Facultad de Ingeniería
ISSN: 0121-1129
ISSN: 2357-5328
revista.ingenieria@uptc.edu.co
Universidad Pedagógica y Tecnológica de Colombia
Colombia

Rodríguez-Ballesteros, Johanna-Elvira; Rodríguez-Loaiza, Diana-Catalina; Peñuela-Mesa, Gustavo Antonio
Comparison of in Batch Aerobic and Anaerobic Processes for the Degradation of Organic Matter in a Tropical Reservoir
Facultad de Ingeniería, vol. 29, no. 54, 2020, -March
Universidad Pedagógica y Tecnológica de Colombia
Colombia

DOI: https://doi.org/10.19053/01211129.v29.n54.2020.10892

Comparison of in Batch Aerobic and Anaerobic Processes for the Degradation of Organic Matter in a Tropical Reservoir

Johanna-Elvira Rodríguez-Ballesteros; Diana-Catalina Rodríguez-Loaiza; Gustavo-Antonio Peñuela-Mesa

Citation: J.-E. Rodríguez-Ballesteros, D.-C. Rodríguez-Loaiza, and G.-A. Peñuela-Mesa, "Comparison of in Batch Aerobic and Anaerobic Processes for the Degradation of Organic Matter in a Tropical Reservoir," *Revista Facultad de Ingeniería*, vol. 29 (54), e10892, 2020. https://doi.org/10.19053/01211129.v29.n54.2020.10892

Received: April 21, 2020; **Accepted:** June 21, 2020;
Published: June 30, 2020

Conflict of interest: The authors state there is no conflict of interest.

Comparison of in Batch Aerobic and Anaerobic Processes for the Degradation of Organic Matter in a Tropical Reservoir

Johanna-Elvira Rodríguez-Ballesteros[1]
Diana-Catalina Rodríguez-Loaiza[2]
Gustavo Antonio Peñuela-Mesa[3]

Abstract

The decomposition of submerged organic matter after the flooding process of a reservoir and the organic matter transported by the tributaries that supply it, gives rise to the formation of greenhouse gases (GHG), such as CO_2 and CH_4, product of the aerobic and anaerobic biological processes that take place both on the surface and at the bottom of the reservoir. In this study, the dynamics of aerobic and anaerobic processes as well as the generation of greenhouse gases in the degradation of organic matter, present in a tropical reservoir, were compared. Batch reactors and plant material extracted from the protection strip were used. Likewise, the behavior of the variation of the COD, physicochemical parameters such as pH, dissolved oxygen, redox potential, and conductivity were evaluated, and the kinetic constants that represent the behavior of organic matter were defined. The results showed that the degradation of the organic material leads to the generation of GHG, however, when using water plus vegetal material, the GHG increased considerably after a time. This process is due to the fact that the plant material suffers the breakdown of its polymer chains and so it degrades more quickly, which increases

---

[1] Universidad Industrial de Santander (Bucaramanga-Santander, Colombia). ORCID: 0000-0001-5479-908X
[2] Ph. D. Universidad de Antioquia (Medellín-Antioquia, Colombia). diana.rodriguez@udea.edu.co. ORCID: 0000-0002-9310-6925
[3] Ph. D. Universidad de Antioquia (Medellín-Antioquia, Colombia). gustavo.penuela@udea.edu.co. ORCID: 0000-0003-3065-0285

Revista Facultad de Ingeniería (Rev. Fac. Ing.) Vol. 29 (54), e10892. 2020. Tunja-Boyacá, Colombia.
L-ISSN: 0121-1129, e-ISSN: 2357-5328, DOI: https://doi.org/10.19053/01211129.v29.n54.2020.10892

the concentration of organic matter available to microorganisms. GHG values were on average 10.290 g CO_{2eq}/m^2.d with water only, and 24.536 g CO_{2eq}/m^2.d with water and vegetal material for aerobic processes. In anaerobic processes, the values were on average 12.056 g CO_{2eq}/m^2.d with water only, and 33.470 g CO_{2eq}/m^2.d with water plus vegetal material. These laboratory scale results allow analyzing the behavior of the reservoir and the incidence of flooded plant material on GHGs.

Keywords: biological processes; discontinuous; greenhouse effect; organic matter.

Comparación de procesos aerobios y anaerobios en batch para la degradación de la materia orgánica en un embalse tropical

Resumen

La descomposición de la materia orgánica sumergida posterior al proceso de inundación de un embalse y la materia orgánica transportada por los tributarios que surten éste, da lugar a la formación de gases de efecto invernadero (GEI) como el CO_2 y CH_4, producto de los procesos biológicos aerobios y anaerobios que se llevan a cabo tanto en la superficie como en el fondo. En este estudio se comparó la dinámica de los procesos aerobios y anaerobios, y la generación de gases de efecto invernadero en la degradación de la materia orgánica presente en el agua de un embalse tropical, empleando reactores en batch y material vegetal extraído de la franja de protección de este. Asimismo, se evaluó el comportamiento de la variación de la DQO, parámetros fisicoquímicos como el pH, oxígeno disuelto, potencial redox y conductividad, y se definieron las constantes cinéticas que representan el comportamiento de la materia orgánica. Los resultados demostraron que la degradación del material orgánico da lugar a la generación de GEI, sin embargo, al emplear agua más material vegetal, los GEI aumentaron considerablemente después de un tiempo, proceso que se debe a que el material vegetal sufre el rompimiento de sus cadenas poliméricas y se puede degradar más rápidamente, lo que incrementa la concentración de materia orgánica disponible para los microrganismos. Los valores de GEI fueron en promedio de 10.290 g CO_{2eq}/m^2.d solo con agua y 24.536 g CO_{2eq}/m^2.d con agua y material vegetal para los procesos aerobios, mientras que en los procesos anaerobios fueron en promedio de 12.056

g $CO_{2eq}/m^2.d$ solo con agua y 33.470 g $CO_{2eq}/m^2.d$ con agua más material vegetal. Estos resultados a escala de laboratorio permiten analizar el comportamiento del embalse y la incidencia que tiene el material vegetal inundado sobre los GEI.

Palabras clave: discontinuo; efecto invernadero; materia orgánica; procesos biológicos.

Comparação de processos aeróbios e anaeróbios em batch para a degradação da matéria orgânica em uma barragem tropical

Resumo

A decomposição da matéria orgânica submergida posterior ao processo de inundação de uma barragem e a matéria orgânica transportada pelos tributários que a surtem, dá lugar à formação de gases de efeito estufa (GEI) como o CO2 e CH4, produto dos processos biológicos aeróbios e anaeróbios que se levam a cabo tanto na superfície como no fundo. Neste estudo comparou-se a dinâmica dos processos aeróbios e anaeróbios, e a geração de gases de efeito estufa na degradação da matéria orgânica presente na água de uma barragem tropical, empregando reatores em batch e material vegetal extraído da faixa de proteção deste. Assim mesmo, avaliou-se o comportamento da variação da DQO, parâmetros físico-químicos como o pH, oxigênio dissolvido, potencial redox e condutividade, e definiram-se as constantes cinéticas que representam o comportamento da matéria orgânica. Os resultados demonstraram que a degradação do material orgânico dá lugar à geração de GEI, porém, ao empregar água mais material vegetal, os GEI aumentaram consideravelmente depois de um tempo, processo que se deve a que o material vegetal sofre o rompimento de suas cadeias poliméricas e pode-se degradar mais rapidamente, o que incrementa a concentração de matéria orgânica disponível para os microrganismos. Os valores de GEI foram em média de 10.290 g CO2eq/m2.d só com água e 24.536 g CO2eq/m2.d com água e material vegetal para os processos aeróbios, enquanto que nos processos anaeróbios foram em média de 12.056 g CO2eq/m2.d só com água e 33.470 g CO2eq/m2.d com água mais material vegetal. Estes resultados a escala de laboratório permitem analisar o comportamento da barragem e a incidência que tem o material vegetal inundado sobre os GEI.

Palavras chave: descontínuo; efeito estufa; matéria orgânica; processos biológicos.

I. INTRODUCTION

Greenhouse gases (GHG) are a problem of great importance, since they give rise to climate change, which directly affects society [1] and leads to problems of droughts or floods [2]. For this reason, the study of greenhouse gases (GHG) is essential, gases such as carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (N_2O), which are released into the environment either naturally or anthropogenically [3]. GHG concentrations in the atmosphere cause an alteration in the terrestrial climate system, either causing an increase or decrease in the Earth's surface temperature [4]. A reservoir is defined as a large body of water that covers a land surface and has been modified to produce hydroelectricity, supply drinking water, for irrigation in agriculture, among other purposes [5].

In the formation and emission of GHGs, one of the most relevant issues underlying the issue of reservoirs is the organic matter in the soil and the biomass of the plants that are flooded [6]. The aerobic / anaerobic degradation of organic matter produces carbon dioxide, which is reduced to methane in an anoxic environment, and is subsequently emitted into the atmosphere [7]. These systems are then forced to rapidly decompose all flooded organic materials in addition to the organic charge entering from the tributaries, producing CO_2 and CH_4 as the final decomposition product [8]. On the other hand, microorganisms require a source of energy and carbon, which they obtain from the degradation of the organic matter present in the reservoir and, additionally, from other constituents of the water in the tributaries such as nitrogen and phosphorous; in the case of aerobic systems, there are also high concentrations of dissolved oxygen in water [9]. Among the metabolic activities carried out by microorganisms, three cases are mainly distinguished [10]: aerobic systems occur when there is dissolved oxygen in the medium and, therefore, the microorganisms use it as an electron acceptor for the transformation of organic matter, resulting in a high energy level in generation, which is later used for cell growth [11]. For anaerobic systems, the final electron acceptor is CO_2 [12], as a result of this biological process, most of the organic matter is transformed to CH_4 [13]. Finally, in anoxic systems, the electron acceptor is usually nitrate, with the final result being the release of N_2O or N_2, depending on the behavior of the present microorganisms [14].

In this study, the generation of greenhouse gases and the factors involved in the transformation of organic matter were evaluated, based on aerobic and anaerobic degradation tests in batch reactors, using water from a tropical reservoir, and simulating the real conditions present in the reservoir before and after filling it.

II. MATERIALS AND METHODS

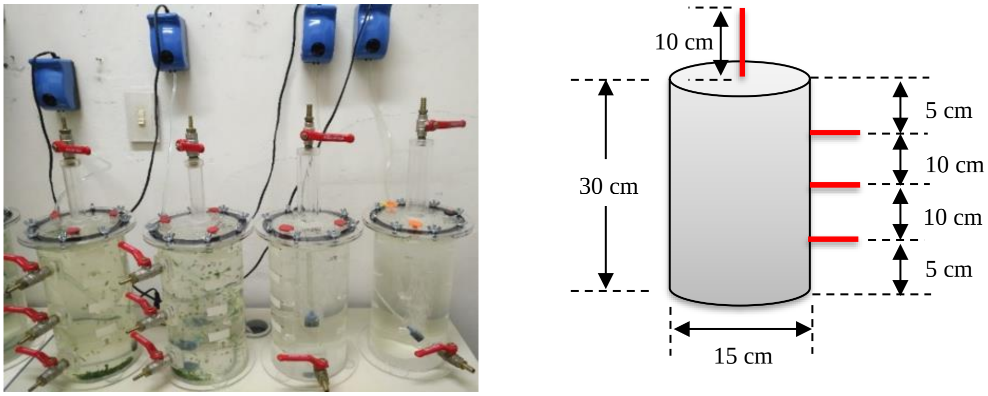
The description of the methodology used in this study is presented below.

A. Sample Study and Collection Area

The samples for laboratory analysis were obtained from a tropical reservoir located in the department of Santander, Colombia; downstream of the Sogamoso river and upstream of the mouth of the Magdalena river [15]. This study focused on two strategic points of the reservoir: P1 that corresponds to the entrance of the Sogamoso river that constitutes one of the main tributaries of the reservoir, in addition to be the confluence between the Suarez river and the Chicamocha river. And the second point, P2, corresponds to the entry point of a creek that presents settlements of nearby populations. Additionally, prior to filling the reservoir, this area had livestock activity as its main use, which leads to the presence of a high load of organic matter, to a point that it generates a high degree of environmental interest. A total of 8 water samples were collected, 4 samples at each point, in the photic zone (20 cm from the water surface), during different times of the year; dry and rain. All samples were collected in plastic containers with a 10-liter capacity, in order to be transported to the laboratory of the Pollution Diagnosis and Control Group (GDCON), where they were refrigerated at 4ºC, and proceeded to the assembly of the reactors and other experiments.

B. Experimental Setup

The experiments were carried out in 16 acrylic reactors; 8 for aerobic tests and 8 for anaerobes (Figure 1), with a useful volume of 5 L each and a height/diameter ratio of 2. For aerobic tests, each reactor had an air pump connected with aeration capacity 1200 cc/min and two fine bubble diffusers. The reactors had three quick-opening valves that allowed water samples to be taken, and an upper valve to collect the gas samples for analysis of CO_2 and CH_4 (every 5 days), using 0.25 L tedlar bags and an extraction pump. GilAir 3 model gases, with an operating flow from 850 to 3000 cc/min and also, avoided the loss of water by evaporation were used. The reactors operated for 200 days, at a temperature of 25°C, pH in the range of 7-8, and, for aerobic reactors, the dissolved oxygen remained > 4 mg/L.



a. b.

Fig. 1. Experimental assembly in reactors. A) Reactors. B) Dimensions of the reactors.

For the experimental analysis, four reactors were used to evaluate the conditions of each sampling point, with water only and water with plant material, under aerobic and anaerobic conditions, both in duplicate. The plant material used was extracted from the protection strip of the reservoir and was composed of grass and leaf litter of different species, which were previously characterized, crushed, sieved at 0.5 μm and added in proportions of 3 g (wet weight) for each reactor, following the methodology described by Lopera et al. [16].

C. Laboratory Analysis

For the analysis of the parameters in situ, a WTW 3210 conductivity meter was used to measure conductivity, as well as an HQ40d multi-parameter equipment for the measurement of dissolved oxygen, and a WTW pH 7110 pH meter to read the pH.

Additionally, the physicochemical parameters of Chemical Oxygen Demand (COD), Total Solids (TS), Volatiles (VS), Total Suspended Solids (TSS), Nitrates (NO_3^-), Total Phosphorus in water, Total Nitrogen Kjeldahl (TNK), and Ammonium (NH_4^+) in vegetal material, followed the analytical criteria of the Standard Methods [17]. For the determination of Dissolved Organic Carbon (DOC), the high-temperature combustion method was used, previously filtering the sample to be analyzed through a 0.45 µm Nylon membrane filter in 40 mL vials, which were previously muffled at an approximate temperature of 550ºC for at least an hour. Then, each of the vials were preserved at pH < 2 using H_3PO_4 phosphoric acid, to be read later on the Apollo 9000 total organic carbon analyzer. The carbon content in the grass and the litter was obtained by the product of dry biomass and organic carbon determined in the laboratory, using method B: Wet oxidation (Walkley and Black Method) of NTC 5403. All analysis were performed in the laboratory of the GDCON group, accredited for water analysis by IDEAM under NTC-ISO/IEC 17025, Resolution 1665 of July 12, 2011.

Gas samples were analyzed using an Agilent 7890B gas chromatograph with a three-valve system and two detectors with 1/8” packed stainless steel columns (HayeSep Q 80/100 UM 3Ft 1/8 2 mm), with 5975C mass detector for the determination of both CO_2 and CH_4. The chromatographic conditions were 100ºC for the oven temperature, 325ºC for the methanizer, and 1 mL of sample in the loop. As reference material, a mixture of certified standard gases (Matheson, USA) containing CO_2 (2030 ppm v / v), CH_4 (2000 ppm v / v), and helium was used as the equilibrium gas. Nitrogen was selected as a carrier gas during chromatographic separation. Retention times were 1,428 min for CH_4 and 2,650 min for CO_2. Finally, the CH_4 results were converted to CO_{2eq} multiplying by 28, according to the guidelines established by the IPCC [3].

D. Statistical Analysis

The correlations between the studied variables of COD, COD and GHG were determined; Pearson correlations in the interval [-1 to 1], with a sample size of 64. Statistical analysis was performed with the 3.1.1 version of the R software.

III. RESULTS AND ANALYSIS

The results found after experimentation with batch reactors are presented below.

A. Initial Characterization

An initial characterization of the water from the sampling stations P1 and P2 selected in this study was performed (Table 1). In the case of organic matter, P1 presented higher concentrations, compared to P2, with a COD concentration of 20.23 mg O_2/L and a DOC concentration of 10.39 mg C/L, compared to concentrations of 16.0 mg O_2/L and 9.90 mg C/L, respectively, for P2. On the other hand, a higher concentration of TS and VS in P2 was evident, with values of 242.6 mg/L and 56.4 mg/L, respectively, compared to P1, in which concentrations of the order of 142.0 mg/L of TS and 47.8 mg/L of VS were found. At both points, it is evident that there is a greater contribution of solids of an inorganic nature, which may be related to the mineral extraction processes carried out near the tail of the reservoir, which introduce a high content of this material in rivers and nearby sources. Additionally, regarding the TSS, values below the detection limit (< 5 mg/L) were reported in both cases, indicating a large contribution of dissolved solids and corroborating the aforementioned. It is highlighted that, in both sampling points, the trend is towards a slightly basic pH, with 8.1 and 7.6 for P1 and P2, respectively. This can be related to the contribution of nutrients at these two points, and especially in P2, where phosphorus total had a value of 0.38 mg P/L, while in P1 the concentration was lower (0.16 mg P/L). It is important to highlight that in P1 there are nearby settlements which can lead to detergent discharges or even contribution by agricultural fertilizers in nearby areas. These results contrast with the calculation of the quality index (ICA) of six variables [10], since in both sampling points the result was a regular water quality with a yellow indicator, being more polluted in this case P2 compared to P1, having the lowest ICA (0.59).

Table 1. Reservoir water characterization

Parameter	Units	Sample station	
		P1	P2
TS	mg/L	142.0	242.6
VS	mg/L	47.8	56.3
TSS	mg/L	< 5.0	< 5.0
DOC	mg C/L	10.39	9.90
COD	mg O_2/L	20.23	16.0
Nitrates	mg NO_3^-/L	0.32	0.54
Total phosphorus	mg P/L	0.16	0.38
pH	-	8.1	7.6
Dissolved oxygen	mg/L	6.4	6.3
Conductivity	uS/cm	180	200
Temperature	ºC	26.4	27.2
Heterotrophs	UFC/mL	7.5×10^5	3.8×10^6
Quality Index*	-	0.62 Regular	0.59 Regular

*Calculated according to IDEAM [10], with 6 variables

Finally, to verify the ratio of organic matter and nutrients necessary to promote the growth of both aerobic and anaerobic microorganisms, the COD/N/P ratio was calculated. For P1 the ratio was 100/2/0.5 (350/5/2) and for P2 it was 100/3/2 (350/11/7). Studies carried out by Escaler and Mujeriego [18], established that a ratio of 100/5/1 is usually optimal for carrying out aerobic biological processes, while Mata [19] determined an optimal ratio of 350/7/1 in anaerobe processes, indicating that anaerobic microorganisms have a lower nutritional requirement compared to aerobes, due to their high energy performance. Taking into account the above, at both sampling points (P1 and P2), the ratio of organic matter, nitrogen, and phosphorus significantly favors anaerobic processes, especially in P2. In both cases, there is a nitrogen deficit to carry out aerobic biological processes.

The initial characterization of the vegetal material (Table 2) was carried out on the grass and leaf litter, the latter being the leaves that fall from the trees and cover the soil. The percentage of both nutrients and organic matter was similar in grass and leaf litter, with values of 82.99% Organic Matter (OM), 48.14% Organic Carbon (OC) and 1.51% Total Kjeldahl Nitrogen (TKN) for the grass. Compared to the litter which had 70.76% of OM, 41.04% of OC and 1.75% of TKN, being in this case the OM and the OC slightly lower and the TKN slightly higher than in the grass. On the other hand, regarding the available nutrients, the litter presented higher concentrations than the grass, with values of 448.38 mg NH_4^+/Kg and 2103.75 mg PO_4^{3-}/Kg. Studies carried out by Aceñolaza et al. [20], suggest that the decomposition of plant material such as leaf litter constitutes the main source of nutrients supply in the soil, which constitute a fundamental part of the biogeochemical cycles of both carbon, nitrogen and phosphorus.

Table 2. Vegetal material characterization

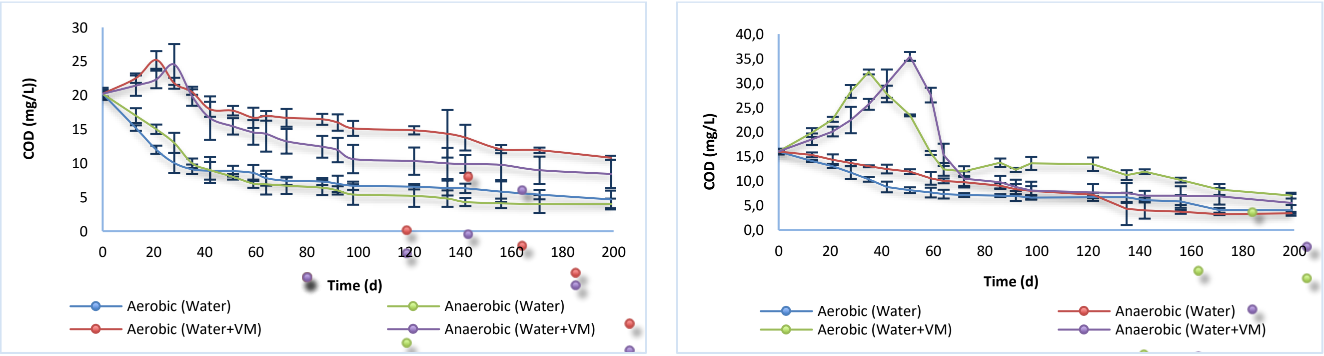
Vegetal Material	OM	OC	TKN	NH_4^+	PO_4^{3-}
	--------- (%)---------			--------- (mg/Kg) ---------	
Grass	82.99 ± 4.28	48.14 ± 2.48	1.51 ± 0.39	284.32 ± 122.18	1033.16 ± 144.66
Leaf litter	70.76 ± 10.73	41.04 ± 6.22	1.75 ± 0.38	448.38 ± 81.96	2103.75 ± 453.61

OM = Organic Matter; OC = Organic Carbon; TKN = Total Kjeldahl Nitrogen

B. Degradation Kinetics of Organic Matter

Figure 2 shows the degradation process of organic matter in batch reactors for sampling point P1 (Figure 2a) and for P2 (Figure 2b), in both cases under both aerobic and anaerobic conditions. In the case of P1, with water only, the results showed that during the first days (0 - 42 d), the degradation rate was higher in the aerobic process compared to the anaerobic one. However, despite the fact that the anaerobic degradation was slower at the beginning, a greater degradation of the COD was reached at a time of 200 d (4.03 mg/L), compared to the COD in the aerobic process, which was 4.68 mg/L for this same time. These results indicate that the aerobic microorganisms in this case used a greater amount of initial energy for their growth, which led to a higher rate of degradation in the first days. On the contrary, for anaerobic processes, although growth could be less in the first days of degradation (0-42 d), they were possibly better adapted to the present conditions, which caused a greater degradation of the final organic matter. Additionally, the aerobic microorganisms could enter the endogenous phase later, due to using a greater amount of substrate in the initial days, as they had a greater amount of biomass and a smaller amount of substrate, which could limit the degradation process. Corrales et al. [13] defined that the maximum growth rate (μmax) for aerobic microorganisms was of the order of 7.2 d^{-1}, much higher compared to anaerobic microorganisms, in which it was defined between 0.45 - 1.0 d^{-1}. Additionally, the performance coefficient (Y) for aerobes was defined as 0.430 g SSV/g COD, and for anaerobes as 0.18 g SSV/g COD, which supports the ratio of degradation of organic matter, compared to the amount of biomass generated in an aerobic and anaerobic biological process. This would mean that, in an aerobic batch reactor having a higher Y, faster endogenous respiration conditions would be achieved, and this would limit the final degradation rate.

Regarding the results using water with vegetal material (VM), it was found that in both processes, during the first days, there was no degradation of organic matter. On the contrary, its concentration increased until day 21 for the aerobic process, and up to day 28 for the anaerobe, with maximum COD values very similar to each other; 25.20 mg/L in aerobic and 24.54 mg/L in anaerobic. After this, in both processes the degradation of organic matter began, until reaching a final value of 10.82 mg/L of COD at 200 d in the aerobic process, and 8.43 mg/L in the anaerobic one, a result that proves the above with respect to endogenous respiration in aerobic processes. The increase in COD concentration the first days is associated with the release of organic material contained in the grass and litter, by breaking the polymer chains, in this case. Tejada et al. [21] defined that this material contains structural polymers and soluble organic compounds such as sugars, amino acids, cellulose and lignin, which would explain the increase in organic matter caused during the first days in the degradation processes.



a. b.

Fig. 2. Degradation of organic matter in terms of COD by aerobic and anaerobic processes. a) Behavior P1. b) P2 behavior.

Finally, in the case of P2 (Figure 2b), the results were similar to those obtained with P1 where, for reactors with only water, the degradation of organic matter was greater in the aerobic process until day 122 and, after this, the anaerobic process achieved a lower final COD, with a result of 3.4 mg/L per day 200, compared to 4.0 mg/L in the aerobic process. For the reactors with water and plant material, the same behavior occurred as in P1, with an increase in COD at day 35 (32.30 mg/L) for the aerobic process and day 51 (34.43 mg/L) for the anaerobe. In the latter case, the COD reached a higher value indicating that the anaerobic process led to a greater decomposition of the polymeric compounds present in the grass and litter. The final COD was 7.00 mg/L in the aerobic and 5.51 mg/L in the anaerobic.

Table 3 shows the kinetic constants calculated from the degradation graphs in terms of COD, it is highlighted that in the case of processes with water plus vegetal material (VM), the constant (K) was calculated with the data from the beginning of the degradation process, that is, the process in which the COD increased as a consequence of the breakdown of the polymer chains contained in the litter, grass was omitted.

Table 3. Equations and kinetic constants of organic matter.

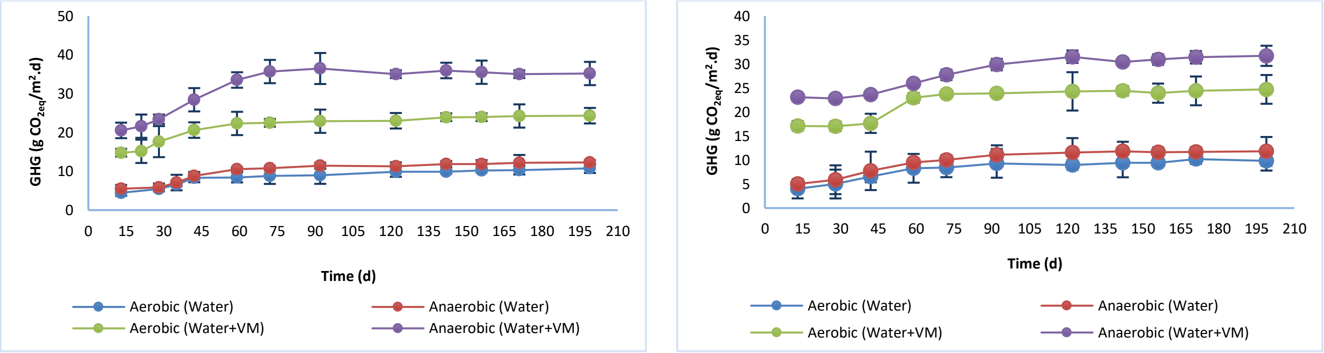
Sample point	**Degradation type**	**Composition**	**K (mg COD/L.d)**	**Equation**	**R^2**
P1	Aerobic	Water	0.3281	Y = -0.3281X + 19.68	0.9750
	Anaerobic		0.2356	Y = -0.2356X + 19.76	0.9693
	Aerobic	Water + Vegetal Material	0.3942	Y = -0.3942X + 34.49	0.9074
	Anaerobic		0.3293	Y = -0.3293X + 31.73	0.9721
P2	Aerobic	Water	0.1430	Y = -0.1430X + 15.74	0.9738
	Anaerobic		0.0788	Y = -0.0788X + 15.79	0.9754
	Aerobic	Water + Vegetal Material	0.6890	Y = -0.6890X + 56.89	0.9874
	Anaerobic		1.2506	Y = -1.2506X + 99.05	0.8659

The results of the K corroborate what was previously mentioned, where the degradation rate was higher in the aerobic processes than in anaerobic ones, with the exception of P2 with water and vegetal material (VM), with K = 1.2506 mg COD/L.d in the anaerobic process, compared to 0.6890 mg COD/L.d for the aerobic process. In all cases, the degradation constant was greater where there was more plant material, which indicates that the initial increase in COD promoted the degradation processes aerobically and anaerobically, that is, in a reservoir, the flooded plant material changes the dynamics of both the microorganisms and the decomposition of organic matter that occurs naturally in the water, accelerating the process and increasing the rate of degradation.

C. Greenhouse Gases Emissions

Figure 3 shows the results of the greenhouse gases (GHG) collected in the reactors. CO_2 was quantified in the aerobic process and both, CO_2 and CH_4, in the anaerobic. In both, P1 (Figure 3a) and P2 (Figure 3b), at the beginning of the anaerobic stage there is a slowdown in the process while strictly anaerobic conditions are established, that is, the generation of GHG during the first 30 days does not show a considerable increase. However, after this process, the increase in GHG is significant and greater compared to the GHG generated in the aerobic process, this situation is associated with the production of methane in the anaerobic process, which is a greenhouse effect gas that has a much higher warming potential than CO_2 (28 times higher) [3]. The highest GHG values were obtained in P1, in the processes in which only water was evaluated, and in those where water plus plant material was evaluated. This was related to the initial concentration of COD available at the beginning of the process, with values 10.764 g $CO_{2eq}/m^2.d$ in the aerobic process and 12.296 g $CO_{2eq}/m^2.d$ in the anaerobic with water only, compared to 9.816 g $CO_{2eq}/m^2.d$ (Aerobic) and 11.816 g $CO_{2eq}/m^2.d$ (Anaerobic) for P2 under the same condition. In the case of the tests with water plus plant material, the results were 24.342 g $CO_{2eq}/m^2.d$ (Aerobic) and 35.210 $CO_{2eq}/m^2.d$ (Anaerobic) for P1, and 24.729 $CO_{2eq}/m^2.d$ (Aerobic) and 31.730 g $CO_{2eq}/m^2.d$ (Anaerobic) for P2.

Comparing the results obtained from the CO_{2eq} fluxes using water plus plant material, with the results reported by the IHA [22] (Table 4), it is found that, for reservoirs in tropical climate, the diffusive flows report values of up to 20.580 g $CO_{2eq}/m^2.d$ and 19.710 g $CO_{2eq}/m^2.d$ for bubbling flows. The former is more associated with aerobic degradation processes and the latter with anaerobic ones; in this study, the results were slightly higher, especially in anaerobic processes. Other authors such as Guerin et al. [23], have reported higher values, in the order of 37.80 ± 17.6 g $CO_{2eq}/m^2.d$. In this sense, it must be taken into account that in the GHG emission there are not only temporal but also spatial variations associated with a reservoir, due to different causes, such as: temperature, type and density of vegetation flooded, carbon charges, among others.



a. b.

Fig. 3. Greenhouse gas (GHG) generation by aerobic and anaerobic processes. a) Behavior in P1. b) Behavior in P2.

Table 4. GHG values for each way for tropical climate. Modified from IHA [22].

Way	GHG (g $CO_{2eq}/m^2.d$)	Reference
Diffusive Fluxes	20.580	[22]
Aerobic P1*	24.342	This study
Aerobic P1*	24.729	This study
Bubbling	19.710	[22]
Anaerobic P1*	35.210	This study
Anaerobic P2*	31.730	This study

*Water + VM

D. Direct measurements

In order to evaluate the aerobic and anaerobic conditions present in each reactor and keep control over time, the measurement of the parameters in situ was performed, shown as an average in Table 5.

Table 5. Direct measurements in reactors

Point	Condition	Processes	Parameter			
			Dissolved Oxygen (mg/L)	Redox Potential (mv)	pH	Conductivity (μs/cm)
P1	Water	Aerobic	6.822 ± 0.33	339.569 ± 19.72	8.011 ± 0.16	232.269 ± 24.22
		Anaerobic	0.871 ± 0.26	-89.22 ± 10.37	7.473 ± 0.29	204.093 ± 13.98
	Water + Vegetal Material Tests	Aerobic	6.740 ± 0.36	235.606 ± 22.76	8.061 ± 0.08	255.375 ± 19.80
		Anaerobic	0.783 ± 0.30	-161.81 ± 19.11	6.673 ± 0.12	252.956 ± 27.10
P2	Water	Aerobic	6.823 ± 0.33	331.156 ± 30.37	8.119 ± 0.17	241.469 ± 11.12
		Anaerobic	0.776 ± 0.29	-76.34 ± 12.56	7.809 ± 0.25	228.841 ± 10.37
	Water + Vegetal Material Tests	Aerobic	6.752 ± 0.37	298.538 ± 41.46	8.132 ± 0.11	277.894 ± 32.74
		Anaerobic	0.276 ± 0.34	-143.653 ± 10.56	7.304 ± 0.48	275.810 ± 18.34

With regard to aerobic and anaerobic conditions, dissolved oxygen and redox potential made it possible to ensure the established conditions. In the case of aerobic processes, the dissolved oxygen values were all greater than 6 mg/L with higher values for conditions where there was water only (6.822 mg/L for P1 and 6.823 mg/L for P2), and slightly lower where there was water plus plant material (6.740 mg/L for P1 and 6.752 mg/L for P2). These results were also proportional at the redox potential where all values were positive and above 200 mV, ensuring aerobic conditions. In the case of anaerobic processes, the redox potential was negative, demonstrating much more anaerobic conditions in the case of water plus plant material, and the dissolved oxygens were all close to 0 mg/L. As for the pH, the aerobic processes were slightly basic with values above 8, while, in the anaerobic processes, a slight acidification was evident compared to the aerobic ones, with values between 6.673 to 7.809. This situation is a product of the anaerobic process in which the formation of volatile fatty acids takes place from the degradation of organic matter, which tends to acidify the medium. Additionally, the results showed an adequate environment for the development of both aerobic and anaerobic microorganisms, which have an optimal pH for their cellular development between pH 6 and 8. Finally, conductivity was higher in the processes in which water kept more plant material, associated with the transformation of organic matter to inorganic compounds, which leads to the release of ions in the medium that increase conductivity.

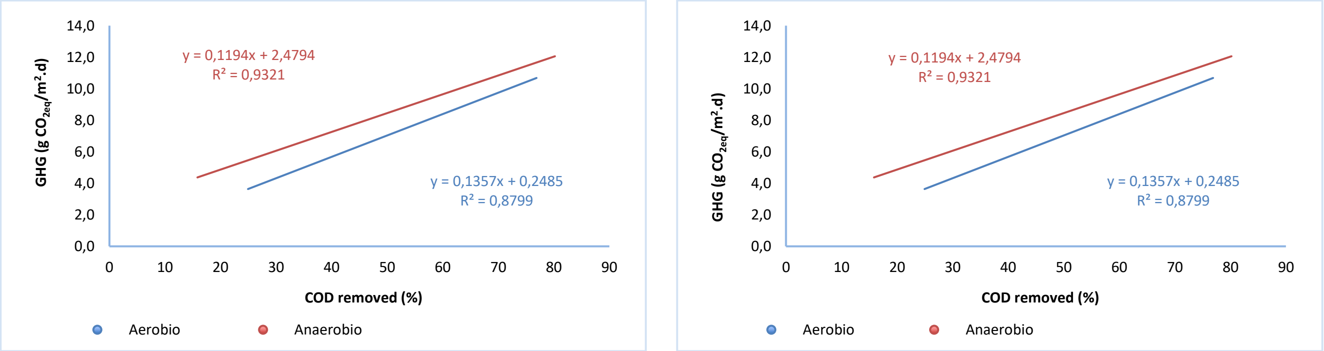
E. Variable Correlation

In order to determine the relationship between the most important variables analyzed in the reactors, a Pearson correlation coefficient analysis was performed between the COD, DOC and GHG variables (Table 6). The value of the linear correlation index varies in the interval [-1 to 1], allowing us to approximate the dependency relationship between two variables, one dependent on the other. A strong positive linear relationship between COD-DOC, that is to say a proportional correlation, and negative between COD-GHG and DOC-GHG, that is to say inversely proportional, was evidenced in both aerobic and anaerobic reactors with water. In the case of reactors with water plus plant material (MV), the correlation was moderate, obtaining the best correlations between the DOC-GHG. Comparing the aerobic processes with the anaerobic ones, the best correlations were found in the aerobic processes, indicating that anaerobic processes are more complex in their operation due to the fact that different microbial populations intervene and the metabolic path remains long, which results in highly complex products. Additionally, the plant matter contains highly complex organic matter, which generally requires a first stage of hydrolysis of the polymers or other types of breaking of polymeric bonds that occur more slowly due to the action of microorganisms, for which they require a period of time, acclimatization and adaptation.

Table 6. Pearson correlation coefficients between parameters.

Point	**Condition**	**Pearson correlation coefficient**		
		COD-DOC	**COD-GHG**	**DOC-GHG**
Water	Aerobic	0.9694	-0.9478	-0.9917
	Anaerobic	0.9682	-0.9351	-0.9429
Water + Vegetal Material	Aerobic	0.8766	-0.6945	-0.8778
	Anaerobic	0.7623	-0.6612	-0.7693

Finally, the behavior of the COD removed vs. GHG was plotted (Figure 4) and it was found that, for both aerobic and anaerobic processes with water only (Figure 4a), the relationship is linear and directly proportional. However, in the anaerobic process with the addition of plant material (Figure 4b), although the correlations are optimal, results were lower than the tests without plant material. In this regard, Ruiz et al. [25] found that the generation of methane in tests with water and plant material was explained using an exponential model and for CO_2 using a linear model, which explains why there is no correlation between these analyzed variables, bearing in mind that in this case the greenhouse gases (GHG) calculated in anaerobic processes correspond to CO_2 and CH_4 in the form of CO_2 equivalent.



a. b.

Fig. 4. Correlation of the removal of organic matter and GHG by aerobic and anaerobic processes. A) Water. B) Water + vegetal material.

IV. CONCLUSIONS

The plant material contained after the flooding process in a reservoir, is biochemically transformed in two stages; a first stage, where the polymer chains are broken and the COD concentration increases, and later, in a second stage, the process of degradation of organic matter begins. The greatest release of gases makes a greenhouse effect, especially through anaerobic processes, since the remaining organic matter is recalcitrant and not easily assimilated by microorganisms, at this point is when the stabilization process of greenhouse gas emissions begins. Additionally, the organic matter contained only in the water, which simulates the conditions of the rivers, also generates greenhouse gases, hence the importance of defining the baseline in reservoir construction projects, in order to quantify the net greenhouse gases that are attributable to the flooding process of plant material.

AUTHORS' CONTRIBUTION

Johanna E. Rodríguez carried out the laboratory tests, sample analysis and information collection. Diana C. Rodríguez drafted the manuscript and adjusted it to journal standards. Gustavo A. Peñuela reviewed the article, administered the project and obtained financing.

FUNDING

The financial support provided by the Colombian Scientific Program in the framework of the call for proposals for the Scientific Ecosystem (Contract No. FP44842-218-2018). In addition, ISAGEN company and the GDCON research group of the "Universidad de Antioquia" for the financing through agreement 47/26: "Quantification of GHG emissions for the Sogamoso Hydroelectric Project."

REFERENCES

[1] R. Prasad, "Climate change assessment impacts of global warming, projections and mitigation of GHG emissions endorsing green energy," *International Educational Scientific Research Journal*, vol. 4 (1), pp. 33-48, Jan. 2018.

[2] H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, "IPCC Guidelines for National Greenhouse Gas Inventories," *Instituto de Estrategias Ambientales Globales (IGES)*, vol. 4, pp. 32., 2006.

[3] H. O. Benavides, and G. E. Aristizabal, "Información técnica sobre gases de efecto invernadero y el cambio climático," *Instituto de Hidrología, Meteorología y Estudios Ambientales*. Subdirección de meteorología, pp. 1-91. 2007.

[4] A. W. Bambace, F. M. Ramos, B. T. Lima, and R. Rosa, "Mitigation and recovery of methane emissions from tropical hydroelectric dams," *Energy*, vol. 32 (6), pp. 1038-1046, Jun. 2007. https://doi.org/10.1016/j.energy.2006.09.008

[5] M. Demarty, and J. Bastien, "GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH_4 emissions measurements," *Energy Policy*, vol. 39 (7), pp. 4197-4206, Jul. 2011. https://doi.org/10.1016/j.enpol.2011.04.033

[6] C. Galy, R. Delmas, C. Jambert, J. F. Dumestre, L. Labroue, S. Richard, and P. Gosse, "Gaseous emissions and oxygen consumption in hydroelectric dams: A case study in French Guyana," *Global Biogeochemical Cycles*, vol. 11(4), pp. 471-483, Dec. 1997. https://doi.org/10.1029/97gb01625

[7] H. D. Cuadros, Y. Cuellar, J. S. Chiriví, and M. Guevara, "GHG diffuse emissions estimation, and energy security to ENSO using MERRA-2 for largely hydroelectricity-based system," *Revista Facultad de Ingeniería*, vol. 91, pp. 70-82, Apr. 2019. https://doi.org/10.17533/10.17533/udea.redin.n91a07

[8] Q. Hao, S. Chen, X. Ni, X. Li, X. He, and C. Jiang, "Methane and nitrous oxide emissions from the drawdown areas of the Three Gorges Reservoir," *Science of the Total Environment*, vol. 660, pp. 567-576, Apr. 2019. https://doi.org/10.1016/j.scitotenv.2019.01.050

[9] M. F. Umbarila., J. S. Prado and R. N. Agudelo, "Remoción de sulfuro empleando ozono como agente oxidante en aguas residuales de curtiembres," *Revista Facultad de Ingeniería*, vol. 28 (51), pp. 25-38, 2019. https://doi.org/10.19053/01211129.v28.n51.2019.9081

[10] G. Roldan, and J. Ramírez, *Fundamentos de limnología neotropical*, Medellín, Colombia: Editorial Universidad de Antioquia, Medellín, 2008

[11] Y. Li, S. Liu, F. Chen, and J. Zuo, "Development of a dynamic feeding strategy for continuous-flow aerobic granulation and nitrogen removal in a modified airlift loop reactor for municipal wastewater

treatment," *Science of The Total Environment*, vol. 714, e136764, Apr. 2020. https://doi.org/10.1016/j.scitotenv.2020.136764

[12] S. Mereu, J. Susnik, A. Trabucco, A. Daccache, L. Vamvakeridou, L. Renoldi, A. Dragan, and D. Assimacopoulos, "Operational resilience of reservoirs to climate change, agricultural demand, and tourism: A case of study from Sardinia," *Science of the total environment,* vol. 543(B), pp. 1028-1038, Feb. 2015. https://doi.org/10.1016/j.scitotenv.2015.04.066

[13] L. C. Corrales, D. M. Antolinez, J. A. Bohorquez, and A. M. Corredor, "Bacterias anaerobias: procesos que realizan y contribuyen a la sostenibilidad de la vida en el planeta," *NOVA*, vol. 13(24), pp. 55-81, Dec. 2015. https://doi.org/10.22490/24629448.1717

[14] Y. Kosugi, N. Matsuura, Q. Liang, and R. Yamamoto, "Nitrogen flow and microbial community in the anoxic reactor of "Sulfate Reduction, Denitrification/Anammox and Partial Nitrification" process," *Biochemical Engineering Journal*, vol. 151, e107304, Nov. 2019. https://doi.org/10.1016/j.bej.2019.107304

[15] M. Ruiz, D. C. Rodríguez, E. Chica, and G. Peñuela, "Calibration of two mathematical models at laboratory scale for predicting the generation of methane and carbon dioxide at the entrance point of the Chucurí river to the Topocoro Reservoir," *Ingeniería y Competitividad*, vol. 21(1), pp. 11-22, Feb. 2019

[16] L. M. Lopera, L. Oviedo, D. C. Rodríguez, and G. Peñuela, "Aplicación de ensayos en discontinuo para la determinación de flujos de metano y dióxido de carbono en la degradación del material vegetal en el embalse Topocoro," *Ingenierías USBMed,* vol. 7(2), pp. 67-73, Oct. 2016. https://doi.org/10.21500/20275846.2598

[17] E. W. Rice, R. B. Baird, and A. D. Eaton, *Standard Methods for the Examination of Water and Wastewater*. Washington D.C. United States: American Public Helth Association (APHA), American Water Works Association (AWWA), Water Environment Federation (WPCF), 2017

[18] I. Escaler, and R. Mujeriego, "Eliminación biológica de nutrientes (nitrógeno y fósforo) mediante un proceso discontinuo de fangos activados," *Ingeniería del agua*, vol. 8(1), pp. 67-77, Mar. 2001. https://doi.org/10.4995/ia.2001.2860

[19] J. Mata, *Biomethanization of the organic fraction of municipal solid wastes*, London, United Kingdom: IWA Publishing, 2003

[20] P. G. Aceñolaza, Z. Zamboni, W. Sione, and F. Kalesnik, "Caracterización de la región superior del Complejo Litoral del Río Paraná: Grandes unidades de ambiente," *INSUGEO*, vol. 17, pp. 293-308, Dec. 2008

[21] C. Tejada, A. Herrera, and A. Villabona, "Assessment of Chemically Modified Lignocellulose Waste for the Adsorption of Cr (VI)," *Revista Facultad de Ingeniería*, vol. 29 (54), e10298, 2020. https://doi.org/10.19053/01211129.v29.n54.2020.10298

[22] IHA (International Hydropower Associate), *GHG measurement guidelines for freshwater reservoir,* London, United Kingdom: UNESCO/IHA, 2010

[23] F. Guerin, G. Abril, S. Richard, B. Burban, C. Reynouard, P. Seyler, and R. Delmas, R. "Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers," *Geophysical Research Letters*, vol. 33(21), L21407, Nov. 2006. https://doi.org/10.1029/2006gl027929