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Particle Swarm Intelligence (PSI): A Particle Decantation Algorithm Application in Borehole Water Treatment

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Abstract:

The cost implication of high iron (III) content in borehole water for domestic use is a common problem globally. Iron (III) is the major cause of the reddish colour in water which gives bad sight as it stains bright surfaces, clothes etc., in homes and other places. For this reason, several methods to reduce it have been proposed. This work employed the principles of particle swarm intelligence (PSI), specifically gravitational search algorithm (GSA) with the idea of decantation of particles.

This research work considered five main parameters in the water sample to ascertain the efficacy of the application of the algorithm which are; Colour, pH value, Electrical conductivity, iron (II) and iron (III). The final outcomes showed that the specific objective to reduce iron (III) (the reddish colour) was achieved. The iron (III) content in the water was reduced from 0.66 to less than 0.01 (mg/l), algorithm eliminated the iron (III) almost completely. Also, the colour value was reduced significantly from; 289.50 to 4.0 (Pt/Co).

Keywords — **Gravitational Search Algorithm (GSA), Decantation, Iron (II), Iron (III), pH Value, Colour Value, Electrical Conductivity.**

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I. INTRODUCTION

Particle swarm intelligence (PSI) is a search algorithm based on the natural behaviour of organisms called particles. There are several organisms existing naturally as swarms, for example; fish schooling, ants, bees, dust particles, firefly etc., are all described as swarm. The challenges to solve existing problems is daunting, therefore, researchers look into different possibilities, especially optimisation problems that have relatively high dimension search solution space for better accuracy. In multi-dimensional search space problems, the classical optimisation methodologies are insufficiently efficient with the exponentially expanding solution space [1]. In recent decades, the affinity to explore natural behaviour of organisms to develop efficient algorithms have grown immensely large [2]. To be candid, there is no single almighty algorithm that solves all optimisation problems, this calls for the need to employ algorithms suitable to solve specific problems. This particular fact has given rise to the development of numerous algorithms, new heuristic optimisation methods in research have become a necessity [3]. Our work is relying on Gravitational Search Algorithm (GSA) which is a particle behavioural algorithm as well, it is the use of the law of gravity [4]. It is an algorithm exploiting Newtonian gravity in which; "Every particle in the universe attracts every other particle with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them".

The principle of the GSA is based on the force of gravity on particles which are the potential solutions in the solution space. Search agents are considered to be objects with various masses, these masses are determined by employing a fitness function where very object's position is corresponding to a possible solution. As the force of gravity acts on each particle, the particles attract one another and it results to a global motion of the particles and they are attracted to the heavier particles [5].

The main goal of this work is the application of this gravitational search algorithm as an aspect of particle swarm intelligence to treat high iron (III) content borehole water, the focus will be to reduce the reddish/brownish colour. Although, iron in water does not necessarily indicate that it is hazardous to health but it poses difficulties such as; staining, smell and poor taste while in use [6]. The brownish colour is as a result of the oxidation of Fe^{2+} [iron II oxide] to iron III oxide (aeration will also assist O_2 transfer for the oxidation of Fe^{2+} to Fe^{3+} [iron (III)]) [7].

The iron Fe^{3+} [iron (III)] (iron hydroxide) has brought so much economic difficulties because after boreholes are sunk in some areas the water becomes unfit for use domestically due to the reddish colour. As a result of these problems there is the need to develop efficient methods to reduce the Fe^{3+} [iron (III)] (iron hydroxide) to usable level. The World Health Organisation (WHO) recommends that water which has iron level of over 0.3 milligrams per litre (mg/L) is advised as being too high to be consumed domestically. It is however, observed that most often, the level of iron is normally lower than 10mg per litres found in water.

II. RELATED WORKS

The necessity to remove Fe^{3+} [iron (III)] (Ferrous) from borehole water which is usually orange brown or reddish colour is very important. It causes eye-sour by staining the tiles and blocking of water pipes, as a result of some of these challenges many researchers have come up with different methods to reduce ferrous in water. In the work "Air Oxidation of Ferrous Iron in Water", air is used for oxidation to give ferrous Fe^{3+} [iron (III)] in water, there work was fixed on oxidation of iron (II) to Fe^{3+} [iron (III)]. The research considered different pH values and the oxidation was done at stationary atmosphere, then catalytic effect of ferric hydroxide was investigated. It focused on the yielding of ferrous iron in different conditions [8]. The research to remove iron from water was surveyed in well water in Gonbad Kavoos City, it was basically aeration. In the work, concentration of iron in samples was measured by spectrophotometer and the results indicate that iron concentration was significantly decreased when comparison was made before and after aeration of the water [10]. Acceleration of oxidation process of iron in supercritical water containing dissolved oxygen by the formation of H_2O_2, this research is about the oxidation of iron in supercritical water which contains oxygen that is dissolved and was studied by ab initio molecular dynamics [11]. The outcome shows that dissolved oxygen in the supercritical water rapidly oxidised the iron. Also, "Adsorption Process of Fe^{3+} [iron (III)] from Borehole Water on Activated Carbon from Nigerian Bamboo" was done [13]. Their research only concentrated on directly passing the water sample through the bamboo activated carbon without in-depth consideration of the presence of the Fe^{2+} iron (II) that is soluble in the borehole water. This soluble and invisible Fe^{2+} iron (II) can go through the bamboo activated carbon then get oxidised to Fe^{3+} [iron (III)] and still retain the orange-brown colouration in the water.

III. BASIC GRAVITATIONAL SEARCH ALGORITHM (GSA)

In the principle of gravitational force; the force of gravity acts in between particles in a solution space. In addition, the Newton's force of gravity is known as "action in a distance, in this principle, the force of gravity influences particles. Here, every particle attracts every other particle due to the effect of the force of gravity. The force of gravity between any two particles is directly proportional to the product of their masses and inversely proportional to the square of the distance between them [9].

Here, the Gravitational Search Algorithm (GSA) which is a swarm intelligence (SI) algorithm and it is dependent on the law of gravity.

A. Velocity of Particles

The Particles of Fe^{3+} [iron (III)] in the water are assumed to be in random motion except some form of force is induced to alter the particles' motion. While in random motion each particle has a velocity, the particles with equal masses are also considered to be in motion with equal velocities. In this course of motion there exists collision of particles where the inelastic collision of particles with equal sizes will result to particles cohesion. Hence, the perturbation of the particles in the water will ensure coagulation which will form flocs of Fe^{3+} iron (III) that become heavier.

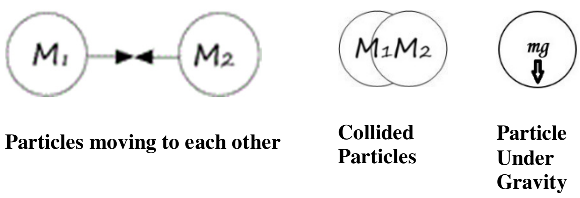

Figure 1. Shows Particles Motion

B. Inelastic Collision of Particles in the Water

An inelastic collision of particles is described as a collision of particles in which the total kinetic energy before the collision is not equal to the total kinetic energy after the collision. In inelastic collision, momentum is conserved but kinetic energy is not. When the particle of equal mass and momentum collide, the particles stick to themselves, sometimes even get deformed. Some of the basic actions are:

(i) The conserved momentum is utilised to estimate the final velocity

(ii) The particles get in motion as one larger particle after collision.

C. Perfectly Inelastic Collision of Particles and Conservation of Momentum

Momentum is a product of mass (m) and the velocity (v), that is:

$p = mv$, and further represented as;

$$m_1 v_1 + m_2 v_2 = m_1 v_1^I + m_2 v_2^I \quad .. (1).$$

In any perfectly inelastic particles-collision, the particles get stuck together to move as a single larger particle. Hence, the final velocities of the particles are equal that is;

$$v_1^I = v_2^I = v^I \quad .... (2).$$

If two particles that have equal masses move from opposite directions to each other with the same velocity then collide will stick together. In this action, the initially combined internal kinetic energy is given as;

$$\frac{1}{2} m v^2 + \frac{1}{2} m v^2 = m v^2 \quad .... (3).$$

And the velocity of the combined particles will be;

$$v^I = \frac{m_1}{m_1 + m_2} v_1 \quad .... (4).$$

Any collision that particles stick to become one bigger particle is known as; perfectly inelastic collision.

D. Law of Gravity and Velocity of Particles

In the solution space, the particles are also called objects whose activeness is measured based on their individual masses where the objects attract one another through the force of gravity. The general movement of the objects is caused by the gravitational force which in turn results to the objects moving globally. As the objects engage in this movement, the objects with smaller masses are attracted toward the objects with heavier masses [12]. With this interaction of objects, the objects with the heaviest masses that move more slowly are considered as the best solutions in the solution space. The particles (objects) are usually under the influence of;

(i) Velocity or Motion: The velocity experienced by a given mass (object) is equal to the sum of the fractions of the previous velocity and the variation in velocity. It is worthy to note that; the velocity of a given mass (object) is equal to the force acted upon the system divided by mass.

(ii) Gravitational Force: Law of gravity; each particle attracts every other particle and the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the distance between them, R.

IV. STATEMENT OF THE PROBLEM

Most often, iron gives water some kind of metallic taste which also will affect food and beverage tastes adversely. The effects of iron in water are not palatable especially in domestic use, iron makes the water reddish, brown or yellow in the surfaces and interiors of water reservoirs, dishes, enamel wares, clothing/fabrics, tiles, etc. Also, iron in domestic water affects the quality, taste and smell of foods. For example; when water with high iron content is used to boil white cowpeas or potato, the iron turns them to blackish colour and with coffee a floating rainbow sheen is usually observed.

Other forms of negative impact of iron include; clogging of garden sprinklers, boreholes, dishwashing machines, etc. To make convenient use of water, high iron content in water must be properly analysis and treatment must be carried out to reduce the iron level to about 0.3 (mg/L). Any quantity of iron above 0.3 (mg/L) value is rejectable even though the value is usually lower than 10 mg/L in water.

The point of emphasis is on; Ferrous iron (“Fe^{2+}: clear-water iron”) and Ferric iron (“Fe^{3+}: red-water iron”), then employ our algorithm to treat the water as a chemical free treatment process.

$$Fe^{(2+)} + 2H_2O + O_2 \rightarrow 4Fe^{(3+)} + 4OH^- \quad \text{....... (5).}$$

Iron (II) in the water is oxidised by oxygen soluble in the water to yield iron (III) (ferric oxide) which is insoluble in the water.

Below is the chemical equation:

$$4FeO\,H_2O(s) + O_2(aq) + 2H_2O(l) \rightarrow 2Fe_2O_3 3H_2O(s) \quad (6).$$

V. METHODOLOGY

As it is known, the preponderance of brownish borehole water poses several great challenges especially for home use. For this reason, several researches have been conducted to proffer solutions to this challenge. One of the methods is oxidation, however, it has its own bottle necks such as the fact that the reddish Fe^{3+} stains virtually every brightly coloured surface. Therefore, the aim of this project is to minimise the Fe^{3+} [iron (III)] content in the borehole water which will eliminate stains in homes and other public spaces.

This work focuses on a non-chemical treatment which makes the process of treatment cost effective, easy and faster. The process basically involves removal of the Fe^{3+} since organic iron including tannins inhibit the oxidation of the divalent iron, the process involves injection of air into the water under atmospheric pressure.

The reddish or orange colour in the borehole water is as a result of the presence of extremely or ultra fine solid particles (colloidal iron) usually with a size (diameter) between 0.1 to 0.001 microns. These ultra fine particulates are so light that they do not settle down, hence, making conventional filtration methods almost incapable of yielding appreciable result.

E. The Experimental Process

(i) Part of the process is by injecting tiny bubbles (about 3.8 microns) of air (more oxygen) into the water to be treated for 20 minutes, this process is repeated in minimum of 4 times on intervals of 60 minutes.

(ii) Perturbation of the oxygenated water is carried out for a minimum of 10 minutes which is repeated four (4) times in an interval of five (5) minutes. This is achieved by pumping large bubbles of air into the water to enhance coagulation/ cohesion of the iron (III) oxide solid particles (floc) formed in the water. The primary reason behind this process is the principle of gravitational force effect on particles and swarm intelligence (particles behaviour).

(iii) Decantation is done by allowing the coagulated Fe^{3+} [iron (III)] floc to settle on the bottom as more dense constituents. The settled/ decantation of the floc of Fe^{3+} [iron (III)] is enhanced due to the effect of the gravitational force acting on each particle.

(iv) Finally, after the decantation, the water in the upper layer is passed through a two-strata layer of fine sand and charcoal. The water comes on top of the decanted iron (III), it is then passed into a separation tank which is filtered as the water peculates through. The particles in the tank are allow to pass through the layers for a minimum of about 12 hours. This permits the absorption of the finer Fe^{3+} [iron (III)] particles and other materials by the absorption property of the charcoal.

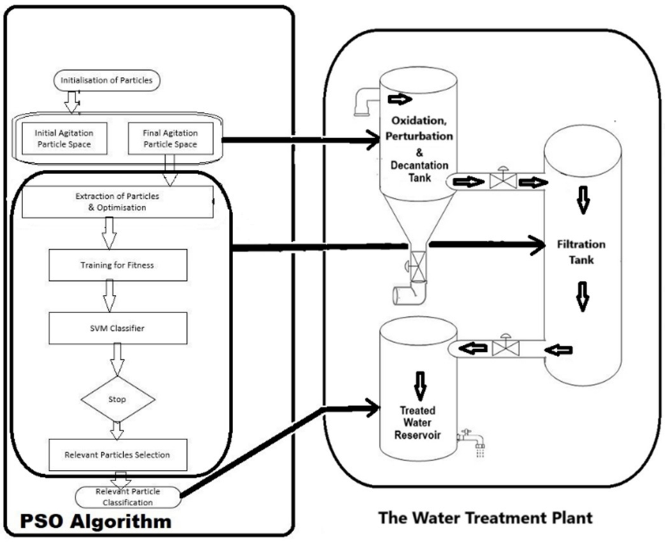

Figure 2. Shows the Algorithm of the Application and Water Treatment Plant

F. Parameters Under Consideration in the Experiment

The project considers five (5) main parameters, these parameters are compared before and after the experiment and the physicochemical analysis of the borehole water samples. The untreated (initial) borehole water sample was analysed in **Laser Engineering & Resources**, a laboratory certified by the Nigeria National Accreditation System **(NiNAS).** The final (treated) water sample was also analysed by **Laser Engineering & Resources** and comparative graphs of purity based on the five (5) parameters that are graphically displayed. These analysed before and after treatment parameters include:

(a). Fe^{2+} (iron II), (b). Fe^{3+} (iron III), (c). Electrical Conductivity, (d). pH, (e). Colour.

G. The Results of the Experiment

The results of the experiment are in two categories, the first result (TABLE 1) is the analysis of the borehole water ***before*** *the experimental treatment* of the water. And the second result (TABLE 2) is the analysis of the borehole water ***after*** *the experimental treatment* of the borehole water.

Below are the two results:

TABLE 1
Before treatment: Physicochemical results (**REPORT NO: ENV-082/09/2024**)

S/N	PARAMETER	UNIT	LAB ID	ENV-082-01/09/2024
			CLIENT'S ID	BOREHOLE WATER
			SOURCE	N/A
			DATE RECEIVED	01/09/2024
			ANALYTICAL METHOD	VALUES
	PHYSICAL PARAMETERS			
1	COLOUR	Pt/Co	ASTM D1209	289.5
2	pH	mg/l	APHA 4500-H+B	5.92
3	ELECTRICAL CONDUCTIVITY	µs/cm	ELECTROMETER	277.1
	METALS			
4	IRON II (Fe^{2+})	mg/l	APHA 3120/MP-AES	0.09
5	IRON III (Fe^{3+})	mg/l	APHA 3120/MP-AES	0.66

TABLE 2
After treatment: Physicochemical results (**REPORT NO: ENV-109/09/2024**)

S/N	PARAMETER	UNIT	LAB ID	ENV-109-09/09/2024
			CLIENT'S ID	BOREHOLE WATER
			SOURCE	N/A
			DATE RECEIVED	09/09/2024
			ANALYTICAL METHOD	VALUES
	PHYSICAL PARAMETERS			
1	COLOUR	Pt/Co	ASTM D1209	4.0
2	pH	mg/l	APHA 4500-H+B	7.62
3	ELECTRICAL CONDUCTIVITY	µs/cm	ELECTROMETER	903.2
	METALS			
4	IRON II (Fe^{2+})	mg/l	APHA 3120/MP-AES	0.035
5	IRON III (Fe^{3+})	mg/l	APHA 3120/MP-AES	<0.01

H. Presentation of the Experimental Results

The experimental results have been analysed and presented in bar charts which are the results of the analysed water samples. The results are as shown below:

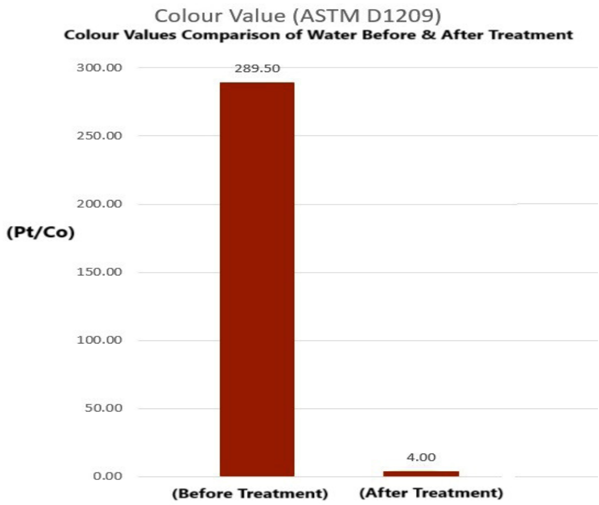

Figure 4. Shows the Variation of Colour Value.

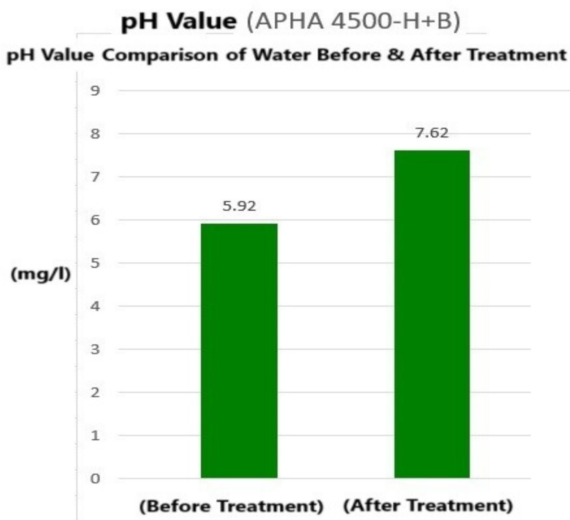

Figure 5. Shows the Variation of pH Value.

The primary objective of this research was to reduce the reddish colour of water for convenient domestic use. It is observed that; after the treatment method was employed, the result reveals a profound reduction of iron III which is the major component that causes the reddish colour in the water on the colour scale, reduced from: 289.50 to 4.0 (Pt/Co). With this final colour value which is invisible to the eyes is an indication of the effectiveness of the algorithm applied in the treatment.

Also, the pH value (APHA-4500-H+B) of the water after the final treatment applying the algorithm, increased from 5.92 to 7.62 (mg/l). This gave a very good value of pH in the drinking water as the WHO recommends that; the pH value in drinking water should be between 6.5 and 8.5 (mg/l).

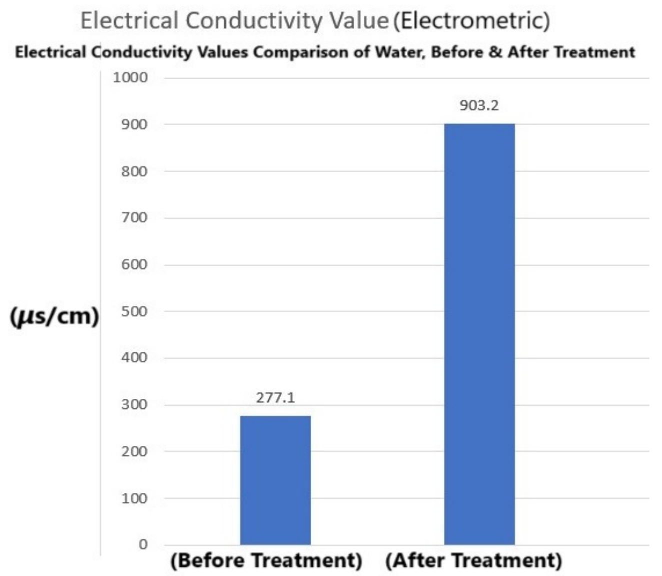

Figure 6. Shows Variation of Electrical Conductivity Value.

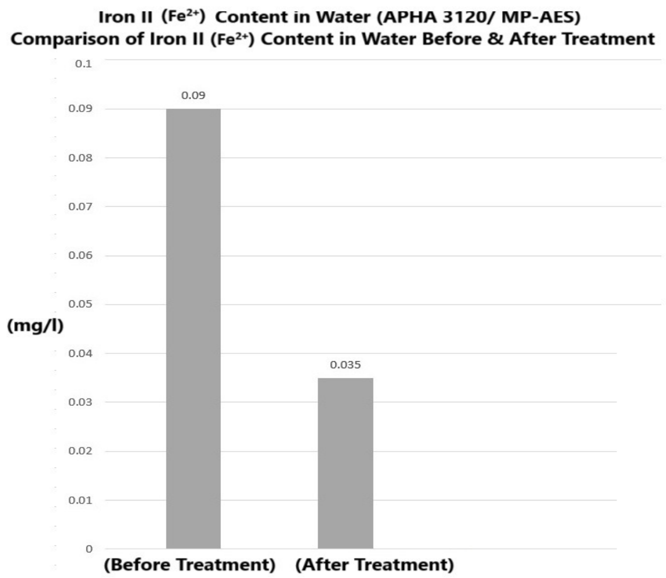

Figure 7. Shows Variation of Iron (II) Value.

As it is stated earlier in this research, the primary objective is to reduce the reddish colour which causes stains that make the water inconvenient for general domestic use. Conductivity level in drinking water depends on many factors in a location, especially a highly mineral dense area. The maximum limit for drinking water conductivity by some regulators is 2500 micro-Siemens per centimetre (µS/cm) while the WHO recommends about 480 (µS/cm).

Another parameter considered in this work is iron II, here the result showed that the value of iron II is reduced from; 0.09 to 0.035 (mg/l) after the treatment which is a significant reduction. Although, iron is not too dangerous, it is healthy to have it in drinking water in this safe value of 0.035 (mg/l).

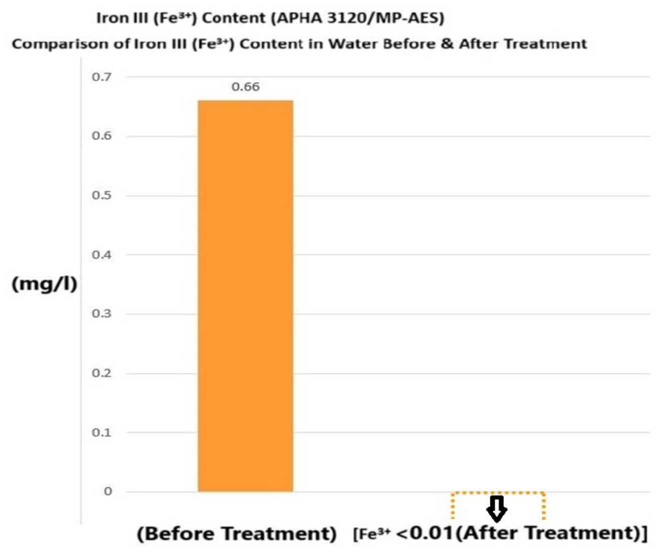

Figure 7. Shows Variation of Iron (III) Value.

The last parameter considered was iron (III), this was the core of the research, that is to reduce it to the lowest possible value for convenient domestic use. The high content of iron (III) in water constitutes high economic costs as it stains almost everything it comes in contact with. The iron (III) value was significantly reduced from 0.66 to less than 0.01 (mg/l) after the treatment, this implies that the application of this algorithm was highly efficient.

VI. CONCLUSION

In conclusion of this research, very significant results were achieved which were verified through the water analyses laboratory reports. The research which is; particle swarm intelligence (PSI) and the area of gravitational search algorithm (GSA) was particularly employed or the treatment process of the borehole water with high iron (III) content. The high iron (III) content caused so much stains when used for general domestic purposes, this is a global problem. Therefore, the need to eradicate it from the water was eminent. During this work, five main parameters were considered to ascertain the efficacy of the application which are; colour, pH value, electrical conductivity, iron (II) and iron (III). Theory of gravitational search algorithm which is a part of particles swarm intelligence (PSI) with decantation principle were employed. A step-by-step rigorous work was carried out and the final outcomes indicate that the objective of the research was achieved as the iron (III) content in the water was reduced from 0.66 to less than (<0.01) mg/l. Also, this reduced iron (III) directly reduce the colour value from; 289.50 to 4.0 (Pt/Co), therefore, the work was highly successful.

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