



Research Paper

Cocaine degradation using a rotating biological disc reactor: Techno-economic and environmental analysis using experimental data

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ABSTRACT

A bacterial mixed culture that utilizes cocaine as the sole carbon and energy sources was isolated and used in a Rotary Disc Reactor as an alternative method for the final disposal of seized cocaine. This study aimed to compare the performances of cocaine incineration (oven) and biodegradation (Rotary Disc Reactor), considering economic and environmental aspects. There was a 99.4% cocaine removal efficiency when bacterial CIT consortium was grown in a Rotary Disc Reactor for 42 h. The economic analysis allowed determining the high potential of the biotechnological cocaine degradation to be evaluated at higher scales. Indeed, the unit disposition price of the biotechnological degradation pathway was 58% higher than the calculated value for the incineration process considering an initial cocaine concentration of 30 g/L. Moreover, the economic sensitivity analysis demonstrated a price reduction of 20% in the unit disposition price of the biotechnological degradation using a rotary disc reactor. Further, cocaine degradation using a rotary disc reactor system presented a better environmental performance than the incineration process considering atmospheric and toxicological impact categories because of the low release of hazardous materials to the atmosphere.

1. Introduction

The illicit commercialization of narcotics and drugs has caused several social and economic problems in developed and developing countries. In consequence, policies addressed to increase the seizure and disposal of these substances have been implemented. Today, most of the seized narcotics are disposed by applying different chemical and thermochemical processes. Colombia is one of the largest producers of cocaine in the world. Most of the seized cocaine in the fields is burned in the open. On the other hand, the seized cocaine in airports and cities is stored and burned in a controlled environment. Nevertheless, the main purpose of the incineration process is to reduce the volume of the alkaloid (Silva et al., 2020) and needs to meet different environmental requirements to avoid affecting the health of operators. Thus, the incineration process involves the burning of cocaine at high temperatures (e.g., 800–1000 °C) until a 90% reduction in the solid volume is

achieved. Although the incineration process has a high technology readiness level (TRL), research to characterize the possible emission of harmful compounds during cocaine incineration must be performed (Brown, 2011).

The incineration process has been selected as the most suitable option to dispose of harmful compounds due to the relative low capital investment, high degradation efficiency, and low disposal unit costs (Kim and Jeong, 2017). Other advantages of the incineration process are related to the requirement of small installation areas, low generation of noise and odor, an energy recovery rate of up to 80%, and high versatility (Silva et al., 2020). Nevertheless, a complete study of cocaine incineration must be carefully achieved since the energy and economic performances of the process strongly depends on the type of solid residue to be disposed (Silva et al., 2020). Indeed, there is little published data related to the economic assessment of cocaine incineration. Therefore, a detailed investigation of the environmental impact of the

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cocaine incineration process must be performed.

Biological degradation of harmful compounds can be profiled as a potential alternative to dispose of narcotics and drugs since this process does not need high energy consumption, high temperatures, or hazardous chemical reagents. Moreover, this process can be performed using several reactor configurations to guarantee the highest degradation rate as well as the lowest capital and operational expenditures. In fact, biological degradation of narcotics and drugs can be performed by using continuous stirred tank bioreactors (CSTBR), moving bed bioreactors (MBBR), and rotating biological disc reactors (RBD). Among these systems, the biological degradation process employing a RBD has some advantages such as low capital and operational expenditures (i.e., low CAPEX and OPEX), low dependence on foreign spare parts, low maintenance requirements, low energy consumption, and not skilled personnel is required. For this reason, this process has been used in several applications. For instance, [Mohammadi et al. \(2019\)](#) reported the production of hydrogen using RBD, [Li et al. \(2019\)](#) reported the use of RBD to perform the post-denitrification of domestic sewage and [Delgado et al. \(2018\)](#) reported the removal of pharmaceutical and personal care products from domestic wastewater. Then, the RBD operated as an RDR system can be proposed as an alternative to degrade narcotics and drugs. This paper proposes the use of a rotary biological disc reactor (RBD) as a more environmental and effective method to dispose of seized narcotics and drugs. In this way, the objective of this work is to explore and compare the economic and environmental performances of the incineration and biological degradation of cocaine. This objective was given in order to approve or deny the following statement: "The biological degradation of cocaine has better economic and environmental performance than the incineration process". For this purpose, the biological degradation of Colombian cocaine base and cocaine hydrochloride was evaluated using an RBD system. The experimental results were used as input data to simulate and compare the economic and environmental performance of the biological degradation process with traditional incineration.

2. Experimental and simulation processes

The analysis of the possible application of an RBD system to degrade cocaine base and cocaine hydrochloride was performed considering an experimental and simulation approach. Hence, a comparison with the traditional disposal process (i.e., incineration) was carried out to elucidate the real potential of the biological degradation route of these alkaloids. Besides, the experimental approach consisted of cocaine base and cocaine hydrochloride degradation using an RBD system at a laboratory scale. Additionally, experimental combustion was performed to determine carbon dioxide and carbon monoxide emissions. Then, the experimental results were used as input data to compare from an economic and environmental perspective the biological degradation process with conventional incineration.

2.1. Experimental set-up and quantification of the biological degradation process

2.1.1. C1T consortium

Two bacterial consortia were used to carry out cocaine degradation. Strains such as *Bacillus cereus*, *Bacillus sp.*, *Bacillus subtilis*, *Pseudomonas stutzeri*, *Pseudomonas putida*, and *Pseudomonas aeruginosa* were previously isolated from a sugarcane plantation and mixed, forming the T1 consortium. Then, a new bacterial consortium named T2 isolated from the rhizosphere of coca crop plantations in Tumaco, Colombia was isolated. The different strains that are part of the T2 consortium are yet to be identified. Consortia T1 and T2 were mixed, thus forming a new bacterial consortium named C1T. These consortia were used for the evaluation of several parameters to increase cocaine degradation referred to as Cocaine Removal Efficiency (CRE).

2.1.2. Chemicals

All chemicals were analytical grade reagents and purchased from Sigma-Aldrich Company Ltd. (USA). All samples were centrifuged at 14,800 rpm, and filtered through a Durapore PVDF membrane of 0.22 μm . The analytical cocaine and Benzoylcegonine (BE) standards were obtained from Lipomed. Seized cocaine base and cocaine hydrochloride were supplied by the Narcotics Division of the Colombian National Police in association with the General Attorney's Office.

2.1.3. Bacterial culture media

Substrate preparation for the RBD was obtained by diluting solid cocaine base in water with acid (HCl 0.1 N) until complete solubility producing cocaine hydrochloride in solution and solid cocaine hydrochloride in the culture saline medium (CSM) with ultrapure water produced by a purification system from Milli-Q from Millipore Corporation until a final cocaine concentration of 10 g/L and cultured for 48 h at 32 °C with constant agitation (150 rpm). Inoculum was prepared using three 250 mL flasks with 100 mL of the substrate solution (cocaine 10 g/L) and cultured for 48 h at 32 °C with constant agitation (150 rpm). This procedure was carried out without exceeding 40% of the total flask volume, to promote aeration and bacterial growth. Then, the culture was added to the RBD and then filled with tap water until a final volume of 3 L. The composition of the CSM used in this study for bioreactor experiments, is as follows (g/L): $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (0.2), K_2HPO_4 (1.5), Na_2HPO_4 (9.0), $(\text{NH}_4)_2\text{SO}_4$ (1), and 1 mL of a trace element solution containing (g/L): $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (1.0), $\text{MnSO}_4 \cdot 4\text{H}_2\text{O}$ (0.5), $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ (2.25), $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (10.0), H_3BO_3 (0.23), $(\text{NH}_4)_2\text{Mo}_7\text{O}_{24}$ (0.2), $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ (2.0), and 10 mL of HCl.

Daily purges of 500 mL were carried out and simultaneously, fresh CSM was added to the RBD until a biofilm was evidenced on the disks. Bacterial development was traced by optical density (OD) at 600 nm in a UV Thermo Scientific Genesis 20 Spectrophotometer. In brief, 2 mL samples were collected and centrifuged at 14,800 rpm for 10 min (Micro-centrifuge Sigma1-14). Then, the resulting biomass was washed twice with 10 mL of sterilized CSM (Durapore PVDF membrane of 0.22 μm), and diluted in 20 mL of freshly CSM. The pH (FiveEasy pHmeter F20-Std-Kit) was only adjusted at 7.2 in the beginning of treatment. The degradation process was monitored by sampling every 6 h during the first 24 h and by sampling every 4 h during the last 24 h.

2.2. Experimental set-up using RBD

The RBD was set in a batch mode (see [Fig. 1](#)). The reactor design was chosen as reported [Pérez \(2010\)](#). Some modifications were made to the original design without compromising functionality. The modifications that were carried out were: the process tank and the reactor support base were made in L316 aluminum with a heating jacket and water pump for the jacket. The pulley system was not necessary due to the direct installation of the motor on the shaft. Other specifications are shown in [Table 1](#).

2.2.1. Cocaine biodegradation

Cocaine removal efficiency at time t (CRE_t) was established according to substrate evolution (C_t) with respect to substrate initial concentration (C_0), as shown in [Eq. \(1\)](#).

$$\text{CRE}_t = (C_0 - C_t) / C_0 \times 100 \quad (1)$$

2.2.2. Chromatographic conditions

Cocaine and BE concentrations were measured by high-performance liquid chromatography (HPLC) in a Shimadzu 2010A HT with a diode array detector and a C18 column in reverse phase (150 mm $\times$ 4.6 mm and 5 μm particle diameter) and a column temperature of 30 °C. Cocaine and BE peaks were measured at 235 nm. Chromatographic peaks were identified by comparing retention times with a saline solution of the standard. The mobile phase was used in an isocratic regime: (A)

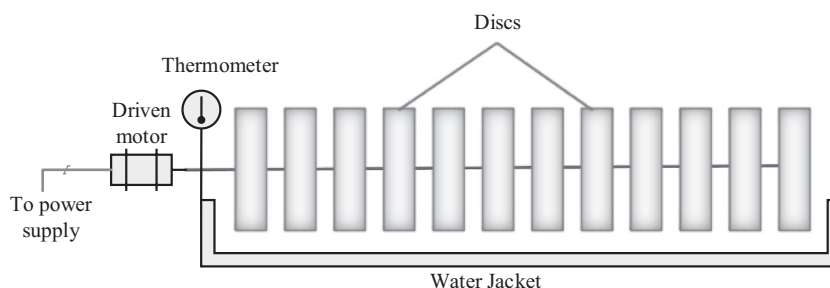


Fig. 1. Schematic diagram of the RBDR used in this study.

Table 1
RBDR Set-up used in this study.

Parameter	Unit	Specification
Disc diameter	m	0.26
Disc submergence	%	40.00
Total surface area	m ²	1.25
Total volume	cm ³	3500
Work volume	cm ³	3000
Number of discs	–	12
Jacket temperature	°C	32
Disc rotation	rpm	2

Phosphate buffer pH 6.0, (B) Acetonitrile (40:60 v:v). The flow rate was 1 mL/min with 20 µL injection volume. Benzoic acid was measured according to the method reported by Pylypiw and Grether (2000) in a Shimadzu LC-20 AT HPLC system with a diode array detector, and a Kromasil C18 column (150 mm × 4.0 mm and 5 µm particle diameter). Mobile phase was kept in an isocratic regime: (A) ammonium acetate buffer. (B) Acetonitrile (90:10 v:v).

2.3. Experimental incineration of cocaine hydrochloride and cocaine base

The cocaine base and cocaine hydrochloride incineration process was experimentally performed to determine the amount of volatilized alkaloid and gas composition. The solid residue yield of the process was used as input data in the simulation process. For this, 50 ± 0.01 g of seized cocaine base and cocaine hydrochloride were weighted in a previously calcined porcelain crucible and then placed on a muffle (Wisd FHPX – 1200 °C). The incineration process was performed by setting a heating rate of 10 °C/min and 15 °C/min for cocaine base and cocaine hydrochloride, respectively. The operating conditions of the process were 800 °C, atmospheric pressure, and 60 min residence time. The gases derived from the incineration process were analyzed to determine the relative composition of CO₂ and CO using a gas analyzer equipment (Gasboard 3100P). Finally, the solid residue derived from the process was weighted and the overall volatilization yield was calculated according to Eq. (2).

$$\text{Volatilization yield(\%)} = \frac{\text{Initial weighted sample} - \text{Final residue}}{\text{Initial weighted sample}} * 100 \quad (2)$$

2.4. Simulation approach: economic and environmental assessment

The economic and environmental assessment of the cocaine base and cocaine hydrochloride degradation was made considering the experimental yields obtained for both processes. Information of seized cocaine in Colombia reported by the United Nations Office on Drugs and Crime was used as input data to set a realistic amount of disposed material in a year. Furthermore, the economic assessment was carried out considering the CAPEX, OPEX, and disposal unit prices as metrics to analyze the feasibility of the RBDR system in comparison with the incineration process. Other investment metrics values such as net present value

(NPV), internal rate of return (IRR), and payback period (PBP) were not included since both processes are focused on the disposition of harmful material and not on the production of a marketable product (Palmeros Parada et al., 2017). Regarding the environmental perspective, toxicological and atmospheric impact categories were assessed. The environmental assessment was performed considering a gate to gate approach to evaluate only the environmental impact caused by these processes and not the environmental impact implied in the coca crop cultivation, distribution, and seizure.

2.4.1. Process description and simulation procedure

The incineration process was simulated considering the operating conditions reported by Martin et al. (1989). These conditions were compared and validated by reviewing the technical specifications of different incinerators used for the disposal of narcotics and hazardous drugs (Inciner8, 2020). In this way, the combustion chamber operates at 800 °C and 1 bar with a residence time lower than 2 min to avoid the production of organic volatile compounds (Gostic et al., 2009). The post-combustion chamber is operated at 1200 °C and 1 bar with a residence time of 2 s. The post-combustion process is carried out to ensure the degradation of possible harmful organic compounds (Mukherjee et al., 2016; Sofian and Fatin, 2018). Blowers supply the required air to accomplish combustion of the material. In this process, a volumetric flow rate of 5 m³/s was considered to reach a complete combustion. Finally, the leaving gases from the incineration process have a fixed temperature of 250 °C. The process was simulated using the Aspen Plus V.9.0 software. The process flow diagram of the incineration process is presented in Fig. 2.

The RBDR plant to dispose of narcotics and drugs is composed of a collection tank, pumps, RBDR, and a sedimentation tank. The inclusion of a sludge holding tank was not considered since the experimental assessment performed does not have a recirculation stream. The RBDR equipment is composed of acrylic disks of a rough surface. A detailed description of the experimental setup of the process can be found in the experimental section. Aspen Plus V.9.0 was the tool used to perform the RBDR process simulation. This software has several ways to perform the simulation of this type of process if the mass balances are known. In this case, yields derived from the biological degradation of cocaine were used as input data. Thus, the final concentrations obtained in the experimental section are significant in this process. The RYield module was used to model the RBDR equipment. The simulation of this process was done using the Aspen Plus V.9.0 software to obtain the mass and energy balances of the process and then perform the economic and environmental assessments. The process flow diagram of cocaine base and cocaine hydrochloride biological degradation plant using a RBDR equipment is shown in Fig. 3.

An alkaloid (i.e., cocaine base/cocaine hydrochloride) mass flow rate of 100 kg/h was considered to perform the simulation of both systems. This mass flow rate is the 30% of the total seized cocaine in Colombia in 2018. Moreover, this flow was calculated considering an operation time of 184 days per year. Thus, a volumetric flow of 240 m³/day was considered in the design of the RBDR equipment. This mass flow rate is

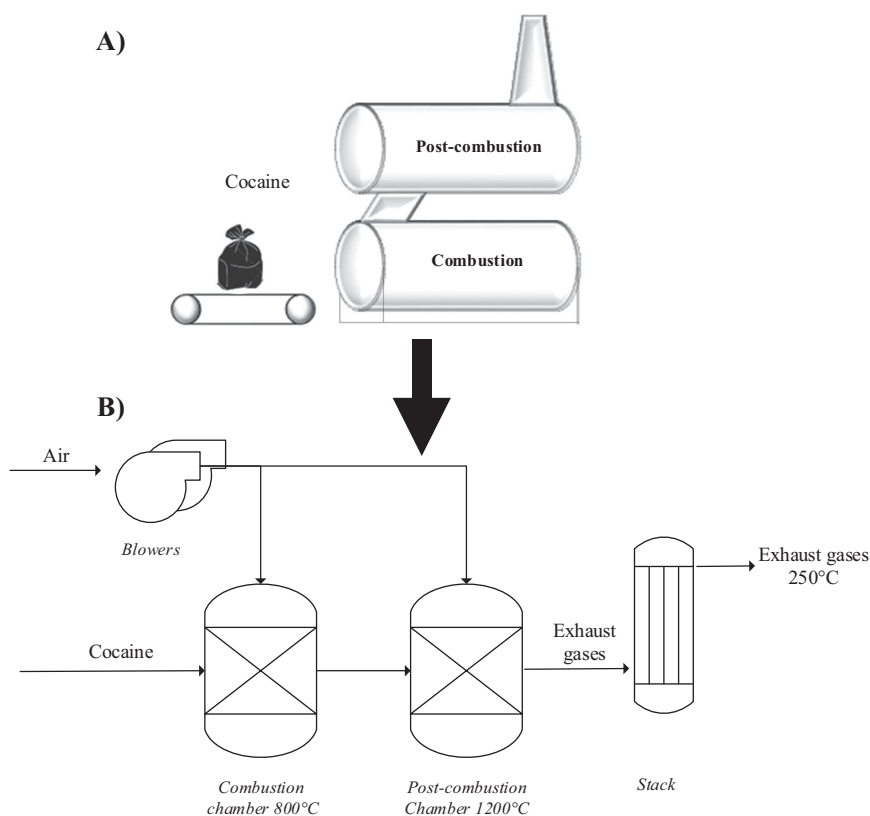


Fig. 2. Incineration process. A) Schematic representation of the incineration equipment used to dispose of narcotics. B) Conceptual process flow diagram of the cocaine incineration process.

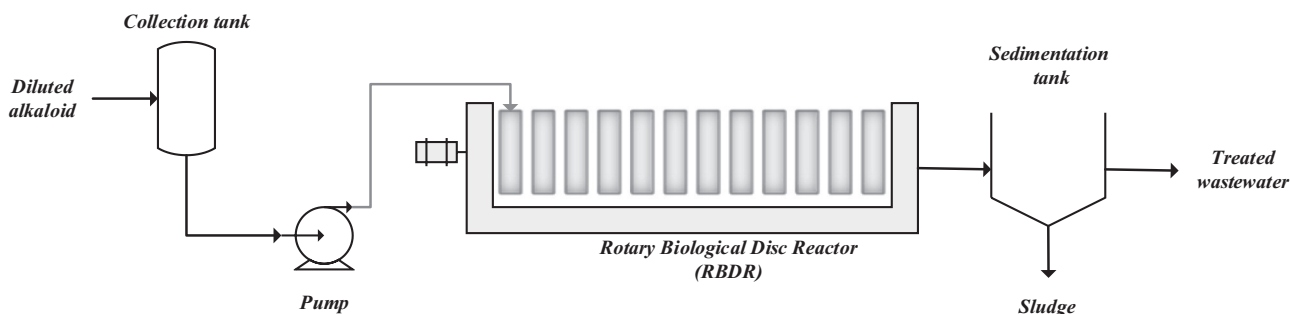


Fig. 3. Biodegradation plant.

supported by the statistics of seized cocaine in Colombia reported by the United Nations Office on Drugs and Crime in 2017 (United Nations Office on Drugs and Crime, 2020). Moreover, this value was obtained considering that only 30% of the total seized cocaine in Colombia is burned in a controlled incineration process. The simulation process requires the specification of the compounds involved in the disposition process. However, cocaine base ($C_{17}H_{21}NO_4$) and cocaine hydrochloride ($C_{17}H_{22}ClNO_4$) are not present in any of the Aspen Plus v9.0 databases. Therefore, the most important properties of these compounds such as molecular weight, acentric factor, enthalpy of formation, free-energy of formation, critical temperature, and pressure were loaded into the software using data reported in the open literature. Even so, the enthalpy and free-energy of formation were calculated using a contribution group method. "All simulation processes were performed using the Non-Random Two Liquids (NRTL) and Peng Robinson equation of state (PR EoS) to describe the behavior of the liquid and vapor phases present in the process. The NRTL activity model was selected since this model can predict the activity coefficients of a mixture involving binary

parameters (available in the software database). Meanwhile, the PR EoS was chosen considering that the pressures in the entire simulation do not exceed 10 bar. Thus, this EoS can be used to give a good description of the vapor phase in the simulation. Moreover, these models that predict the behavior of the vapor and liquid phases were selected based on the fact that there is no vapor phase association (i.e., vapor-liquid equilibrium, vapor-liquid-liquid equilibrium) involved in any stage of the simulated processes" (Cardona Alzate et al., 2018). The mass and energy balances of both processes were obtained from the simulation process. These balances were used to determine equipment size in the Aspen Process Economic Analyzer v9.0 (APEA) software and the environmental assessment using the WAR GUI software. A summary of process conditions, purposes, and aspen models used to perform the simulation are presented in Table 2.

The Aspen Models selected to simulate the cocaine degradation processes were selected considering the available experimental and theoretical data. The main objective of the simulation process is to provide the mass and energy balances of the cocaine degradation

Table 2

Summary of aspen models, purposes, and conditions specified to perform the simulation of cocaine incineration and biological degradation processes.

Unit	Purpose	Conditions	Aspen Model
Incineration process			
Combustion chamber	Thermal degradation of cocaine base and cocaine hydrochloride.	1 bar, 800 °C	RGibbs
Post-combustion chamber	Thermal degradation of organic volatile compounds.	1 bar, 1200 °C	RGibbs
Heat exchanger	Temperature decrease of post-combustion gases.	1 bar, 250 °C	Heater
Biological degradation process – RBDR process			
RBDR	Degrades cocaine	1 bar, 32 °C	RYield
Pump	Delivers diluted cocaine to the RBDR	1 bar, 25 °C	Pump
Collection tank	Homogenizes cocaine in solution (10 kg/m ³)	1 bar 25 °C	Mixer
Sedimentation tank	Separates sludge from treated wastewater	1 bar, 32 °C	Spitler

processes at the defined processing scale (100 kg/h – a share of the Colombian cocaine production). Fig. 4 shows the general scheme to calculate the mass and energy balances of any equipment in the Aspen Plus software. The simulation of both processes was specified using stream and process variables such as mass flow, mass fraction, temperature, and pressure. The simulation of both processes estimates the compositions and conditions of the outlet streams.

In Fig. 4, f is the mass flow. The script F (Feedsotck), Reag (Reagents), Util (Utilities), RF (Remaining feedstock), P (Product), and waste were used to describe each one of the inlet and outlet streams in the equipment involved in the simulation. Most of the equipment do not have chemical conversion or phase change. Thus, the mass and energy balances of these unit operations was performed following the mass and energy balances principle. In this way, the total and component mass flows are the same. Those equipment involving chemical conversions (i.e., combustion, post-combustion, and biological degradation) were modeled following different approaches to estimate the outlet stream composition. In both cases, the utility balance can be referred to as the need for steam or water to maintain temperature or electricity use.

In the case of incineration, the combustion and post-combustion processes were simulated using a RGibbs reactor. This equipment can estimate the composition of the outlet stream of the process without the need of a stoichiometric equation or yield. The calculations are based on minimizing the Gibbs energy of the system. In this sense, the reactor was specified using the temperature of the combustion and post-combustion processes and the pressure of the system (1 bar). Besides, the calculation method of the outlet composition was specified considering the estimation of phase equilibrium and chemical equilibrium. The results of

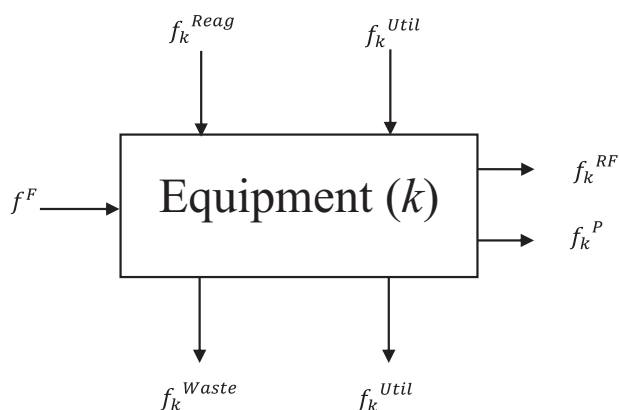


Fig. 4. General scheme to calculate the mass and energy balances of any equipment.

the process are the composition of the gaseous outlet stream (incineration gases) and the heat duty of the reactor. On the contrary, the RBDR was simulated considering a RYield reactor. This reactor is specified using the experimental yields obtained. Thus, the mass balance of the process is specified. The energy balance of this block is calculated considering the thermodynamic properties of the components and the operating conditions. The other equipment involved in the simulations does not involve a high level of complexity. Therefore, the specification way of this equipment is not described.

2.4.2. Economic assessment

The economic assessment of both processes was performed to identify the most influential factor in the disposal unit cost of seized cocaine base and cocaine hydrochloride. Further, the purpose of the economic assessment is to give an economic guess estimate of the CAPEX and OPEX involved in the implementation of the RBDR plant. Accordingly, the mass and energy balances obtained from the simulation process were used as input data to perform the sizing of all the equipment involved in the cocaine incineration and biological degradation processes. The APEA software was used to estimate the investment requirements of capital projects based on data collected from EPC companies and equipment manufacturers (Towler and Sinnott, 2012). The APEA software can estimate the costs of the equipment involved in the simulation. Additionally, the APEA software also considers operating costs associated with raw materials, utilities, maintenance, labor, plant overhead, and general charges. This information was calculated given the raw material price, utility costs, shifts worked in the plant, and employees' salaries. In this way, the cocaine prices were assumed as 20 USD/tonne, which was stipulated considering only the transportation costs to the degradation process plant (i.e., incineration or biological degradation) covering a 200 km distance (Solarte-Toro et al., 2019). Costs related to process diesel, water, cooling water, and low-pressure steam were the same values reported by García-Velásquez and Cardona (2019). According to the Colombian law, the disposal of narcotics and drugs must be performed in the presence of government and police officials. Thus, both plants consider one supervisor (1.58 USD/h), two operators (1.05 USD/h), one police officer (3.05 USD/h), one PIPH officer (3.05 USD/h), one district attorney (11.42 USD/h), and one government official (11.42 USD/h). The given salaries are based on Colombian wages in 2019. Finally, the annual interest rate and tax rate were fixed at 17% and 35%, respectively (Serna-Loaiza et al., 2018).

2.4.3. Environmental assessment

A gate to gate analysis of the incineration and biological degradation process was performed to elucidate the environmental impact of these processes based on toxicological and atmospheric impact categories. For this process, the systematic approach to determine the potential environmental impact (PEI) proposed by Young and Cabezas (1999) was applied. The Waste Reduction Algorithm (WAR), developed by the National Risk Management Research Laboratory from the U.S. Environmental Protection Agency (EPA), was used. The WAR software calculates the PEI impact considering global atmospheric and toxicological categories (Moncada et al., 2016). The global atmospheric categories involve the calculation of the global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), and photochemical oxidation potential (PCOP) as impact categories. Moreover, the toxicological categories involve human (i.e., human toxicity potential by ingestion (HTPI), human toxicity potential by inhalation or exposure (HTPE)), ecological (i.e., aquatic toxicity potential (ATP), and terrestrial toxicity potential (TTP)) impact categories (Fu et al., 2000). The WAR algorithm calculates the PEI per unit of time or mass of products as the weighted sum of all impact categories. In this work, the weights for each impact category were assumed as equal in both processes, thus, default values were used. Cocaine is not present in the database of the WAR software. Therefore, the lethal doses (LD50), lethal concentration (LC50), and ecotoxicity (EC50) of cocaine were manually

introduced using the values reported in the open literature. The LD50, LC50, and EC50 values used were 95.1 mg/kg (Bedford et al., 1982), 4.1727 mM (Badisa and Goodman, 2012), and 9.7 mM (Grant and Acosta, 1994), respectively.

3. Results and discussion

3.1. Experimental results of biological degradation

Biodegradation of cocaine (10 g/L) was carried out in a RBDR (see Fig. 5) by the C1T consortium which showed a cocaine removal efficiency (CRE) = 99.4%. This result was achieved in 42 h with the production of BE (0.24 ± 0.01 g/L) and benzoic acid (0.17 ± 0.01 g/L) as degradation products. These substances were then consumed by the C1T consortium as carbon sources for growth and energy supply after cocaine was consumed.

3.2. Lab-scale incineration

Incineration of cocaine base and cocaine hydrochloride performed at lab-scale showed similar volatilization yields. The weights recorded at the beginning and at the end of the process are presented in Table 3. In both cases, volatilization was higher than 90%. These results suggest a high-volume reduction of the seized cocaine base and cocaine hydrochloride. Thus, solid residues derived from the incineration process do not overcome 10% of the initial amount of the cocaine burned. The obtained results confirm the selection of the incineration process to dispose of this kind of material. In consequence, the incineration process seems to be the best route due to the high volume reduction, the destruction of the narcotics, and the low issues related to the final disposition of the ashes (i.e., ashes can be disposed of in a landfill). Similar results related to cocaine base and cocaine hydrochloride volatilization yields were reported by Gostic et al. (2009). Nevertheless, these authors reported cocaine recoveries in a gaseous phase lower than 85%, which implies a poor thermal decomposition of the problem molecule. This fact can be explained by the operating conditions of the process. Gostic et al. (2009) performed the incineration process at 450 °C for 7 s (i.e., a sample volatilization to time ratio of 7 mg/s). In contrast, the incineration process carried out in this research was performed at 800 °C for 2 min (i.e., a sample volatilization to time ratio of 14 mg/s) to ensure a complete cocaine degradation. Therefore, process variables such as temperature, time, and incineration media composition are the main variables to be assessed.

The results of the exhaust gases from the incineration process indicate a complete cocaine base and cocaine hydrochloride combustion since CO₂ was the most abundant compound obtained (see Table 4). A 95% CO₂ volumetric composition was obtained in all cases and trace amounts of CO were also registered. This analysis can serve as base to set

Table 3

Overall volatilization yield of cocaine base and cocaine hydrochloride.

Sample	Initial weight (%w/w)	Final weight (% w/w)	Overall volatilization yield (%)
Cocaine base	50.01	3.00	94.00
Cocaine hydrochloride	50.01	4.03	91.94

*Incineration assays were done by duplicate.

Table 4

Incineration gases CO₂ and CO content.

Sample	CO ₂ (%)	CO (%)
Cocaine base	96.32	3.68
Cocaine hydrochloride	95.56	6.44

the experimental conditions to avoid the formation of incomplete combustion products such as CO, and N₂O₃, which have a high environmental impact (Rakopoulos et al., 2011). Unfortunately, there is no information on the complete composition of the exhaust gases obtained during the cocaine incineration process at pilot scale. Therefore, the authors suggest to carry out an isokinetic assessment to find the mass flow of the different pollutants produced in this process, which can harm and affect human health (Wang et al., 2019). Moreover, the lack of information on the net emissions generated in the incineration of alkaloids in terms of greenhouse gases (e.g., CO₂), may be due to a greater interest in the analysis of other gaseous products such as methylecgonidine (AEME), benzoic acid, and carbomethoxycycloheptatrienes (CMCHTs) (Gostic et al., 2009; Martin et al., 1989). Besides, special care should be considered during cocaine base and cocaine hydrochloride volatilization and after the post-combustion process to ensure a complete decomposition of any volatile organic material in the exhaust gases stream. From the environmental perspective, the incineration process has a lower environmental impact compared to other thermochemical processes such as diesel combustion for heat and power generation.

3.3. Simulation results

3.3.1. Economic assessment of the incineration process and RBDR plant

The economic assessment of the method to dispose of seized cocaine was addressed to determine (i) the distribution costs of each process, (ii) the most influential factor to the process economics, (iii) the disposal unit costs, (iv) OPEX, and (v) CAPEX. The cost distribution of both processes includes different items such as raw materials, utilities, labor, maintenance, general charges, and depreciation. These costs are calculated on one period basis, which was defined as the time required to degrade the total amount of seized cocaine in a year considering a mass flow of 100 kg/h. The cost distribution for both processes is shown in Fig. 6.

The costs associated with labor are the most influential factors in both processes. The labor costs were around 50,000 USD per period. This value is attributed to the high salaries of the process watchers from the police, district attorney's department, government official, and PIPH officer. These high labor costs directly affect the disposal unit cost in each process. Therefore, a reduction in the salary of these process watchers could increase the economic feasibility of the RBDR plant hence making this option a reliable alternative to dispose of seized cocaine. In the specific case of the incineration process, another influential factor is the utilities costs due to the constant supply of diesel fuel to maintain the process temperatures. The fuel consumption of a commercial incineration equipment with a loading capacity between 40 and 100 kg/h has been estimated in 10–15 L/h. Therefore, the incineration of 147.2 tonnes of cocaine requires 22 m³ of diesel to complete the degradation process. This fuel consumption represents a total cost of 12.055 USD/period, which is higher than the total raw material cost

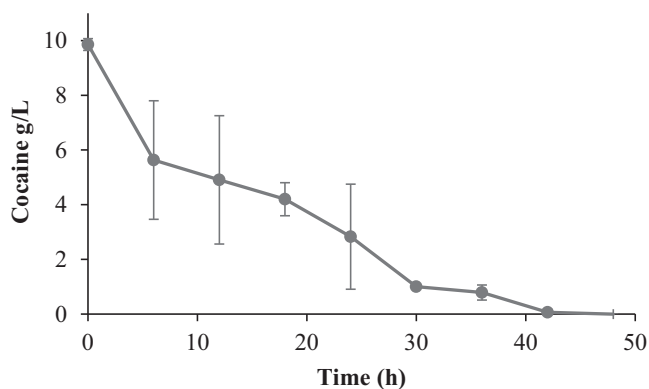


Fig. 5. Cocaine biodegradation in an RBDR. Bars represent the SD of triplicate experiments.

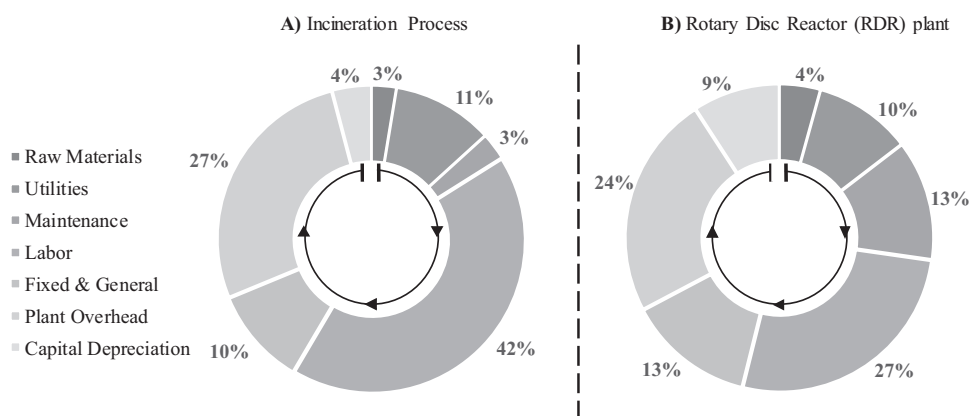


Fig. 6. Cost distribution of different alternatives to dispose of seized cocaine. A) Incineration process. B) Rotary Disc Reactor (RBDR) plant.

(2.944 USD/period) explained by the considered price for the diesel fuel (0.546 USD/L) and raw material (0.02 USD/kg). On the contrary, the lowest costs associated with the incineration process are related to raw materials acquisition, maintenance, and depreciation values. Maintenance ensures the proper function of the different parts of the incineration equipment. This process involves a periodical cleansing of the equipment to guarantee the total elimination of seized cocaine. The cost of this activity was calculated from the total capital investment of the process (maintenance costs were 3,202 USD/period). Finally, depreciation was calculated without considering any salvage value for the incinerator. This value is directly related to the total capital investment of the equipment (46,400 USD). In the RBDR plant, labor costs is also the most influential factor since the same staff is considered similar to the incineration process. Nevertheless, the share of the labor costs in this plant was 27%. This reduction of the labor costs share is attributed to the higher capital investment involved in the RBDR plant. Moreover, maintenance, raw material, and utilities shares are higher in the RBDR plant than in the incineration process. Raw materials costs are higher since water is required to dilute the seized cocaine until 10 kg/m³. Furthermore, due to the addition of Na₂PO₄, KH₂PO₄, MgSO₄•7H₂O, and (NH₄)₂SO₄, the share of raw materials costs can increase reaching values between 35% and 65% of the process. Nevertheless, these salts were not considered in the RBDR plant because of other cheaper bulk chemicals such as diammonium phosphate (DAP) could be supplied as nutrients at pilot or industrial scales. In contrast, the total depreciation cost of the RBDR plant is 16,527 USD/period, which is fourfold higher than the total capital depreciation of the incineration process. For this reason, the share of maintenance is higher in the case of the RBDR plant. Finally, the most important utility required in the RBDR plant is electricity. This utility is used to maintain rotating the RBDR reactor at the specific frequency (2 rpm) and to guarantee a constant influent supply through a centrifugal pump. The total utility cost in the RBDR plant was 18,574 USD/period.

The disposal unit costs of the incineration and RBDR plant were 0.77 USD/kg and 1.22 USD/kg, respectively. The incineration process is a more economically feasible alternative to dispose of cocaine. However, the unit cost to dispose of 1 kg of cocaine using the RBDR process is not high in comparison to the advantages offered by this process. The first advantage related to the RBDR process is that it can dispose of more than 99% of the cocaine processed in the plant. Meanwhile, the incineration process can only upgrade until 90% of the seized material with ashes generation. Another advantage of the RBDR process, compared with the incineration process, is related to the low environmental impact caused by the effluent of the RBDR equipment. The RBDR process does not use fossil fuels as energy sources. The electricity required in this process can be provided by hydraulic-energy, which is the primary energy source in Colombia. Thus, the RBDR process could be promoted as a green-process and receive some benefits from the Colombian government. A sensitivity

analysis of the disposal unit price as a function of the initial cocaine concentration in the influent of the RBDR reactor was performed to find the minimal disposition unit price. The results of the sensitivity analysis are presented in Fig. 7.

The disposal unit price of cocaine using a RBDR plant decreases as cocaine initial concentration increases. If the biological degradation process is performed with an initial concentration of 30 g/L, the disposal unit price decreases by 15%. A maximum decrease (20%) in the disposal unit price is reached when cocaine initial concentrations are higher than 100 g/L. Nevertheless, the degradation of a liquid stream with an initial concentration higher than 100 g/L requires a better adaptation of microorganisms and higher residence times; conditions that warrant future studies. As shown in Fig. 7, the biological degradation process will not reach the same disposal unit cost of the incineration process. Furthermore, due to the high degradation performance of the process, cocaine base and cocaine hydrochloride biological degradation can be considered as an attractive technology if the initial concentration is increased up to 50 g/L (i.e., 0.93 USD/kg). Hence, this biological process can be profiled from the economic perspective as a promising alternative.

The OPEX of the incineration process and RBDR plant was 708,760 and 1'137,520 USD, respectively. This difference is attributed to the great gap among the costs of raw materials, utilities, maintenance, and capital depreciation. On the other hand, the CAPEX of the incineration process and RBDR plant was 46,400 and 331,506 USD, respectively. These values are similar to other reports in the open literature. The capital investment of the incineration process was calculated based on a direct quotation of an incinerator of the Inciner8 enterprise and the APEA software. However, the capital investment of the RBDR plant has an uncertainty between of 30 and 50% since the equipment costs were calculated from data in the APEA software (Cardona Alzate et al., 2018).

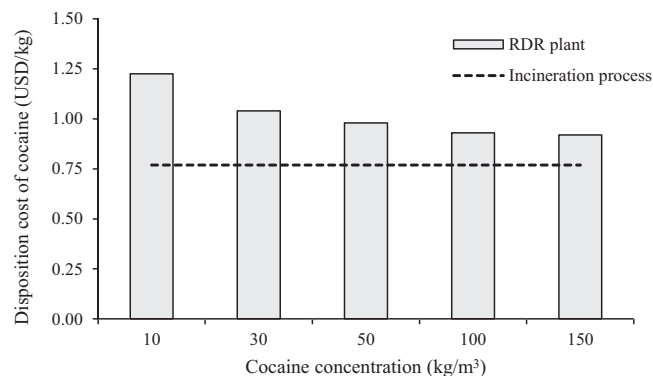


Fig. 7. Sensitivity analysis of cocaine disposal unit price with respect to the initial concentration in the RBDR equipment.

Thus, the CAPEX of the incineration process is a reliable value considering the scale of the process (100 kg/h). Effectively, an incinerator for narcotics destruction with high capacity may have a commercial value of 700,000 USD (Inciner8, 2020). Moreover, the capital investment results obtained for the incineration process were compared with the economic analysis performed by Nasserzadeh et al. (1991). The capital investment reported by these authors of a waste incinerator with a capacity of 10 tonnes per hour was 19.5 million dollars. This value was given by the authors considering the real value of an installed incineration system in Sheffield, England. Therefore, the incinerator value may be considered as a reference point to discuss the reliability of the capital cost results of the incineration system. A similar result to the reported value in this work is obtained once the “six-tenths rule” is applied to the obtained value (Towler and Sinnott, 2012). The CAPEX of the biological degradation process was compared with the data reported by Nasr et al. (2007). These authors report a capital cost for the RBDR system of 22,807 USD in 2007. Accordingly, this information was extrapolated to an equipment price in 2019 considering the same capacity and using CEPCI, cost escalation index, and the economy of scale concept. In this way, the RBDR equipment cost by Nasr et al. (2007) has an equipment price of 232,978 USD. The equipment price given by the APEA software was 250,300 USD. Hence, a correct mapping of the RBDR system was performed and the CAPEX value reported for the proposed process is reliable. The CAPEX obtained for both processes is lower than the CAPEX reported by several authors concerning thermochemical and biological processes (García et al., 2017; Martínez-Ruano et al., 2018). Nevertheless, these processes are designed to be operated as high-scale processes, which have a direct influence on the total capital investment of the projects as well as the process economics (Serna-Loaiza et al., 2018).

3.3.2. Environmental assessment

The results of the environmental assessment are discussed considering global atmospheric and toxicological categories. The toxicological impact categories results of the environmental evaluation for both processes are presented in Fig. 8. In general terms, since most of the degradation products are not harmful to humans, the RBDR plant presents a low environmental impact compared with the incineration process. Cocaine base and cocaine hydrochloride degradation can produce benzoylecgonine and ecgonine methyl ester according to the metabolic pathway reported by Shimomura et al. (2019). These are classified as inactive compounds since their effects are different than cocaine, therefore cocaine degradation products are not considered as harmful compounds. The TPP impact category has a relatively high value in the

environmental assessment due to a pH change registered during cocaine biological degradation. This change is attributed to the release of H_3O^+ from the cleavage of the chemicals bonds in the cocaine base and cocaine hydrochloride molecules. Similar results in terms of the HTPE and ATP impact categories are obtained when other biotechnological conversion routes are evaluated (Parra-Ramírez et al., 2020; Serna-Loaiza et al., 2018). Regarding the incineration process, all the impact categories had a relatively high value. Besides, the emissions resulting from the cocaine thermochemical disposal may render a negative consequence on human health. Finally, HCl and NO_x probable emissions may cause acid precipitation.

The results for the global atmospheric impact categories are presented in Fig. 9. The incineration process shows a greater environmental impact than the RBDR plant. The GWP impact category has a high relative value because of the high amount of CO₂ generated as product of a complete combustion. Moreover, other compounds such as NO₂, SO_x, and particulate matter (PM) produced in the diesel co-combustion also contribute to this impact category. On the other hand, the OPD impact category has a high value due to the possible presence of organochlorine compounds in the exhaust gases derived from the thermal degradation of cocaine hydrochloride (Wagner and Green, 1993). In this sense, the possible formation of chemical compounds with a C_xH_yCl formula could be the main reason for the high impact on the ODP impact category (Reimann et al., 2018). In fact, there is a high concentration of these compounds (i.e., C_xH_yCl) derived from the combustion process (Blankenship et al., 1994) hence the importance of the post-combustion process. The possible presence of other non-methane volatile organic compounds (NMVOC) can also contribute to this impact category. The AP impact category has the highest value of PEI/h due to nitrogen and chlorinated compounds emissions, that can cause acid precipitation and terrestrial acidification (Sánchez and Cardona, 2012). The overall results obtained of the incineration process are similar to those reported by Beylot et al. (2018), where the life cycle assessment methodology was used to analyze the environmental impact of municipal solid waste incineration. Additionally, the climate change (CC), photochemical ozone formation (POF), acidification (A) as well as terrestrial eutrophication (TE), and marine eutrophication (ME) impact categories are the most affected by the direct emissions of the exhaust gases derived from the incineration process.

In the RBDR plant, the results of the global atmospheric impact categories are lower than 10 PEI/h. The highest value obtained for this process was related to the AP impact category due to the solubilization of nitrogen and chlorinated compounds. Nevertheless, the values presented in Fig. 9 show the global atmospheric advantages of the RBDR

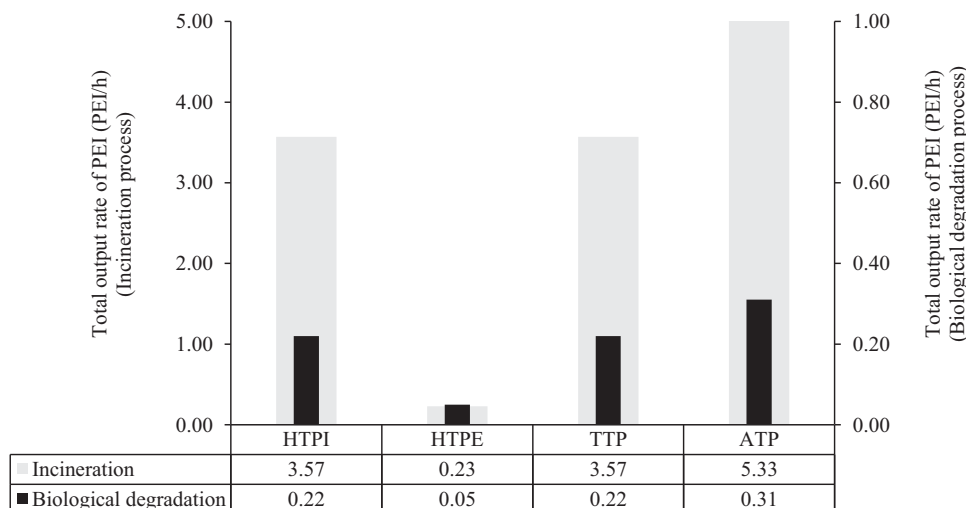


Fig. 8. Comparison of toxicological impact categories from cocaine base and cocaine hydrochloride incineration and biological degradation.

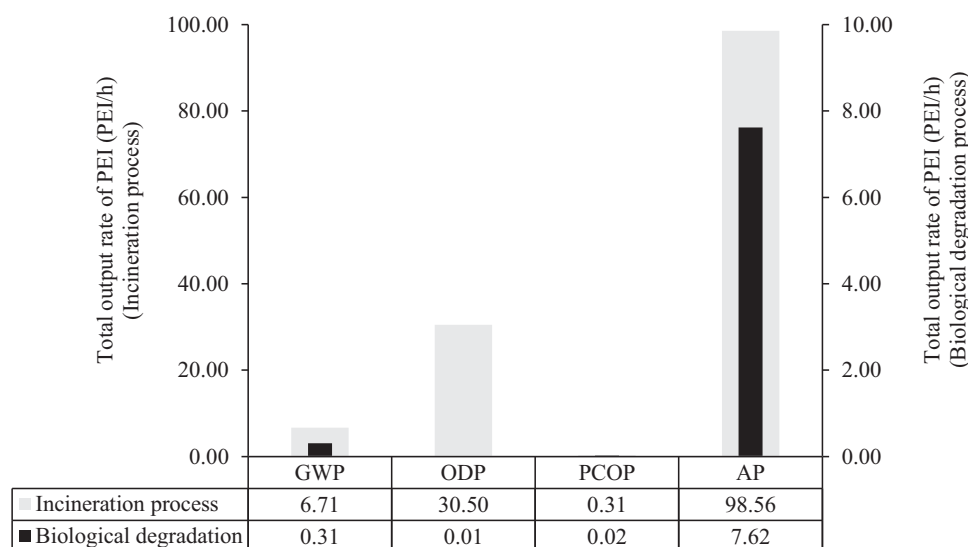


Fig. 9. Global atmospheric impact categories: comparison of cocaine base and cocaine hydrochloride incineration and RBDR plant.

plant. The other impact categories such as GWP, ODP, and PCOP are negligible when compared to the environmental impact caused by the incineration process. The results of the RBDR plant have the same trend than other studies reported in the open literature for biological processes. For instance, Duque et al. (2015) reported the same global atmospheric impact categories to evaluate the environmental performance of a bioethanol producing plant using several raw materials as feedstock. These authors reported a negligible contribution of the GWP and ODP impact categories. However, the values of the total output rate of the bioethanol production process are higher than the values obtained for the RBDR plant. This difference can be explained by the release of more pollutant streams in the bioethanol production process since liquid waste from the pretreatment unit and stillage are not treated. Finally, the environmental assessment of both processes was performed considering the same weighting factors (default values given by the software). The addition of each impact category gives the total environmental impact of the process. In this way, the biological degradation of cocaine base and cocaine hydrochloride is 23-fold lower than the incineration process. Hence, this way to dispose of cocaine base and cocaine hydrochloride has great potential. Further studies are necessary to improve the economic feasibility of the process that could make possible its implementation in developing countries.

The comparison between biological degradation routes and thermochemical disposition alternatives considering the environmental perspective has been reported in the open literature. However, the best performance is not always obtained for the biological pathway. In fact, Di Maria and Micale (2015) developed a better environmental performance of the incineration process than the anaerobic digestion of municipal solid waste since the last option has high gaseous emissions with high greenhouse gas potential.

4. Conclusions

Cocaine base and cocaine hydrochloride biological degradation using an RBDR is a feasible and reliable alternative when compared to the conventional incineration process. RBDR had a CRE = 99.4% which represents the highest cocaine degradation ever reported for bacteria and the economic analysis of the biodegradation process presented a reasonable disposal unit price (1.22 USD/kg) in comparison with the thermochemical route (0.77 USD/kg). Moreover, the RBDR process showed good environmental performance because of the lowest environmental impact values obtained in the atmospheric and toxicological categories. Therefore, the alternative to degrade cocaine using an RBDR

process can be proposed as a tangible alternative to replacing cocaine incineration as the final disposal treatment in Colombia. In this sense, this methodology is a promising alternative for scaling up the alkaloid degradation process. However, more studies are recommended to assess cocaine solubility to determine the maximum amount of cocaine base and cocaine hydrochloride to be degraded by the biological conversion route.

CRediT authorship contribution statement

Carlos A. Díaz: Conceptualization, Methodology, Writing - Original draft, Writing - review & editing, Formal analysis, visualization. **Juan C. Solarte-Toro:** Methodology, Writing - review & editing, software, visualization. **Liz W. Cuadros Veloza:** Conceptualization, methodology, funding acquisition. **Carlos A. Cardona Alzate:** Methodology, Writing - review & editing, validation. **Elisabeth Restrepo-Parra:** Conceptualization, methodology, Writing - review & editing, supervision. **Juan C. Higueta:** Conceptualization, methodology, Writing - review & editing, project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declarations of interest

The authors do not have any conflict of interest.

References

- Badisa, R.B., Goodman, C.B., 2012. Effects of chronic cocaine in rat C6 astroglial cells. *Int. J. Mol. Med.* 5, 687–692. <https://doi.org/10.3892/ijmm.2012.1038>.
- Bedford, J., Turner, C., Elsohly, H., 1982. Comparative lethality of coca and cocaine. *Pharmacol. Biochem. Behav.* 17, 1087–1088. [https://doi.org/10.1016/0091-3057\(82\)90499-3](https://doi.org/10.1016/0091-3057(82)90499-3).

- Beylot, A., Muller, S., Descat, M., Ménard, Y., Villeneuve, J., 2018. Life cycle assessment of the French municipal solid waste incineration sector. *Waste Manag.* 80, 144–153. <https://doi.org/10.1016/j.wasman.2018.08.037>.
- Blankenship, A., Chang, D.P.Y., Jones, A.D., Kelly, P.B., Kennedy, I.M., Matsumura, F., Pasek, R., 1994. Toxic combustion by-products from the incineration of chlorinated hydrocarbons and plastics. *Chemosphere* 28, 183–196. [https://doi.org/10.1016/0045-6535\(94\)90212-7](https://doi.org/10.1016/0045-6535(94)90212-7).
- Brown, R.C., 2011. Thermochemical processing of biomass: conversion into fuels. *Chem. Power.* <https://doi.org/10.1002/9781119990840>.
- Cardona Alzate, C.A., Solarte-Toro, J.C., Peña, Á.G., 2018. Fermentation, thermochemical and catalytic processes in the transformation of biomass through efficient biorefineries. *Catal. Today* 302, 61–72. <https://doi.org/10.1016/j.cattod.2017.09.034>.
- Delgado, N., Marino, A.N.D., Ronco, G.A.P.A., 2018. Removal of pharmaceuticals and personal care products from domestic wastewater using rotating biological contactors. *Int. J. Environ. Sci. Technol.* <https://doi.org/10.1007/s13762-018-1658-2>.
- Di Maria, F., Micale, C., 2015. Life cycle analysis of management options for organic waste collected in an urban area. *Environ. Sci. Pollut. Res.* 22, 248–263. <https://doi.org/10.1007/s11356-014-3330-9>.
- Duque, S.H., Cardona, C.A., Moncada, J., 2015. Techno-economic and environmental analysis of ethanol production from 10 agroindustrial residues in Colombia. *Energy Fuels* 29, 775–783. <https://doi.org/10.1021/ef5019274>.
- Fu, Yan, Diwekar, Urmila M., Young, Douglas, Cabezas, Heriberto, Fu, Y., Diwekar, U.M., Young, D., Cabezas, H., 2000. Process design for the environment: a multi-objective framework under uncertainty. *Clean. Prod. Process* 2, 92–107. <https://doi.org/10.1007/s100980000060>.
- García-Velásquez, C.A., Cardona, C.A., 2019. Comparison of the biochemical and thermochemical routes for bioenergy production: a techno-economic (TEA), energetic and environmental assessment. *Energy* 172, 232–242. <https://doi.org/10.1016/j.energy.2019.01.073>.
- García, C.A., Betancourt, R., Cardona, C.A., 2017. Stand-alone and biorefinery pathways to produce hydrogen through gasification and dark fermentation using *Pinus patula*. *J. Environ. Manag.* 203 (part 2), 695–703. <https://doi.org/10.1016/j.jenvman.2016.04.001>.
- Gostic, T., Klemenc, S., Stefane, B., 2009. A study of the thermal decomposition of adulterated cocaine samples under optimized aerobic pyrolytic conditions. *Forensic Sci. Int.* 187, 19–28. <https://doi.org/10.1016/j.forsciint.2009.02.009>.
- Grant, R., Acosta, D., 1994. Comparative toxicity of tetracaine, proparacaine, and cocaine evaluated with primary cultures of rabbit corneal epithelial cells. *Exp. Eye Sci. Res.* 58, 469–478. <https://doi.org/10.1006/exer.1994.1040>.
- Inciner8, 2020. Drug & Contraband Incinerators [WWW Document]. URL (<https://www.inciner8.com/drug-incinerators.php>) (Accessed 20 June 2020).
- Kim, J., Jeong, S., 2017. Economic and environmental cost analysis of incineration and recovery alternatives for flammable industrial waste: the case of South Korea. *Sustainability* 9, 1–16. <https://doi.org/10.3390/su9091638>.
- Li, N., Zeng, W., Yang, Y., Wang, B., Li, Z., Peng, Y., 2019. Oxygen mass transfer and post-denitrification in a modified rotating drum biological contactor 144, 48–56.
- Martin, B., Lue, L., Boni, J., 1989. Pyrolysis and volatilization of cocaine. *J. Anal. Toxicol.* 13, 158–162. <https://doi.org/10.1093/jat/13.3.158>.
- Martínez-Ruano, J.A., Caballero-Galván, A.S., Restrepo-Serna, D.L., Cardona, C.A., 2018. Techno-economic and environmental assessment of biogas production from banana peel (*Musa paradisiaca*) in a biorefinery concept. *Environ. Sci. Pollut. Res.* 25, 35971–35980. <https://doi.org/10.1007/s11356-018-1848-y>.
- Mohammadi, M., Mohammadi, P., Karami, N., Barzegar, A., Mohamad-Annuar, M.S., 2019. Efficient hydrogen gas production from molasses in biological contactor. *Int. J. Hydrog. Energy* 44, 2592–2602. <https://doi.org/10.1016/j.ijhydene.2018.12.033>.
- Moncada, J., Tamayo, J.A., Cardona, C.A., 2016. Techno-economic and environmental assessment of essential oil extraction from Oregano (*Origanum vulgare*) and Rosemary (*Rosmarinus officinalis*) in Colombia. *J. Clean. Prod.* 112, 172–181. <https://doi.org/10.1016/j.jclepro.2015.09.067>.
- Mukherjee, A., Debnath, B., Kumar, S., 2016. A review on technologies of removal of dioxins and furans from incinerator flue gas. *Proc. Environ. Sci.* 35, 528–540. <https://doi.org/10.1016/j.proenv.2016.07.037>.
- Nasr, F., Doma, H., Abdel-Halim, H., El-Shafai, S., 2007. Chemical industry wastewater treatment. *Environ. Syst. Decis.* 27, 275–286. <https://doi.org/10.1007/s10669-007-9004-0>.
- Nasserzadeh, V., Swithenbank, J., Scott, D., Jones, B., 1991. Design optimization of a large municipal solid waste incinerator. *Waste Manag.* 11, 249–261. [https://doi.org/10.1016/0956-053X\(91\)90072-D](https://doi.org/10.1016/0956-053X(91)90072-D).
- Palmeros Parada, M., Ossseweijer, P., Posada Duque, J.A., 2017. Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. *Ind. Crops Prod.* 106, 105–123. <https://doi.org/10.1016/j.indcrop.2016.08.052>.
- Parra-Ramírez, D., Solarte-Toro, J.C., Cardona-Alzate, C.A., 2020. Techno-Economic and environmental analysis of biogas production from plantain pseudostem waste in Colombia. *Waste Biomass Valoriz.* 11, 3161–3171. <https://doi.org/10.1007/s12649-019-00643-8>.
- Pérez, J.D., 2010. Application and Evaluation of a Rotary Biological Contactor (RBC) at Laboratory Scale as a Treatment of the Lixiviados Generated in the Pradera Landfill. (Title in Spanish: Aplicación y evaluación de un reactor de contactores biológicos rotativos (RBC o biodiscos) a escala laboratorio como tratamiento de los lixiviados generados en el relleno sanitario de la pradera). Universidad De Medellín, Medellín-Colombia (Master Thesis).
- Pylypiw, H.M., Grether, M.T., 2000. Rapid high-performance liquid chromatography method for the analysis of sodium benzoate and potassium sorbate in foods. *J. Chromatogr. A* 883, 299–304. [https://doi.org/10.1016/S0021-9673\(00\)00404-0](https://doi.org/10.1016/S0021-9673(00)00404-0).
- Rakopoulos, D.C., Rakopoulos, C.D., Giakoumis, E.G., Dimaratos, A.M., Founti, M.A., 2011. Comparative environmental behavior of bus engine operating on blends of diesel fuel with four straight vegetable oils of Greek origin: sunflower, cottonseed, corn and olive. *Fuel* 90, 3439–3446. <https://doi.org/10.1016/j.fuel.2011.06.009>.
- Reimann, S., Elkins, J.W., Fraser, P.J., Hall, B.D., Kurylo, M.J., Mahieu, E., Montzka, S.A., Prinn, R.G., Rigby, M., Simmonds, P.G., Weiss, R.F., 2018. Observing the atmospheric evolution of ozone-depleting substances. *Comptes Rendus Geosci.* 350, 384–392. <https://doi.org/10.1016/j.crte.2018.08.008>.
- Sánchez, Ó.J., Cardona, C.A., 2012. Conceptual design of cost-effective and environmentally-friendly configurations for fuel ethanol production from sugarcane by knowledge-based process synthesis. *Bioresour. Technol.* 104, 305–314. <https://doi.org/10.1016/j.biortech.2011.08.125>.
- Serna-Loaiza, S., Carmona-García, E., Cardona, C.A., 2018. Potential raw materials for biorefineries to ensure food security: the Cocoyam case. *Ind. Crops Prod.* 126, 92–102. <https://doi.org/10.1016/j.indcrop.2018.10.005>.
- Shimomura, E., Jackson, G., Dev Paul, B., 2019. Cocaine, Crack Cocaine, and Ethanol: A Deadly Mix. In: Dasgupta, A. (Ed.), *Critical Issues in Alcohol and Drugs of Abuse Testing*. Academic Press, pp. 215–224. <https://doi.org/10.1016/C2017-0-02017-7>.
- Silva, L.J., de, V.B., da, Santos, I.F.S., dos, Mensah, J.H.R., Gonçalves, A.T.T., Barros, R. M., 2020. Incineration of municipal solid waste in Brazil: an analysis of the economically viable energy potential. *Renew. Energy* 149, 1386–1394. <https://doi.org/10.1016/j.renene.2019.10.134>.
- Sofian, K., Fatin, S., 2018. Trends in environmental analytical chemistry dioxins and furans: a review from chemical and environmental perspectives. *Trends Environ. Anal. Chem.* 17, 1–13. <https://doi.org/10.1016/j.teac.2017.12.001>.
- Solarte-Toro, J.C., Ortiz-Sánchez, M., Alonso-Gómez, L.A., Cardona-alzate, C.A., 2019. Energy valorization of oil palm agro-residues by air-down draft gasification: technical and economic analysis. In: *Atmaca, A. (Ed.), 4th International Energy & Engineering Congress*. Gaziantep University, Turkey, pp. 1191–1214.
- Towler, G.P., Sinnott, R., 2012. Capital costs estimating. In: *Chemical Engineering Design*. Butterworth-Heinemann, pp. 307–354. <https://doi.org/10.1016/C2009-0-61216-2>.
- United Nations Office on Drugs and Crime, 2020. Annual drug seizures [WWW Document]. Stat. data.
- Wagner, J.C., Green, A.E.S., 1993. Correlation of chlorinated organic compounds emissions from incineration with chlorinated organic input. *Chemosphere* 26, 2039–2054. [https://doi.org/10.1016/0045-6535\(93\)90030-9](https://doi.org/10.1016/0045-6535(93)90030-9).
- Wang, C., Shao, N., Xu, J., Zhang, Z., Cai, Z., 2019. Pollution emission characteristics, distribution of heavy metals, and particle morphologies in a hazardous waste incinerator processing phenolic waste. *J. Hazard. Mater.* 121751. <https://doi.org/10.1016/j.jhazmat.2019.121751>.
- Young, D.M., Cabezas, H., 1999. Designing sustainable processes with simulation: the waste reduction (WAR) algorithm. *Comput. Chem. Eng.* 23, 1477–1491. [https://doi.org/10.1016/S0098-1354\(99\)00306-3](https://doi.org/10.1016/S0098-1354(99)00306-3).