exceeded.

The process of determining the environmentally-friendly wastewater discharge rate, the environmentally-friendly pollution load per pollutant and the corresponding production rate of the finished goods of a company; in order to ensure that the maximum allowable pollution load per pollutant in the wastewater is not exceeded; is hereby defined as the *novel pollution prevention process design for regulating industrial wastewater*. The novel pollution prevention process design for regulating industrial wastewater, involves the steps in the following examples.

Note: The design examples 1, 2 and 3 of the novel pollution prevention process for regulating industrial wastewater are as presented in the supplementary material.

Table 2 shows the Nigerian FEPA Act [8] regulatory effluent limits of some heavy metals and the corresponding maximum allowable concentration deduced from them.

2.3. Better protection for the environment and public health

As aforesaid, the pollution load of a pollutant is a measure of the environmental damage caused by the pollutant or a measure of the potential environmental damage due to that pollutant. The larger the pollution load, the larger the environmental damage and vice versa. This implies that, any process that reduces the pollution load of a pollutant, reduces the potential environmental damage due to that pollutant and consequently reduces the associated potential danger or risk to public health, thereby offering protection for the environment and public health. Therefore, protection of the environment and public health in this context, relates to reduction in the pollution load of a pollutant in the environment because the reduction in pollution load translates to reduction in the potential environmental damage and the associated danger or risk to public health due to the pollutant. Ref. [12] reported that lead pollution of soil, water and air is dangerous as exposure to a small amount of lead can cause neurological effects and intellectual disability in children; exposure to a large amount of lead can cause anemia, weakness, kidney damage, miscarriage, stillbirth and infertility in adults while exposure to a very large amount of lead can cause death.

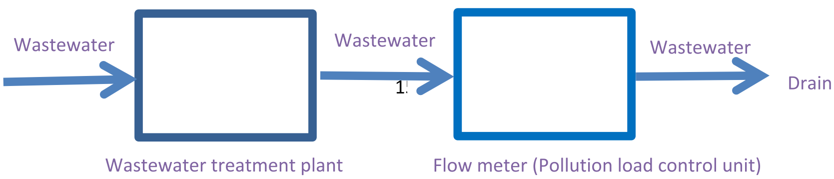

Fig. 1. Wastewater treatment plant and the pollution load control unit of the novel pollution prevention process for regulating industrial wastewater.

Table 1
Start-up cost estimate for wastewater treatment and pollution load control unit of the novel pollution prevention process for regulating industrial wastewater.

Type	Cost	Flow rate	Remarks
Wastewater treatment plant	$0.5 m–$1.5 m	0.57 m^3/min	Equipment, Engineering and installation [14]
Flow meter (Pollution Load Control Unit)	$12,000/unit	0.57 m^3/min	Digital flow meter [13]

Table 2
Regulatory effluent limits of some heavy metals and the maximum allowable concentrations deduced from the regulatory effluent limits.

S/N	Heavy metal	Regulatory effluent limit (mg/l)	Maximum allowable concentration deduced from the regulatory effluent limits (mg/l)
i	Lead	<1 mg/l	0.999 mg/l
ii	Cadmium	<1 mg/l	0.999 mg/l
iii	Chromium	<1 mg/l	0.999 mg/l
iv	Copper	<1 mg/l	0.999 mg/l
v	Iron	20 mg/l	20 mg/l
vi	Manganese	5 mg/l	5 mg/l
vii	Zinc	<1 mg/l	0.999 mg/l

From Equation (10):

$$P_l = cq$$

where:

P_l = Pollution load of the pollutant in kg/day, c = concentration of the pollutant in kg/m^3; q = wastewater discharge rate in m^3/day.

Equation (10) shows that the pollution load of a pollutant discharged into the environment is the product of its concentration and the wastewater discharge rate. This implies that wastewater treatment which reduces concentrations of pollutants, protects the environment and public health because the reduction of the concentration of a pollutant also reduces its pollution load as can be deduced from Equation (10). Similarly, the novel pollution prevention process which reduces wastewater discharge rate also protects the environment and public health because the reduction of wastewater discharge rate also reduces the pollution load of a pollutant as can also be deduced from Equation (10). But the numerical magnitude of the concentration of a pollutant in industrial wastewater is always very small (Figs. 2 and 3) compared to the numerical magnitude of wastewater discharge rate (Fig. 9). Hence, the wastewater discharge rate is the dominant factor that determines the magnitude of the pollution load of a pollutant.

Therefore, reducing the concentration of a pollutant in wastewater (wastewater treatment) makes much smaller contribution to the reduction of its pollution load in the environment than reducing the wastewater discharge rate (novel pollution prevention process). This implies that, the novel pollution prevention process for regulating industrial wastewater, provides greater protection for the environment and public health than wastewater treatment. Furthermore, the novel pollution prevention process applies the concept of maximum allowable pollution load per pollutant to also reduce the pollution loads of pollutants discharged into the environment. Therefore, it is evident from the aforesaid that the application of the novel pollution prevention process alongside wastewater treatment will provide better protection for the environment and public health than wastewater treatment alone.

In a situation, where wastewater treatment has failed, e.g., where the concentration of a pollutant in a treated wastewater is non compliant and wastewater discharge rate is also excessive, the novel pollution prevention process as demonstrated with the design examples, recommends the enforcement of a reduced wastewater discharge rate (environmentally-friendly wastewater discharge rate) and consequently a reduced discharge pollution load (environmentally-friendly pollution load) of the pollutant for protection of the environment and public health. This is absent in the present global practice of wastewater treatment where there is no protection for

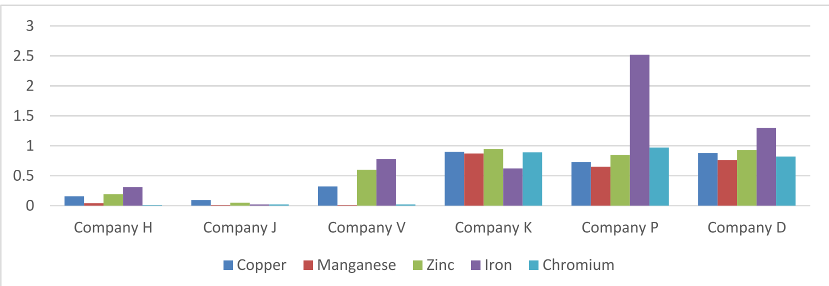

Fig. 2. Heavy metal concentrations (mg/l) in the wastewater samples of some of the companies investigated (Compliant with the regulatory limits in Table 2 – Nigerian FEPA Act [8]).

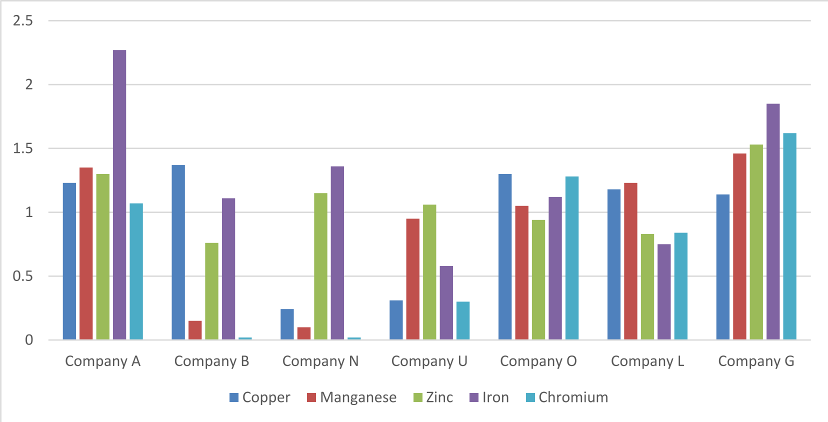

Fig. 3. Heavy metal concentrations (mg/l) in the wastewater samples of some of the companies investigated (Not compliant with the regulatory effluent limits in Table 2 – Nigerian FEPA Act [8]).

the environment and public health in such a situation; until the erring company takes action to reduce the concentration of the pollutant to within allowable limits. Therefore, the application of the novel pollution prevention process alongside wastewater treatment will provide better protection for the environment and public health than wastewater treatment alone. This can also be quantitatively illustrated using data from design example 1 as shown in Table 3.

From Table 3, the initial pollution load of Copper discharged by the company's wastewater treatment plant is 0.0024 kg/day. Application of the novel pollution prevention process for regulating industrial wastewater, reduced the discharged Copper pollution load to the environmentally-friendly pollution load of 0.00053946 kg/day, thereby preventing the potential environmental damage

Table 3
Better protection of the environment and public health, applying the novel pollution prevention process for regulating industrial wastewater alongside wastewater treatment.

S/N	Regulatory Practice	Values of Parameters	Remarks
	Wastewater treatment (regulating concentrations of pollutants)		a) No regulation of pollution load. b) No regulation of industrial wastewater discharge rate.
i	Initial wastewater discharge rate of the company	2 m^3/day	See design example 1
ii	Regulatory effluent limit of the pollutant (Copper = less than 1 mg/l or less than 0.001 kg/m^3)	0.000999 kg/m^3	Ref. [8] or design example 1
iii	Actual concentration of Copper in the wastewater	0.0012 kg/m^3	Environment and public health are not protected. The concentration of Copper is above its regulatory effluent limit.
iv	Pollution load corresponding to the regulatory effluent limit of copper at the initial wastewater discharge rate of the company	0.001998 kg/day	Pollution load corresponding to the regulatory effluent limit of Copper at the initial wastewater discharge rate = initial wastewater discharge rate x regulatory effluent limit of Copper = 2 m^3/day x 0.000999 kg/m^3 = 0.001998 kg/day).
v	Initial pollution load of Copper discharged by the company	0.0024 kg/day	Initial pollution load of Copper = actual concentration of copper x initial wastewater discharge rate of the company = 0.0012 kg/m^3 x 2 m^3/day = 0.0024 kg/day. Environment and public health are not protected. The pollution load discharged by the company is above the pollution load corresponding to the regulatory effluent limit of Copper calculated in (iv) above.
	The novel pollution prevention process for regulating industrial wastewater		a) Regulating pollution load of pollutants a) Regulating industrial wastewater discharge rate
vi	Regulatory wastewater discharge rate	0.6 m^3/day	See design example 1.
vii	Pollution load corresponding to the regulatory effluent limit of copper at the regulatory wastewater discharge rate (Maximum allowable pollution load)	0.0005994 *kg/day*	Pollution load corresponding to the regulatory effluent limit of Copper = regulatory wastewater discharge rate x regulatory effluent limit of Copper = 0.6 m^3/day x 0.000999 kg/m^3 = 0.0005994 kg/day.
viii	Environmentally friendly wastewater discharge rate (design wastewater discharge rate)	0.44955 m^3/day	See design example 1.
ix	Environmentally-friendly Pollution load (design discharge pollution load) of Copper	0.00053946 kg/day	See design example 1. Environment and public health are better protected because the environmentally-friendly pollution load (design discharge pollution load) is much less than the initial pollution load discharged by the company as calculated in (iv) above and also less than the pollution load corresponding to the regulatory effluent limit of Copper obtained in (v) and (vii) above.

and associated danger or risk to public health due to 0.0024 kg/day of Copper. This implies better protection for the environment and public health when the novel pollution prevention process for regulating industrial wastewater will be applied alongside wastewater treatment.

2.4. *Novel pollution prevention process and environmental laws/regulations/policies*

The novel pollution prevention process for regulating industrial wastewater aligns with existing environmental laws, regulations and policies in the aspect of regulatory effluent limits of pollutants. The regulatory effluent limits of pollutants in the industrial effluent regulations or environmental laws of a country are mandatory for its application. However, new environmental laws, regulations and policies (or appropriate amendments) may be required in every country to enable regulatory agencies to enforce wastewater discharge rate and pollution load controls.

3. . Results

The results of the questionnaire survey are presented in the supplementary material. The results of the design examples 1, 2 and 3 of the novel pollution prevention process are presented in Table 4.

Results of the wastewater analysis (Figs. 2 and 3), pollution load (Figs. 4–8) and wastewater discharge rates (Fig. 9) of the companies investigated are as follows: *The concentrations and the pollution loads of the pollutants discharged are hereby presented in mg/l and mg/day respectively and the wastewater discharge rates are presented in litre/day for simplicity and better understanding.*

The numerical data used for this work are the measured wastewater discharge rates of the companies surveyed and the concentrations of the selected heavy metals obtained from the analysis of their wastewater. Assuming normal distribution, the parameters (mean, variance and standard deviation) were used for the statistical analysis of the data. Ref. [15] stated that for normal distributions, standard deviation and variance are preferred measures of variability while the mean is the commonly used measure for central tendency of a data set. Ref. [16] wrote that the mean, variance and standard deviation can be calculated as stated in Equations (22)–(24).

$$\text{Mean}, \overline{Y} = \frac{\sum Y_i}{n} \tag{22}$$

$$\text{Variance}, S_y{}^2 = \frac{\sum (y_i - \overline{y})^2}{n - 1} \tag{23}$$

$$\text{Standard deviation}, S_y = \sqrt{\frac{\sum (y_i - \overline{y})^2}{n - 1}} \tag{24}$$

The results of the statistical analysis are as presented in Tables 5–7.

With the heavy metal concentrations and the wastewater discharge rates measured, sensitivity analysis was used to validate the mathematical models developed in this work and the results are as presented in Tables 8–12.

4. . Discussion

The questionnaire survey revealed that the major factor responsible for non-treatment of wastewater by some companies in the Niger Delta is the cost implication. Therefore, it is hereby recommended that Government should make the ownership of a functional wastewater treatment plant a condition for registration of new manufacturing companies and the renewal of the operational licenses of manufacturing companies. Government should also empower environmental regulatory agencies to provide start-up training courses

Table 4
Results of design examples 1, 2 and 3 of the novel pollution prevention process for regulating industrial wastewater.

Design	Initial production rate of finished goods, kg/day	Pollutant: Heavy metal	Maximum allowable Pollution Load, kg/day	Environmentally-friendly pollution load per pollutant, kg/day	Environmentally- friendly discharge rate, m^3/day	Design production rate of finished goods, kg/day
1	2000	Copper	0.0005994	0.00053946	0.44955	449.55
2	1000	Cadmium	0.0005994	0.00035964	0.2997	208.266
		Chromium	0.0005994	0.00044955		
		Copper	0.0005994	0.00041958		
		Iron	0.012	0.0074925		
		Manganese	0.003	0.0017982		
		Zinc	0.0005994	0.00053946		
3	800	Iron	0.012	0.003853287	0.3853287	181.33
		Copper	0.0005994	0.000308263		
		Cadmium	0.0005994	0.00050093		
		Chromium	0.0005994	0.00046239		
		Zinc	0.0005994	0.00053946		

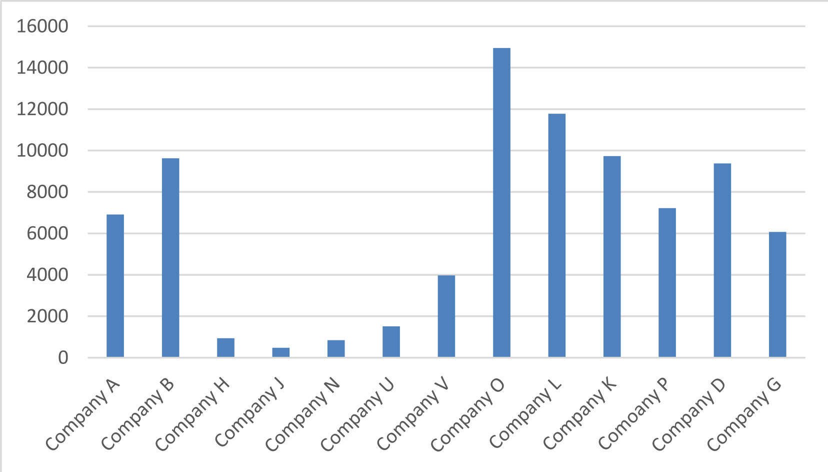

Fig. 4. Copper pollution load (mg/day) discharged by companies investigated.

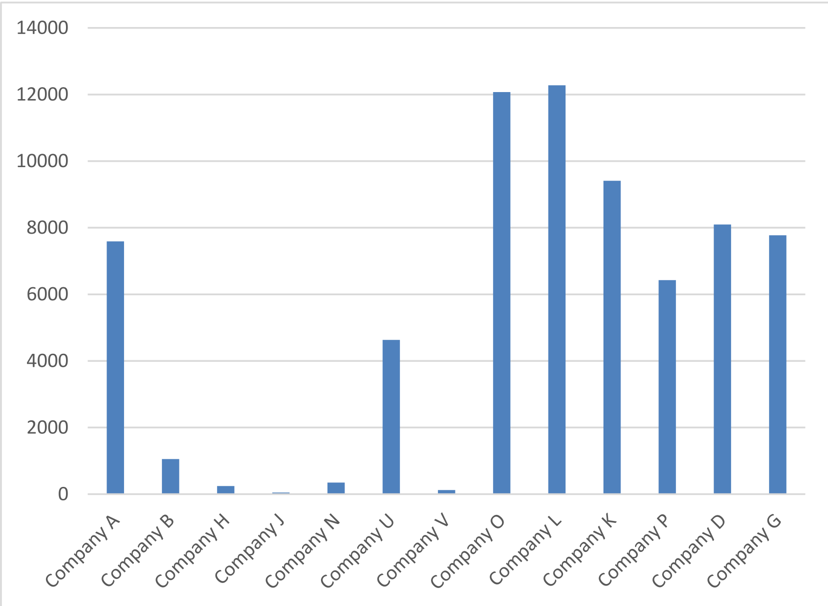

Fig. 5. Manganese pollution load (mg/day) discharged by companies investigated.

and refresher training courses on wastewater treatment for manufacturing companies. Ref. [17] asserted that there are enough laws and regulations for the management of waste in Nigeria but the regulatory agencies are not sufficiently empowered to enforce the regulations. Ref. [18] wrote that water pollution control is expensive and that investment to reduce pollution of rivers, lakes and other surface water in the USA has exceeded $1.9 trillion since 1960.

A strong message conveyed by Fig. 2 is that the wastewater of a company must be analyzed in the Laboratory before classifying it as compliant or non-compliant regarding any pollutant, even when the company has no wastewater treatment plant. This assertion emanated from the results of the wastewater analysis (Fig. 2) where the wastewater effluents of companies J, H, V, P, D and K are compliant with the industrial effluent regulations in the Nigerian FEPA Act [8] regarding the heavy metals investigated. The questionnaire survey reported that the companies do not treat their wastewater. This can be ascribed to any or combination of these factors: the sources and purity of their feed water, feed water treatment, quality control processes, purity of raw materials or types of finished goods produced. It will be the subject of future research work. The wastewater effluents of companies A, B, O, L, N, U and G are not compliant regarding one or more of the heavy metals investigated as evidenced by Fig. 3.

Equations (7) and (10) are very significant. Equation (7) shows that environmental damage caused by a pollutant (or potential environmental damage due to a pollutant) is a function of its pollution load discharged into the environment. Equation (10) in relation to Equation (7) implies that to control environmental damage caused by a pollutant released via wastewater, the pollution load of the

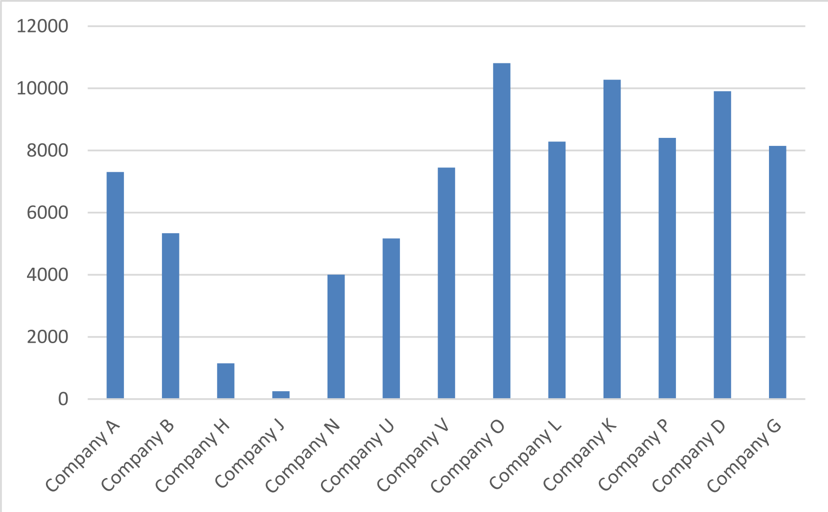

Fig. 6. Zinc pollution load (mg/day) discharged by companies investigated.

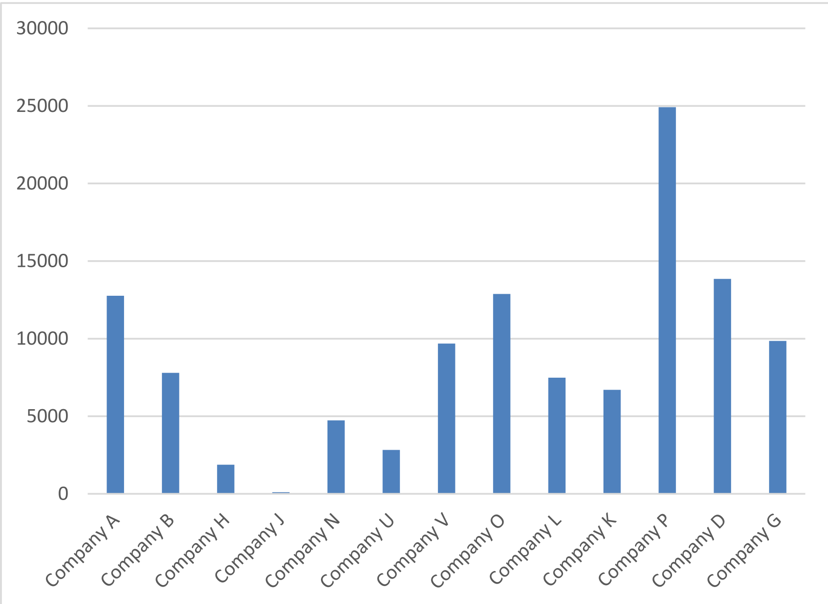

Fig. 7. Iron pollution load (mg/day) discharged by companies investigated.

pollutant, concentration of the pollutant and the wastewater discharge rate must be controlled. Equation (7) conveys the information that the larger the pollution load of a pollutant, the larger the environmental damage caused by the pollutant and vice versa. Equation (7) also implies that the pollution load of a pollutant discharged into the environment can be used as a qualitative measure of the potential environmental damage due to that pollutant or caused by the pollutant. This is supported by the fact that for any particular type of environmental damage e.g., poor soil quality or poor water quality, caused by a pollutant; the larger the amount of the pollutant in the water or soil, the poorer the water quality or soil quality.

Therefore, regulating the pollution load of a pollutant in wastewater discharged into the environment is tantamount to controlling the potential environmental damage due to that pollutant or caused by the pollutant. Considering Equation (10) and the fact that the numerical magnitude of the wastewater discharge rate (Fig. 9) is usually very much larger than the numerical magnitude of the concentration of a pollutant (Figs. 2 and 3); indicate that wastewater discharge rate makes much larger contribution to the magnitude of the pollution load than the concentration of a pollutant. This highlights one of the inadequacies of the current global practice of regulating only the concentrations of pollutants through wastewater treatment without regulating wastewater discharge rates and pollution loads of pollutants alongside. This also justifies the relevance of applying the novel pollution prevention process for

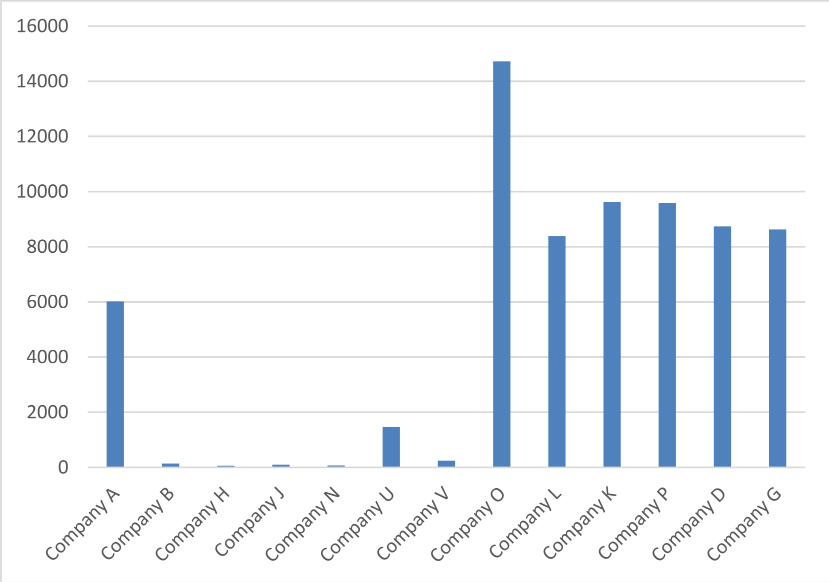

Fig. 8. Chromium pollution load (mg/day) discharged by companies investigated.

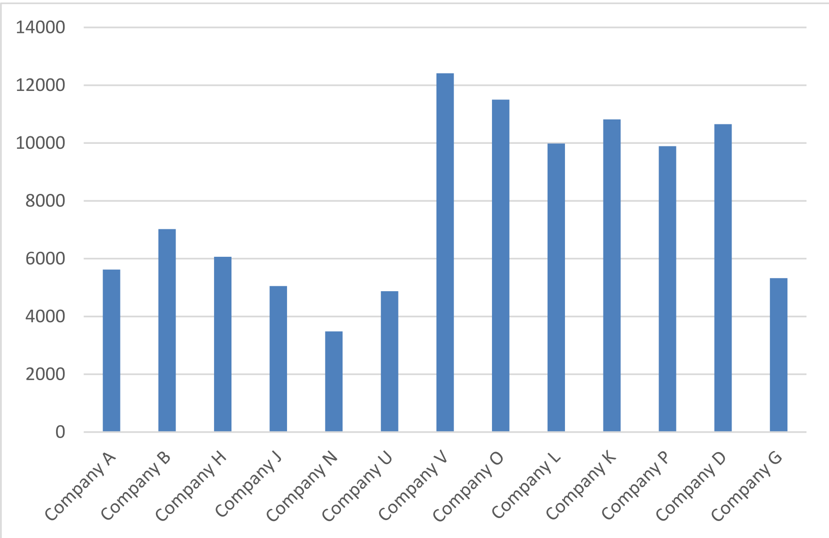

Fig. 9. Wastewater discharge rate (litre/day) of companies investigated.

regulating industrial wastewater alongside wastewater treatment.

Considering a specific heavy metal; the Copper pollution load of the non-compliant wastewater of company O is the largest (Fig. 4) while the wastewater of company J has the least Copper pollution load among the industrial wastewater investigated. Using pollution load as a measure of environmental damage, the wastewater of company O will consequently cause the largest or worst Copper-related environmental damage while the wastewater of company J will cause the least Copper-related environmental damage. Ref. [19] reported that only few plants can survive in Copper-rich soil and no much plant diversity can be found in the vicinity of Copper-disposing factories.

Similarly, the Chromium pollution load (Fig. 8) of the wastewater of Company O is the largest while the Chromium pollution load of the wastewater of company H is the least among the wastewater of the companies investigated. Therefore, using pollution load as a measure of environmental damage, the wastewater of company O will cause the largest or worst Chromium-related environmental damage while the wastewater of company H will cause the least Chromium-related environmental damage. Ref. [20] reported that Chromium in water and soil poses serious environmental threats with excessive exposure leading to dangerous health effects in animals and hindering metabolic activities, growth, yield and grain quality in plants.

Table 5
Statistical analysis: wastewater discharge rate, concentrations of copper and manganese.

Coy	Wastewater discharge rate, m^3/day	Residuals $(y_i - \bar{y})^2$	Copper, kg/m^3	Residuals $(y_i - \bar{y})^2$	Manganese, kg/m^3	Residuals $(y_i - \bar{y})^2$
A	5.622	5.189284	0.00123	0.0000743389	0.00135	0.000000470807
B	7.024	0.767376	0.00137	0.0000719443	0.00015	0.000000264038
D	10.654	7.584516	0.00088	0.0000804968	0.00076	0.00000000924559
G	5.325	6.630625	0.00114	0.0000758989	0.00146	0.000000633861
H	6.063	3.374569	0.000155	0.0000940318	0.00004	0.000000389184
J	5.052	8.111104	0.000095	0.000095199	0.00001	0.000000427515
K	10.816	8.503056	0.0009	0.0000801383	0.00087	0.0000000424995
L	9.983	4.338889	0.00118	0.0000752036	0.00123	0.00000032053
N	3.482	19.518724	0.000242	0.0000923521	0.0001	0.000000317922
O	11.5	12.96	0.0013	0.0000731367	0.00105	0.000000149115
P	9.89	3.9601	0.00073	0.0000832109	0.00065	0.000000000191712
U	4.875	9.150625	0.00031	0.0000910498	0.00095	0.0000000818841
V	12.415	20.385225	0.00032	0.000090859	0.00001	0.000000427515
	$\sum Y_i = 102.701$	$\sum (y_i - \bar{y})^2 = 110.474093$	$\sum Y_i = 0.009852$	$\sum (y_i - \bar{y})^2 = 0.00107786$	$\sum Y_i = 0.00863$	$\sum (y_i - \bar{y})^2 = 0.00000353431$
	$\bar{Y} = 7.90$	$S_y^2 = 9.206174$	$\bar{Y} = 0.000757846$	$S_y^2 = 0.0000898217$	$\bar{Y} = 0.000663846$	$S_y^2 = 0.000000294526$
		$S_y = 3.034168$		$S_y = 0.009477431$		$S_y = 0.0005427025$

Table 6
Statistical analysis: concentrations of zinc and iron.

Coy	Zinc, kg/m^3	Residuals $(y_i - \bar{y})^2$	Iron, kg/m^3	Residuals $(y_i - \bar{y})^2$
A	0.0013	0.000000196317	0.00227	0.00000131367
B	0.00076	0.00000000939407	0.00113	0.0000000000378717
D	0.00093	0.00000000534025	0.0013	0.0000000310302
G	0.00153	0.000000453033	0.00185	0.0000005273
H	0.00019	0.000000444786	0.00031	0.000000662345
J	0.00005	0.000000651125	0.00002	0.00000121848
K	0.00095	0.00000000866333	0.00062	0.000000253861
L	0.00083	0.000000000724848	0.00075	0.000000139761
N	0.00115	0.0000000858941	0.00136	0.0000000557687
O	.0.00094	0.00000000690179	0.00112	0.0000000000147917
P	0.00085	0.0000000000479279	0.00252	0.00000194925
U	0.00106	0.0000000412403	0.00058	0.000000295768
V	0.0006	0.0000000660094	0.00078	0.00000011823
	$\sum Y_i = 0.01114$	$\sum (y_i - \bar{y})^2 = 0.00000196948$	$\sum Y_i = 0.01461$	$\sum (y_i - \bar{y})^2 = 0.00000658551$
	$\bar{Y} = 0.000856923$	$S_y^2 = 0.000000164123$	$\bar{Y} = 0.001123846$	$S_y^2 = 0.000000547126$
		$S_y = 0.00040512097$		$S_y = 0.00073967966$

Table 7
Statistical analysis: concentrations of chromium.

Coy	Chromium, kg/m^3	Residuals $(y_i - \bar{y})^2$
A	0.00107	0.000000215153
B	0.00002	0.000000343577
D	0.00082	0.0000000457301
G	0.00162	0.00000102788
H	0.00001	0.0000003554
J	0.00002	0.000000343577
K	0.00089	0.0000000805686
L	0.00084	0.000000054684
N	0.00002	0.000000343577
O	0.00128	0.000000454068
P	0.00097	0.000000132384
U	0.0003	0.0000000937303
V	0.00002	0.00000034577
	$\sum Y_i = 0.00788$	$\sum (y_i - \bar{y})^2 = 0.00000383391$
	$\bar{Y} = 0.000606154$	$S_y^2 = 0.000000319492$
		$S_y = 0.000565236234$

Table 8
Sensitivity analysis: copper.

Coy	Regulatory wastewater discharge rate = 0.6 m^3/day						
	Wastewater discharge rate q, m^3/day	Copper concentration c, kg/m^3	Initial effluent pollution load, kg/day	Nominal discharge rate, m^3/day	Environmentally-friendly discharge rate m^3/day	Maximum allowable pollution load, kg/m^3	Environmentally-friendly pollution load, kg/day
			$P_l = cq$	$q_n = \frac{P_{imax}}{c}$	$q_{ef} = 0.9\, q_n$	$P_{imax} = C_{max} q_r$	$P_{ief} = cq_{ef}$
A	5.622	0.00123	0.00691506	0.487317073	0.438585366	0.0005994	0.00053946
B	7.024	0.00137	0.00962288	0.437518248	0.393766423	0.0005994	0.00053946
D	10.654	0.00088	0.00937552	0.681136364	0.613022727	0.0005994	0.00053946
G	5.325	0.00114	0.0060705	0.525789474	0.473210526	0.0005994	0.00053946
H	6.063	0.000155	0.00093977	3.867096774	3.480387097	0.0005994	0.00053946
J	5.052	0.000095	0.00047994	6.309473684	5.678526316	0.0005994	0.00053946
K	10.816	0.0009	0.0097344	0.666	0.5994	0.0005994	0.00053946
L	9.983	0.00118	0.01177994	0.507966102	0.457169492	0.0005994	0.00053946
N	3.482	0.000242	0.00084264	2.476859504	2.229173554	0.0005994	0.00053946
O	11.5	0.0013	0.01495	0.461076923	0.414969231	0.0005994	0.00053946
P	9.89	0.00073	0.0072197	0.82109589	0.738986301	0.0005994	0.00053946
U	4.875	0.00031	0.00151125	1.933548387	1.740193548	0.0005994	0.00053946
V	12.415	0.00032	0.0039728	1.873125	1.6858125	0.0005994	0.00053946

Table 9
Sensitivity analysis: manganese.

Coy	Regulatory wastewater discharge rate = 0.6 m^3/day						
	Wastewater discharge rate q, m^3/day	Manganese concentration c, kg/m^3	Initial effluent pollution load kg/day	Nominal discharge rate m^3/day	Environmentally friendly discharge rate, m^3/day	Maximum allowable pollution load, kg/day	Environmentally friendly pollution load, kg/day
			$P_l = cq$	$q_n = \frac{P_{imax}}{c}$	$q_{ef} = 0.9\, q_n$	$P_{imax} = C_{max} q_r$	$P_{ief} = cq_{ef}$
A	5.622	0.00135	0.0075897	0.444	0.3996	0.0005994	0.00053946
B	7.024	0.00015	0.0010536	3.996	3.5964	0.0005994	0.00053946
D	10.654	0.00076	0.00809704	0.788684211	0.709815789	0.0005994	0.00053946
G	5.325	0.00146	0.0077745	0.410547945	0.369493151	0.0005994	0.00053946
H	6.063	0.00004	0.00024252	14.985	13.4865	0.0005994	0.00053946
J	5.052	0.00001	0.00005052	59.94	53.946	0.0005994	0.00053946
K	10.816	0.00087	0.00940992	0.688965517	0.620068966	0.0005994	0.00053946
L	9.983	0.00123	0.01227909	0.487317073	0.438585366	0.0005994	0.00053946
N	3.482	0.0001	0.0003482	5.994	5.3946	0.0005994	0.00053946
O	11.5	0.00105	0.012075	0.570857143	0.513771429	0.0005994	0.00053946
P	9.89	0.00065	0.0064285	0.922153846	0.829938462	0.0005994	0.00053946
U	4.875	0.00095	0.00463125	0.630947368	0.567852632	0.0005994	0.00053946
V	12.415	0.00001	0.00012415	59.94	53.946	0.0005994	0.00053946

The wastewater of company O has the largest manganese pollution load (Fig. 5) while the wastewater of company J has the least manganese pollution load among the wastewater of companies investigated. Using pollution load as a measure of environmental damage, this implies that the wastewater of company O will cause the largest or worst manganese-related environmental damage while the wastewater of company J will cause the least manganese-related environmental damage among the industrial wastewater investigated. Ref. [21] stated that exposure to a large quantity of manganese can lead to irritation of the lungs and pneumonia.

Furthermore, the compliant wastewater of companies P, D, K have larger Copper pollution loads than the wastewater of companies A and G which are not compliant regarding the regulatory effluent limit of Copper (Fig. 3). Therefore, using pollution load as a measure of environmental damage, the wastewater of companies P, D, K will cause larger Copper-related environmental damage than the wastewater of companies A and G. Therefore, it can be deduced from the aforesaid, that the wastewater of a company can be compliant in terms of the regulatory effluent limit of a pollutant but still pose a greater threat to the environment due to the larger pollution load of the pollutant than a wastewater which is non-compliant but has less pollution load of that pollutant. This captures the dominant effect of wastewater discharge rate on the magnitude of the pollution load of a pollutant; which cannot be accounted for in the current global practice of regulating only concentrations of pollutants through wastewater treatment without regulating pollution load and wastewater discharge rate alongside, This further justifies the relevance of applying the novel pollution prevention process for regulating industrial wastewater, alongside wastewater treatment. Figs. 6 and 7 respectively depict the pollution loads of Zinc and Iron in the wastewater of the companies investigated.

The results of design examples 1, 2 and 3 presented in Table 4 are very significant. It is evident from Table 4 that the

Table 10
Sensitivity analysis: zinc.

Coy	Regulatory wastewater discharge rate = 0.6 m^3/day						
	Wastewater discharge rate q, m^3/day	Zinc concentration c, kg/m^3	Initial effluent pollution load kg/day	Nominal discharge rate m^3/day	Environmentally friendly discharge rate, m^3/day	Maximum allowable pollution load, kg/day	Environmentally friendly pollution load, kg/day
			$P_l = cq$	$q_n = \frac{P_{imax}}{c}$	$q_{ef} = 0.9\ q_n$	$P_{imax} = C_{max} q_r$	$P_{ief} = cq_{ef}$
A	5.622	0.0013	0.0073086	0.461076923	0.414969231	0.0005994	0.00053946
B	7.024	0.00076	0.00533824	0.788684211	0.709815789	0.0005994	0.00053946
D	10.654	0.00093	0.00990822	0.644516129	0.580064516	0.0005994	0.00053946
G	5.325	0.00153	0.00814725	0.391764706	0.352588235	0.0005994	0.00053946
H	6.063	0.00019	0.00115197	3.154736842	2.839263158	0.0005994	0.00053946
J	5.052	0.00005	0.0002526	11.988	10.7892	0.0005994	0.00053946
K	10.816	0.00095	0.0102752	0.630947368	0.567852632	0.0005994	0.00053946
L	9.983	0.00083	0.00828589	0.722168675	0.649951807	0.0005994	0.00053946
N	3.482	0.00115	0.0040043	0.521217391	0.469095652	0.0005994	0.00053946
O	11.5	0.00094	0.01081	0.637659574	0.573893617	0.0005994	0.00053946
P	9.89	0.00085	0.0084065	0.705176471	0.634658824	0.0005994	0.00053946
U	4.875	0.00106	0.0051675	0.565471698	0.508924528	0.0005994	0.00053946
V	12.415	0.0006	0.007449	0.999	0.8991	0.0005994	0.00053946

Table 11
Sensitivity analysis: iron.

Coy	Regulatory wastewater discharge rate = 0.6 m^3/day						
	Wastewater discharge rate q, m^3/day	Iron concentration c, kg/m^3	Initial effluent pollution load kg/day	Nominal discharge rate m^3/day	Environmentally-friendly discharge rate, m^3/day	Maximum allowable pollution load, kg/day	Environmentally friendly pollution load, kg/day
			$P_l = cq$	$q_n = \frac{P_{imax}}{c}$	$q_{ef} = 0.9\ q_n$	$P_{imax} = C_{max} q_r$	$P_{ief} = cq_{ef}$
A	5.622	0.00227	0.01276194	5.286343612	4.757709251	0.012	0.0108
B	7.024	0.00113	0.00793712	10.61946903	9.557522124	0.012	0.0108
D	10.654	0.0013	0.0138502	9.230769231	8.307692308	0.012	0.0108
G	5.325	0.00185	0.00985125	6.486486486	5.837837838	0.012	0.0108
H	6.063	0.00031	0.00187953	38.70967742	34.83870968	0.012	0.0108
J	5.052	0.00002	0.00010104	600	540	0.012	0.0108
K	10.816	0.00062	0.00670592	19.35483871	17.41935484	0.012	0.0108
L	9.983	0.00075	0.00748725	16	14.4	0.012	0.0108
N	3.482	0.00136	0.00473552	8.823529412	7.941176471	0.012	0.0108
O	11.5	0.00112	0.01288	10.71428571	9.642857143	0.012	0.0108
P	9.89	0.00252	0.0249228	4.761904762	4.285714286	0.012	0.0108
U	4.875	0.00058	0.0028275	20.68965517	18.62068966	0.012	0.0108
V	12.415	0.00078	0.0096837	15.38461538	13.84615385	0.012	0.0108

environmentally-friendly pollution load of each pollutant discharged is less than its maximum allowable pollution load, thus ensuring compliance and protection for the environment and public health. The environmentally-friendly wastewater discharge rate is also less than the assumed regulatory wastewater discharge rate of 0.6 m^3/day used for the designs. The results depict the fact that, the novel pollution prevention process for regulating industrial wastewater, can be applied to determine the environmentally-friendly wastewater discharge rate, environmentally-friendly pollution load per pollutant and the corresponding amount of finished goods produced per day by industry. This is to ensure better protection for the environment and public health than the present global practice of regulating only concentrations of pollutants through wastewater treatment without regulating pollution load and wastewater discharge rate alongside. This assertion is corroborated by Ref. [7] which stated that heavy metals, chemical compounds and toxic substances are very difficult to remove from wastewater by wastewater-treatment and Ref. [22] which reported that wastewater treatment plants and combined sewer overflows are major routes through which pollutants reach receiving waters bodies.

It is evident from Tables 5–7, that the values of the standard deviation and variance of the concentration data of each of the heavy metals are relatively low. The values of the standard deviation and variance of the wastewater discharge rate data are higher than those of the concentration data of each heavy metal. The higher values of the standard deviation and variance obtained with the discharge rate data set are not surprising because the liquid whose flow rate was measured is not clean water but wastewater containing solids, chemicals, bubbles, particulates etc which would definitely affect the accuracy of the output of any flow meter. The aforesaid suggests that, in applying the novel pollution prevention process for regulating industrial wastewater, companies should use their wastewater for the calibration of their flow meters for better results. Ref. [15] stated that the amount of variability (standard deviation and

Table 12
Sensitivity analysis: chromium.

Coy	Regulatory wastewater discharge rate = 0.6 m^3/day						
	Wastewater discharge rate q, m^3/day	Chromium concentration c, kg/m^3	Initial effluent pollution load kg/day	Nominal discharge rate m^3/day,	Environmentally friendly discharge rate, m^3/day	Maximum allowable pollution load, kg/day	Environmentally friendly pollution load, kg/day
			$P_I = cq$	$q_n = \frac{P_{imax}}{c}$	$q_{ef} = 0.9\ q_n$	$P_{imax} = C_{max} q_r$	$P_{ief} = cq_{ef}$
A	5.622	0.00107	0.00601554	0.560186916	0.504168224	0.0005994	0.00053946
B	7.024	0.00002	0.00014048	29.97	26.973	0.0005994	0.00053946
D	10.654	0.00082	0.00873628	0.73097561	0.657878049	0.0005994	0.00053946
G	5.325	0.00162	0.0086265	0.37	0.333	0.0005994	0.00053946
H	6.063	0.00001	0.00006063	59.94	53.946	0.0005994	0.00053946
J	5.052	0.00002	0.00010104	29.97	26.973	0.0005994	0.00053946
K	10.816	0.00089	0.00962624	0.673483146	0.606134831	0.0005994	0.00053946
L	9.983	0.00084	0.00838572	0.713571429	0.642214286	0.0005994	0.00053946
N	3.482	0.00002	0.00006964	29.97	26.973	0.0005994	0.00053946
O	11.5	0.00128	0.01472	0.46828125	0.421453125	0.0005994	0.00053946
P	9.89	0.00097	0.0095933	0.617938144	0.55614433	0.0005994	0.00053946
U	4.875	0.0003	0.0014625	1.998	1.7982	0.0005994	0.00053946
V	12.415	0.00002	0.0002483	29.97	26.973	0.0005994	0.00053946

variance) determines how well results from a sample can be generalized to a population and that low variability is preferred because it implies that information can be better predicted about the population based on the sample data.

The regulatory wastewater discharge rate and the maximum allowable pollution load constitute the game-changer in the novel pollution prevention process for regulating industrial wastewater, that will give environmental regulatory agencies of a country, the robust technical leverage to make companies comply with the regulatory effluent limits of pollutants for better protection of the environment and public health. The novel pollution prevention process confers responsibility on the Government of a country to stipulate the regulatory wastewater discharge rate in the industrial effluent regulations or relevant environmental laws of the country. Once the regulatory wastewater discharge rate is fixed, it will automatically define the maximum allowable pollution load of each regulated pollutant. The novel pollution prevention process offers a win-win regulatory framework that will encourage industry to treat their wastewater to keep concentrations of pollutants below their regulatory effluent limits. This can be understood from the three regulatory scenarios inherent in the novel pollution prevention process, assuming a wastewater with a single pollutant and discussed as follows:

a) When the concentration of a pollutant in the treated wastewater of a company is equal to its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be equal to the regulatory wastewater discharge rate. Therefore, in that situation, the wastewater discharge rate of the company must not exceed the regulatory wastewater discharge rate in order not to exceed the maximum allowable pollution load of the pollutant. This can also be deduced from Equation (13). Therefore, in such a situation, the novel pollution prevention process for regulating industrial wastewater, confers responsibility on the relevant environmental regulatory agency in a country to issue a written official notice to the company, advising it against allowing its wastewater discharge rate to exceed the regulatory wastewater discharge rate, in order to ensure protection for the environment and public health.
b) When the concentration of a pollutant in the treated wastewater of a company is less than its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be higher than the regulatory wastewater discharge rate. This can be confirmed from the results of the sensitivity analysis (Tables 8–12). Therefore, in such a situation, the novel pollution prevention process for regulating industrial wastewater, confers responsibility on the relevant environmental regulatory agency in a country to grant the company (based on a written application from the company) a written official permit for a wastewater discharge rate higher than the regulatory wastewater discharge rate. The higher wastewater discharge rate granted the company should be determined as per design example 1 or 2 or 3 (as appropriate) after verifying and confirming that the concentration of the pollutant in the company's treated wastewater is consistently below its regulatory effluent limit, provided that the *maximum allowable pollution load of the pollutant* is *not exceeded.* Therefore, the novel pollution prevention process for regulating industrial wastewater, provides a win-win regulatory framework for companies to treat their wastewater to reduce the concentrations of pollutants below regulatory effluent limits to enable them secure approval for wastewater discharge rates higher than the regulatory wastewater rate. The accompanying benefits of increased production rate of finished goods and profitability will be enjoyed by the companies.
c) When the concentration of a pollutant in the treated wastewater of a company is higher than its maximum allowable concentration (regulatory effluent limit), the nominal wastewater discharge rate calculated from Equation (17) will be less than the regulatory wastewater discharge rate. In such a situation, the novel pollution prevention process for regulating industrial wastewater, confers responsibility on the relevant environmental regulatory agency in a country, that while taking appropriate action to make the company reduce the concentration of the pollutant to within allowable limits, the environmental regulatory agency should also

take immediate action to make the company reduce its treated wastewater discharge rate to the appropriate environmentally-friendly wastewater discharge rate alongside the corresponding production rate of finished goods, determined in accordance with design examples 1 or 2 or 3 (as appropriate). This is to ensure protection of the environment and public health. The propensity for increased production rate of finished goods and associated profitability will encourage the company to take effective measures to treat its wastewater to compliant level and get official permit from the relevant environmental regulatory agency for a higher wastewater discharge rate and corresponding production rate of finished goods. This is another sterling advantage of the novel pollution prevention process for regulating industrial wastewater, that will encourage companies to apply more effective treatment technologies to treat their wastewater to ensure that the concentration of every regulated pollutant is less than its regulatory effluent limit. The aforesaid implies that a company can only secure official permit to discharge higher wastewater discharge rate than the regulatory wastewater discharge rate only when the concentration of the pollutant in its treated wastewater is below the regulatory effluent limit and it has been verified and confirmed to be consistently so, by the responsible environmental regulatory agency.

The results of the sensitivity analysis presented in Tables 8–12 are very significant. They depict the robustness of the novel pollution prevention process for regulating industrial wastewater. It is evident from the results of the sensitivity analysis, that the higher the concentration of a pollutant in the wastewater, the lower the corresponding nominal wastewater discharge rate and the environmentally-friendly wastewater discharge rate. Furthermore, it is also evident from the results of the sensitivity analysis that the smaller the concentration of a pollutant in the wastewater of a company, the higher the corresponding nominal wastewater discharge rate and environmentally-friendly wastewater discharge rate, provided that the maximum allowable pollution load of the pollutant is not exceeded. The environmentally-friendly wastewater discharge rate and the environmentally-friendly pollution load are safety windows that help to ensure that the maximum allowable pollution load of a pollutant is not exceeded. The magnitude of the environmentally-friendly wastewater discharge rate is 10 % less than the magnitude of the nominal wastewater discharge rate. Therefore, any wastewater discharge rate lower than the environmentally-friendly wastewater discharge rate is also environmentally-friendly because the resultant pollution load at the particular concentration of the pollutant, will not exceed its maximum allowable pollution load. It is obvious from Tables 8–12, that each value of environmentally-friendly wastewater discharge rate is 10 % less than the corresponding value of nominal wastewater discharge rate while each value of the environmentally-friendly pollution load is also 10 % less than its corresponding maximum allowable pollution load, thus validating the respective mathematical models and ensuring protection for the environment and public health.

It is worthy to recognize that when enforced by legislation in a country; the novel pollution prevention process for regulating industrial wastewater, will prompt companies to match production rate of finished goods with the environmentally-friendly pollution load per pollutant to ensure that the stipulated maximum allowable pollution load per pollutant is not exceeded, as depicted by the design examples. Matching industrial production with environmentally-friendly pollution load per pollutant as showcased by the design examples is tantamount to pollution reduction at source, also known as pollution prevention. Pollution prevention is very important. Ref. [19] stated that pollution prevention reduces financial costs, environmental costs and protects the environment by conserving and protecting natural resources alongside increasing economic growth through more efficient production in industry with less need for domestic, industrial and communal waste management. Ref. [23] stated that the high operational cost of wastewater treatment plants is a function of high energy consumption which largely depends on volume of treated wastewater or wastewater flow rate and organic load.

Pollution of surface water by industrial wastewater also affects land and air because of natural transport of pollutants between

Table 13
Novel pollution prevention process for regulating industrial wastewater versus industrial wastewater treatment.

S/N	Industrial wastewater treatment	Novel pollution prevention process for regulating industrial wastewater
1	Wastewater treatment is designed to reduce only concentrations (concentration control) of pollutants in wastewater prior to discharge into the environment.	The novel pollution prevention process for regulating industrial wastewater, is designed to be applied alongside industrial wastewater treatment to reduce at source, the pollution load of each pollutant in industrial wastewater and the wastewater discharge rate; for better protection of the environment and public health.
2	Concentration control by wastewater treatment exerts little control over environmental damage because the concentration values of pollutants are usually very small compared to the discharge rates of industrial wastewater.	The novel pollution prevention process for regulating industrial wastewater, exerts larger control over environmental damage because it reduces at source, pollution loads of pollutants and wastewater discharge rate. The numerical magnitude of wastewater discharge rate is usually much larger than that of the concentration of a pollutant.
3	Wastewater treatment is designed to reduce the concentrations of targeted pollutants only.	It reduces the pollution load of every pollutant; including pollutants targeted by wastewater treatment and pollutants not targeted by wastewater treatment.
4	Wastewater treatment does not always ensure compliance with the regulatory effluent limits of pollutants.	It ensures that the pollution load of each pollutant is always less than or equal to its maximum allowable pollution load (Table 4).
5	Not part of wastewater treatment	It can be applied to determine the environmentally-friendly wastewater discharge rates; environmentally-friendly pollution load per pollutant and the corresponding industrial production rate of finished goods as evidenced by design examples 1, 2 and 3.

water, land and air. Therefore, considering the aforesaid sterling benefits of the novel pollution prevention process for regulating industrial wastewater, it is evident that its global application alongside wastewater treatment, will provide better protection for the environment and public health in every country. Ref. [23] reported that large organic pollution load in industrial wastewater constitutes serious hazards to living organisms and ecosystems in receiving water bodies. Ref. [24] wrote that water pollution is dangerous to aquatic life and humanity. Ref. [25] stated that water pollution is the leading cause of death and diseases worldwide, accounting for the death of over 1.8 m people in year 2015.

Table 13 highlights how the novel pollution prevention process for regulating industrial wastewater, complements industrial wastewater treatment. The complementary functions also depict its novelty.

It is worthy to re-emphasize that the novel pollution prevention process for regulating industrial wastewater, can be applied to any pollutant in industrial wastewater provided that its regulatory effluent limit is stipulated in the industrial effluent regulations or environmental laws of the country of interest. Heavy metal removal was used for demonstration purposes only, in the design examples. The novel pollution prevention process for regulating industrial wastewater recommends that Government of every country (where applicable) should establish well-equipped Laboratories for environmental regulatory agencies to promote regular, proactive periodic sampling, testing of industrial wastewater and swift enforcement of regulatory controls.

The novel pollution prevention process is especially applicable to manufacturing companies and the wastewater treatment plants in the following sectors: chemical and allied industry, mineral-based industry (e.g. cement companies, Iron and steel manufacturing companies), textile industry and the beverages industry (e.g. Breweries and soft drink manufacturing companies). Adaptability to different industrial sectors or application in any country worldwide is easy. It only requires replacing the regulatory effluent limits in the design examples with the regulatory effluent limits of pollutants in the country of interest and following the procedure in the design examples. The regulatory effluent limit of a pollutant is a key parameter for the application of this novel process. It cannot be applied to unregulated pollutants. Limitations encountered during this research work were funding and equipment.

5. . Conclusion

The cost of acquiring wastewater treatment infrastructure is responsible for the inability of some companies to treat their wastewater in the Niger Delta.

Pollution loads of pollutants and the discharge rate of industrial wastewater should be regulated (novel pollution prevention process for regulating industrial wastewater) alongside regulating concentrations of pollutants (wastewater treatment).

The novel pollution prevention process for regulating industrial wastewater, provides the robust framework for Government to regulate pollution loads of pollutants and the discharge rate of industrial wastewater alongside industrial wastewater treatment for better protection of the environment and public health. It has global applicability. It can be applied in every country.

The novel pollution prevention process provides the excellent technical leverage for environmental regulatory agencies to make companies treat their wastewater to reduce concentrations of pollutants to within regulatory effluent limits.

The global application of the novel pollution prevention process for regulating industrial wastewater alongside wastewater treatment will promote environmental protection, public health, life expectancy, recreational activities, aquatic life and economic life for humanity.

Data availability statement

The data are in the article and the supplementary material referenced in the article.

CRediT authorship contribution statement

William Ejuvweyerome Odiete: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

No funding was received from any source for this research work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25308.

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