Assessment of the efficiency of the wastewater treatment plant: a case of Gacuriro Vision City

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Abstract. Wastewater is the liquid waste generated after being used for different purposes. It has a great impact on the environment when discharged untreated or partially treated. The poor management of wastewater at Gacuriro wastewater plant leads to the discharge of subsequently untreated and partially treated wastes. Therefore, the research focused on the assessment of the efficiency of Gacuriro wastewater treatment plant. Samples of wastewater were collected at the inlet and outlet of the treatment plant for laboratory analysis. Parameters tested include pH, Temperature, Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Coliform (TC), Oil and Grease, and Total Phosphorus (TP). Inlet and outlet results are 112.5-364.5 mg/l, 60-190.2 mg/l for BOD; 447-820 mg/l, 46.6-300 mg/l for COD, 19-24 mg/l, 12-18 mg/l for TSS; 6.8-9.05 mg/l, 6.4-5.75 mg/l for TP, 2419.6-50000 counts/100 ml, 1730-30000 counts/100 ml for TC, and 1.012-1.079 mg/l ,0.75-0.923 mg/l for Oil and Grease. Their percentage reduction of efficiency were in the range of TSS (62.50-75%), COD (63.05-78.74%), BOD₅ (69.97-83.70%), Oil and Grease (48.67-62.19%), TP (49.26-60.82%), TC (57.14-64.00%) while average inflow and outflow discharge are 2.5 l/s and 1.5 l/s, respectively. The effluent from the treatment plant needs improvement in disinfection systems to remove bacteria out of discharged effluent.

1. Introduction

Water is a valuable commodity, yet scarce in most countries and one of the challenges to engineers, hydrologists, technologists, and scientists is protecting the water resources [1]. World Health Organization (WHO) reported that 80% of illnesses and infections in the world are due to inadequate treatment of sewage, and more than 3.4 million people die annually because of pathogens living in the aquatic environment [2]. Wastewater is essentially the liquid waste conveyed after a variety of uses has fouled it. The water supplied to a given region or apartment has several chemical substances and microbial bacteria during its application such that the wastewater needs a polluting potential and becomes a health and environmental hazard. Communicable diseases of the intestinal tract such as cholera, typhoid, dysentery and water-borne diseases like infectious hepatitis are spread from uncontrolled disposal of wastewater, and therefore prevention of communicable diseases and protecting public health attracts the primary objective of sanitary wastewater disposal [2]. However, management and handling of wastewater have been one of the main challenges facing developing
countries due to population growth and the lack of sanitation and wastewater management practices. About 80–90% of the generated wastewater in developing countries is discharged directly into water bodies. For example, 62% of the urban population in sub-Saharan Africa disposes wastewater directly to water bodies due to the lack of sanitation infrastructures. Although Rwanda as a country that achieved the Millennium Development Goal (MDG) targets on improved sanitation, there are still unsafe and unreliable decentralized wastewater treatment practices. Kigali City has experienced a rapid urban increase in population in the last few years because of rural-urban migration. According to the observation, Kigali City has no centralized public sewerage system while the few semi-centralized wastewater treatment plants (SCWWPs) or semi-centralized sewerage system (SCSSs) do not function appropriately as initially designed. 81.6% of the improved sanitation in Rwanda use pit latrines with solid slab due to the absence of a sewage system/network in the country. Hotels, hospitals, and significant commercial buildings are obligatorily required to install private SCSSs for the treatment of their wastewater before discharging into the environment. However, due to inadequate governmental monitoring, the standards for their discharged treated wastewater do not meet the national standards [3]. The City’s wastewater management system has not been able to deal with the current demands. Private residential areas within the city do not have elaborate sewerage network. Gacuriro, sewage treatment plant, is one of the semi-centralized sewage treatment plants in Kigali City; however, poor management of the plant has led to the subsequent discharge of raw untreated and partially treated sewage into the environment. This has resulted in the pollution of the rivers, poor health and reduced quality of life within the treatment area and to other users. It is, therefore, necessary to assess the efficiency of Gacuriro wastewater treatment plant and propose any possible improvements and solutions. At any wastewater treatment plant, there is an incoming wastewater flow; this flow is treated before it is allowed to be returned to the environment, lakes, or streams. Wastewater treatment plants operate waste at a critical point of the water cycle and helping nature from excessive pollution [4].

For the Gacuriro wastewater treatment plant, when its performance is efficient and effective, this will have a positive impact on the rivers in which it is discharged, as the components of wastewater like oil, grease, and dissolved solids removed in rivers meet environmental regulations regarding the ecosystem protection. This implies that it has to meet the quality standards established by Rwandan environment institutions and WHO, hence having a positive impact on the ecosystem in general. Besides, the plant has a positive effect on the surrounding environment as the bad odour of wastewater is handled in the plant, and its disposal done conveniently. Thus, the efficiency and performance of the Gacuriro wastewater treatment plant will have a significant impact on the environment. Given the characteristics of raw wastewater and the requirements of disposal or reuse, the wastewater usually requires some preparation or treatment before it rendered fit for disposal or reuse. Mostly, the situations involving domestic wastewater, its treatment consists of removal of total suspended solids and, 20°C BOD5, which are the two most parameters of interest. The degree of treatment provided to the wastewater primarily based on the effluent standards prescribed by the regulatory agencies when the treated effluent discharged into a watercourse or land. If the effluent reused, the quality of the effluent required to support such reuse will indicate the degree of treatment necessary. The complete procedure of wastewater done by a sequential combination of several physical unit operations and chemical and biological unit processes. The general indicator of evaluating the performance of a sewage treatment plant is the degree of reduction of BOD, and suspended solids, which constitute organic pollution [5]. The efficiency of the treatment plant depends not only on proper design and construction but also on good and maintenance and operation [2].

The current research paper focused on Gacuriro Vision City to evaluate the efficiency of wastewater treatment plant by measuring the inlet, and outlet discharge, the mass concentration of wastewater parameters and determination of the effectiveness of percentage reduction in the pollution load.
2. Research methods

2.1. Study area

Gacuriro Vision City (see figure 1) was constructed in 2011 by Ultimate Develops Ltd financed by the Rwanda Social Security Board (RSSB) to provide housing for 22,000 people. The wastewater treatment plant project located at Gacuriro village, Kinyiya sector, Gasabo District in Kigali city (see figure 2). The tract of land for the entire project is 158 hectares. Before the commencement of the work, 3000 residents relocated, and some removed forcefully. The average number of population at the end of 2018 was 8000 people and those connected to the sewer of its sewage treatment plant of Air oxy 4000 P.E which was designed for the treating capacity of 600 m³/day [6].

![Figure 1. Gacuriro vision city](image1.png)

![Figure 2. Part of Gacuriro vision city](image2.png)

2.2. Data source

Wastewater samples used in the current study were collected at the inlet and outlet of a treatment plant using 2.5 and 2.0-litre polythene bottles. Before receiving the examples, the bottles were thoroughly cleaned with hydrochloric acid, washed with tap water to render free of acid, washed with distilled water twice, again rinsed with the water sample to be collected and then fill up the bottle with the example leaving only a small air gap at the top. The sample bottles sealed with paraffin wax. The samples from the influent and the effluent of the Gacuriro wastewater treatment plant were then taken to the laboratory in a considerable period for testing the chosen parameters. Samples collected from February to April 2019. These samples were taken using standard methods of wastewater. The samples for analysis were collected in sterilized glassware previously washed with laboratory detergent and rinsed with deionized water and treated with 1M HNO₃ for overnight. The measured parameters were total Coliform, Total Phosphorous (TP), Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Oil and Grease. Sampling was done referring to Rwanda Standard Bureau (RSB) as well as an international standard. The measured parameters chosen are of particular interest since they are responsible for oxygen level depletion in receiving water, thus promoting unpleasant odour around the living environment.

2.3. Methodology for the estimation of inlet and outlet discharge

2.3.1. Outlet estimation. We estimated the inlet amount of wastewater per day as the product of population and per capita of water demand (see equation 1). The per capita sewage generation considered 80% of the per capita water supplied per day. The increase in population also results in an increase in per capita water demand and hence, per capita production of sewage. This increase in water demand occurs due to a rise in living standards, betterment in economic condition, changes in the habit of people, and enhanced demand for public utilities. The sufficient and adequate primary market depends on the water use habits as well as on climatic and cultural conditions. A sufficient essential supply can achieved with 20 to 40 litres per inhabitant per day. WHO (World Health Organization): 30 l/c/d) [7]. The used water (80%) becomes wastewater; hence, the wastewater generated is calculated using equation 2.

\[ Q_d = \text{Population} \times \text{Per capita water consumed per day} \]  \hspace{1cm} (1)

\[ Q = 0.8 \times Q_d \]  \hspace{1cm} (2)
Where \( Q \) is inlet discharge, \( Q_d \) is water demand, and water consumption per capita per day = 30l/d

2.3.2. Outlet discharge. Outlet discharge was determined using a bucket and stopwatch where the bucket of 20 l placed at effluent discharge and stopwatch (chronometer) set at 10 seconds. This was done thrice, and then the average was the final discharge that was used to determine the quantity of effluent.

2.4. Methodology for measuring the parameters

2.4.1. pH. The pH of samples was noted using a direct reading pH meter (pH meter compact MT 04955) already standardized by using a buffer solution of known value before analyses

2.4.2. Temperature. The temperature was noted using the thermometric method at the site of sampling using a portable calibrated mercury thermometer.

2.4.3. Total Suspended Solids (TSS). TSS are particles of solids that remain on the filter paper. Suspended solids (SS) contain silt, clay, fine particles of organic and inorganic matter that is regarded as a type of contamination because water high in concentration of SS may adversely affect the growth and replica rates of aquatic fauna and flora. To determine the amount SS in wastewater analyzed; the known amount of sample was filtered through a filter paper with a known mass \((M_p)\). Then both paper and retained solids were dried to 103°C-105°C and weighed; the obtained mass \((M_{ps})\) were noted. The number of SS in wastewater was determined using Equation 3.

\[
TSS = M_{ps} - M_p
\]  

(3)

2.4.4. Biological Oxygen Demand (BOD). The BOD level is got by comparing the dissolved oxygen (DO) level of a water sample taken immediately with the DO level of a water sample that was incubated at a temperature of 20°C for five days [8]. The principal difference between the two levels represents the amount of oxygen required for the decomposition of organic materials; hence, BODs (20°C) is the difference between the initial DO and the final DO. The sample was poured in bottles with specific volume then measured immediately the quantity of DO using Oximeter. After, they were incubated at a temperature of 20°C for five days in a darkened environment.

2.4.5. Chemical Oxygen Demand (COD). A boiling mixture of chromic and sulphuric acids oxidizes most types of organic and inorganic matter. A sample is refluxed with a strong acid solution of a known excess of \(K_2Cr_2O_7\). At the end of this process, the remaining non-reduced \(K_2CrO_7\) is titrated with ferrous ammonium sulfate to determine the amount of \(K_2CrO_7\) consumed and the oxidizable organic and inorganic matter calculated in terms of oxygen equivalent. This was indicated by the change of orange colour in green colour, as shown in Equation 4.

\[
Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O
\]  

(4)

After the titration, the orange colour does not correctly change because of \(K_2Cr_2O_7\) not reduced thus the colourimetric method used to calculate the quantity of \(K_2Cr_2O_7\) consumed by oxidizable matters of sample and this is calculated in terms of equivalent oxygen. The intensity of the colour is proportional to organic issues available in the example. The data used while calculating the efficiency of the onsite system in this paper are exclusively for the Gacuriro site.

2.4.6. Oil and grease. We put 100 ml of the sample into a 250 ml separating funnel. We added three drops of sulphuric acid to bring the pH to 2 to prevent oxidation. 50 ml of n-hexane at 50°C then added, and the mixture was shaken so that any oil or grease present in the aqueous phase could move to the organic solvent phase. After thoroughly mixing, the lower layer was drained off, and the upper organic layer was collected into a conical flask filled with anhydrous sodium sulfate to remove water. The contents of the conical flask were then filtered into a pre-weighed 250 ml round-bottomed flask.
The organic layer then evaporated using a hot water bath leaving the Oil and Grease. The flask then weighed for the determination of Oil and Grease.

2.4.7. Total coliform. 14 g of nutrient agar was weighed dissolved in 500 ml of distilled water. This was then heated using a hot plate for complete dissolution. The solution was then put into an autoclave for 15 minutes for sterilization. 0.1, 0.5 and 1.0 ml of the Inlet, and outlet samples diluted two times respectively were put into a beaker. 15 ml of the culture media were added. The examples were then cultured in an incubator for 24 hours.

2.4.8. Total phosphorus. The tube test heater was turned on, set to 105°C and allowed to heat up to 105°C. The caps of the Tube tests, TP was removed, and 2.0 ml of the three sets of the samples were added using a pipette. Two digest ox tablets were added to each tube, crushed and then mixed until it dissolved. The cap tightly replaced and the cells inverted gently until combined. The tube contents were digested for one hour then removed; the tubes placed in the test tube rack and allowed to cool.

2.4.9. Pollution load. Pollution Load is the product of the concentration of the pollutant at effluent (mg/l) and the volume of water at effluent flow (l/s). Percentage efficiency reduction of each parameter is given by Equation 5.

\[
Ca = \frac{Q1Ca1 - Q2Ca2}{Q1Ca1} \times 100
\]  

Where; \( Ca_1 \) is the mass concentration at system influent expressed in mg/l, \( Ca_2 \) is the mass concentration at system outlet shown in mg/l, \( Q_1 \) is the discharge at policy influent expressed in m\(^3\)/s, and \( Q_2 \) is the discharge at system outlet expressed in m\(^3\)/s.

2.4.10. Compliance index. A compliance index is a statistical tool that shows at a glance, the effectiveness of treatment works. The compliance index value of less than one implies compliance with the set standards while a value higher than one means non-compliance. This means that the effluent discharged into the environment have concentrations of given parameters more elevated than the ones set by the environmental protection bodies. Compliance Index for each parameter was, therefore computed, as shown in equation 6.

\[
\text{Compliance index} = \frac{\text{Effluent concentration}}{\text{Maximum allowable value}}
\]  

3. Results and discussion

3.1. Inlet and outlet discharge

The result of the inlet and outlet discharge were summarized in table 1 and table 2, respectively. It was observed that the discharge outlet was ranging from 1.46; 1.45 and 1.48 l/s, thus giving an average of 1.46 l/s. The maximum of 1.5 l/s was used.

| Population | Water demand (l/p/d) | Coefficient of sewage | Inlet discharge (l/s) |
|------------|---------------------|-----------------------|---------------------|
| 8000       | 30                  | 0.8                   | 2.5                 |

Table 2. Results of outlet discharge

| Numbers | Discharge in 10s | Discharge (l/s) | Average discharge (l/s) |
|---------|------------------|----------------|-------------------------|
| 1       | 14.6l            | 1.46           |                         |
| 2       | 14.5l            | 1.45           | 1.46                    |
| 3       | 14.8l            | 1.48           |                         |
3.2. pH

Analyses of the pH were done on-site. The findings were recorded, as shown in table 3. The influent recorded in April was relatively low compared to the other two months. This could have been due to the torrential downpour, which characterized these months, particularly the last two months. The rains most likely might have contributed to an increase in the pH through dilution. An increase in pH of the effluent was noticed from February to April compared to the corresponding influent values for the same months. The growth could have been due to the gradual increase in the dilution of wastewater because of the rains, which occurred in February and April.

Table 3. Results for pH analysis for the period ranging from February to April

| Month  | Influent pH | Effluent pH | RSB 110:2017 of tolerance limit of Discharged wastewater |
|--------|-------------|-------------|--------------------------------------------------------|
| February | 7.09        | 7.29        | 5-9                                                   |
| March   | 7.21        | 6.08        |                                                       |
| April   | 7.00        | 7.20        |                                                       |

3.3. Total Suspended Solids

February recorded a TSS value of 43 mg/l while March recorded 24 mg/l for the influent and April recorded a TSS value of 19 mg/l, as shown in table 4. It was noticed that there was a general decrease in the values of TSS recorded from February to April; this reduction was caused by the dilution of rain, splash in wastewater and the same contact with runoff.

Table 4. Results for TSS analysis for the period ranging from February to April

| Month  | Influent (mg/l) | Effluent (mg/l) | Discharge inlet (l/s) | Discharge outlet (l/s) | Efficiency removal (%) |
|--------|----------------|-----------------|-----------------------|------------------------|------------------------|
| February | 43            | 18              | 2.5                   | 1.5                    | 74.0                   |
| March   | 24            | 10              | 2.5                   | 1.5                    | 75.0                   |
| April   | 19            | 12              | 2.5                   | 1.5                    | 62.5                   |

The efficiency removal of TSS in figure 3 shows the range between 75% and 62.5%. The efficiency in April is lower than the one of other months. This could have been caused by wastes from kitchen resulting in the increase of sediments in sewage.

Figure 3. Percentage in the reduction efficiency of TSS for the period of February to April

3.4. Chemical Oxygen Demand (COD)

Table 5 depicts the COD values. The COD for the influent recorded in February, March, and April was 900, 447 and 820 mg/l, respectively. The COD effluent is higher than the tolerance limit of discharged wastewater of 250 mg/l; this showed that there was a massive load of organic pollutants in this plant.
Table 5. Results for COD analysis for the period ranging from February to April

| Month   | Influent mg/l | Effluent mg/l | Discharge inlet l/s | Discharge outlet l/s | Efficiency removal (%) |
|---------|---------------|---------------|---------------------|----------------------|------------------------|
| February| 900           | 349           | 2.5                 | 1.5                  | 76.70                  |
| March   | 447           | 270           | 2.5                 | 1.5                  | 63.74                  |
| April   | 820           | 300           | 2.5                 | 1.5                  | 78.05                  |

The percentage reduction efficiency for COD was low for all the months, as seen in figure 4, ranging from 63.74-78.05% as illustrated in Figure 4. However, the average efficiency of removal for COD (72.83%) does not meet the limits of the World Health Organization (WHO), which is 75%.

Figure 4. Percentage efficiency reduction of COD in the period of February to April

3.5. Biochemical oxygen demand for five days (BOD₅)

The influent and the effluent BOD values are seen in Table 6. The effluent of BOD for all months is higher than the allowable limit of 50 mg/l. Increases in BOD can be due to the heavy discharge of wastewater influent, which contains crop wastes and domestic sewage. BOD values have been widely adopted as a measure of the pollution effect. It is included in the most common measures of pollutant organic material in water. It indicates the amount of organic matter present in water. This could be because of the inability of the plant to have effective BOD reduction.

Table 6. Results for BOD₅ analysis for the period ranging from February to April

| Month  | Influent (mg/l) | Effluent (mg/l) | Discharge inlet (l/s) | Discharge outlet (l/s) | Efficiency removal of (BOD₅) (%) |
|--------|-----------------|-----------------|-----------------------|------------------------|---------------------------------|
| February| 364.5           | 99              | 2.5                   | 1.5                    | 83.70                           |
| March  | 112.5           | 60              | 2.5                   | 1.5                    | 68.00                           |
| April  | 380             | 190.2           | 2.5                   | 1.5                    | 69.97                           |

The percentage reduction efficiency in the BOD₅ concentration from influent to effluent shown in figure 5. With February recording the highest reduction efficiency of 83.7 % but its average (73.86%) does not meet with the limit of WHO which is 80%.
3.6. Oil and grease

The influent values of Oil and Grease obtained over the period (see table 7) were lower than the recommended amount of 10 mg/l.

Table 7. Results for Oil and Grease analysis for the period ranging from February to April.

| Month | Influent (mg/l) | Effluent (mg/l) | Discharge inlet (l/s) | Discharge outlet (l/s) | Efficiency removal |
|-------|----------------|----------------|-----------------------|-----------------------|--------------------|
| February | 1.079           | 0.923           | 2.5                   | 1.5                   | 48.67%             |
| March   | 1.012           | 0.75            | 2.5                   | 1.5                   | 55.53%             |
| April   | 1.587           | 1.000           | 2.5                   | 1.5                   | 62.19%             |

The percentage reduction efficiency was in the range of 62.19-48.67%. April recorded percentage reduction efficiency of 62.19% is higher than in other months, as shown in figure 6.

Figure 6. Percentage reduction efficiency for BODs for the period of February to April

3.7. Total phosphorus

The phosphate values obtained for the effluent over the period from March to February, as seen from table 8 were much higher than the allowable limits of 5 mg/l PO₄. This could be due to the high discharge of phosphate-containing substances such as detergents into the sewer lines. There was a gradual increase in the influent values with April recording 9.25 mg/l PO₄.

Table 8. Results for phosphate analysis for the period ranging from February to April

| Month | Influent (mg/l PO₄) | Effluent (mg/l PO₄) | Discharge inlet (l/s) | Discharge outlet (l/s) | Efficiency removal Of PO₄ |
|-------|---------------------|---------------------|-----------------------|-----------------------|--------------------------|
| February | 9.05                | 7                   | 2.5                   | 1.5                   | 53.59%                   |
| March   | 6.8                 | 5.75                | 2.5                   | 1.5                   | 49.26%                   |
| April   | 9.25                | 6.04                | 2.5                   | 1.5                   | 60.82%                   |
The percentage reduction efficiency for phosphates is as shown in figure 7. The range lying from 60.8% to 49.26% was below the limit efficiency of RSB, which is 85%, and this shows that the plant performance for Total Phosphorus is not complying with the environment.

3.8. Total coliform

A general decrease in the values of total coliform was observed from February to April. February recorded 70000 counts/100 ml, and March recorded 50000 counts/100 ml while April recorded 2419.6 Total Coliforms for influent. The effluent values were also lower compared with the respective influent values. However, in February, the highest values for total coliforms were recorded for the influent, as seen in table 9.

| Month  | Influent | Effluent | Discharge inlet ( l/s) | Discharge outlet ( l/s) | Efficiency removal (%) |
|--------|----------|----------|------------------------|------------------------|------------------------|
| February | 70000    | 50000    | 2.5                    | 1.5                    | 57.14                  |
| March   | 50000    | 30000    | 2.5                    | 1.5                    | 64.00                  |
| April   | 2419.6   | 1730     | 2.5                    | 1.5                    | 57.10                  |

The percentage reduction efficiency of TC range was 64 -57.1%, as shown in figure 8. This means that the plant needs improvement in disinfection. The effluent concentration is also higher than the maximum allowable discharge into the environment, which is 400 cfu/100ml. This could be due to the accumulation of the indigestible faecal matter.

3.9. Pollution loading

Pollution loading refers to stress placed upon an ecosystem through pollution by either physical or chemical means or both. Pollution loading provides exhaustive information about the level of impact of the pollutants on the environment. It is a function of pollutants concentration and water flow.
Pollution loading can be calculated for different parameters. For this research study pollution load was computed for TSS, BOD, COD, Total Phosphorus, Oil and Grease, and Total Coliforms (see table 10).

### Table 10. Pollution loading of an individual parameter

| Parameter            | Average concentration (mg/l) for the Effluent | Average Outflow volume (l/s) | Pollution loading (mg/s) |
|----------------------|----------------------------------------------|------------------------------|--------------------------|
| TSS                  | 13.3                                         |                              | 19.95                    |
| BOD                  | 116.4                                        |                              | 174.6                    |
| COD                  | 231.8                                        | 1.5                          | 347.7                    |
| Total Phosphorus     | 6.23                                         |                              | 9.345                    |
| Oil and Grease       | 0.891                                        |                              | 1.3365                   |
| Total Coliform       | 12243.33                                     |                              | 18364.995                |

### 4. Conclusion

This study examined the efficiency of the semi-centralized wastewater treatment system located at Gacuriro Vision City. The effluent of TSS and Oil and Grease were within RSB guidelines. The effluent of total phosphorus was close to the RSB guidelines. Particular parameters of interest were 69.97 to 83.7% for BOD, 63.05 to 78.74% for COD, 62.5 to 75.0% for TSS, 49.26 to 60.82% for Phosphorus and 57.14 to 64.0% Total Coliform and 49.26 to 60.82% for Oil and Grease respectively. However, despite the high percentage efficiency reduction, the effluent values of COD (except for March), BOD, and Total coliform were higher than maximum allowable limits. The low efficiency in the removal of such parameters serves as the source of unpleasant odour around the environment. Both the COD and BOD values are a measure of the relative oxygen-depletion effect of a waste contaminant, and this greatly degraded the quality of water due to oxygen depletion. Furthermore, this indicates the weakness of onsite treatment systems. Therefore, the results from this piece of work should serve as the framework for the future upgrading of the existing systems and new systems.

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