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Modeling of a Batch bioreactor to bioleach waste electrical and electronic equipment in Guayaquil, Ecuador

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Abstract

The use of electrical and electronic equipment (EEE) has increased considerably worldwide, generating large amounts of waste electrical and electronic equipment (WEEE) of which only 17% is treated. The processing and extraction of metals from printed circuit boards (PCBs) of WEEE is done by a combination of physical and chemical methods, which become highly polluting. Therefore, it is necessary to formulate new eco-friendly strategies to prevent the impact of environmental pollution. The present research proposes to design a Batch bioreactor for the recovery of Cu from WEEE. For this purpose, equations of the modeling of a Batch bioreactor were coupled with real parameters and values taken from the city of Guayaquil and then designed using these values in the AutoCAD design software. A bioreactor was obtained with an optimal agitation considering 8 flat blades for mixing, also the appropriate material is stainless steel, and the optimum working temperature is 28°C. Applying these parameters, a Cu recovery of 96% is obtained in the city of Guayaquil.

Keywords: modeling, Batch bioreactor, EEE, bioleaching, waste, PCBs

Modelización de un biorreactor discontinuo para lixiviar residuos eléctricos y electrónicos en Guayaquil, Ecuador

Resumen

El uso de aparatos eléctricos y electrónicos (AEE) ha aumentado considerablemente en todo el mundo, generando grandes cantidades de residuos de aparatos eléctricos y electrónicos (RAEE) de los cuales sólo el 17% son tratados. El procesamiento y extracción de los metales de las placas de circuitos impresos (PCBs) de los RAEE se realiza mediante una combinación de métodos físicos y químicos, que llegan a ser altamente contaminantes. Por lo que es necesario, formular nuevas estrategias eco-amigables para prevenir el impacto de la contaminación ambiental. La presente investigación plantea diseñar un biorreactor tipo Batch para la recuperación de Cu a partir de los RAEE. Para lo cual se acoplaron ecuaciones del modelado de un biorreactor tipo Batch tomando parámetros y valores reales tomados de la ciudad de Guayaquil y luego se diseña tomando estos valores en el Software de diseño AutoCAD. Se obtuvo un biorreactor con una agitación óptima considerando 8 aspas planas para la mezcla, además el material adecuado resulta ser el acero inoxidable, la temperatura óptima de trabajo 28°C. aplicando estos parámetros se obtiene la recuperación de Cu en la ciudad de Guayaquil del 96%.

Palabras clave: Modelado, biorreactor tipo Batch, RAEE, biolixiviación, residuos, PCBs

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INTRODUCTION

The use of electrical and electronic equipment (EEE) has increased considerably in recent decades throughout the world, generating large amounts of waste electrical and electronic equipment (WEEE) (Das, S. & Ting, Y. 2017). According to a United Nations report in 2019, 53.6 million tons of EEE waste were produced and only 17% was properly processed (ONU, 2021). In Ecuador in 2017 there was 97 kt of EEE on the market, generating 5.5kg per capita of WEEE (Potysz, 2015). WEEE is a very rich source of various metals of economic importance, such as Fe, Cu, Al, Au, Ag, and Pb, however, they also contain toxic and polluting compounds, such as Pb, Cd, Hg, Cr VI, and polychlorinated biphenyls (Das, S. & Ting, Y. 2017).

The processing and extraction of metals from WEEE printed circuit boards is mostly done by a combination of physical and chemical methods. Hydrometallurgy is a branch of metallurgy that deals with the extraction and recovery of metals using a liquid, aqueous or organic solutions. Within biohydrometallurgy is bioleaching, a technique recently recognized as promising for the treatment of electronic waste, and more specifically printed circuit boards (PCBs) (El Universo, 2017.). The conventional recovery methods present several drawbacks, such as high consumption of acids and bases, long residence times, the need for high temperatures, and the complexity of the process, which leads to high costs (Rao et al., 2016; Walawalkar, Nichol, & Azimi, 2016; Pérez, 2016). With the recovery of metals from lean ores and secondary resources, the use of biotechnology has become one of the most promising techniques (Ehrlich, 2004; Petersen et al., 2001). Currently, research is focused on finding strategies for the recovery of critical raw materials from waste electrical and electronic equipment to generate less impact on the environment. (RAEE) (Barmettler, Castelberg, Fabbri y Brandl, 2016; Fathollahzadeh, Eksteen, Kaksonen y Watkin, 2019). Therefore, the development of technologies that apply biological methods, such as a batch-type bioreactor, is necessary, as they are more cost-effective and environmentally friendly routes compared to costly and polluting chemical methods.

For bioleaching, the *Leptospirillum, Acidithiobacillus*, and *Sulfobacillus* genera are the most predominant of this bacterial consortium, with the greatest capacity for Cu biolixiviation in batch bioreactor conditions. Recent research has given promising results in the treatment of PCBs, that is, acidophilic bioleaching in a batch bioreactor, the bacteria are capable of oxidizing various metals and in this way, the recovery would be effective, economical, and eco-friendly (Protomastro, 2013). In Ecuador, the recycling product is not used, so the waste is exported to other countries where the extraction of metals, minerals, and other components is carried out by different methods. It is for this reason that this research proposes the design of a batch bioreactor for the recovery of Cu from WEEE.

Bibliometric analysis

The bibliometric analysis aims to analyze the scientific production regarding the topic " Modeling of a Batch bioreactor to bioleach waste electrical and electronic equipment in Guayaquil, Ecuador". The data is obtained from a bibliographic search in the PubMed repository; this platform is used because the available material is open access, and other databases such as Scopus, Science, or Scielo are discarded since they require credentials for their use.

The keywords used as search criteria are bioreactor OR batch bioreactor, waste electrical AND electronic equipment, AND WEEE, OR bioleaching, getting a total of 369 articles. The data is filtered with a time cut of 5 years corresponding to the period from 2018 to 2022, obtaining a total of 217 articles to be analyzed. For the analysis, the bibliometric library of the statistical software R is used, which generates a graphic report of the search metrics as detailed below:

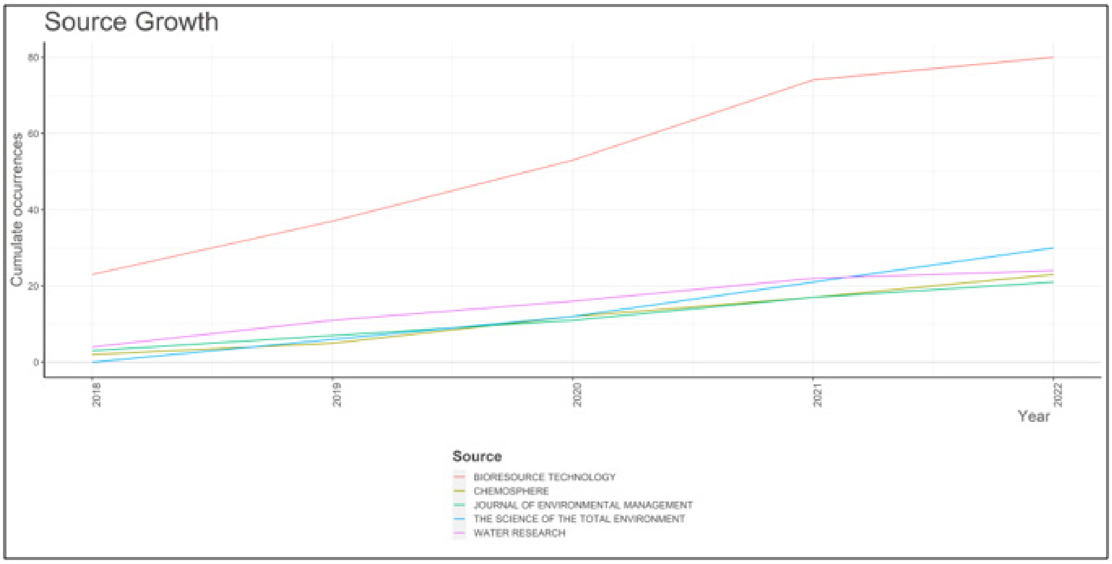

Fig 1. Source Growth. Increase in bibliographic material by source for the period 2018 -2022

The figure 1 shows a greater production of bibliographic material regarding the subject in the period from 2020 to 2021, with Bioresource technology being the source that leads the research related to the search criteria used by a wide difference.

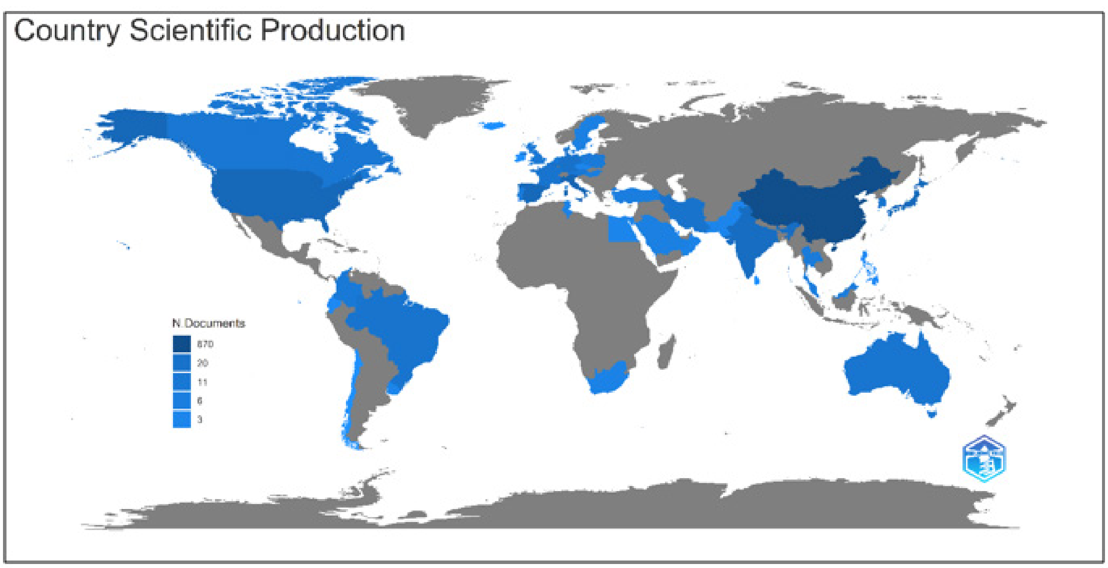

Fig 2. Country Scientific Production.

The figure 2 shows that the largest amount of scientific information on the subject is being generated in Asia and North America, with China being the country that heads the list, followed by the United States. In Europe, Spain and Italy stand out while in Latin America the country with the highest production in Brazil. It is also observed that in Ecuador there is a deficit in terms of this type of research, however, it is not a foreign topic to its lines of work, since there are at least three occurrences related to the topic.

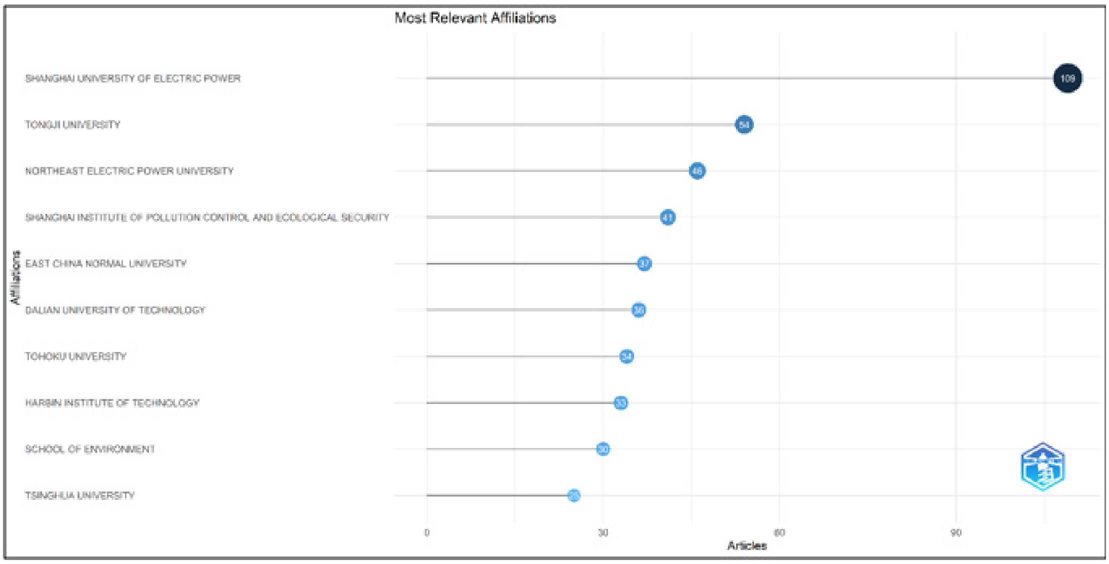

Fig 3. Most Relevant Affiliations.

This figure 3 shows that institutionally the scientific production of the content of interest is highly focused and is a highly specialized topic. Of the total occurrences of the search, the Shanghai University of Electric Power produces about twice as much information as the other institutions, followed by Tongji University.

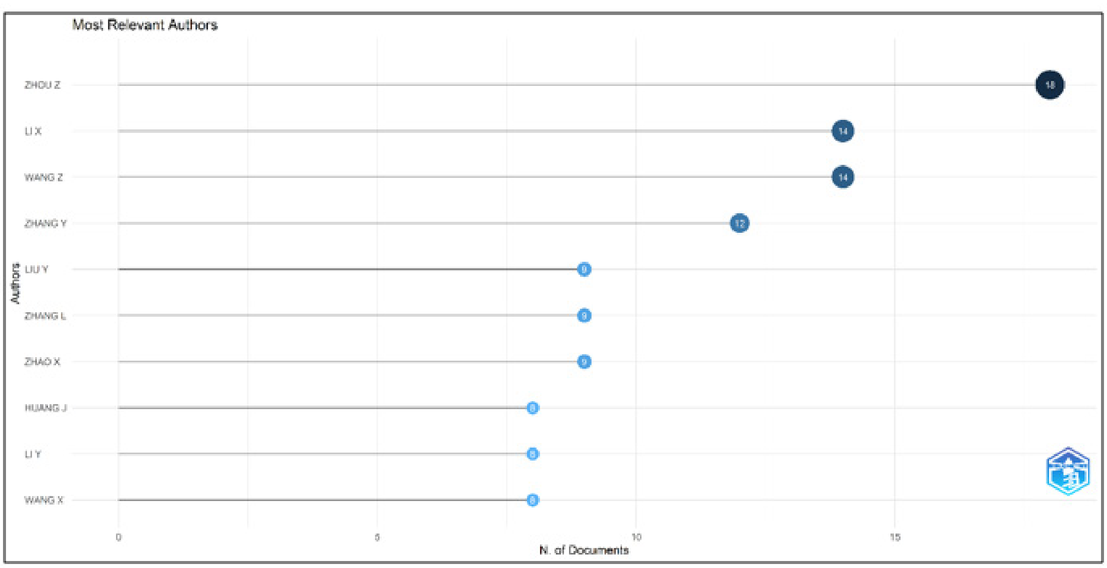

Fig 4. Most Relevant Authors

The figure 4 provides the names of the most relevant authors in the field of research of the selected topic. Zhou, Z. heads the list of authors with the most number of documents in which he participates. According to Scopus (2022), Zhou is a professor at the Faculty of Environment and Resources at a University in China and has published more than 30 articles related to bioreactors and methane production. Authors Li and Wang are next on the list with a total of 14 publications.

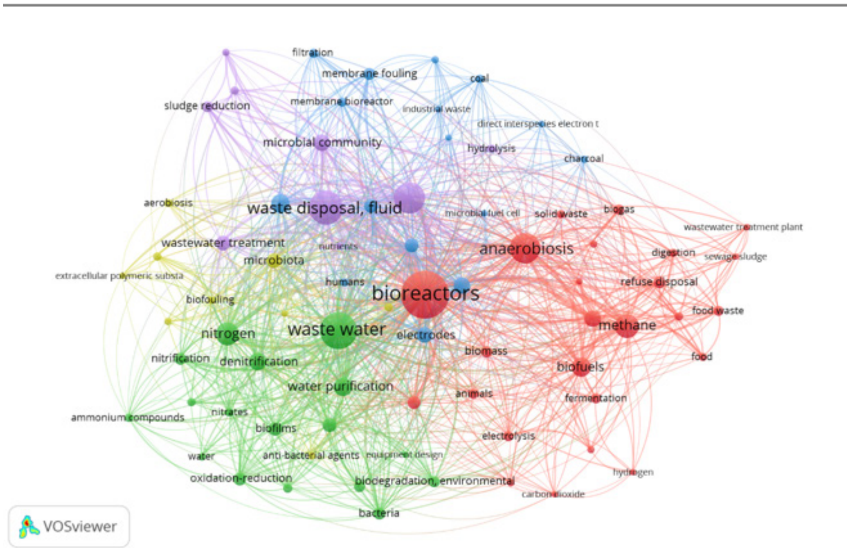

Fig 5. Co-occurrence network of keywords.

The figure 5 is a graphic representation of a network of co-occurrences of the keywords of the different articles analyzed. In the figure, it can be seen that the words bioreactors, wastewater, waste disposal, and anaerobiosis are the most relevant and most used. 3 main groups are identified: red, in which words such as methane, biofuels, biomass, and biogas are found, referring to everything that the mechanism of a bioreactor entails. On the other hand, the purple group has words like microbial community, industrial waste, and hydrolysis. And finally green, with words like nitrogen, nitrification, biodegradation, and environmental.

The results of the bibliometric analysis show that the main information regarding the topic "Modeling of a Batch bioreactor to bioleach waste electrical and electronic equipment in Guayaquil, Ecuador" comes from China, shown in fig 2, and can be evidenced again in fig 4 as Zhou, a Chinese researcher, is the author with the most allusive publications. to the topic. It should be taken into account for future information searches that the most frequent and relevant keywords on the subject are biorectors, waste disposal, and waste water, as evidenced in figure 5.

Body

Materials and methods

- **Parameters and conditions**

This paper shows the equations and variables that are applied to model the bioreactor, considering the reaction kinetics as a fundamental parameter for the approach of other unknowns, as well as the adequacy of this by means of the Arrhenius equation.

Table 1. Equations and variables applied for the calculation of the bioreactor design.

Number	Calculation	Equation	Variables
1	Concentration of recovered ore	$C = Be^{-kt}$	B= maximum concentration of recovered ore K= reaction kinetics t= time
2	Adequacy of Arrhenius reaction kinetics	$k = \frac{Ln\left(\frac{C}{B}\right)}{-t}$	B= Maximum concentration of mineral obtained C= Reactant concentration t= time
3	Adecuación de cinética de reacción de Arrhenius	$K1 = K2e^{\frac{Ea(T1-T2)}{R*T1*T2}}$	K1= Kinetics to obtain K2= Reference kinetics T1= Reference temperature T2= Working temperature Ea= Activation energy constant R= Universal gas constant. B= Maximum concentration of mineral obtained C= Reactant concentration K= Reaction kinetics

4	Holding time Hydraulic THR	$t = \frac{Ln\left(\frac{C}{B}\right)}{-k}$	B= Maximum concentration of mineral obtained C= Reactant concentration K= Reaction kinetics
5	Bioreactor volume	$V = HRT * Vd$	HRT= hydraulic retention time Vd= daily inflow volume

Note: Table 1. details the equations for bioreactor design calculation from Masari (2016), Barrera-Herrera et all (2020) & Habau et all (2020).

- **Bioreactor design**

For the design of the bioreactor, it is ensured that each part of the fermentation system has the same conditions to guarantee its maximum efficiency, the AutoCAD 2023 program is made at a 1:1 scale.

In addition, for correct optimization, the following operating rules proposed by Hernández et al. (2013): constant fermentation volume (no leaks), temperature/pH control, no entry of contaminating microorganisms, and properly mixed culture volume with evenly distributed cells.

On the other hand, among the basic components to take into account in the design of the reactor is the material, the air inlet or outlet, the culture medium inlet, the product outlet obtained, and the mechanical agitation system (Venkata Dasu et al., 2003).

Table 3. Equations needed for bioreactor sizing.

Name	Equations	Where:
Useful volume	$V_u = V_p * t$	*V_p=production volume per month*
Total volume	$V_T = V_u + (V_u * 0.2)$	*0.2=secutity factor*
Fermentation chamber height	$h = \sqrt[3]{\frac{49}{9} * \frac{V_T}{\pi}}$	*V_T=total volume*
Fermentation chamber diameter	$d = \frac{6h}{7}$	*h=fermentation chamber height*
Stirrer width	$D = \frac{2d}{3}$	*d=chamber diameter*
Agitator-tank base distance	$C = \frac{d}{6}$	*d=chamber diameter*
Blade width	$W = \frac{D}{8}$	*D=stirrer width*
Power number	N_p	*It is calculated graphically: the relationship between the Reynolds number and the power number (depending on the shape of the agitator blade)*
Power supplied	$P = N_p * \rho * N^3 * D^5$	*N_p=power number ρ=bioreactor mix density N=rotation speed D=stirrer width*

Source: Coupled from Riet & Tramper (1991).

Results

- **Value table**

The following parameters are proposed according to the environmental conditions where the bioreactor is intended to implement, in addition to the state estimates in terms of WEEE recovery and therefore PCBs, the study is implemented for the recovery of copper asking to adapt to other metals present in the PCBs that react with Lewis acids and bases

Table 2. Real values and parameters

Parameter	Value
Working temperature (°C)	28
Monthly PCBs mass (Kg)	14000
Reaction kinetics K (1/d)	0.415
Bioreactor Volume (m3)	15.08

Hydraulic retention time THR (days)	5.8
Monthly copper production (Kg)	130
Particle size (µm)	750

The following parameters are proposed based on the environmental conditions for the bioreactor design, in addition to the state estimates in terms of WEEE recovery and consequently PCBs. The study is implemented for the recovery of copper that can be adapted to other metals present in the PCBs that react with Lewis acids and bases.

Table 2 shows the values proposed based on previous research to optimize the volume of the bioreactor and maximize performance.

Table 4. Real values that are used in modeling.

Parameter	Value
Useful volume	$V_{util}= 62\ m^3$
Total volume	$V_T=74.5\ m^3$
Fermentation chamber height	$h= 5\ m$
Fermentation chamber diameter	$d=4.3\ m$
Stirrer width	$D=2.9\ m$
Agitator-tank base distance	$C= 0.71\ m$
Blade width	$W=0.36\ m$
Power supplied	$P= 8.86x10^6\ W$

Following the parameters mentioned above, the design of the Batch-type bioreactor suitable for the recovery of metals from electronic waste is created in AutoCAD 2023.

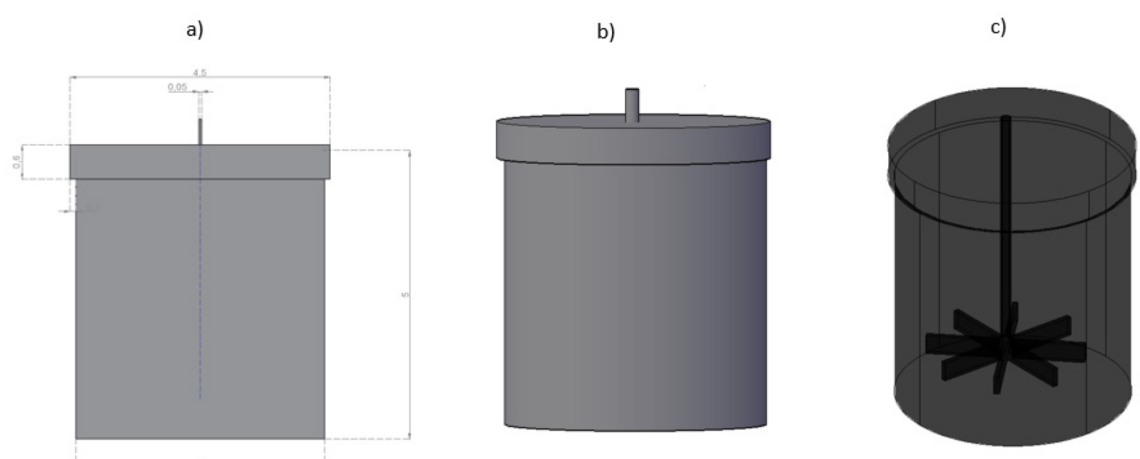

Figure 6. Batch-type bioreactor design. a) Plan of the fermentation tank.
b) Fermentation tank in 3D. c) 3D fermentation tank in internal view.
Source: Own elaboration

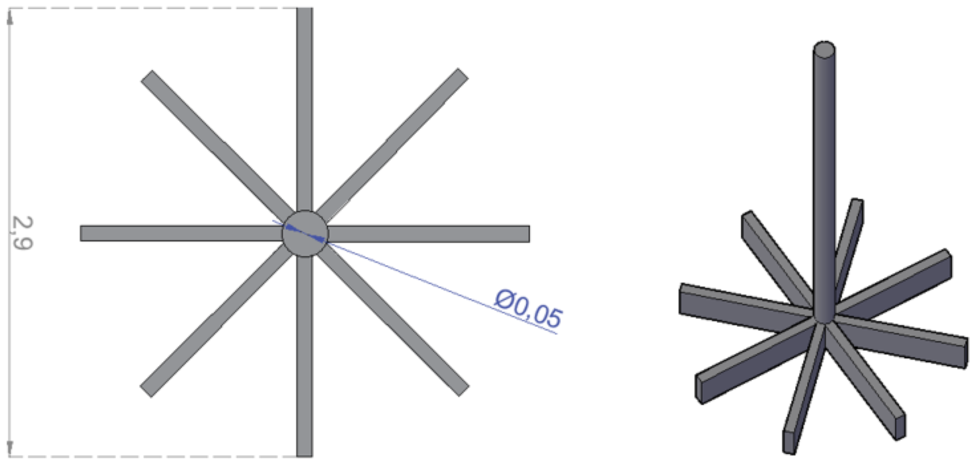

Figure 6. Stirring paddle design. a) Pallet plane. b) 3D fermentation palette. c) Fermentation tank in 3D
Source: Own elaboration

Discussion

On average, 90% of the intrinsic economic value of PCBs is found in the precious metals contained in the plates, Au, Ag, Cu, Zn, among others (Cui and Zhang, 2008). The genera Leptospirillum, Acidithiobacillus, and Sulfobacillus used for the treatment of PCBs work in acidophilic consortium BRGM-KCC in batch bioreactors, and previous research has shown them to be efficient in the treatment of WEEE.

The predominant microorganisms of the BRGM-KCC consortium belong to the Leptospirillum, Acidithiobacillus and Sulfobacillus genera, which more efficiently oxidize iron or sulfur, or both in Batch bioreactor conditions mentioned by Dueñas A., (2021). According to Hubau et al., (2020) the optimum hydraulic retention time (HRT) is 48 hours (2d) for a 96% recovery of Cu from WEEE at 36°C. To maintain allowable margins of error, 80% Cu leaching is taken as a reference. This is significantly higher compared to obtaining metals by the pyrometallurgical process which only recovers 37.7%. Therefore, it is demonstrated that the implementation of a batch type bioreactor using the equations in Table 1 is capable of estimating the appropriate parameters to recover metals in this case Cu.

In a study conducted by Hubau et al., (2020) it is reported that the optimum temperature of the consortium is 36°C, however in the proposed location (Guayaquil) the lowest temperature per year is 20°C and the maximum temperature is 32°C, arbitrarily 23°C is used as reference expecting that most of the year there will be unfavorable environmental conditions, through appropriate working conditions such as the addition of greenhouse and thermal insulation in the bioreactor it is assumed that it increases 5°C to the conditions reaching 28°C.

Equation (5) is used to obtain the volume of the Barrera-Herrera (2020) bioreactor in Table 1, where Vd is estimated based on the percentage of water (99%) and PCB dust (1%) proposed by Hubau (2020), here it is considered that only 2% of the total WEEE is PCB (Permanyer, 2013). It is proposed to treat the WEEE produced annually in Ecuador, according to the Ministry of the Environment (2022).

Both the fermentation tank and the stirring paddles meet the main characteristics of being sterilizable, resistant to corrosion, and built with non-toxic materials (Riet & Tramper, 1991). Therefore, the use of type 304 austenitic stainless steel is proposed due to its ductility and excellent weldability (Norris et al., 2013). On the other hand, for the optimal agitation of the bioreactor, 8 flat-blade turbine-type blades are considered, since this generates a radial movement, as well as a vertical movement concerning the agitator stem, that is, it can produce a vortex in the mixture (Hernández et al., 2013).

Conclusion

Biohydrometallurgy is a subject little explored in Ecuador, with China being the largest producer of scientific content related to the subject. However, the scientific production in this regard is constantly increasing. It is also concluded that Guayaquil is a suitable city for the implementation of this project, due to its environmental conditions, which are coupled with the necessary parameters to carry out the bioreactor, allowing this method to carry out leaching of 80% Cu, showing to be more effective concerning the pyrometallurgical process that only has a 37.7. This research is of environmental, social, and economic relevance, continuing with this line of research will allow the implementation of WEEE treatment plants in Ecuador.

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