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# Environmental Assessment of Water Treatment Plants of the Republic of Ecuador and Comparative Analysis of Water Disinfection Technologies using the LCA Method

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**Abstract**: In the study, the environmental sustainability of two small water treatment plants with water intake from surface water sources with a high content of organic substances was evaluated. The life cycle assessment was used as a tool to compare two scenarios developed to solve the problem of disinfection by-products (DBPs) formation in drinking water. Various stages of the obtaining drinking water process were evaluated – from flocculation-coagulation to disinfection. The functional unit was defined as 1 $m^3$ of drinking water produced at a water treatment plant. The proposed scenarios were developed to replace the chlorine disinfection with the UV disinfection of varying intensity (30 $mJ/cm^2$ for the first scenario and 186 $mJ/cm^2$ for the second scenario), followed by chloroamination. The data were analyzed using the Ecoinvent v.3.01 database, modeled and processed in the OpenLCA software. The results showed that at both water treatment plants, the coagulation-flocculation process has the greatest impact on the environment, which is mainly due to the chemical nature of the coagulant. It was revealed that from the point of view of environmental impact, the UV disinfection with an intensity of 30 $mJ/cm^2$ is preferable, since the global warming potential (GWP) was 80% less than in the second scenario, while the acidification potential (AP), eutrophication potential (EP), marine aquatic ecotoxicity potential (MAEP), terrestrial ecotoxicity potential (TETP) and human toxicity potential (HTP) were less by 78%, 71%, 72%, 74% and 79%, respectively.

***Keywords***: life cycle assessment, water treatment plant, Republic of Ecuador, UV disinfection

## 1. INTRODUCTION

The main task of water treatment is to provide consumers with drinking water of proper quality. The treatment includes protection from microorganisms, removal of natural organics and toxic substances, preservation of aesthetic quality, and protection of pipelines from corrosion and re-contamination [1, 2].

Drinking water treatment plants in Ecuador are usually supplied with surface water (mainly rivers), where water flows from the water catchment area into the water supply network by gravity. According to the Economic Commission for Latin America and Caribbean (CELAC), water purification processes in Ecuador are traditional and usually include coagulation, flocculation, precipitation, filtration, and disinfection [3]. These processes require high energy and big amount of chemicals to provide a good quality product for human consumption. However, excessive energy consumption or the use of chemicals, such as coagulants, flocculants, pH stabilizers and disinfectants, not only affect the health of consumers, but also have an impact on the environment [4–6]. This has caused considerable public and industrial interest in the development of new strategies aimed at improving environmental performance throughout the life cycle of water resources management [4, 7],

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as well as obtaining cleaner and more sustainable processes to ensure a better quality of life for the consumer of the final product [8].

According to a study conducted by the National Institute of Statistics of Ecuador, 215 drinking water treatment plants in Ecuador use chlorine at the disinfection stage [9]. At these plants, a high dose of chlorine is usually required to meet the desired pathogen inactivation and 0.5 mg/l of disinfectant residue according to the Ecuadorian standard 1108 [10]. On the other hand, the high content of natural organics in surface water sources (which is common for reservoirs located in Andean ecosystems) [11, 12], combined with a high dosage of chlorine, can lead to a break of the minimum level of disinfection by-products (DBPs), therefore, new technologies such as membrane technologies or UV-disinfection are increasingly used in the water management [13]. As usual, the choice of the "best" water treatment system is based primarily on economic and technical constraints. However, the water treatment industry may be responsible for significant global environmental impacts. Thus, the complexity of water treatment systems makes it possible to apply broader methods of environmental assessment, such as life cycle analysis regulated by international standards ISO 14040 [14] and 14044 [15].

Life cycle assessment (LCA) is a tool that can be used to obtain information about the environmental impact of water treatment systems. The LCA serves to assess global environmental damage potentially caused by a product, process, or service in the "cradle-to-grave" approach [16]. Consequently, LCA offers a more comprehensive approach to quantifying the environmental characteristics of a system or technology to inform management decisions [17]. This method provides a systematic basis for preventing partial optimization, shifts the environmental impact between the stages of the life cycle and helps to identify the main impact factors [18].

The scientific literature on water engineering science includes important studies in which the LCA has been used over the past five years. These studies are attracting more and more attention as they are applied to the processes of drinking water treatment plants in developed and developing countries [5, 6, 19, 20]. Klopfer and Curran (2014) [21] stated the importance of LCA-related research for some countries that have not been embedded the idea of life cycle. Ecuador is one of these countries. Thus, this study represents one of the first LCA studies conducted in Ecuador on the purification of drinking water.

The purpose of this study is to assess the environmental impact of two technological cycles for the drinking water purification, implemented at water treatment plants located in the Andean region of Ecuador, and to identify environmental "hot spots" of the purification process. The purpose of this study also covers the analysis of the impact of the proposed technologies on the environment as an alternative to chlorine disinfection, improving the understanding of the accommodations of technological solutions while meeting the desired water quality requirements.

## 2. LIFE CYCLE ASSESSMENT OF DRINKING WATER TREATMENT PLANTS

The LCA study is carried out in four stages: determination of the purpose and scope of the study, inventory analysis, impact assessment and interpretation of the results.

### *2.1 Definition of the purpose and scope of the study*

The purpose of this study is to assess the life cycle of 1 $m^3$ of drinking water produced by two water treatment plants located in Ecuador. The first water treatment plant is located in Latacunga, Cotopaxi province, and has a purification capacity of 0.035 $m^3/s$ of water coming from the Retamales river [22]. The second station is located in the canton of Pedro Vicente

Maldonado, Pichincha province, and processes an average of 0.030 $m^3/s$ of water from the Talala river [23].

The physical boundary of the two systems covers the following stages: coagulation-flocculation, precipitation, filtration, and disinfection. There are also sub-stages included such as the supply of aluminum sulfate, chlorine gas, caustic soda and polyaluminium chloride (PAC).

The water supply network is beyond the scope of this study. Infrastructure and decommissioning of water treatment plants are not considered, as the results of other studies indicate that the environmental impact is insignificant compared to the operation stage [24, 25]. Since this study is not aimed at comparing stations, the results are not subject to mandatory uncertainty analysis at the level of installations as a whole (according to ISO standards). Fig. 1 shows the purification processes carried out at the Latacunga and Pedro Vicente Maldonado water treatment plants. During the purification the flow of water from the catchment area into the water supply network flows by gravity, so there is no energy consumption during sedimentation and filtration. Therefore, only coagulation-flocculation and disinfection processes were considered for the assessment.

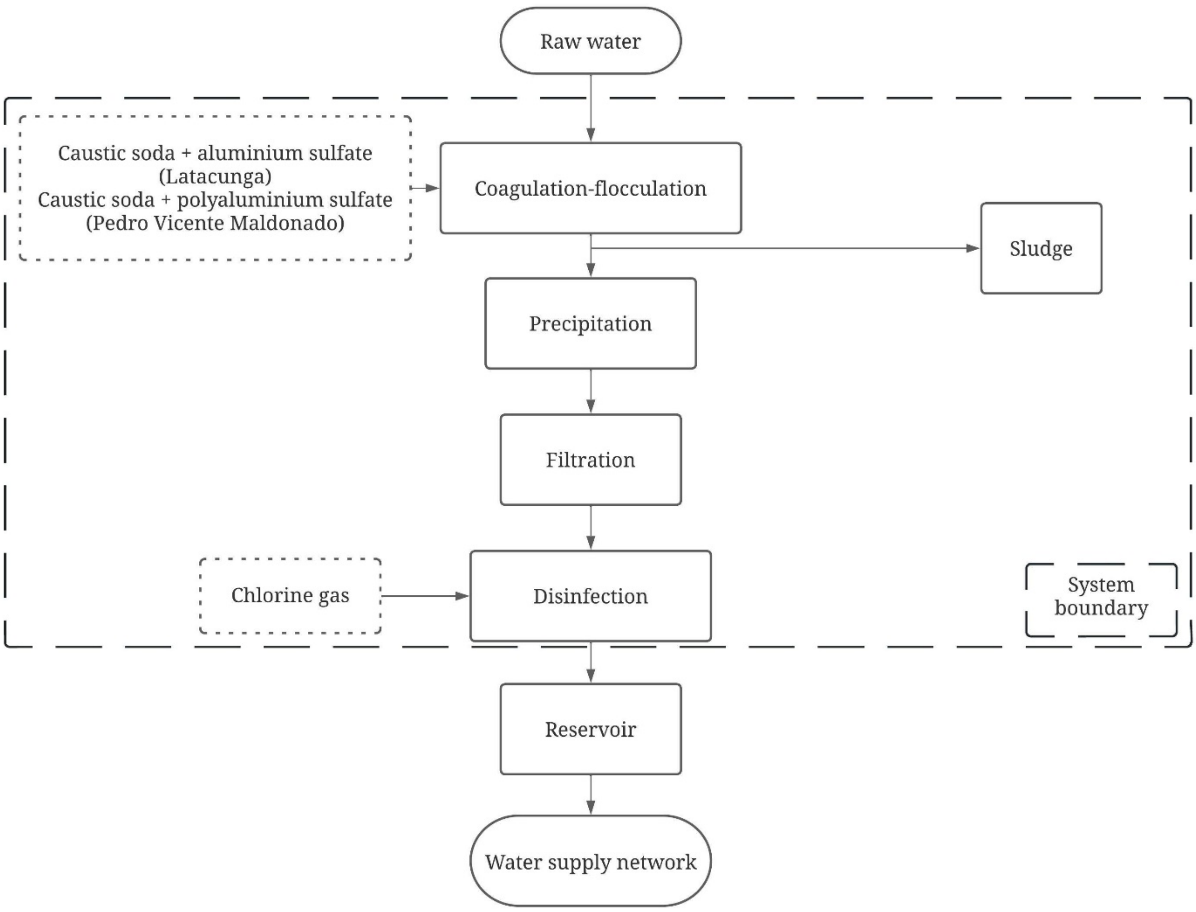


**Fig. 1.** System boundaries of the process at the studied water treatment plants. The chemical reagents used for each process are indicated by a dotted line

### *2.2 Life cycle inventory analysis*

At this stage, an inventory of the water treatment system was carried out, based not only on information about the electricity consumption and the amount of chemicals needed in the process of preparing drinking water, but also on the equivalent pollution factor. Both primary and secondary sources of information were used for this inventory. The primary source corresponded to the data provided by the technical staff of the studied water treatment plants, who collected information during the 12-month operation period, from January to December 2019. The secondary source corresponded to the Ecoinvent v3.1 database [26], designed to provide general bench-mark data on products and processes used at drinking water treatment plants. It should also be noted the main limitation of the study: there are no specific baseline data for Ecuador, therefore average technological data for Peru were used, since the levels of technology and environmental performance are similar from the point of view of the studied process. Table 1 shows the inventory of chemical reagents and the amount of electricity at each of the studied plants.

**Table 1.** Inventory data of the investigated water treatment plants, expressed in the functional unit (1 $m^3$) of drinking water produced at the stations.

| Process | Operational data | Drinking water treatment plant of Latacunga city | Drinking water treatment plant of Pedro Vicente Maldonado canton |
|---|---|---|---|
| Coagulation-Flocculation | Caustic soda (kg) | 0.005 | 0,006 |
| | Aluminium sulfate (kg) | 0.0445 | - |
| | Polyaluminium chloride PAC (kg) | - | 0.0168 |
| | Energy consumption (Kwh) | 0.0022 | 0.0017 |
| Disinfection | Chlorine gas (Kg) | 0.0011 | 0.0017 |
| | Energy consumption (Kwh) | 0.0020 | 0.0024 |

Chemical reagents are supplied by manufacturers located on the territory of Ecuador. Table 2 shows the logistics data.

**Table 2.** Transportation of chemical reagents

| Chemicals | Approximate transportation distance (Km) | | Type of transportati on, city |
|---|---|---|---|
| | Drinking water treatment plant of Latacunga city | Drinking water treatment plant of Pedro Vicente Maldonado canton | |
| Caustic soda | 100 | 130 | Truck, Quito city |
| Aluminum sulfate | | | |
| Polyaluminium chloride (PAC) | | | |
| Chlorine gas | | | |

The OpenLCA v. 10.3 software was used to simulate the systems under study. The CML 2001 method [27] was used to transform input and output streams into impact categories. The exposure categories selected in this study included global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAEP) and terrestrial ecotoxicity potential (TETP).

### *2.3 Impact assessment and interpretation of results*

Table 3 presents the general results obtained by applying environmental impact indicators for the two studied water treatment plants, in comparison with the literature data.

**Table 3.** Comparison of the environmental impact data obtained with the literature data

| Reference | Main assumption | GWP (Kg $CO_2$ eq) | AP (Kg $SO_2$ eq) | EP (Kg $PO_4$ eq) | HTP (Kg 1,4-DB eq) | TETP (Kg 1,4-DB eq) |
|---|---|---|---|---|---|---|
| Latacunga water treatment plant | Distribution network excluded | 4.40E-2 | 5.20E-4 | 9.26E-5 | 3.45E-2 | 1.50E-4 |
| Pedro Vicente Maldonado water treatment plant | Distribution network excluded | 1.68E-2 | 1.40E-4 | 3.16E-5 | 1.26E-2 | 6.01E-5 |
| Ortiz et al. (2016) [5] | Distribution network excluded | 2.21E-2 | 2.28E-4 | 5.03E-5 | 8.04E-3 | N/A |
| Amores et al. (2013) [19] | Distribution network excluded | 1.77 E-1 | 6.72E-4 | 6.87E-5 | N/A | N/A |
| Friedrich and Buckley 2002 [24] | Distribution network excluded | 1.73E-1 | 1.02E-3 | 6.54E-5 | 3.31E-3 | 2.30E-1 |
| Friedrich et al. (2012) [4] | Distribution network excluded | 1.85E-1 | 1.10E-3 | 7.40E-5 | 4.09E-3 | 2.59E-1 |
| Saad et al. (2018) [20] | Distribution network excluded | 3.42E-1 | 1.13E-3 | 1.06E-4 | 1.65E-2 | 2.55E-4 |

Regarding the categories of GWP, AP, EP and HTP, the results of this study are either in the range or close to the literary values indicated for the traditional water purification process [4, 5, 19, 20, 24]. However, for TETP, the results of this study are below those given in the literature. Differences between the results and the literature data may be related to different operations at the water treatment plant included in the traditional purification process, certain geographical conditions of the place or changes in the configurations of water treatment plants.

Each process contributes to different impact categories. Figures 2 and 3 present the results of the characteristics of LCA processes, which show the proportion of each process in different categories of impact.

 

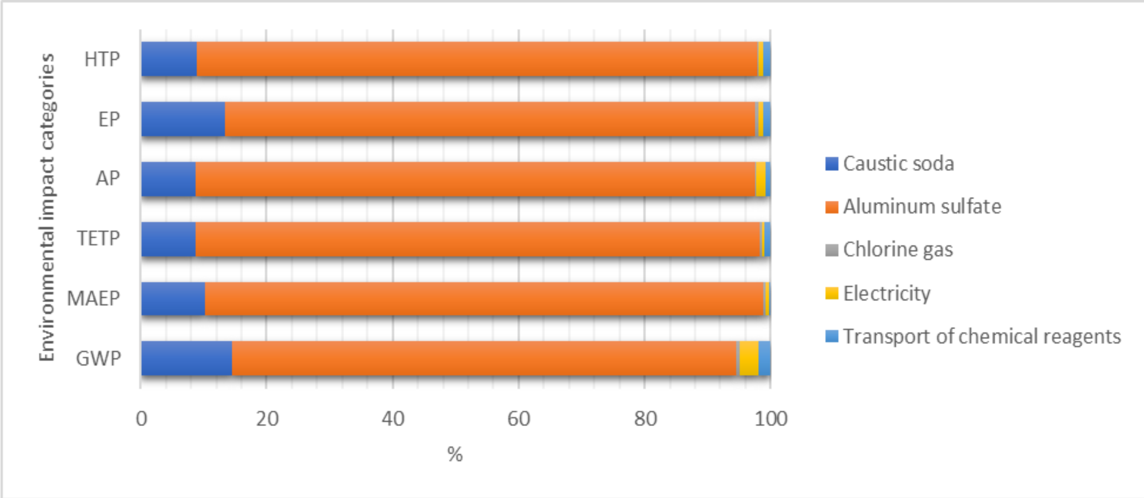


**Fig. 2.** Contribution of caustic soda, aluminum sulfate, chlorine gas, electricity, and transport of chemical reagents to the environmental impact at the Latacunga water treatment plant.

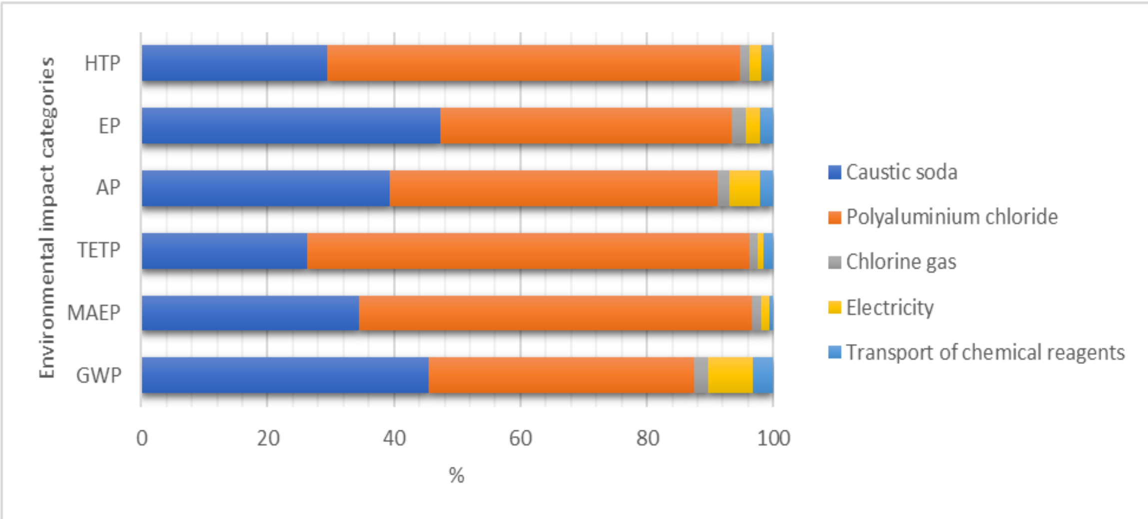


**Figure 3.** Contribution of caustic soda, polyaluminium chloride, chlorine gas, electricity, and transport of chemical reagents to the environmental impact at the Pedro Vicente Maldonado water treatment plant.

The exposure profile in the Fig. 2 shows that approximately 96% of the total amount of HTP, AP and TETP is formed during the coagulation-flocculation process (88% aluminum sulfate and 8% caustic soda). About 98% of the total amount of MAEP is accounted for by the coagulation-flocculation process (88% aluminum sulfate and 10% caustic soda). The coagulation-flocculation process accounts for 94% of the total GWP (80% aluminum sulfate and 14% caustic soda).

According to the results of the Fig. 3, at the water treatment plant in the canton of Pedro Vicente Maldonado, approximately 94% of the total amount of HTP is formed from PAC (65%) and caustic soda (29%). About 93% of the total EP is accounted for by caustic soda (47%) and polyaluminium chloride (46%). Also 91% of the AP is formed from polyaluminium chloride (52%) and caustic soda (39%). About 96% of the total TETP is accounted for by polyaluminium chloride (70%) and caustic soda (26%). Approximately 96% of all MAEP is formed during coagulation-flocculation (62% polyaluminium chloride and 34% caustic soda). About 87% of the total GWP is accounted for by the coagulation-flocculation process (caustic soda 45% and polyaluminium chloride 42%).

 

At two water treatment plants, the transportation of chemicals is minimal (from 0.3 to 3.2%) in all impact categories. These results are comparable to the literature data. Thus, the environmental impact associated with the transportation of chemicals is insignificant [18].

The greatest environmental stress or "trouble spot" of studied systems occurs during coagulation-flocculation process due to the use of coagulating agents and pH stabilizers. Some studies report that the greatest contribution to the environmental impact is made by electricity used for cleaning processes [4, 20, 25], while other studies show that the greatest contribution to the environmental impact is made using chemical reagents [5, 6, 28, 29].

In an ideal scenario, water treatment plants involved in providing a sustainable supply of drinking water should reduce the environmental load throughout the process. For example, the use of PAC can be reduced using natural coagulants. In addition, it is important to control the water source of water treatment plant since its misuse leads to pollution of the water to be treated. Such pollution consists in non-compliance with the standards of chromaticity, turbidity, and suspended solids, and, consequently, the amount of coagulant needed for water purification increases. The best way to reduce an amount of coagulation is to analyze the effectiveness of the pretreatment process designed to improve the physico-chemical characteristics of water entering the water treatment plant.

The disinfection process at both water treatment plants has the smallest impact in all categories of exposure (from 0.3 to 2%). Although this process poses no danger from an environmental point of view, the use of chlorine gas as a disinfectant is widely discussed because of its possible negative impact on human health [30, 31]. Chlorine gas reacts with water to form hypochlorous acid. In the presence of bromine, brominous acid is also formed. Hypochlorous and brominous acids form strong oxidizing agents in water and react with a wide variety of compounds, so they are one of the most effective disinfectants. However, these acids also react with natural organics to form DBPs [31].

## 3. LIFE CYCLE ENVIRONMENTAL IMPLICATION TO REDUCE DBPs

DBPs can be controlled using one of three main strategies:

1) modification of disinfection methods;
2) enhanced removal of DBPs precursors; and
3) removal of DBPs after formation [32].

In this study, the first strategy of DBPs control in the development of alternative scenarios was studied.

### *3.1 Definition of the purpose and scope of the study*

The two scenarios based on UV-disinfection were identified and evaluated from an environmental point of view. Considering the operational capacity of the studied subjects, a reference water flow rate (0.030 $m^3/s$) was used to represent the system. The LCA was carried out mainly by data obtained as a result of design calculations based on processes, the Ecoinvent database and relevant literature [33, 34].

The first scenario: a combination of UV radiation at a dose of 30 $mJ/cm^2$ and disinfection with chlorine is used to achieve the required 4-log inactivation of viruses and 3-log inactivation of *Cryptosporidium* and *Giardia* [35]. Chloramine is used for residual disinfection, which is achieved by adding anhydrous ammonia to hypochlorite (Fig. 4a).

The second scenario: a UV dose of 186 $mJ/cm^2$ is added to achieve both 4-log virus inactivation and 3-log inactivation of *Cryptosporidium* and *Giardia* [35]. As it was in the first scenario, chloramine also provides residual disinfection (Fig. 4b).

 

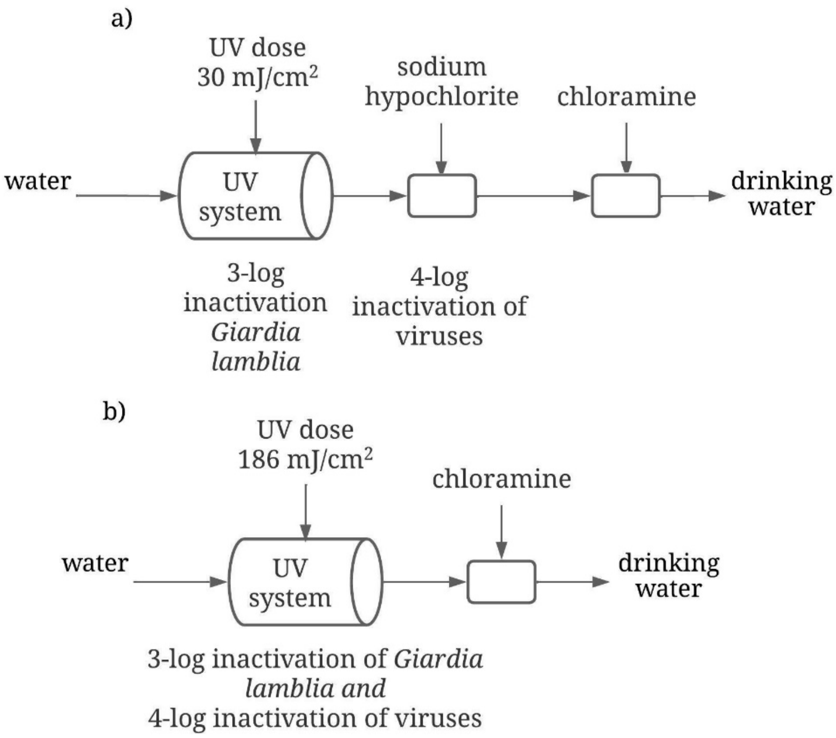


**Fig. 4.** Schemes of the proposed disinfection processes based on UV-radiation.
a) UV dose 30 mJ/cm$^2$; b) UV dose 186 mJ/cm$^2$

### *3.2 Inventory analysis*

The type and quantity of materials for the infrastructure of UV disinfection systems were based on the results presented by Mo et al. (2018) [33]. In this study, the entire infrastructure was designed for a peak load of 0.033 m$^3$/s and an average concentration of organic carbon of 4.6 mg/l. The infrastructure of the UV disinfection system includes the following components: UV lamps, quartz sleeve, sleeve cleaning system, UV sensor for monitoring of UV radiation, and a control system for the entire UV system.

The energy values for existing UV disinfection systems operating at a dose of 30 mJ/cm$^2$ were set to the corresponding consumption (0.033 m$^3$/s); electricity indicator was set at 0.041 kWh/m$^3$. This value corresponds to the theoretical values for UV disinfection of drinking water (from 0.01 to 0.05 kWh/m$^3$).

Disinfection by UV radiation affects the amount of sodium hypochlorite used as the main disinfectant. In the first scenario, hypochlorite is used to achieve 4-log virus inactivation. To calculate the required amount of hypochlorite, a contact timetable provided by the US Environmental Protection Agency was used [36]. At an average temperature of 15 °C with a pH of 6-9, a contact time of 4 min-mg/l is required to achieve 4-log virus inactivation. Assuming the contact time is 30 minutes, 0.13 mg/l of free chlorine is required. For residual disinfection, anhydrous ammonia is added to produce chloramine. Since chloramine has a low disinfection efficiency, a residual chlorine concentration of 1.0 mg $Cl_2$/l is required. Considering that the formation of chloramine requires a 5:1 weight ratio of chlorine to ammonia, the amount of hypochlorite required for residual disinfection should be 4.45 mg $Cl_2$/l, and the amount of ammonia should be 0.89 mg N/L. In the second scenario, an additional amount of hypochlorite is not required. To completely avoid the formation of DBPs, chloramine is used as a residual disinfectant. The processes considered at the operational stage are described in detail in Table 4.

 

**Table 4.** The amount of electricity and chemicals required for the proposed disinfection scenarios. The values are given for a functional unit of 1 $m^3$ for 1 year (for a reference water flow rate of 0.03 $m^3/s$)

| Process | Units | Quantity (for the first scenario) | Quantity (for the second scenario) |
|---|---|---|---|
| UV energy consumption | KWh | 39320.45 | 275243.15 |
| Liquid Hypochlorite (Chlorine) | Kg | 2144.27 | 1886.16 |
| Anhydrous Ammonia | Kg | 1022.44 | 1022.44 |

### *3.3 Impact assessment and interpretation of results*

The results of the LCA for each impact category for both scenarios are presented in Table 5.

**Table 5.** Results of environmental impact assessment of two disinfection scenarios

| Impact category | Unit | First scenario | Second scenario | Difference (%) |
|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 1.73 | 8.77 | 80 |
| AP | kg $SO_2$ eq | 107.01 | 508.76 | 78 |
| EP | kg $PO_4$ eq | 17.09 | 59.04 | 71 |
| MAEP | kg 1,4 DB eq | 1.15 | 4.16 | 72 |
| TETP | kg 1,4-DB eq | 36.63 | 145.55 | 74 |
| HTP | kg 1,4-DB eq | 1.13 | 5.46 | 79 |

As can be seen from the Table 5, the second scenario has higher environmental impacts compared to the first. This is primarily due to the large amount of electricity needed just for UV disinfection to achieve 4-log virus inactivation. This is consistent with the conclusions of Cashman et al. (2014) [37] and Carré et al. (2017) [38], who reported that the use of traditional UV technology increases the environmental impact during disinfection by increasing the dose of UV radiation, since more electricity is consumed.

The global warming potential (GWP) in the first scenario is 80% less than in the second scenario, and the impact of acidification, eutrophication, marine aquatic ecotoxicity, terrestrial ecotoxicity and toxicity to humans in the first scenario is less by 78 %, 71%, 72%, 74% and 79%, respectively.

The relative contribution of the infrastructure and the operational phase of the first scenario to various categories of impacts is shown in Figure 5.

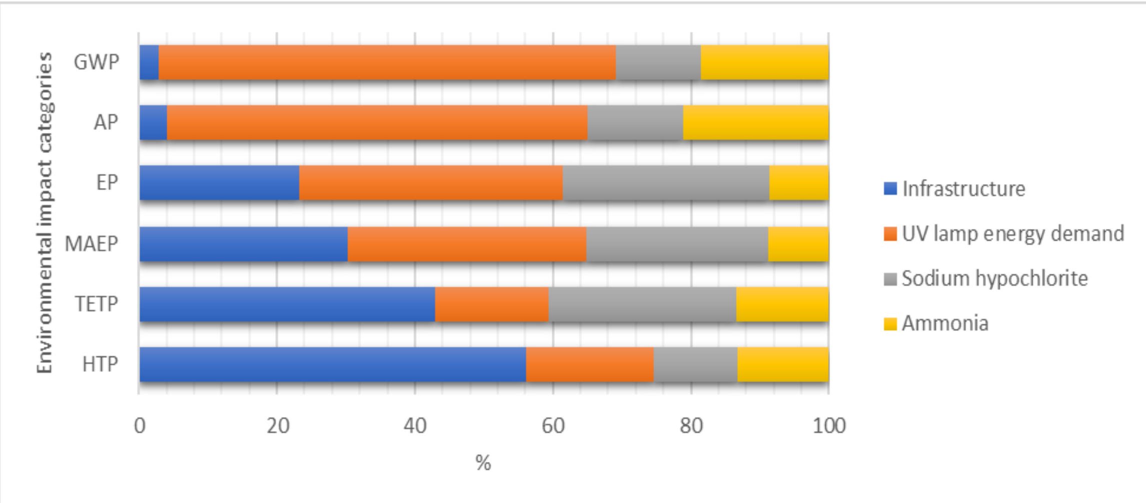


**Figure 5.** The contribution of infrastructure, energy consumption of UV lamps and chemicals to environmental impact of the UV disinfection system at a dose of 30 $mJ/cm^2$

According to the results shown in Figure 5, the largest impact on global warming, acidification, eutrophication, and marine aquatic ecotoxicity is accounted for by electricity: 66%, 60%, 38% and 34%, respectively. The infrastructure of the UV disinfection system has a minimal impact of global warming and acidification, which ranges from 2 to 4%. On the other hand, the infrastructure of the UV disinfection system has a significant impact in several categories, where it ranges from 40% for terrestrial ecotoxicity to 56% for the category of human toxicity exposure. These results are consistent with Carré et al. (2018) [38], where it was indicated that the infrastructure of the UV disinfection system can contribute most to certain categories of environmental impact, depending on the nature of the materials used. However, in other studies, all impacts on the infrastructure of UV systems were insignificant compared to operational impacts [34, 37]. Several studies show that the impact on infrastructure becomes increasingly insignificant as energy consumption increases [29] or the complexity of the water treatment system rises (i.e., the number of processes, the amount of chemicals and energy) [25, 37].

The use of UV technology increases the environmental impact during disinfection by increasing electricity consumption but eliminates the formation of disinfection by-products and significantly reduces the use of dangerous chlorine. In general, the negative impact of the UV disinfection system far outweighs the benefits of refusing chlorine, and the use of chlorine or at least partial use of chlorine is environmentally preferable.

## 4. CONCLUSIONS

This study applied a life cycle environmental assessment methodology to assess the environmental impact of two small drinking water treatment plants located in Ecuador, fed from surface waters with a high content of natural organics. Two scenarios for solving the problem of disinfection by-products have been developed and compared in terms of life cycle assessment and environmental impact. The results show that the greater environmental damage caused by water treatment plants is mainly explaining by use of coagulants such as aluminum sulfate and polyaluminium chloride. At the Latacunga water treatment plant, aluminum sulfate has the largest impacts, while at the Pedro Vicente Maldonado water treatment plant, the contribution of polyaluminium chloride is 65%, 52%, 70% and 62% of the global warming potential, acidification potential, terrestrial ecotoxicity potential and marine aquatic ecotoxicity potential, respectively. It also was revealed that UV disinfection with an intensity of 30 $mJ/cm^2$ for an estimated water consumption of 0.030 $m^3/s$ has the least impact on the environment compared to the second scenario, where the dose of UV radiation is 186 $mJ/cm^2$. For most of the studied criteria, the stage of operation (energy demand of UV lamps, sodium hypochlorite and ammonia) globally has the greatest impact, although for some criteria, such as terrestrial ecotoxicity and human toxicity potential, the main contribution is made by the infrastructure of the UV disinfection system. The environmental impact of the process is only one of the criteria that should be considered when choosing this technology there. In addition, for a comprehensive assessment, it is also necessary to measure operating costs. Therefore, for future research, it is recommended to focus on the integration of environmental and economic life cycle assessment.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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