

Alternatives for cocaine disposal: An experimental, techno-economic, and environmental comparison between incineration and biological degradation

Carlos A. Díaz-Vargas ^{a, **}, Juan C. Solarte-Toro ^b, Liz Wendy Cuadros Veloza ^d,
Carlos A. Cardona Alzate ^b, Elisabeth Restrepo-Parra ^c, Juan C. Higueta ^{a, *}

^a Universidad Nacional de Colombia sede Manizales, Laboratorio de Ciencias Biológicas y Moleculares, Departamento de Ingeniería Química, Km 07 vía al Magdalena, Manizales, Colombia

^b Universidad Nacional de Colombia sede Manizales, Instituto de Biotecnología y Agroindustria, Laboratorio de Equilibrios Químicos y Cinética Enzimática, Departamento de Ingeniería Química, Km 07 vía al Magdalena, Manizales, Colombia

^c Universidad Nacional de Colombia sede Manizales, Laboratorio de Física del Plasma, Departamento de Física y Química, Km 07 vía al Magdalena, Manizales, Colombia

^d International Center of Strategic Studies Against Drug Trafficking, Narcotics Division Policía Nacional de Colombia, Bogotá, Colombia

ARTICLE INFO

Article history:

Received 9 July 2020

Received in revised form

24 January 2021

Accepted 18 February 2021

Available online 22 February 2021

Handling editor: Prof. Jiri Jaromir Klemes

Keywords:

Biological degradation

Cocaine

Economic assessment

Environmental impact

Final disposal

ABSTRACT

Worldwide trends in the area under coca crops cultivation have been primarily motivated by illegal advances in Colombia around cocaine production. Thus, alternative ways for the final disposal of cocaine are needed and the evaluation of their possible economic and environmental advantages. This work aimed to compare incineration and biological degradation of cocaine by considering techno-economic and environmental aspects. There was a cocaine removal efficiency of 99.7% when bacterial *CIT consortia* was grown using cocaine as the sole carbon source. The biological degradation process exhibited a specific energy consumption and total potential environmental impact, 5 and 10 fold lower than the incineration process, respectively. The biological degradation process can also reach similar disposition unit prices as the incineration process (i.e., 1.00 USD/kg).

© 2021 Elsevier Ltd. All rights reserved.

1. Introduction

The upgrading of organic compounds into other molecules has been the basis of the chemical industry. Moreover, many processes and technologies are available to dispose of different organic and inorganic materials derived from anthropogenic activities. Thermochemical and biotechnological conversion pathways have been researched to dispose of municipal solid waste (MSW), harmful waste, and toxic compounds (e.g., narcotics and drugs). Traditionally, the incineration process has been used for the final disposal of

dangerous materials. This process can reduce the solid volume by up to 90% and, therefore, disappear any problem associated with storing these kinds of substances. Besides, this process has been improved in energy efficiency, fuel consumption, and gaseous releases. However, few studies are related to the incineration of narcotics and drugs. Therefore, a complete characterization of the emissions derived from the thermochemical degradation of drugs has not been reported in the open literature.

Alkaloids can be disposed of by applying three different pathways. The first pathway is incineration. This process is the most used technology to dispose of alkaloids in developing countries. Efforts related to the characterization of chemical compounds derived from the thermal degradation of alkaloids have been done in the last years. For instance, Gostic et al. (2009) report some chemical compounds derived from the thermal decomposition of adulterated cocaine samples. Different studies related to health damages or problems derived from the narcotics thermal

* Corresponding author. Universidad Nacional de Colombia – Sede Manizales, 170003, Manizales, Caldas, Colombia.

** Corresponding author.

E-mail addresses: caadiazva@unal.edu.co (C.A. Díaz-Vargas), jchiguitav@unal.edu.co (J.C. Higueta).

decomposition have been conducted. For example, [Erzouki et al. \(1995\)](#) studied the effect of the products generated by cocaine pyrolysis on rabbit hindbrain cardiac and respiratory centers. The second pathway to dispose of alkaloids is the so-called “Chemical method.” This disposal alternative involves using strong inorganic acids (e.g., sulfuric acid, nitric acid) or strong bases (e.g., sodium hydroxide) to decompose alkaloids into other chemical compounds. The third pathway is related to biological processes since microorganisms can degrade alkaloid molecules into small chemical compounds without any adverse effect on humans. The advantages and disadvantages of the three pathways to degrade alkaloids are presented in [Table 1](#).

As shown in [Table 1](#), the biological degradation process to dispose of alkaloids seems to be a good approach. This process is a promising alternative for this type of application since microorganisms can degrade alkaloids into non-hazard and non-pollutant compounds. Moreover, biological processes have been characterized by lower energy requirements than thermochemical processes. There are few reports about cocaine disposal since it is an illegal substance. Nevertheless, the biological degradation of cocaine has been described by several researchers through the action of specialized enzymes such as butyrylcholinesterase (BChE), hepatic carboxylesterase (hCE-1 and hCE-2) in humans and bacterial cocaine esterase (CocE) in *Rhodococcus* sp., MB1. In humans, cocaine is almost completely metabolized by enzymatic hydrolysis, with plasma BChE and hepatic hCE-1 esterases being the main enzymes responsible for the formation of their metabolites such as methyl ecgonine, ecgonine, and BE. Besides, BChE is the main enzyme that metabolizes cocaine in plasma, both in humans and in other species ([Bosron and Hurley, 2002](#)). In addition, in aqueous media and in eukaryotic metabolic pathways, the cocaine molecule suffers different hydrolysis reactions (mainly to benzoylecgonine, ecgonine methyl ester, and ecgonine), and its kinetics has been reported as a function of pH, temperature, and the protonation state of tertiary nitrogen ([Szöcs et al., 2017](#)). Additionally, under chlorination and sunlight irradiation, other compounds such as norcocaine and benzoylecgonine have also been identified ([Bijlsma et al., 2013](#)). On the other hand, Díaz and coworkers (2020) established a bacterial degradation of cocaine on a Rotary Biological Disc Reactor (RBDR) generating benzoylecgonine and benzoic acid as degradation products after 42 h of treatment ([Díaz et al., 2020](#)). Moreover, [Burns-Edel \(2016\)](#) revealed that amphibious species sustaining prolonged exposure to cocaine in their aquatic ecosystems may suffer species decline for the action of adding cocaine to water sources (mainly rivers) as a final disposal method of this alkaloid. Bijlsma and coworkers (2013) studied the chemical hydrolysis of cocaine (0.5 mg/L) in an aquatic environment and BE was

only produced after 15 days and [Kiszka, Buszewicz, and Mýdro \(2000\)](#) studied the stability of cocaine and BE where only at low pH (6–5) cocaine is stable. Thus, biological processes can be pushed as a sustainable and reliable option to dispose of organic compounds since several research papers have been focused on this objective. For instance, the biological degradation of dyes has been extensively researched using microorganisms to decrease the environmental damage caused by these waste streams ([Varjani et al., 2020](#)). This alternative has higher removal efficiencies than activated carbon. In this way, the biological degradation of alkaloids could be a feasible option to dispose of other organic molecules such as alkaloids. Indeed, there are few reports of the biological degradation of narcotics in sewage sludge. Nonetheless, the Pseudomonadacea family can be adapted to degrade several organic compounds including tropane alkaloids ([Bartholomew et al., 1996](#)). Consequently, the study of the microbial metabolism of atropine as a tropane alkaloid in the Pseudomonadacea family has received significant attention for the production of this tropane derivative ([Britt et al., 1992](#)). In the case of the Bacillaceae family, there are no previous reports about cocaine degradation ([Ray and Kalia, 2017](#); [Sella et al., 2014](#)). Parthipan et al. (2017) reported that different microorganisms of the *Bacillus* genus can degrade complex compounds of high molecular weight (MW) such as crude oil, with a biodegradation efficiency of 87%. [Mccall et al. \(2016\)](#) published a critical review on the stability of illicit substances (e.g., cocaine, amphetamine, opiates, and cannabinoids) in sewers and wastewater samples with the conditions to perform a biological degradation of these compounds. Nevertheless, more development and study of the biological degradation of alkaloids is required because there is not much information related to the microorganism behavior during alkaloid degradation in the open literature. Thus, this paper aimed to compare the incineration and biological degradation of cocaine base and cocaine hydrochloride as the final disposal of this hazardous waste, considering techno-economic and environmental perspectives.

2. Experimental and simulation processes

The techno-economic and environmental comparison between incineration and biological degradation was done considering the experimental results derived from lab-scale incineration of cocaine base and cocaine hydrochloride as well as the biological degradation of these alkaloids by a microorganism consortium. Then, a simulation using the Aspen Plus v 9.0 was done. The next subsections describe the experimental and simulation approaches applied in this paper.

Table 1
Advantages and disadvantages of three degradation pathways to dispose of alkaloids.

Incineration	
Advantages • High decomposition rate and yield • Mature technology • Low capital investment and disposal cost Chemical method	Disadvantages • Fossil fuels consumption as ignitor (e.g., diesel) • Dangerous emissions to the atmosphere • Emission of greenhouse gases
Advantages • High decomposition yield.	Disadvantages • High disposal cost • Use of environmentally dangerous compounds (e.g., strong acids) • Generation of dangerous gaseous and liquid residues
Biological degradation	Disadvantages
Advantages • Low gaseous emissions and energy consumption • High degradation yield • No by-products formation. • More environmentally friendly	Disadvantages • Relative low decomposition rate • High capital investment • High disposal cost

2.1. Experimental set-up and quantification

2.1.1. C1T consortium

Several bacterial 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 to form the *T1* consortium. A new bacterial consortium named *T2* was then isolated from the rhizosphere of coca crop plantations in Tumaco, Colombia. The different strains that are part of the *T2* consortium have not been identified. Consortia *T1* and *T2* were mixed, thus forming a new consortium named *C1T*. This new consortium was used to evaluate several parameters like Cocaine Removal Efficiency (CRE) at 10 g/L.

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 the Durapore PVDF membrane of 0.22 μm . Analytical cocaine and Benzoylecgonine (BE) standards were obtained from Lipomed. The confiscated cocaine hydrochloride was supplied from drug confiscations made by the Narcotics Division of the Colombian National Police in collaboration with the General Attorney's Office.

2.1.3. Culture media

The composition of the different solutions used in this study for bioreactor experiments carried out with cocaine as the only carbon source, were (g/L): $(\text{NH}_4)_2\text{SO}_4$ (1), K_2HPO_4 (1.5), $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (0.2), Na_2HPO_4 (9.0), 1 mL of a trace element solution containing (g/L): $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (10.0), $\text{MnSO}_4 \cdot 4\text{H}_2\text{O}$ (0.5), $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ (2.25), $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (1.0), $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ (2.0), H_3BO_3 (0.23) $(\text{NH}_4)_2\text{Mo}_7\text{O}_{24}$ (0.2), and 10 mL of HCl. Ultrapure water was produced by a purification system from Milli-Q from Millipore Corporation. The inoculum preparation for the batch mode experiments was developed by using three 250 mL flasks with 100 mL of the cocaine saline medium (CSM) cultured for 48 h at 32 °C. The resulting biomass was then separated by centrifugation (14,800 rpm during 10 min), washed twice with 25 mL of sterilized CSM, and diluted in 50 mL of freshly sterilized CSM. All media were sterilized 15 min at 121 °C and cooled to 32 °C before use (López et al., 2012).

2.1.4. Determination of cell density

Biomass concentration was traced by optical density (OD) at 600 nm in a UV Thermo Scientific Genesis 20 Spectrophotometer and additionally measured by dry weight. In brief, 2 mL samples were collected and centrifuged at 14,800 rpm for 10 min (Microcentrifuge Sigma1-14). Then, dried at 60 °C until a constant weight was achieved. Before measurements, samples were stored in a desiccator for 24h and weighed (Analytical Balance Wisd-220 $\pm$ 0.1 mg).

2.1.5. Bioreactor bacterial growth

Batch experiments were carried out in a 1.3L lab fermenter (Biotron Lifluf GX) with a 1.0L work volume. The bioreactor vessel was sterilized at 121 °C for 20 min with a pH adjusted at 7.2. During the batch process, the dissolved oxygen was kept constant at an aeration rate of 3.7 L/min, 32 °C, and 150 rpm.

2.1.6. Kinetic parameters

The specific growth rate (μ , day^{-1}) was calculated by taking the slope value in linear regression for dry weight vs. time, considering the cell concentration at the beginning (X_1) and the end (X_2) of the exponential growth phase, according to Equations (1) and (2), where t_2 and t_1 are the final and initial times on the exponential phase, respectively.

$$\mu = \ln(X_2 / X_1) / t_2 \quad (1)$$

$$\mu_{\max} = \ln(X_2 / X_1) / (t_2 - t_1) \quad (2)$$

2.1.7. Cocaine biodegradation

Cocaine removal efficiency at time t (CRE_t) was established according to substrate evolution (C_t) concerning initial concentration (C_0), by Equation (3).

$$\text{CRE}_t = (C_0 - C_t) / C_0 \times 100 \quad (3)$$

2.1.8. Biomass yield on substrate

The association between biomass concentration and cocaine consumption ($Y_{x/s}$) was measured according to equation (4), where X_0 and X_f are the cell concentrations at the beginning and end of the culture time, respectively. C_0 is the cocaine concentration at the beginning of the process, and C_t is the final cocaine concentration.

$$Y_{x/s} = (X_f - X_0) / (C_0 - C_t) \quad (4)$$

2.1.9. Analytical methods

Cocaine and BE concentrations were measured by high-performance liquid chromatography (HPLC) in a Shimadzu 2010A HT with a diode array detector, a C18 column in reverse phase (150 mm $\times$ 4.6 mm and 5 μm particle diameter), and a column temperature of 30 °C. The peaks of cocaine and BE 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) 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 Kromasil C18 column (150 mm $\times$ 4.0 mm and 5 μm particle diameter). The mobile phase was kept in an isocratic regime: (A) ammonium acetate buffer. (B) Acetonitrile (90:10 v: v).

2.1.10. Experimental incineration of cocaine hydrochloride and cocaine base

Cocaine base and cocaine hydrochloride were experimentally burned to determine the amount of volatilized alkaloid and the gases composition derived from the experimental incineration process. For these, $50.00 \pm 0.01\text{g}$ of cocaine base and cocaine hydrochloride were weighed in a previously calcined porcelain crucible and placed on a muffle (Wisd FHPX – 1200 °C). The incineration process was then performed, setting a heating rate of 10 °C/min and 15 °C/min for cocaine base and cocaine hydrochloride, respectively. The incineration process was carried out at 800 °C for 60 min. A positive displacement pump was used to suck the incineration gases. The pumped gases were sent to a gas analyzer equipment (Gasboard 3100P) to determine the relative composition of CO_2 and CO, after the combustion process.

2.2. Techno-economic and environmental assessments

Two processes are proposed and evaluated from a techno-economic and environmental perspective. The first process involves the conventional incineration procedure, where the alkaloid

was degraded until a mixture of gaseous products (e.g., CO₂, NO_x, and H₂O). The second process involves the biological degradation of the alkaloid using a bacterial consortium. The mass and energy balances derived from the simulation of each process are used as input data to perform both the economic and environmental evaluations.

2.2.1. Process description and simulation procedure

The incineration process consists of a commercial incineration plant used by different countries to dispose of alkaloids. The incineration equipment consists of the main combustion chamber, a post-combustion chamber, blowers, and a stack. The operating conditions of the incineration process were fixed considering the process conditions evaluated by [Martin et al. \(1989\)](#). On the other hand, the process conditions were compared and validated by reviewing the technical specification of different commercialized incinerators to perform the final disposal of narcotics and hazardous drugs ([Inciner8, 2020](#)). In this way, the main combustion chamber operates at 800 °C and 1 bar with a residence time lower than 2 min to avoid producing volatile organic compounds such as benzoic acid and methylecgonidine (AEME) ([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 produced during cocaine thermal degradation. Moreover, this process also provides the degradation of dioxins derived from the thermal degradation of plastics and other materials introduced into the incinerator ([Mukherjee et al., 2016](#); [Sofian and Fatim, 2018](#)). Blowers supply the required air to accomplish material combustion. In this process, a volumetric flow rate of 5 m³/s was considered to reach complete combustion. Finally, the leaving gases from the incineration process have a fixed temperature of 250 °C. The process flow diagram of the incineration process is presented in [Fig. 1](#).

The biological degradation process was simulated, considering a continuous stirred tank bioreactor (CSTBR). The biological process consists of the following stages: (i) alkaloid solubilization and (ii) alkaloid degradation. In this paper, the effluents of the biological degradation process have a low organic load. Therefore, a wastewater treatment plant was not considered in the conceptual design of this alternative. The process flow diagram is limited to a reservoir for alkaloid solubilization, a CSTBR, and a hydrocyclone for solids separation (i.e., cells). The resulting cells can be disposed or recirculated to increase the degradation performance of the process. In this sense, a water volumetric flow rate of 15 m³/h was considered to ensure an initial substrate concentration of 10 g/L. The dilution rate (D) and the CSTBR volume were calculated using the obtained experimental yields ([Blanch and Clark, 1997](#)). Finally, hydrocyclone acts as a solid-liquid separator using the parameters described by [Nielsen et al. \(2003\)](#). The process flow diagram of the biological degradation process is presented in [Fig. 2](#).

Both processes (i.e., incineration and biological degradation) were simulated using the simulation tool Aspen Plus v 9.0. This simulation software was chosen to estimate the mass and energy balances of the incineration and biological degradation processes using, as a starting point, the Colombian seized and disposed of alkaloid in 2018. Besides, Aspen Plus v.9.0 has been the most widely used software to estimate the total capital investment of different processes due to the complete database of equipment and materials collected from several Engineering, Procurement, and Construction companies ([Towler and Sinnott, 2013](#)). In this way, an alkaloid (i.e., cocaine base/cocaine hydrochloride) mass flow rate of 100 kg/h was used to meet the commercial specification of the incineration equipment. Typical operations for seized alkaloids have a loading capacity of 100 or 150 kg ([Inciner8, 2020](#)). Moreover, this value was also fixed considering the total cocaine seized in

2018 ([United Nations Office on Drugs and Crime, 2020](#)). Since cocaine base (C₁₇H₂₁NO₄) and cocaine hydrochloride (C₁₇H₂₂ClNO₄) are not included in the Aspen Plus database, the main properties of these compounds (e.g., critical temperature, pressure, acentric factor, boiling point, among others) were estimated using the Aspen Properties tool. Furthermore, the Peng-Robinson (PR) equation of state (EoS) was selected to model the vapor phase, and the Non-random two liquids (NRTL) was the chosen activity model ([Cardona Alzate et al., 2018](#)). Once the simulation process of both alternatives was performed, the mass and energy balances were used to carry out the economic and environmental evaluations. Finally, these two options for cocaine degradation were compared using different cost indicators ([Palmeros Parada et al., 2017](#)) and different impact categories ([Young et al., 2000](#)). A summary of the process conditions, purposes, and aspen model used to achieve the simulation is presented in [Table 2](#).

2.2.2. Techno-economic assessment

The techno-economic evaluations of the incineration and biological degradation processes were performed considering the mass and energy balances obtained from the simulation process. In this way, performance metrics such as specific energy consumption and degradation yield were calculated, considering the efficiency indicators reported by [Ruiz-Mercado et al. \(2012\)](#) and [Alonso-Gómez et al. \(2020\)](#). On the other hand, the economic assessment of both processes was carried out using the Aspen Process Economic Analyzer (APEA) software, considering a project lifetime of 10 years and the straight-line depreciation method. This software was used to perform equipment sizing according to the mass flow rate considered in the simulation. The operating costs related to labor and raw material were also included. The price of cocaine base and cocaine hydrochloride was 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](#)). Other costs related to fuel consumption (i.e., diesel), process water, and low-pressure steam were the same values reported by [García-Velásquez and Cardona \(2019\)](#). The labor cost includes the presence of operators, supervisors, police officers, and government officials. The cost per hour of each of the actors is presented in [Table 3](#). Finally, the annual interest rate was fixed at 17% ([Solarte-toro et al., 2019](#)). The economic comparison was done considering economic cost indicators such as capital expenditures (CAPEX), operational expenditures (OPEX), and the cost to degrade one metric tonne of alkaloid.

2.2.3. Environmental assessment

The environmental assessment of the incineration and biodegradation processes was done considering a gate-to-gate approach defined by ISO 140040. This analysis attempts to follow the life cycle assessment (LCA) methodology. For this, the environmental analysis is composed of four stages. 1) Goal and Scope definition, 2) Life cycle inventory (LCI), 3) Environmental impact assessment, 4) Discussion and analysis of the results. The goal of the environmental assessment of different approaches to degrade alkaloids is to elucidate the better pathway to dispose of cocaine base and cocaine hydrochloride from a techno-economic and environmental point of view. The results of the environmental assessment are given per kilogram of alkaloids. On the other hand, the life cycle inventory is related to the mass and energy balances of both processes. These balances were calculated by the Aspen Plus v.9.0 software using a mass flow of 100 kg/h. The environmental impact assessment was carried out using a systematic approach to determine the potential environmental impact (PEI) proposed by [Young et al. \(2000\)](#). The Waste Reduction Algorithm (WAR), developed by

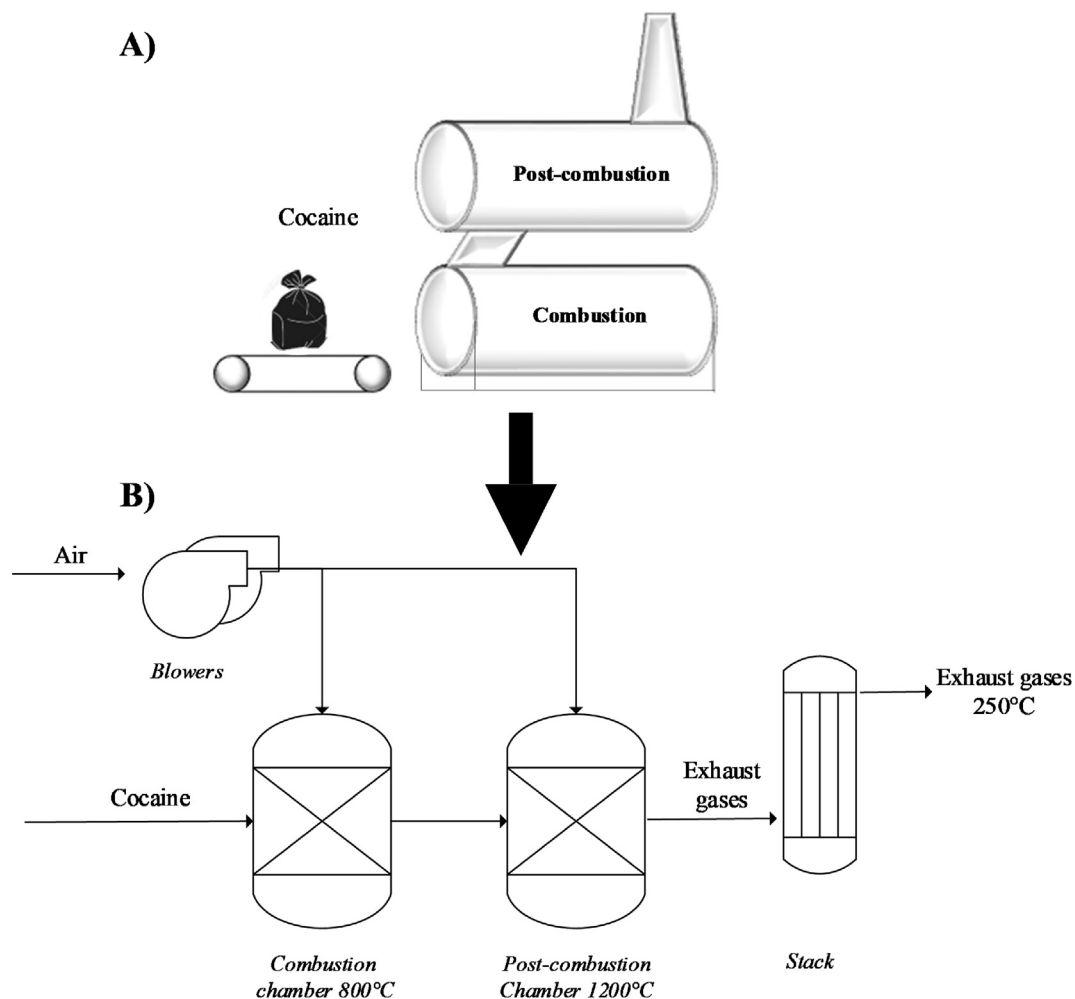


Fig. 1. Incineration process. **A)** Schematic representation of incineration equipment used to dispose of narcotics. **B)** Conceptual process flow diagram of the cocaine incineration process.

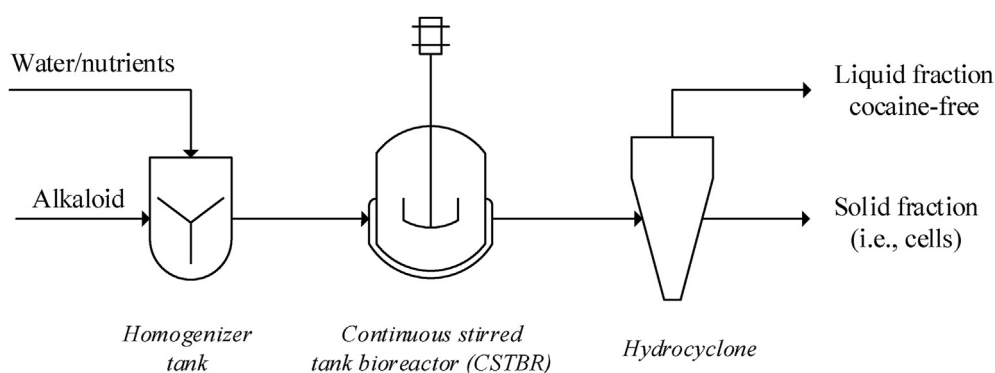


Fig. 2. Biological degradation pathway of cocaine using a CSTBR.

the National Risk Management Research Laboratory from the U.S. Environmental Protection Agency (EPA), was used. The WAR software performs the PEI impact considering global atmospheric and toxicological categories (Moncada et al., 2016). Thus, the environmental assessment was based on the estimation of two different groups of impact categories. The global atmospheric category involves the calculation of the global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), and

photochemical oxidation potential (PCOP) as impact categories. These impact categories are the base to calculate mid-point and end-point impact categories related to the environment (e.g., climate change and natural environment). The toxicological category involves human (i.e., human toxicity potential by ingestion (HTPI), human toxicity potential by inhalation or exposure (HTPE)) and ecological (i.e., aquatic toxicity potential (ATP), and terrestrial toxicity potential (TTP)) impact categories (Fu et al., 2000).

Table 2

Summary of aspen models, purposes, and conditions specified to perform the simulation of the 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 volatile organic compounds	1 bar, 1200 °C	RGibbs
Heat exchanger	Temperature decrease of post-combustion gases.	1 bar, 250 °C	Heater
Biological degradation process			
Homogenizer	Dilute cocaine base/cocaine hydrochloride un 10 g/L	1 bar, 20 °C	Mixer
CSTBR	Biological degradation	1 bar, 32 °C Experimental yield used	RYield
Hydrocyclone	Separate cells from liquid fraction.	Separation efficiency 85%.	HyCyc

Table 3

Personnel wages involved in the degradation of cocaine base and cocaine hydrochloride in Colombia.

Charge	Salary (USD/h)	Amount
Operator	1.05 ^a	1
Supervisor	1.58 ^b	2
Police officer	3.05	1
PIPH analyst ^c	3.05	1
District attorney	11.42	1
Government official	11.42	1

^a Salary based on the Colombian minimum wage per hour in 2019.^b Salary 50% higher than the Colombian minimum wage per hour in 2019.^c Approved Initial Preliminary Test officer.

Similarly, these impact categories are the starting point to estimate mid-point and end-point impact categories related to health and safety (e.g., human toxicity and human health). The WAR algorithm calculates the PEI per unit of time or mass of products as the weighted sum of all impact categories. In this paper, the weights for each impact category were assumed as equal in both processes. Hence default values were used. Regarding the environmental assessment system boundaries, the WAR algorithm performs a gate-to-gate analysis (Gerardo J. Ruiz-Mercado et al., 2012). Finally, the cocaine base and cocaine hydrochloride are not present in the database of the WAR software. Then, cocaine lethal doses (LD50), lethal concentration (LC50), and ecotoxicity (EC50) 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.

Other assumptions used to carry out the techno-economic and environmental evaluation of the cocaine and cocaine hydrochloride are listed below:

- 100 kg/h represents 30% of the total cocaine disposed of using incinerators in Colombia in 2018.
- No-scaling-up rules were applied. Thus, the same conditions, yields, and results at the experimental level were used in the simulation.
- Microorganisms thermodynamic properties and chemical formula were based on the information reported by the National Renewable Energy Laboratory (NREL) (Wooley and Putsche, 1996).
- A salvage value of zero was considered to perform the estimation of the depreciation cost.
- The transportation cost given for cocaine and cocaine hydrochloride only considers terrestrial transportation by trucks. Other costs related to logistics were not involved.
- Financial support given by the Colombian government was not considered in the economic evaluation.
- The annual interest rate was fixed, considering the Colombian economic condition in 2019.

- No further degradation is considered in the simulation. Thus, the environmental analysis only involved the identified decomposition products in the experimental section.

3. Results and discussion

3.1. Experimental results

Cocaine degradation in a CSTBR by *CIT* consortium under agitation and aeration controlled rates conditions showed a $Y_{x/s} = 0.09 \pm 0.006$ and $\mu = 1.31 \text{ day}^{-1}$ with a pH decrease from 7.2 to 6.25. Various bacterial strains can render low $Y_{x/s}$ values, which can be attributed to secondary metabolites such as polysaccharides and CO_2 from respiration processes (Molinari, 2011). Besides, low $Y_{x/s}$ values can be explained by related by-products formation (e.g., BE and benzoic acid). Thus, some microorganisms can generate a reduction in cellular performance because their carbon source is used to produce other metabolites that contain carbon instead of being used to produce biomass (Rincón Santamaría et al., 2019).

3.1.1. Biological degradation

Fig. 3 shows *CIT* consortium growth in a CSTBR with a cocaine initial concentration of 10 g/L. A CRE = 99.7% was achieved at 24 h of culture with the simultaneous production of BE and benzoic acid (see Fig. 4). As shown in Fig. 4, BE and benzoic acid were produced in the first 24 h, followed by a decrease in their amount in the liquid culture. It is possible that both BE and benzoic acid were utilized by the *CIT* consortium as carbon sources for growth and energy supply after cocaine was exhausted.

3.1.2. Lab-scale incineration

The cocaine base and cocaine hydrochloride lab-scale incineration results show a similar overall yield concerning the volatilized

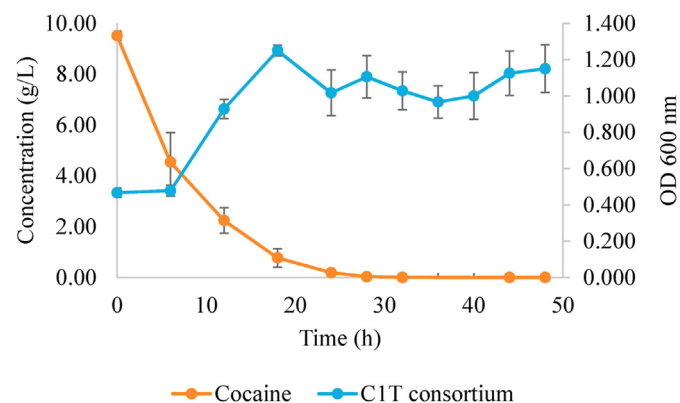


Fig. 3. Bacterial growth and cocaine consumption in batch fermenter. Bars represent the Standard Deviation (SD) of triplicate experiments.

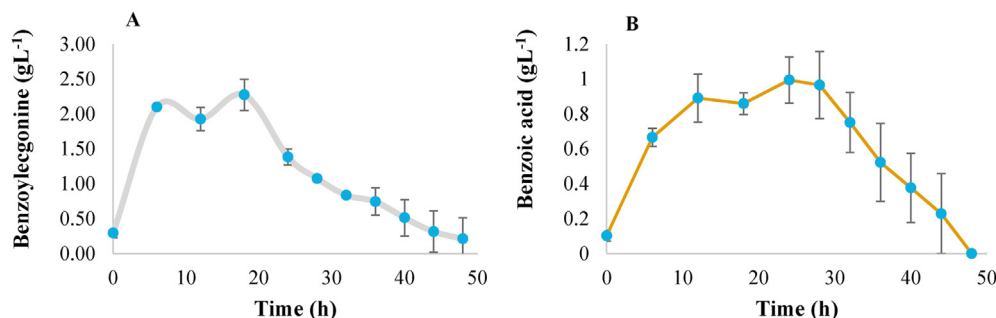


Fig. 4. Biodegradation of cocaine by-products in a batch fermenter. A) BE production and consumption. B) Benzoic acid production and consumption. Bars represent the SD of triplicate experiments.

material. Table 4 presents the initial and final weight of combusted samples. In both cases, volatilization higher than 90% was evidenced, which implies a high reduction in the seized narcotics volume. Indeed, less than 10% of solid residues were obtained after the incineration procedure, which validates the selection of thermochemical routes (e.g., combustion) for the final disposal of this kind of material. From this perspective, the incineration process seems to be the best route due to the high-volume reduction, the destruction of the narcotics, and the easy disposition of the ashes (e.g., ashes disposed of in a landfill). Similar results related to the volatilization yield of cocaine base and cocaine hydrochloride were reported by Gostic et al. (2009). Nevertheless, the authors report cocaine recoveries in the gaseous phase lower than 85%. This high recovery is related to the operating conditions of the process. The incineration procedure carried out in this research was accomplished at 800 °C for 60 min, (i.e., a sample volatilization to time ratio of 14 mg/s). In contrast, Gostic et al. (2009) carried out the incineration at 450 °C and 7s (i.e., a sample volatilization to time ratio of 7 mg/s). Therefore, temperature, time of incineration, and incineration media composition are the main variables to assess the process.

Since the CO₂ content obtained during the incineration of cocaine base and cocaine hydrochloride is higher than 95% in all cases, it could be concluded that complete combustion was achieved (see Table 5). Nevertheless, trace amounts of CO were also registered. This analysis can then serve as the base to set 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). Besides, there is no information related to the composition of exhaust gases derived from the incineration of these materials in the open literature. Therefore, the authors recommended an isokinetic analysis to verify the primary pollutants released into the atmosphere as hazardous pollutants (Wang et al., 2019). On the other hand, the interest in the analysis of other gaseous products such as methyl-ecgonidine (AEME), benzoic acid, and carbomethoxycycloheptatrienes (CMCHTs) has been preferred to assess the impact of these gases on human health (Gostic et al., 2009; Martin et al., 1989). Therefore, special care should be considered during the cocaine

Table 5

Incineration gases: CO₂ and CO compositions.

Sample	CO ₂ (%)	CO (%)
Cocaine 1	96.32	3.68
Cocaine 2 ^a	97.81	2.19
Cocaine hydrochloride 1	95.56	6.44
Cocaine hydrochloride 2 ^a	96.63	3.37

^a Duplicates.

base and cocaine hydrochloride volatilization. Perhaps further steps after the post-combustion process should be included to ensure the complete decomposition of any volatile organic material. From the environmental perspective, the cocaine base and cocaine hydrochloride incineration processes have a lower environmental impact than other hazardous materials (Singh and Prakash, 2007).

3.2. Simulation results

3.2.1. Techno-economic analysis: incineration vs. biological degradation

Simulations of the incineration and biodegradation processes were used to generate the respective mass and energy balances. Then, this information was used to perform the techno-economic and environmental analyses. Both simulations were validated with the experimental data obtained in both processes carried out in the experimental stage. Regarding the mass indicators, the incineration process has a degradation efficiency of up to 95% and a solid waste generation yield of 5 kg of ashes per tonne of burned substance. In contrast, the biological degradation process has a degradation efficiency of up to 99%, which implies the destruction or deactivation of the alkaloid. Thus, the biological degradation process is a better process to dispose of the seized cocaine base and cocaine hydrochloride from this data. However, the degradation rate of 1 kg of cocaine is higher in the incineration process. The incineration process can degrade this amount of material in 0.6 min, while the biological degradation process requires 24 h to degrade a water stream with an alkaloid concentration of 10 g/L.

Table 4

Overall volatilization yield of cocaine and cocaine hydrochloride.

Sample	Initial weight (g)	Final weight (g)	Overall volatilization yield (%).
Cocaine base 1	50.006	3.000	94.00
Cocaine base 2 ^a	50.006	3.000	94.00
Cocaine hydrochloride 1	50.010	4.030	91.94
Cocaine hydrochloride 2 ^a	50.010	4.030	91.94

^a Duplicates.

The energy efficiency indicators are favorable to the biological degradation process. The specific energy consumptions of the incineration and biological degradation processes were 184.9 and 38.1 MJ/kg, respectively. The high specific energy demand of the incineration process is due to the high temperatures needed to carry out the process (i.e., 850 °C–1200 °C). However, the way to supply the energy demand of the incineration process involves using direct fuels such as diesel, natural gas, or propane, which, in turn, increases the utility costs of the process. Furthermore, the incineration process can be classified as an allothermal process (Bhaskar et al., 2013). In contrast, the biological degradation process energy demand must be supplied continuously using electric resistance heating or a heating utility (e.g., hot water, low-pressure steam) (Mandegari et al., 2017). These technical aspects provide different criteria to be considered by the decision-makers to choose the best option to dispose of seized cocaine.

Since these processes do not generate value attributed to the upgrading of the cocaine molecule, the economic assessment of both approaches was focused on the analysis of the CAPEX, OPEX, and unit price of cocaine base/cocaine hydrochloride disposal. Thus, economic metrics related to cash flow analysis such as net present value (NPV), internal rate of return (IRR), payback period (PBP), and profitability index (PI) were not calculated (Moncada et al., 2014). Table 6 shows the annualized costs for the incineration and biological degradation processes.

The results presented in Table 6 show the differences between the cost distribution of the incineration and biological degradation processes. Indeed, the OPEX of the biological degradation process is higher than that of the incineration process. This behavior can be attributed to the high costs associated with capital depreciation and maintenance. This fact can be explained due to the high total capital investment required in the biological alternative. On the other hand, the biological degradation process had higher raw materials costs than the incineration process due to the need to dilute the cocaine base and cocaine hydrochloride with tap water. Moreover, the biological degradation process requires other trace compounds to maintain active microbial consortia to accomplish a high degradation of the interest compounds. Regarding the utility costs, the incineration process presented high costs due to the need to feed 15 L per hour of diesel to maintain process temperatures (diesel price 0.546 USD/L). Meanwhile, the biological degradation process only requires hot water to keep the process temperature at 32 °C, which results in a cheaper utility than in the incineration process. The maintenance costs were higher in the biological degradation case, which can be associated with the rigorous monitoring of equipment operation. Furthermore, the depreciation share of the biological degradation process is higher than the

depreciation share reported by other authors working with biotechnological conversion processes (Moncada et al., 2014; Quintero et al., 2013). Nonetheless, this share is highly dependent on the number of equipment installed in the facility and the costs related to each unit. Also, this share is affected by the costs associated with raw materials and utilities. The labor costs of both processes are equal because the same staff to dispose of cocaine base and cocaine hydrochloride was considered. Besides, the same time to dispose of the total amount of alkaloid was considered. The incineration and biological degradation processes required 1472 h to degrade the total amount of seized cocaine base and cocaine hydrochloride in 2017. Thus, the incineration process can operate with 1 shift per day for 184 days (i.e., 6 months) or 3 shifts per day for 61 days (i.e., 2 months); while the biological degradation process can only operate with 3 shifts per day during 61 days to degrade all the seized cocaine taking into account that this is a continuous process. In this way, the biological degradation process can degrade more cocaine than the incineration process in a year owing to the standardized operation of the bioreactor. This fact can be supported bearing in mind the time consumed during the startup of the incineration equipment, the periodic review of different parts (e.g., blowers, grater, and flare system), and atypical situations such as excessive fuel consumption and out of range pressure.

CAPEX was one of the evaluated metrics to compare the biological degradation and the incineration processes. The CAPEX of the incineration and biological degradation process was 46,400 USD and 580,600 USD, respectively. From this data, the incineration process requires a lower capital investment than the biological degradation process. 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, which gives a high level of confidence with respect to the values calculated in Table 4. However, the capital investment of the biological degradation process was estimated only considering the correlations involved in the APEA software, which gives an uncertainty between 30% and 50% (Cardona Alzate et al., 2018). The CAPEX of the incineration process is a reliable value in light of the scale of the process (100 kg/h). An incinerator for narcotics destruction with high capacity can have a commercial value of 700,000 USD (Inciner8, 2020). Thus, the capital investment results obtained for the incineration process were compared with the economic analysis performed by Nasserzadeh et al. (1991). These authors reported the capital investment for a waste incinerator with a capacity of 10 tonnes per hour was 19.5 million dollars. The authors gave this value working with the real value of an installed incineration system in Sheffield, England. Therefore, the incinerator value can be considered a reference point to discuss the reliability of the results of this work. Effectively, a similar result to the reported value in this paper is obtained once the “six-tenths rule” is applied (Towler and Sinnott, 2012). On the other hand, the CAPEX of the equipment involved in the biological degradation process agrees with previous results (Humbird et al., 2011). Consequently, incineration is cheaper than the biological degradation process in terms of equipment costs and installation. A similar result was reported by Panepinto and Genon (2012) when comparing incineration and anaerobic digestion. These authors concluded that the cheapest alternative to dispose of solid waste is the incineration process since a lower capital investment is required.

Table 7 summarizes the technical and economic aspects of the incineration and biological degradation processes.

Finally, the economic assessment of the incineration and biological degradation processes involves comparing the associated costs to degrade 1 kg of seized cocaine. The disposal unit prices for the incineration and biodegradation processes were 0.77 USD/kg

Table 6

Annualized cost distribution of two alternatives to dispose of seized cocaine considering a processing scale of 100 kg/h.

Process	Incineration		Biological degradation (CSTBR)	
Feature	USD/year	Share (%)	USD/year	Share (%)
Raw materials	2944	2.60	7743	3.08
Utilities	12,055	10.64	9560	3.80
Maintenance	3202	2.83	40,061	15.94
Labor	48,035	42.41	48,035	19.11
Fixed & General	11,640	10.28	35,037	13.94
Plant overhead	30,742	27.14	52,858	21.03
Capital depreciation	4640	4.10	58,060	23.10
Total	113,258	100.00	251,354	100.00
OPEX	70,876	USD/year	163,459	USD/year
CAPEX	46,400	USD	580,600	USD
Disposal unit price	769.42	USD/tonne	1707.57	USD/tonne

Table 7

Technical information of the incineration and biological degradation processes to dispose of 100 kg/seized cocaine.

Item	Incineration	Biological degradation (CSTBR)
Alkaloid destruction	>95%	>99%
Degradation rate	0.6 kg/min - 2.5 kg/min	10 g/L in 24 h
Specific energy consumption	184.9 MJ/kg	38.1 MJ/kg
Type of process	Allothermal	Allothermal
Utility required	Diesel, Natural gas or Propane	Electricity, Hot water, or LP steam
Utility supply	Each hour of processing	The entire process
Emissions description	Exhaust gases released at 250 °C, Emissions can include NO _x , and C _x H _y Cl _z compounds. Solid waste generation yield of 5 kg/tonne. No liquid waste produced.	CO ₂ is released. No solid waste generation. Liquid effluents could have trace elements such as methanol, and BE.
OPEX (USD/year)	70,876	163,459
CAPEX (USD)	46,400	580,600

and 1.71 USD/kg, respectively. The higher disposal cost obtained for the biological process can be attributed to several factors such as reactor volume, operation time, and microbial degradation conditions. If the reactor volume is decreased, the operation time will increase the labor costs of the entire process. Therefore, a decrease in the reactor volume while maintaining the same initial cocaine base or cocaine hydrochloride concentration is not the best choice. Alternatives to decrease the disposal unit cost can be addressed from two perspectives. The first perspective is related to the total capital investment of the process. In the simulation of the biological degradation process, stainless-steel was considered as the building material of the reactor. However, other cheaper alternatives can be considered (e.g., carbon steel). Another option to increase the economic feasibility of the biological degradation process is related to the reactor configuration. The biological degradation process could be performed in a rotating disc reactor (RDR), obtaining the same degradation yield at lower capital expenditure (Nasr et al., 2007).

The second perspective to increase the economic performance of the biological degradation process is addressed to reduce the operating costs. The first way to decrease the disposal unit price of alkaloids is to consider the salvage value of the equipment at the end of the project lifetime different from zero. For instance, if 15% of salvage value is considered, the disposal unit price is decreased to 1.65 USD/kg. Another option is addressed to reduce the labor costs since this item covers more than 25% of the OPEX. If the labor cost is reduced by 10%, the disposal unit price can also be decreased to 1.65 USD/kg. Finally, the most promising way to reduce the disposal unit price of the biological degradation process is to increase the initial concentration of alkaloids. A sensitivity analysis of the effect of the initial concentration of alkaloids on the disposal unit cost is presented in Fig. 5.

The cocaine disposal unit price using the biological degradation process 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 31%. A maximum decrease in the disposal unit prices is obtained when cocaine initial concentrations are higher than 100 g/L (i.e., 50%). Nevertheless, the degradation of a liquid stream with an initial concentration higher than 100 g/L requires a better adaptation of the microorganisms. As shown in Fig. 5, the biological degradation process will not reach the same disposal unit cost of the incineration process. Even so, the biological alternative can be considered as an attractive technology to degrade cocaine base and cocaine hydrochloride if the initial concentration is increased to 50 g/L (i.e., 1.00 USD/kg) due to the high degradation performance of the process. Thus, cocaine biological degradation can be profiled as a promising alternative from an economic perspective.

3.2.2. Environmental assessment

The environmental assessment of the incineration and biological degradation processes was carried out to elucidate the best alternative to dispose of cocaine base and cocaine hydrochloride. These results are discussed, analyzing the global atmospheric impact and toxicological categories. The global atmospheric impact category results for both processes are presented in Fig. 6. The incineration process has a more significant environmental impact (i.e., global atmospheric impact) than the biological degradation process due to the gaseous emissions of this process. The GWP impact category is greater due to the high amount of CO₂ generated as a product of the complete combustion of the cocaine compounds. Additionally, other trace compounds such as NO₂ are also produced. 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 formula C_xH_yCl could be the main reason for the high value on the ODP impact category (Reimann et al., 2018). The concentration of these compounds (i.e., C_xH_yCl) derived from the combustion process is high (Blankenship et al., 1994). From this, the importance of implementing a post-combustion process has been stipulated by the Colombian government through the publication of resolution 058–2002, as a requirement to carry out incineration processes (Ministerio de ambiente, 2002). On the other hand, 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 the emissions of nitrogen and chlorinated compounds, which can cause acid precipitation and terrestrial acidification (Sánchez and Cardona, 2012). The overall results obtained for the incineration process are similar to those reported by Beylot et al. (2018). The life cycle assessment methodology was used to analyze the environmental impact of municipal solid waste incineration. The most affected impact categories by the direct emissions of the exhaust gases derived from the incineration process are climate change (CC), photochemical ozone formation (POF), acidification (A), terrestrial eutrophication (TE), and marine eutrophication (ME).

Concerning the biological degradation process, all values obtained for each global atmospheric impact category 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. However, the values shown in Fig. 6 allow elucidating the global atmospheric advantages of the biological degradation process. The other impact categories such as GWP, ODP, and PCOP are negligible for the environmental impact caused by the incineration process. Indeed, the biological degradation

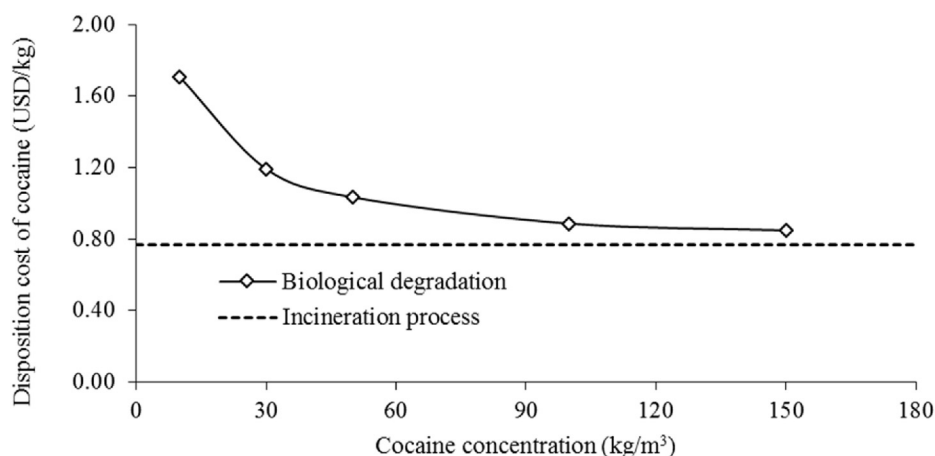


Fig. 5. Sensitivity analysis of the cocaine disposal unit price varying the initial concentration in the bioreactor.

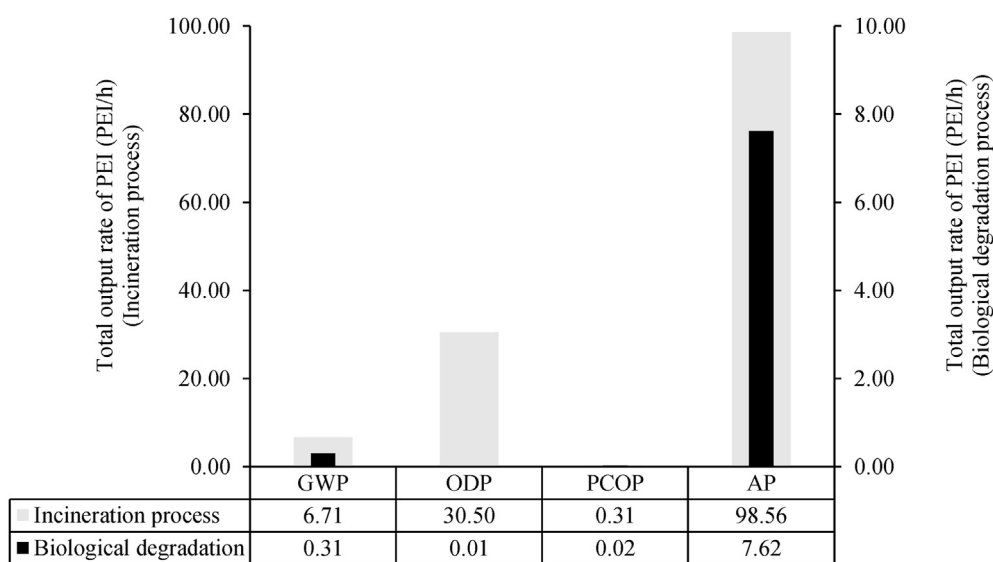


Fig. 6. Comparison of the global atmospheric impact categories for cocaine base and cocaine hydrochloride incineration and biological degradation.

process has a similar environmental impact to other biological processes such as ethanolic fermentation, anaerobic digestion, and acetone-butanol-ethanol (ABE) fermentation. For instance, [Moncada et al. \(2014\)](#) performed the environmental assessment of two biorefinery configurations using sugarcane as raw material. The main products from the proposed processes were sugar, electricity, glycerol, biodiesel, and ethanol. The environmental analysis of the proposed configurations showed a low global atmospheric environmental impact. Similarly, [Parra-Ramírez et al. \(2019\)](#) presented the environmental assessment of the anaerobic digestion process of plantain pseudostem. The results obtained by these authors are similar to those reported for the biological degradation of cocaine base and cocaine hydrochloride. Finally, [Carmona et al. \(2019\)](#) report a similar behavior for the global atmospheric impact categories of the bio-butanol production process using coffee-cut stems as raw materials. Therefore, it can be said that the environmental impact caused by biotechnological routes is similar. So, the global atmospheric impacts of a process are a direct function of the type of compounds to be upgraded or degraded.

The toxicological impact categories of the cocaine incineration and biological degradation processes are presented in [Fig. 7](#). The

biological degradation process has a lower environmental impact than the incineration process since most of the degradation products are not harmful to humans. The cocaine base and cocaine hydrochloride biological degradation can produce different compounds such as benzoylecgonine and ecgonine methyl ester through hydrolysis, which have a high environmental impact ([Lewis et al., 2004](#)). Nevertheless, the final concentrations of these products (i.e., <0.2 g/L) in the outlet stream of the reactor does not have any adverse effect on human health. Moreover, these compounds are classified as inactive since they do not produce the same effects of cocaine ([Shimomura et al., 2019](#)). The TPP impact category is highly affected due to the pH change obtained during the biological degradation process, which suggests the production of some acidic compounds like benzoic acid. Similar results were obtained in the HTPe and ATP impact categories when the fermentation to produce ethanol, lactic acid, and butanol were evaluated ([Parra-Ramírez et al., 2020](#); [Serna-Loaiza et al., 2018](#)). Regarding the incineration process, all the impact categories showed greater values in the thermochemical conversion than biological degradation. This behavior is explained by the emissions of chemical compounds such as HCl and NO_x, which can cause acid

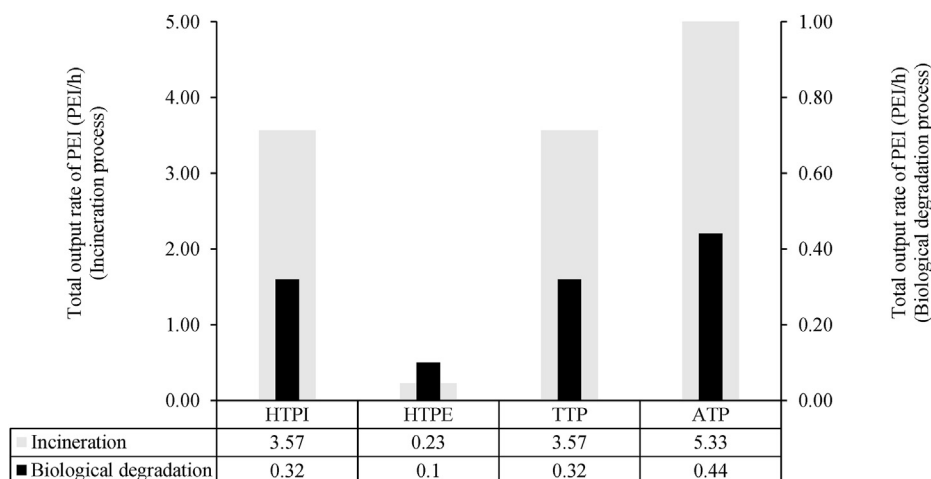


Fig. 7. Toxicological impact categories comparison of cocaine base and cocaine hydrochloride incineration and biological degradation.

precipitation.

Finally, the environmental assessment of both processes was performed considering the same weighting factors (default values given by the software). The sum of each impact category gives the total environmental impact of the process. Accordingly, cocaine incineration has a more significant environmental impact than the biological degradation process (i.e., 148.78 PEI/h and 9.14 PEI/h, respectively). Thus, the biological route to dispose of cocaine base and cocaine hydrochloride has great potential and warrants further studies.

4. Conclusions

Using a simulation methodology, the high potential of cocaine biological degradation was evidenced from a techno-economic and environmental perspective. The biological degradation process showed lower specific energy consumption (5-fold lower) and total potential environmental impact (10-fold lower) values than the incineration alternative. Moreover, the biological degradation process can reach similar disposition unit prices as the incineration process (i.e., 1.00 USD/kg). Therefore, this biological alternative has a significant opportunity to be implemented in the Colombian context. The initial cocaine concentration in the biological degradation process was identified as the most important aspect to be studied in the future. It is paramount to improve the degradation rate of the process and improve economic parameters. An initial concentration of 50 g/L is recommended as a feasible value to increase the economic opportunity of the cocaine biological degradation process.

5. Perspectives

In order to understand the real equipment required in the biological degradation process, a detailed design is needed. This is necessary to secure and make feasible the biological degradation process as a novel and attractive alternative for the final disposal of cocaine base and cocaine hydrochloride. Moreover, a more comprehensive analysis of the degradation products of cocaine base and cocaine hydrochloride is needed to improve the rigor of the environmental analysis of the process.

Statement of novelty

Cocaine has caused several social, political, and economic issues

in developed and developing countries. According to the United Nations office of drugs and crime, Colombia is the largest producer of cocaine in the world. Thus, the Colombian government has increased efforts to seize this alkaloid through military and police operations in airports, cities, and rural zones. So far, the unique legal way for cocaine disposal is through an incineration process either in a controlled atmosphere or in the open. Nevertheless, a high environmental risk associated with air pollution and greenhouse gases emissions is perceived. For this reason, alternative ways for the final disposal of cocaine are in need and the evaluation of their possible economic and environmental advantages. In this sense, this paper proposes a biological degradation process as an alternative to disposing of cocaine. Moreover, a comparison using experimental and simulation data is performed to provide insights into the economic and environmental aspects of this alternative biological process.

CRediT authorship contribution statement

Carlos A. Díaz-Vargas: Conceptualization, Methodology, Writing – original draft, preparation, Writing – review & editing, Formal analysis, Visualization. **Juan C. Solarte-Toro:** Methodology, Writing – review & editing, Software, Visualization. **Liz Wendy 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.

Acknowledgements

The authors gratefully acknowledge COLCIENCIAS for the doctoral scholarship awarded in the frame of the Colombian National Program for Doctoral Formation 647–2015, and Policía Nacional de Colombia-Narcotics Division for their technical and economic support.

References

- Alonso-Gómez, L., Solarte-Toro, J.C., Bello-Pérez, L.A., Cardona-alzate, C.A., 2020. Performance evaluation and economic analysis of the bioethanol and flour production using rejected unripe plantain fruits (*Musa paradisíaca* L.) as raw material. *Food Bioprod. Process.* 121, 29–42. <https://doi.org/10.1016/j.fbp.2020.01.005>.
- 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>.
- Bhaskar, T., Balagurumurthy, B., Singh, R., Kumar, M., 2013. Thermochemical route for biohydrogen production. In: Pandey, A., Chang, J.-S., Hallenbeck, P., Larroche, C. (Eds.), *Biohydrogen*. Elsevier, pp. 285–316. <https://doi.org/10.1016/B978-0-444-59555-3.00012-X>.
- Bijlsma, L., Boix, C., Niessen, W.M.A., Ibáñez, M., Sancho, J.V., Hernández, F., 2013. Investigation of degradation products of cocaine and benzoylecgonine in the aquatic environment. *Sci. Total Environ.* 443, 200–208. <https://doi.org/10.1016/j.scitotenv.2012.11.006>.
- Blanch, H.W., Clark, D.S., 1997. *Bioreactor design and analysis*. In: *Biochemical Engineering*. Marcel Dekker, Inc., New York.
- 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).
- Bosron, W.F., Hurley, T.D., 2002. Lessons from a bacterial cocaine esterase. *Nat. Struct. Biol.* 9 (1), 4–5. <https://doi.org/10.1038/nsb0102-4>.
- Burns-Edel, 2016. Environmental impacts of illicit drug production. *J. Global Societies* 4 (1), 1–14. Permalink: <http://escholarship.org/uc/item/4w64g29s>.
- Cardona Alzate, C.A., Solarte-Toro, J.C., Peña, A.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>.
- Carmona-García, E., Ortiz-Sánchez, M., Cardona, C.A., 2019. Analysis of the coffee cut stems as raw material for the production of sugars for acetone – butanol – ethanol (ABE) fermentation: techno- economic analysis. *Waste and Biomass Valorization* 10, 3793–3808. <https://doi.org/10.1007/s12649-019-00632-x>.
- Díaz, C.A., Solarte-Toro, J.C., Cuadros, L.W., Cardona, C.A., Restrepo-Parra, E., Higuaita, J.C., 2020. Cocaine degradation using a rotating biological disc reactor: techno-economic and environmental analysis using experimental data. *J. Hazard Mater.* 124219. <https://doi.org/10.1016/j.jhazmat.2020.124219>.
- Erzouki, H.K., Allen, A.C., Newman, A., Goldberg, S., Schindler, C., 1995. Effects of cocaine, cocaine metabolites, and cocaine pyrolysis products on the hindbrain cardiac and respiratory centers of the rabbit. *Life Sci.* 57, 1861–1868. [https://doi.org/10.1016/0024-3205\(95\)02166-g](https://doi.org/10.1016/0024-3205(95)02166-g).
- 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* 232–242. <https://doi.org/10.1016/j.energy.2019.01.073>.
- 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>.
- Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., Dudgeon, D., 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. *Renew. Energy* 303, 147. <https://doi.org/10.2172/1013269>.
- Inciner8, 2020. Drug & contraband incinerators [WWW document]. URL <https://www.inciner8.com/drug-incinerators.php>. accessed 6.20.20.
- Kiszka, M., Buszewicz, G., Mýdro, R., 2000. Stability of cocaine in phosphate buffer and in urine. *Z. Zagadnień Nauk dowych*, z. 44, 7–23.
- Lewis, R.J., Johnson, R.D., Angier, M.K., Ritter, R.M., 2004. Determination of cocaine, its metabolites, pyrolysis products, and ethanol adducts in postmortem fluids and tissues using Zymark® automated solid-phase extraction and gas chromatography-mass spectrometry. *Anal. Chem.* 806, 141–150. <https://doi.org/10.1016/j.jchromb.2004.03.045>.
- López, J.A., Naranjo, J.M., Higuaita, J.C., Cubitto, M.A., Cardona, C.A., Villar, M.A., 2012. Biosynthesis of PHB from a new isolated *Bacillus megaterium* strain: outlook on future developments with endospore forming bacteria. *Biotechnol. Bioproc. Eng.* 17, 250–258. <https://doi.org/10.1007/s12257-011-0448-1>.
- Mandegari, M.A., Farzad, S., Görgens, J.F., 2017. Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries. *Biofuel Res. J.* 4, 704–712. <https://doi.org/10.18331/BRJ2017.4.3.7>.
- 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>.
- Mccall, A., Bade, R., Kinyua, J., Lai, F.Y., Thai, P.K., Bijlsma, L., Van Nuijs, A.L.N., Ort, C., 2016. Critical review on the stability of illicit drugs in sewers and wastewater samples. *Water Res.* 88, 933–947. <https://doi.org/10.1016/j.watres.2015.10.040>.
- Ministerio de ambiente, vivienda y desarrollo territorial, 2002. Resolución 058 de 2002 Por la cual se establecen las normas y límites máximos permisibles de emisión para incineradores y hornos crematorios de residuos sólidos y líquidos. IDEAM, Colombia.
- Molinari, M., 2011. Production of Fructooligosaccharide Exopolysaccharides Type by *Gluconacetobacter Diazotrophicus*. Universidad Nacional de La Plata.
- 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>.
- Moncada, J., Tamayo, J.A., Cardona, C.A., 2014. Integrating first, second, and third generation biorefineries: incorporating microalgae into the sugarcane biorefinery. *Chem. Eng. Sci.* 118, 126–140. <https://doi.org/10.1016/j.ces.2014.07.035>.
- Mukherjee, A., Debnath, B., Kumar, S., 2016. A review on technologies of removal of dioxins and furans from incinerator flue gas. *Procedia 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).
- Nielsen, J., Villadsen, J., Lidén, G., 2003. *Design of fermentation processes*. In: *Bio-reaction Engineering Principles*. Kluwer Academic/Plenum Publishers, New York, pp. 339–423.
- Palmeros Parada, M., Osseweijer, P., Posada Duque, J.A., 2017. Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. *Ind. Crop. Prod.* 106, 105–123. <https://doi.org/10.1016/j.indcrop.2016.08.052>.
- Panepinto, D., Genon, G., 2012. Carbon dioxide balance and cost analysis for different solid waste management scenarios. *Waste and Biomass Valorization* 3, 249–257. <https://doi.org/10.1007/s12649-012-9120-z>.
- Parra-Ramírez, D., Martínez, A., Cardona, C.A., 2019. Lactic acid production from glucose and xylose using the lactogenic *Escherichia coli* strain JU15: experiments and techno-economic results. *Bioresour. Technol.* 273, 86–92. <https://doi.org/10.1016/j.biortech.2018.10.061>. (Accessed October 2018).
- 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 and Biomass Valorization* 11, 3161–3171. <https://doi.org/10.1007/s12649-019-00643-8>.
- 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).
- Quintero, J.A., Moncada, J., Cardona, C.A., 2013. Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: a process simulation approach. *Bioresour. Technol.* 139, 300–307. <https://doi.org/10.1016/j.biortech.2013.04.048>.
- 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. *Compt. Rendus Geosci.* 350, 384–392. <https://doi.org/10.1016/j.crte.2018.08.008>.
- Rincón Santamaría, A., Cuellar Gil, J.A., Valencia Gil, L.F., Sánchez Toro, O.J., 2019. Kinetics of gluconacetobacter diazotrophicus growth using cane molasses and sucrose: assessment of kinetic models. *Acta Biol. Colomb.* 24, 38–57. <https://doi.org/10.15446/abc.v24n1.70857>.
- Ruiz-Mercado, Gerardo, J., Smith, R.L., Gonzalez, M.A., 2012a. Sustainability indicators for chemical processes: II. Data needs. *Ind. Eng. Chem. Res.* 51, 2329–2353. <https://doi.org/10.1021/ie200755k>.
- Ruiz-Mercado, Gerardo, J., Smith, R.L., Gonzalez, M.A., 2012b. Sustainability indicators for chemical processes: I. Taxonomy. *Ind. Eng. Chem. Res.* 51, 2309–2328. <https://doi.org/10.1021/ie102116e>.
- Sánchez, O.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. Crop. 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>.
- Singh, S., Prakash, V., 2007. Toxic environmental releases from medical waste incineration: a review. *Environ. Monit. Assess.* 132, 67–81. <https://doi.org/10.1007/s10661-006-9503-3>.
- 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.
- Solarte-toro, J.C., Romero-garcía, J.M., Susmozas, A., Ruiz, E., 2019. Techno-economic feasibility of bioethanol production via biorefinery of olive tree prunings (OTP): optimization of the pretreatment stage. *Holzforschung* 73, 3–13. <https://doi.org/10.1515/hf-2018-0096>.
- Szöcs, L., Völgyi, G., Urai, Á., Hosztafi, S., Tóth, G., Gergő, L., Noszá, B., 2017. Site- and species-specific hydrolysis rates of cocaine. *J. Pharmaceut Biomed* 145, 372–378. <https://doi.org/10.1016/j.jpba.2017.07.005>.
- 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>.
- Towler, G.P., Sinnott, R.K., 2013. *Chemical Engineering Design. Principles, Practice and Economics of Plant and Process Design*, First. ed. Chemical Engineering Design. Elsevier. <https://doi.org/10.1016/B978-0-08-096659-5.00022-5>.
- United Nations Office on Drugs and Crime, 2020. Annual Drug Seizures [WWW Document]. Stat. data.
- Varjani, S., Rakholiya, P., Ng, H.Y., You, S., Teixeira, J.A., 2020. Microbial degradation of dyes: an overview. *Bioresour. Technol.* 314, 123728. <https://doi.org/10.1016/j.biortech.2020.123728>.
- 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>.
- Wooley, R.J., Putsche, V., 1996. Development of an Aspen Plus Property Database for Biofuels Components. National Renewable Energy Laboratory h <https://doi.org/NREL/MP-425-20685>.
- Young, D., Scharp, R., Cabezas, H., 2000. The waste reduction (WAR) algorithm: environmental impacts, energy consumption, and engineering economics. *Waste Manag.* 20, 605–615. [https://doi.org/10.1016/S0956-053X\(00\)00047-7](https://doi.org/10.1016/S0956-053X(00)00047-7).