Engineering and economics of the hazardous wastes in Colombia: the need for a circular economy model

Ingeniería y economía de los desechos peligrosos en Colombia: la necesidad de un modelo de economía circular

Edisson Ordóñez-Ordóñez[1]
Gloria Echeverry-Lopera[2]
Henry Colorado-Lopera[3]

[1] Universidad de Antioquia-UdeA; Universidad Autónoma Latinoamericana-Unaula; (Colombia); correo: edisson.ordonez@udea.edu.co

[2] Universidad Autónoma Latinoamericana-Unaula; (Colombia); correo: gloria.echeverrilo@unaul.edu.co

[3] Universidad de Antioquia-UdeA; (Colombia); correo: henry.colorado@udea.edu.co

Recibido: 19-02-2019 Aceptado: 04-06-2019

Cómo citar: Ordoñez-Ordoñez, Edisson; Echeverry-Lopera, Gloria; Colorado-Lopera, Henry (2019). Engineering and economics of the hazardous wastes in Colombia: the need for a circular economy model. *Informador Técnico*, *83*(2), 155-173.
https://doi.org/10.23850/22565035.2041

Abstract

This document collects and organizes data on not only the generation and current situation of hazardous wastes from Colombia, but also in a Latin American and global context. These materials were studied regarding the current economic model, regulations and implications in society. In addition, the numbers are presented from different reports from waste generating companies and, more importantly, from the data officers of the National Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). We also analyzed the activities that contribute most to these wastes and their relationship with various aspects, such as gross domestic product and Oil production in different regions of the country. Therefore, the main objective of this project is to analyze the state of hazardous waste in Colombia in quantitative form, in order to begin to give real solutions towards the use, research and commercialization of derivative products that help reduce their negative effect on the environment.

Keywords: circular economy; waste management; waste treatment; waste per capita; waste indicators.

Resumen

En este documento se recopilan y organizan datos no solo sobre la generación y la situación actual de los desechos peligrosos de Colombia, sino también en un contexto latinoamericano y mundial. Estos materiales se estudiaron con respecto al modelo de economía actual, las regulaciones y las implicaciones en la sociedad. Además, los números se presentan a partir de diferentes informes provenientes de las empresas generadoras de residuos y, lo que es más importante, de los datos oficiales del Instituto Nacional de Hidrología, Meteorología y Estudios Ambientales (IDEAM). También se analizaron las actividades que más contribuyen a estos desechos y su relación con diversos aspectos, como el producto interno bruto y la producción de petróleo en diferentes regiones del país. Por lo tanto, el objetivo principal en este Proyecto es analizar el estado de los residuos peligrosos en Colombia en forma cuantitativa, con el fin de comenzar a dar soluciones reales hacia el aprovechamiento, la investigación y la comercialización de productos derivados que ayuden a reducir su efecto negativo en el medio ambiente.

Palabras clave: gestión de residuos; tratamiento de residuos; residuos per cápita; indicadores de residuos, desechos; economía circular.

Introduction

The constant increase of the population and its consequent relation with the increase of the consumption in all the industrial sectors impacts on the growth of the generation of dangerous waste. As a result, industry, government, and consumers are increasingly aware of the importance of proper handling of hazardous waste. Factors such as economic development, traditional production techniques, massive extraction activities of natural resources are the main source of generation of hazardous waste in countries such as the United States or China (Duan; Huang; Wang; Zhou; Li, 2008). Increased demand for resources, such as land and energy, together with strict environmental regulations, have made the problem of hazardous waste management more complex (Nema; Gupta, 1999). The different characteristics of the different hazardous waste add considerable complexity to the management problem, since the different types of waste have different management protocols, treatment possibilities and disposal alternatives (Batstone; Smith; Wilson; 1989; LaGrega; Buckingham; Evans, 1994). In recent years, the impact of pollution and waste on the environment and on public health is very important worldwide (Orloff; Falk, 2003), so the objective of hazardous waste management has focused on guaranteeing collection, the transportation, treatment, and disposal of waste safely, efficiently and economically. The proper implementation of facilities for the treatment, disposal, and disposal of hazardous waste has both economic and social implications. Hazardous waste recycling facilities are established to treat, store or dispose of hazardous waste. Inadequate control of this waste can result in a serious threat to the environment. Therefore, the control of contamination by hazardous waste is key in the protection of the environment. An effective strategy for the management of hazardous waste is recycling (Orloff; Falk, 2003) where waste becomes a resource (Andrews, 2015).

In the past years the concept of Circular Economy (CE) has been implemented which can produce bigger environmental benefits than the traditional linear model (Ness, 2008), which not only has produced environmental but also social and economic issues, which are necessary actors to be involved in a real solution for improving each area of development (Lett, 2014). CE offers optimal use of natural resources, with a new business model, and promising employment opportunities (Ellen MacArthur Foundation, 2013).

The circular economy model has been developed through the evolution of several concepts, which include those from the environmental economics (Pearce; Turner, 1990) based on several pioneer works (Boulding, 1966). The circular system is now a requirement for the sustainability on earth, a closed system ideally without a matter of interchange with the exterior of the system with three basic economic functions: provision of resources, life support system, waste sink, and emissions.

Similar to other economic functions, these three basic ones should have an associated economic price. However, most of the time there is no price or market for the environmental goods (such as air and water quality, or public goods), even if they have a clear value or utility for individuals and societies. Economic instruments such as environmental taxes were designed to encourage better use and conservation of resources, mitigation of environmental burden, as well as the promotion of a transition to CE concepts (Andersen, 2007; Yong, 2007).

Because the current linear economy model is reaching its production limits (Requier-Desjardins, 1999), alternatives are proposed to improve this model. Therefore, in order to combine environmental and economic aspects, a new economy model called circular economy (Korhonen; Honkasalo; Seppälä, 2018) is proposed, which involves not only recycling, reuse, and repair of waste for consumer products in the economic model, but also the design of materials and processes that minimize the generation of waste. The circular economy implies a model where the use of raw materials is minimized during a production process, where waste can be reused as a resource in innovative ways, and where a product can be used several times for the original purpose (Zhijun; Nailing, 2007). According to The Growth Within a Circular Economy Vision for a Competitive Europe Report of the Ellen MacArthur Foundation (2015), the circular economy concept is based on three fundamental principles: (i) preserving and improving natural capital, (ii) optimize the yields of the resources in use; and (iii) promote the effectiveness of the system (Ellen MacArthur Foundation, 2015).

In Colombia, there has been an important effort in terms of creating new regulations and research using hazardous wastes in new (Colorado; Garcia; Buchely, 2016; Loaiza; Cifuentes; Colorado, 2017; Loaiza; Garcia; Colorado, 2018; Loaiza;

Colorado, 2018) circular economy, and innovation (Gu *et al*., 2012; Zhu *et al*., 2014). However, it is clear that there is a wide gap between real needs and the current results. Due to the complexity of the problem with the wastes, now is clear that more applications need to be created which can go to fields such as nanotechnology (Colorado; Nino; Restrepo, 2018; Colorado; Colorado, 2017; Quan; Colorado; Yeh; Yang, 2016), advanced (Restrepo; Colorado, 2018; Revelo; Colorado, 2018), and green materials and solutions (Colorado; Singh, 2014; Colorado; Wang; Yang, 2015; Colorado; Hiel; Hahn; Yang, 2011; Hernández; Carriazo; Almanza, 2006; Vergara; Damgaard; Gomez, 2016).

In the field of hazardous waste, it is considered that there is still much to be done regarding the use and treatment of these, but initially it is necessary to have a thorough knowledge of all the parameters that are present in the generation of such waste, so this issue is addressed into account the economic factor since it directly affects the production of so-called hazardous solid waste (Hazardous waste). In the search of the main factors that lead to the generation of hazardous waste, it is necessary to identify the sources of generation at the national level, it is also appropriate to inquire if the economic activities of a certain region are linked to the production of hazardous waste. For this reason, this paper analyzes the municipalities in Colombia that generate the greatest amount of Hazardous waste and its relation to Gross Domestic Product (GDP).

In the framework of hazardous waste is a sector that is constantly growing, the technological, this is because people every day demands increase, and the urge to get each time the most updated devices or with the best features and a personal dependence increasingly increasing regarding these elements, makes the production of technological waste increase directly. For this reason, this work is of great importance for the circular economy model since it shows relevant data regarding the devices that are acquired and the final disposal that these have at the end of their useful life.

Methodology

The methodology used in the development of this research is structured in 3 steps: information collection, calculation of the generation of hazardous waste and classification of hazardous waste.

Collection of information

The information on the generation of waste was obtained from the national reports on the generation of hazardous waste between 2011 and 2017 published by the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). These data recompile the information from the platform of the "Register of Hazardous Waste Generators" (Figure 1), which, before being published in the reports, were validated and transmitted by the 41 Environmental Authorities of the country in the 2016 balance sheet period reported by 13033 establishments with court date of october 6, 2017 (IDEAM, 2012, 2015, 2016).

The Register of Hazardous Waste or Waste Generators, which was implemented since 2008, is also considered and constitutes the information capture tool established in Decree 4741 of 2005 by which the prevention and management of waste is partially regulated, or hazardous waste generated within the framework of integral management (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2005a).

Through Resolution 1362 of 2007, the Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2007a) established the requirements and procedures for the Registration of Hazardous Waste or Waste generators referred to in Articles 27 and 28 of Decree 4741 of 2005.

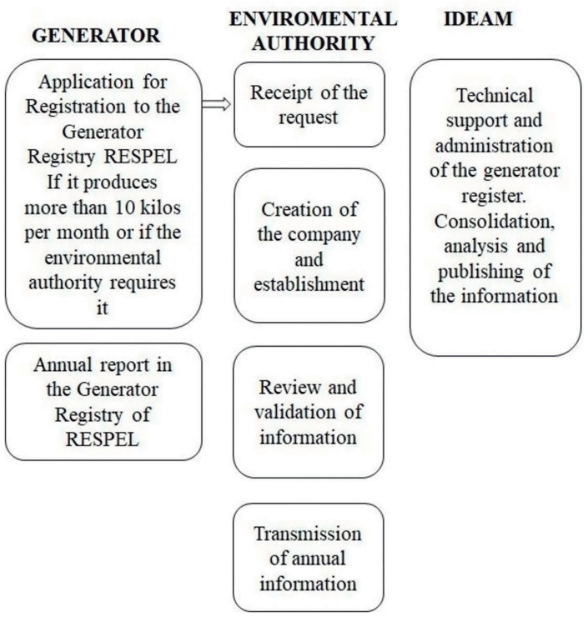

Figure 1. Process of reporting hazardous waste before the IDEAM. Source: own.

Calculation of the generation of hazardous waste (IDEAM, 2010):

The generation of hazardous waste in Colombia is given by the following components:

A2: Storage in the generator installations at the end of the balance period (kg).
A1: Storage in the generator facilities at the beginning of the balance period (kg).
B2: Storage by third parties at the end of the balance period less (kg).
B1: Storage by third parties at the beginning of the balance sheet period (kg).
C: Use and/or valuation by third parties during the balance period (kg).
D: Treatment by third parties during the balance period (kg).
E: Arrangement by the generator during the balance period (kg).
F: Disposal by third parties during the balance period (kg).
G: (ton) = (A2-A1) + (B2-B1) + C + D + E + F / 1000

The generation formula does not take into account the treatment and the use made by the generator.

Classification

According to the Ministerio de Ambiente y Desarrollo Territorial (2007b), hazardous waste is that which presents corrosive, reactive, explosive, toxic, flammable, infectious or radioactive characteristics that may cause risk or damage to human health and the environment. Likewise, containers, packaging, and packaging that have been in contact with them are considered hazardous waste or waste.

On the other hand, in Decree 4741 of 2005 in Annex I the hazardous waste is divided depending on the process of economic activity and is classified into 45 categories from Y1 to Y45. In addition, in Annex II of this same decree, hazardous waste is classified by waste streams by 4 subdivisions, A1 Metal waste or containing metals (A1XXX), A2 Waste containing mainly inorganic constituents, which may contain metals or organic matter (A2XXX), A3 Wastes containing mainly organic constituents, which may contain metals and inorganic matter (A3XXX), and A4 Wastes that may contain inorganic or organic constituents (A4XXX). Annex III is classified according to the characteristics of the waste or hazardous waste.

The Situation of hazardous waste

Colombia regarding leading economies

With the intention of grouping and consolidating the information, the data shown in Figure 2 was organized, presenting a global scenario of hazardous waste generation. This is compared with the generation per capita, in order to obtain a comparable indicator among other countries in the world.

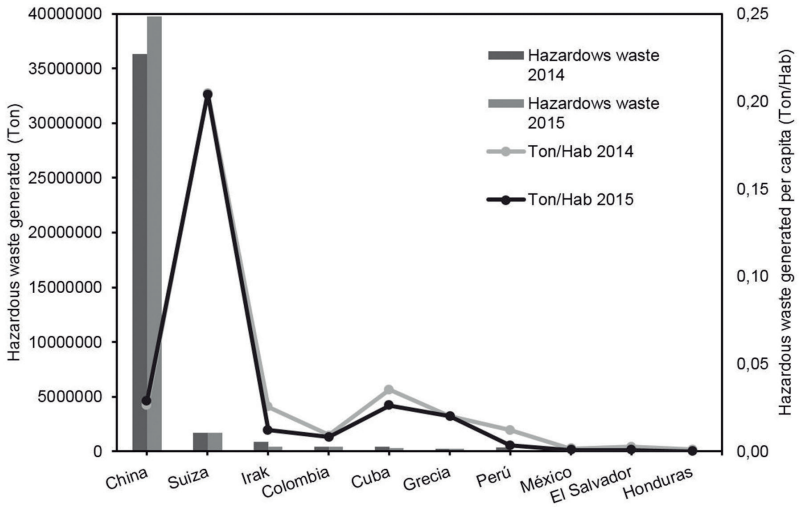

Figure 2. Generation of hazardous waste in tons and generation per capita for some countries of the world in 2014 and 2015. Source: IDEAM (2015).

The generation of hazardous waste in the world is a problem in constant growth due to the materials used in everyday objects such as batteries, electronic devices, elements used in hospitals, petroleum products, among others. In Colombia, the outlook is similar to that observed in the world, because the generation of hazardous waste increases over time. In order to compare the current situation in Colombia, a comparison is made regarding the generation of hazardous waste by each inhabitant, which is an important indicator since the generation of waste is independent of the number of inhabitants and can be compared between different countries of the world and even, at the national level, between the different departments of Colombia.

Colombia compared to Latin American standards

In the Latin American context, the management of hazardous waste in Colombia, Argentina, Chile, Cuba, Ecuador, Nicaragua, Mexico, and Uruguay, give it adequate final disposal due to the fact that they report special sanitary landfills for hazardous waste (Sáez; Urdaneta, 2014). In Latin America, Colombia is one of the pioneer countries in the recovery of hazardous waste (El Espectador, 2014).

Solid waste in Colombia: internal radiography

Observing the behavior of the generation of hazardous waste in Colombia in Figure 3, we see that the situation is not very positive: between 2011 and 2014, the generation trend has been rising considerably until reaching a worrying 453642 tons, reported by the establishments. However, there is a decrease in this trend between 2014 and 2016, which is associated with the entry into force of regulations that mitigate the negative impact of waste.

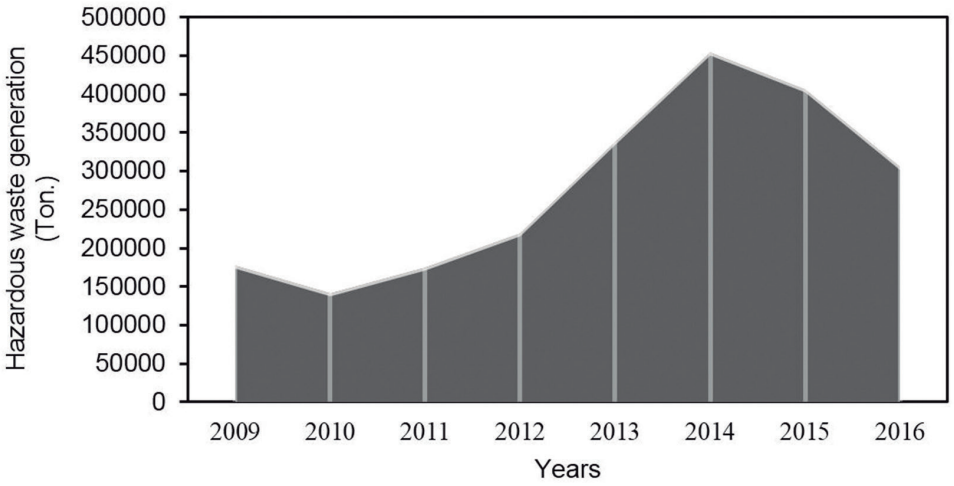

Figure 3. Hazardous waste generated in Colombia between 2006 and 2016.
Source: IDEAM (2012, 2015, 2016).

There is a big problem when quantifying the information on hazardous waste in Colombia since there are data that are not recorded, as shown in Table 1. In addition, not all the registered establishments generate a report of the waste generated, such as shown in Figure 4, for this reason, the volume of officially reported hazardous waste approximates the real number. However, with these data we can observe the behavior and the tendency with respect to previous years and the effectiveness of the implementation of some standards.

Table 1.
Establishments that report the generation of hazardous waste

Colombia 2016	
Registered establishments	30009
Establishments with report	13033

Source: IDEAM (2010; 2016).

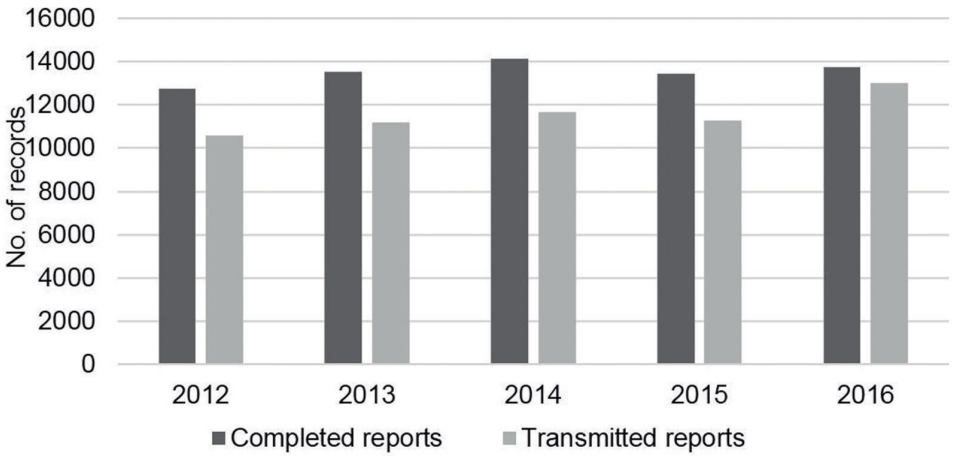

Figure 4. Reports of hazardous waste.
Source: IDEAM (2010; 2016).

Due to the fact that currently many of the technologies for the use of hazardous waste still have an incipient development in the world and even more in Colombia as a developing economy, it is necessary to address the problem as it has been shown to be more successful in developed countries; reducing the generation of waste from the source. In addition, minimizing the use of products that cause harm to the environment and human health such as asbestos and lead, which are widely used in different productive sectors very important for the Colombian economy. A clear example of a material with terrible consequences for the human health is asbestos, regulated in the law "Ley Ana Cecilia Niño", which established their use in the country. In the country, there are municipalities that generate a high volume of hazardous waste (see Figure 5), including major cities with very high population such as Bogotá, Medellín and Cali; and municipalities with a low population, but with a very high generation of hazardous waste, mainly due to the economic activity located in these small towns, such as Aguazul, Yopal, Malambó.

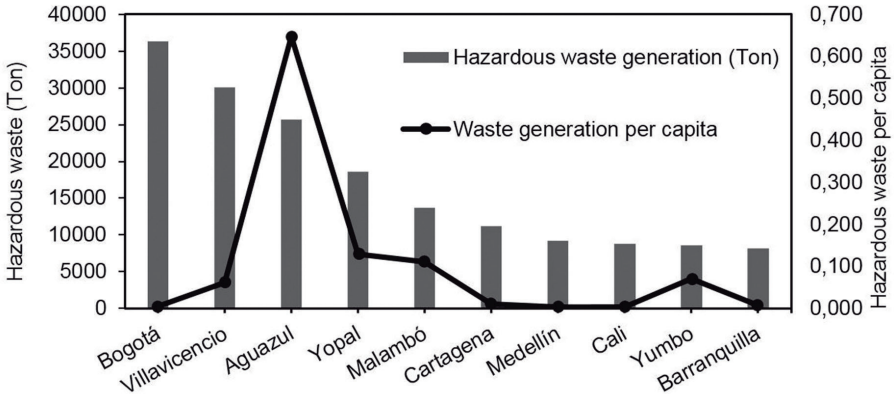

Figure 5. Main cities generating hazardous waste in Colombia 2016.
Source: DANE (2016a); IDEAM (2016).

In the search for the main factors that lead to the generation of hazardous waste, it is necessary to identify the sources of generation at the national level, for this reason, it is advisable to investigate whether the economic activities of a certain region are linked to the production of hazardous waste. For this reason, an analysis is made of the municipalities in Colombia that generate the greatest amount of hazardous waste and its relationship with the GDP summarized in Figure 6 and Table 2, which presents the main generating activities (by codes) of hazardous waste in Colombia for the year 2016. There it can be shown that one of the main sources of hazardous waste is related to the extraction and treatment of crude oil and given that the oil sector is very important in the economy of many regions, it is important to verify the relationship that the GDP may have with the generation of waste and with the production of oil.

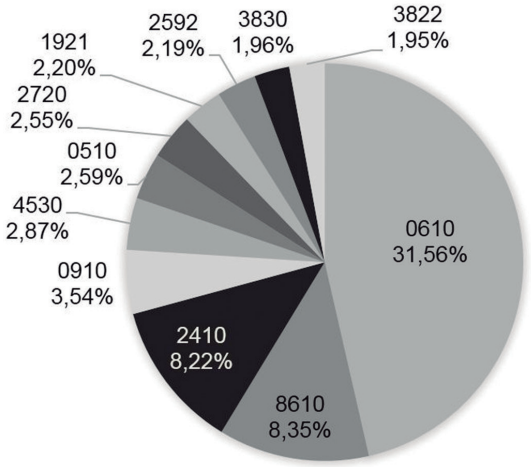

Figure 6. Economic activities in Colombia that generate more hazardous waste (CIIU Code) 2016.
Source: IDEAM (2016).

Table 2.
CIIU Code for economic activities that generate hazardous waste in Colombia

Economic activity	CIIU Code
Extraction of crude oil	0610
Activities of hospitals and clinics, with hospitalization	8610
Basic industries of iron and steel	2410
Support activities for the extraction of oil and natural gas	0910
Trade of parts, parts (auto parts) and accessories (luxuries) for motor vehicles	4530
Extraction of coal (coal of stone)	0510
Fabrication of batteries and electric accumulators	2720
Fabrication of petroleum refining products	1921
Treatment and coating of metals, machining	2592
Material recovery	3830
Treatment and disposal of hazardous waste	3822

Source: IDEAM (2016).

Figure 7 shows the departments that generate the largest amount of hazardous waste in Colombia, led by Casanare and Meta, where there is also a high production of oil, which is related to the figures that show that in Colombia one of the sectors that produce the most hazardous waste is oil. Municipalities such as Bolívar and Atlántico have a high production of waste due to the steel and battery industries.

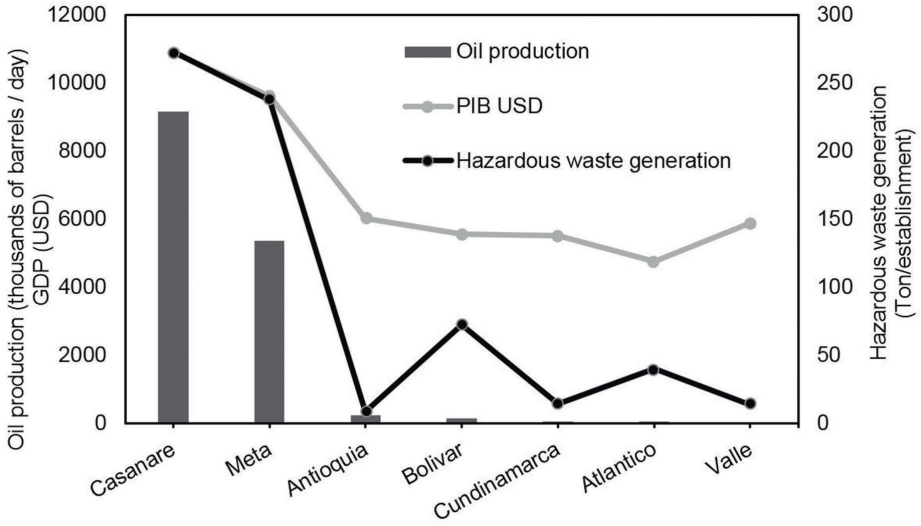

Figure 7. Main departments generating hazardous waste in Colombia 2016.
Source: Agencia Nacional de Hidrocarburos (2016); DANE (2016b); IDEAM (2016).

Regulations for the handling and treatment of hazardous waste

In the framework of the management, management, and generation of waste both globally and nationally, it is necessary to comply with standards, some of which are designed to help quantify and give better treatment to both information and waste. In the case of hazardous waste in Colombia, the Basel Convention is followed, one of the most important initiatives worldwide because it regulates and organizes the information pertinent to the quantities generated from Hazardous waste and where a classification of waste is generated. Same in order to deal adequately and specifically with each type of hazardous material. The following is an outline of the legislation currently in force in Colombia regarding hazardous waste.

- Decree 2811 of 1974: Code of renewable natural resources and of protection to the environment (Presidencia de la República, 1975).
- Law 09 of 1979: By which sanitary measures are dictated (El Congreso de Colombia, 1979).
- Basel Convention: On the control of border movements of hazardous waste.
- Law 99 of 1993: By which the Ministry of Environment is created, the public sector in charge of the management and conservation of the environment and renewable natural resources is ordered and the National Environmental System, SINA, is created (El Congreso de Colombia, 1993).
- Law 253 of 1996: By which the Basel Convention is approved (El Congreso de Colombia, 1996).
- Law 430 of 1998: by which prohibitive measures are issued in environmental matters regarding hazardous waste (El Congreso de Colombia, 1998).
- Decree 1609 of 2002: Regulates the handling and transportation by land of dangerous goods (Presidencia de la República, 2002).
- Environmental Policy for Comprehensive Management of HAZARDOUS WASTE (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2005b).
- Decree 4741 of 2005: Partially regulates the prevention and management of the generated HAZARDOUS WASTE within the framework of integral management (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2005a).
- Resolution 1362 of 2007: Establishes requirements and procedures for the registration of HAZARDOUS WASTE generators (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2007a).
- Resolution 043 of 2007: General standards for the collection of data, processing, transmission, and dissemination of information for the Register of Waste Generators or Hazardous Waste (IDEAM, 2007).
- Resolution 0062 of 2007: The laboratory analysis protocols for the characterization of HAZARDOUS WASTE are adopted (IDEAM, 2007b).
- Law 1252 of 2008. By which prohibitive norms are dictated in environmental matter referring to the HAZARDOUS WASTE (El Congreso de Colombia, 2008).
- Decree 1076 of 2015: By means of which the single regulatory decree of the environment and sustainable development sector is issued (Presidencia de la República, 2015).
- 2017 environmental policy for the integral management of electrical and electronic devices. 2017 – 2032. (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2017).

In Colombia, the development of regulations is affected to a large extent by the lack of implementation and rigorous monitoring in some sectors, in addition to informality regarding the treatment of waste. However, this legislation is followed, which is evidenced by the tendency to reduce hazardous waste as of 2014, a fact associated with the fact that many generating companies have become aware of the problem caused by the bad disposal of hazardous waste and the benefits that the company has when performing an adequate treatment.

Observing the data of completed records it can be affirmed that only 43.43 % of the establishments correctly report the generation of HAZARDOUS WASTE in Colombia, so that it is still very far from the goal of obtaining a record with 100 % of the national production.

In the future, it is expected not only to reduce the generation of hazardous waste, but also to improve its treatment, disposal, or even to increase the life cycle of the products, which impacts the reduction of waste. Moreover, it is necessary to rethink all the processes as the circular economy proposes, where it is conceived from the same product design, as will be its final disposal. For example, this may lead to a product that previously generated Hazardous waste, is redesigned with materials that are not toxic, or that its recycling is easy. In China there is already a regulation that requires taking measures regarding the reduction or elimination of substances harmful to human health and the environment in the manufacture of electronic items, which implies a very important economic intervention from the design of the components to its final manufacture (Hotta; Elder; Mori; Tanaka, 2008; Yu, 2010). In Europe there is a series of guidelines that basically propose 4 objectives (Comisión Europea, 2000; Unión Europea, 2018), the first one is to ensure that all people have basic access to waste management in order to avoid bad disposal; the second is to control hazardous waste by preventing them from coming into contact with people or the environment; the third is to focus on reducing waste production, that is, attacking the problem from the source; finally the implementation of materials that are not harmful to the environment in the manufacture and reuse or recycling and use of materials that have already completed their cycle in order to give them a second use.

Important indicators related to hazardous waste in Colombia and in the world

With the intention of grouping and consolidating the information found about hazardous waste, Colombia's information is presented regarding a global scenario of hazardous waste generation and compared with the generation per capita, in order to obtain a relatable indicator between countries of the world. Data are presented regarding the number of establishments generating Hazardous waste registered, the number of reports generated and transmitted in the national IDEAM hazardous waste report. Next, we will see the information corresponding to the type of management that is given to the hazardous waste currently in Colombia and a brief description of the most used treatments; also, the activities that generate this type of waste and the relationship they have different aspects such as GDP and oil production in different regions of the country. Figure 2 shows an overview of the generation of hazardous waste in some countries of the world against the generation of waste per capita, which shows that the production of waste has an important relationship with the number of inhabitants. It is observed that China, which generates a large amount of hazardous waste, its indicator of waste per capita is similar to that of countries such as Cuba or Greece that have a smaller population. In contrast, Switzerland has a low waste production, but due to its relatively low population, it registers a high per capita waste indicator. If the indicators such as the production of waste per capita and the GDP per capita are compared as in Figure 8, it is observed that the behavior of the two curves is similar, which indicates in general as the economy of an economy improves. The country has negatively affected the generation of hazardous waste.

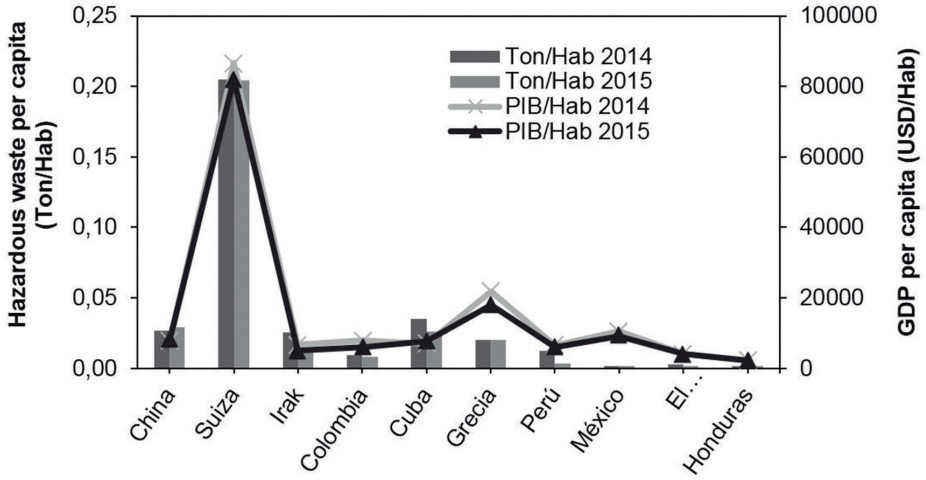

Figure 8. Hazardous waste generation in tonnes and GDP per capita for some countries in the world in 2014 and 2015.
Source: Banco Mundial (2018a); IDEAM (2015).

Figure 9 shows that China has a high production of Hazardous waste, but due to its high population density, the indicator of generation per capita is considerably reduced, contrary to Switzerland, since its high production of waste and its relatively low population make it the indicator increases substantially. In the cases of Colombia, Iraq, Greece, and Peru there is a similarity with respect to the generation per capita. With respect to the treatment given to waste, Figure 10 summarizes the quantities of waste that are used, treated, or disposed of in landfills.

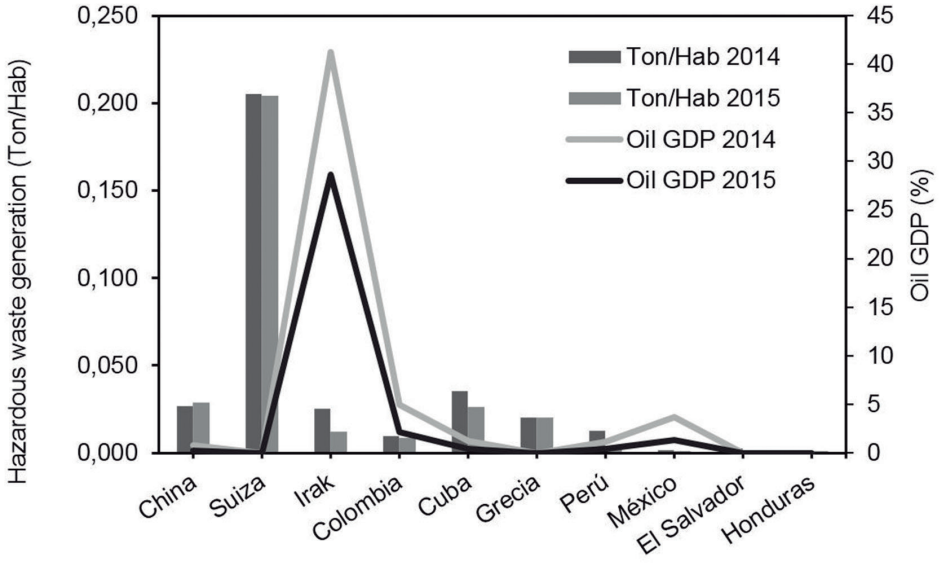

Figure 9. Production of hazardous waste per capita and GDP of oil for some countries of the world. Source: Banco Mundial (2018b); IDEAM (2015); U.S. Energy Information Administration (2015).

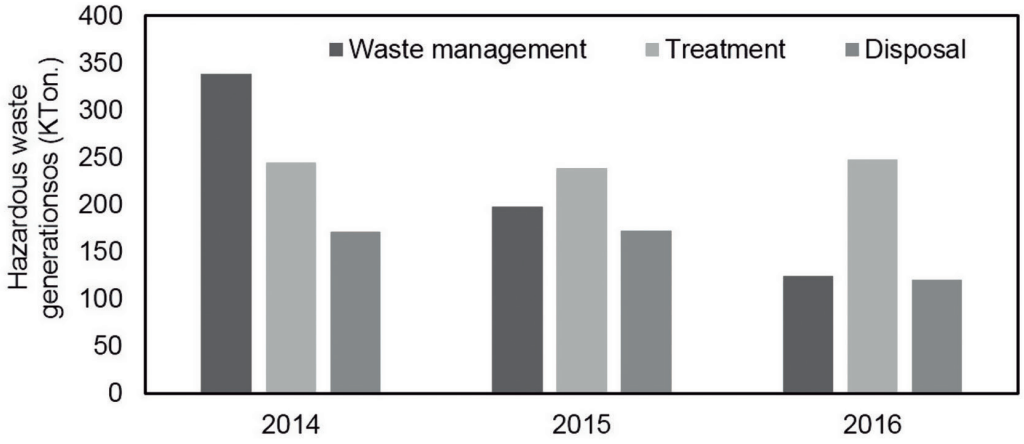

Figure 10. Management of hazardous waste in Colombia (2014 - 2016). Source: IDEAM (2012, 2015, 2016).

Figure 11 shows the information corresponding to the production of hazardous waste in the main industrial corridors of Colombia. It is observed that, although these cities present a large generation of waste, in the rest of the country there is still a significant percentage of the total national waste generation, for this reason, it is decided to deepen this issue in order to analyze other areas that they can possibly be critical regarding the production of hazardous waste.

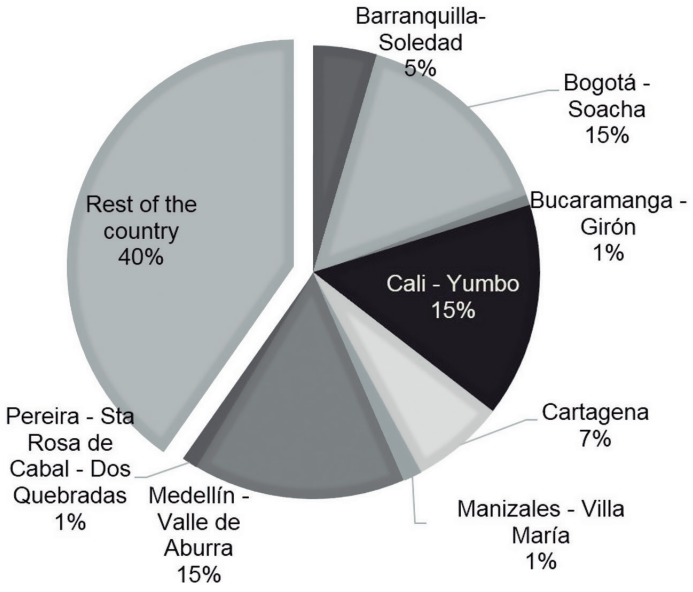

Figure 11. National participation of industrialized cities in the generation of hazardous waste in Colombia (2014). Source: IDEAM (2015).

In the search for the main factors that lead to the generation of hazardous waste, it is necessary to identify the sources of generation at the national level, for this reason, it is advisable to investigate whether the economic activities of a certain region are linked to the production of hazardous waste. It is important to analyze the municipalities in Colombia that generate the greatest amount of hazardous waste and its relationship with the economy.

Analysis and discussion

A relation between the generation of hazardous waste and the GDP / inhabitant of each one of the countries can be evidenced. The lowest indicator in China refers to the fact that although its generation of waste and its GDP are high, due to its large population, the indicator is reduced and comparable with other countries; On the contrary, countries like Switzerland have high values but a considerably smaller population.

Here we present the values of generation of hazardous waste for the main industrial corridors of the country, where major cities such as Medellin or Bogota have a high production of waste, however, there is a majority of hazardous waste that comes from the rest of the country, for this reason it is investigated in the departments with the highest generation of Hazardous waste and compared with the value of generation per capita. A comparison is also made with the production of oil in each region of the country, because it was found that the high generation of Hazardous waste in some departments is directly related to the production of crude, which is explained because the extraction and processing of petroleum is considered one of the activities of greater generation of Hazardous waste.

The municipalities of Colombia where most hazardous wastes were generated in 2016 were Bogotá (36,280 Tonnes), Villavicencio - Meta (30,063 Tonnes), Aguazul - Casanare (25,674 Tonnes), Yopal -Casanare (18,551 Tonnes) and Malambo - Atlántico (13,740). Tonnes). In Bogotá, the largest generation of Hazardous waste is associated with activities of hospitals and clinics with hospitalization. In Villavicencio and Yopal, to the activities of extraction of oil and gas as already indicated. In Malambo, it is associated with economic activities related to the steel industry and the manufacture of batteries, electric batteries, and accumulators.

The municipalities with the lowest Hazardous waste generation in the country were Villa Nueva and Urumita in La Guajira, and Convención and Abrego in Norte de Santander.

All this indicates that because oil production is one of the greatest sources of generation of hazardous waste, Colombia could quickly have a great improvement in the reduction of Hazardous waste, because it is an industrial sector that mostly increases the problem, alternatives for reuse and treatment could be sought to help reduce the impact generated by this type of waste. Through the circular economy, Colombia could lead innovative initiatives that put the country at the forefront of technologies that reduce the negative impact of the oil industry on the environment, which would have a not only local but global impact, and therefore the search for resources itself could be co-financed by international organizations.

Conclusions

Observing the results presented and the calculated indicators, it can be concluded that the generation of hazardous waste is directly related to the activities related to the extraction and processing of crude oil and also to a high GDP, this is because all the activities that they move around the oil and their extraction generates a high flow of money, but at the same time a high contamination that with a reduced or null treatment can generate very serious environmental impacts and even, sometimes, irreversible.

The production of hazardous waste in Colombia presented a maximum generation in 2014, but has been decreasing over the years, due to the regulations that are implemented where production is expected to be reduced from the source, that is, to minimize the generation.

The collection of information at the national level has certain shortcomings, since there are establishments that produce less than 10 kilos per month which are not reported, there are also establishments that do not adequately report the generation of waste and for this reason, are not reflected in the statistics. However, the existing data show a global panorama of the national trend regarding generation, use, and treatment.

Indicators such as per capita GDP or per capita oil production reflect a similar trend as the generation of hazardous waste.

The main cities of Colombia produce a large amount of hazardous waste due to the presence of different industries, but there are cities and municipalities that have a smaller population and also produce large amounts of waste such as Villavicencio, Aguazul, Yopal, and Malambó.

It is observed that the amount of waste that is brought to final disposal tends to be diminished over the years. This is beneficial since the environmental impact produced by landfill disposal is reduced.

From this research work, it is clear that there is much to improve regarding the use of solid waste in Colombia and that it is far from a Circular Economy model. Improving these indicators would increase the life of landfills, increase the production efficiency of companies by giving a second use to materials that are currently discarded, increase the country's competitiveness, and public health of people.

The collected data present a national panorama regarding the potential of hazardous waste exploitation, giving the beginning to the implementation of circular economy concepts in some regions of Colombia.

Acknowledgments

The authors would like to thank the Universidad Autónoma Latinoamericana and the Universidad de Antioquia for the sponsorship for the corresponding research.

References

Agencia Nacional de Hidrocarburos (2016). *Producción fiscalizada crudo 2016*. Retrieved from: http://www.anh.gov.co/Operaciones-Regalias-y-Participaciones/Sistema-Integrado-de-Operaciones/Paginas/Estadisticas-de-Produccion.aspx

Andersen, Mikael (2007). An introductory note on the environmental economics of the circular economy. *Sustainability Science*, *2*(1), 133–140. https://doi.org/10.1007/s11625-006-0013-6

Andrews, Debora (2015). The circular economy, design thinking and education for sustainability. *Local Economy*, *30*(3), 305–315. https://doi.org/10.1177/0269094215578226

Banco Mundial. (2018b). *Población Mundial*. Retrieved February 6, 2018, from: https://datos.bancomundial.org/indicador/sP.POP.TOTI

Banco Mundial. (2018a). *PIB (US$ a precios actuales)*. Retrieved February 6, 2018, from: https://datos.bancomundial.org/indicador/NY.GDP.MKTP.CD

Batstone, Roger; Smith, James; Wilson, David (1989). *The safe disposal of hazardous wastes: The special needs and problems of developing countries (World Bank Technical Paper Number 93)*. Washington, D.C.: The World Bank. Retrieved from: http://documents.worldbank.org/curated/en/695131468764392542/pdf/multi-page.pdf

Boulding, Kenneth (1966). The economics of the coming spaceship earth. In Jarrett, Henry (Ed.), *Environmental quality in a growing economy: Essays from the sixth resources for the future forum*. Johns Hopkins University Press: Baltimore (pp. 3–14).

Colorado, Henry A.; Garcia, Edwin; Buchely, M. F. (2016). White Ordinary Portland Cement blended with superfine steel dust with high zinc oxide contents. *Construction and Building Materials*, *112*, 816–824. https://doi.org/10.1016/j.conbuildmat.2016.02.201

Colorado, Henry A.; Hiel, Clem; Hahn, Thomas; Yang, Jenn-Ming (2011). Wollastonite-based chemically bonded phosphate ceramic composites. In *Metal, ceramic and polymeric composites for various uses*. InTech. https://doi.org/10.5772/17120

Colorado, Henry A.; Nino, Juan; Restrepo, Oscar (2018). Applications and Opportunities of Nanomaterials in Construction and Infrastructure. In: Li B. et al., (eds) *Characterization of Minerals, Metals, and Materials 2018 TMS 2018* (pp. 437-452). Springer, Cham: The Minerals, Metals & Materials Series. https://doi.org/10.1007/978-3-319-72484-3_46

Colorado, Henry A.; Singh, Dileep (2014). High-sodium waste streams stabilized with inorganic acid–base phosphate ceramics fabricated at room temperature. *Ceramics International*, *40*(7- Part B), 10621–10631. https://doi.org/10.1016/j.ceramint.2014.03.045

Colorado, Henry A.; Wang, Zhe; Yang, Jenn-Ming (2015). Inorganic phosphate cement fabricated with wollastonite, barium titanate, and phosphoric acid. *Cement and Concrete Composites*, *62*, 13–21. https://doi.org/10.1016/j.cemconcomp.2015.04.014

Colorado, S. A.; Colorado, Henry A. (2017). Manufacturing of zinc oxide structures by thermal oxidation processes as scalable methods towards inexpensive electric generators. *Ceramics International*, *43*(17), 15846–15855. https://doi.org/10.1016/j.ceramint.2017.08.156

Comisión Europea. Dirección General del Medio Ambiente (2000). *La UE apuesta por la gestión de residuos*. Retrieved from: http://ec.europa.eu/environment/waste/publications/pdf/eufocus_es.pdf

Departamento Administrativo Nacional de Estadística (2016a). *Población Nacional y Departamental Colombia*. Retrieved from: http://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion.

Departamento Administrativo Nacional de Estadística (2016b). *Producto Interno Bruto por Departamento*. Retrieved from: https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-departamentales

Duan, Huabo; Huang, Qifei; Wang, Qi; Zhou, Bingyan; Li, Jinhui (2008). Hazardous waste generation and management in China: A review. *Journal of Hazardous Materials*, *158*(2–3), 221–227. https://doi.org/10.1016/j.jhazmat.2008.01.106

El Congreso de Colombia (24 de enero de 1979). *Por la cual se dictan Medidas Sanitarias*. [Ley 9 de 1979]. DO: 35308. Retrieved from: http://www.secretariasenado.gov.co/senado/basedoc/ley_0009_1979.html

El Congreso de Colombia (22 de diciembre de 1993). *Por la cual se crea el Ministerio del Medio Ambiente, se reordena el Sector Público encargado de la gestión y conservación del medio ambiente y los recursos naturales renovables, se organiza el Sistema Nacional Ambiental, SINA y se dictan otras disposiciones*. [Ley 99 de 1993]. DO: 41.146. Retrieved from: http://www.secretariasenado.gov.co/senado/basedoc/ley_0099_1993.html

El Congreso de Colombia (9 de enero de 1996). *Por medio de la cual se aprueba el Convenio de Basilea sobre el control de los movimientos transfronterizos de los desechos peligrosos y su eliminación, hecho en Basilea el 22 de marzo de 1989*. [Ley 253 de 1996]. DO: 42.688. Retrieved from: http://www.minambiente.gov.co/images/normativa/leyes/1996/ley_0253_1996.pdf

El Congreso de Colombia (16 de enero de 1998). *Por la cual se dictan normas prohibitivas en materia ambiental, referentes a los desechos peligrosos y se dictan otras disposiciones*. [Ley 430 de 1998]. DO: 43.219. Retrieved from: http://observatorio.epacartagena.gov.co/wp-content/uploads/2016/10/LEY-430-DE-1998.pdf

El Congreso de Colombia (27 de noviembre de 2008). *Por la cual se dictan normas prohibitivas en materia ambiental, referentes a los residuos y desechos peligrosos y se dictan otras disposiciones*. [Ley1252 de 2008]. Retrieved from: http://www.minambiente.gov.co/images/BosquesBiodiversidadyServiciosEcosistemicos/pdf/Normativa/Leyes_/ley_1252_271108.pdf

El Espectador (1 de diciembre de 2014). Empresa colombiana es pionera en América Latina en reciclaje de residuos metálicos. *El espectador*. Retrieved from: https://www.elespectador.com/noticias/medio-ambiente/empresa-colombiana-pionera-america-latina-reciclaje-de-articulo-530777

Ellen Macarthur Foundation (2013). *Towards the circular economy. Opportunities for the consumer goods sector. Vol. 2*. Retrieved from: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/TCE_Report-2013.pdf

Ellen Macarthur Foundation (2015). *Circularity Indicators: An Approach to Measure Circularity*. Retrieved from: https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Project-Overview_May2015.pdf

Gu, Hongbo; Rapole, Sowjanya; Sharma, Jaishri; Huang, Yudong; Cao, Dongmei; Colorado, Henry A.; Luo, Zhiping; Haldolaarachchige, Neel; Young, David; Walters, Bryan; Wei; Suying; Guo; Zhanhu (2012). Magnetic polyanilinenanocompositestowardtoxichexavalentchromiumremoval. *RSC Advances*, *2*(29), 11007–11018. https://doi.org/10.1039/c2ra21991c

Hernández, Y.; Carriazo, J. G.; Almanza, O. (2006). Characterization by XRD and electron paramagnetic resonance (EPR) of waste materials from "Cerro Matoso" Mine (Colombia). *Materials Characterization*, *57*(1), 44–49. https://doi.org/10.1016/j.matchar.2005.12.003

Hotta, Y.; Elder, M.; Mori, H.; Tanaka, M. (2008). Policy Considerations for Establishing an Environmentally Sound Regional Material Flow in East Asia. *The Journal of Environment & Development, 17*(1), 26-50. https://doi.org/10.1177/1070496507312562

Instituto Nacional de Hidrología, Meteorología y Estudios Ambientales (14 de marzo de 2007a). *Por la cual se establecen los estándares generales para el acopio de datos, procesamiento, transmisión y difusión de información para el Registro de Generadores de Residuos o Desechos Peligrosos.* [Resolución No. 043 del 2007]. Retrieved from: http://www.ideam.gov.co/documents/51310/526371/Resolucion+043+2007+ESTANDARES+PARA+ACOPIO.pdf/f531d10e-5437-4cae-9423-fd61e2280d0f

Instituto Nacional de Hidrología, Meteorología y Estudios Ambientales(2007b). *Por la cual se adoptan los protocolos de muestreo y análisis de laboratorio para la caracterización fisicoquímica de los residuos o desechos peligrosos en el país.* [Resolución No. 0062 del 2007]. Retrieved from: https://www.dropbox.com/s/s928p5xmvmior8i/Resolucion_0062_de_2007%20muestreo%20de%20respel.pdf?dl=0

Instituto de Hidrología, Meteorología y Estudios Ambientales (2010). *Manual de diligencamiento via web del registro de generadores de residuos o desechos peligrosos.* (Segunda edición- año 2010). Retrieved from: http://www.ideam.gov.co/documents/51310/69494/Manual+diligenciamiento+Web..pdf/2b5e3129-8d6b-4ad9-9116-6478ca23c751

Instituto de Hidrología, Meteorología y Estudios Ambientales (2012). *Informe nacional Generación y Manejo de Residuos Peligrosos en Colombia* (Año 2011). Retrieved from: http://documentacion.ideam.gov.co/openbiblio/bvirtual/022431/INFORMENACIONALWEB.pdf

Instituto de Hidrología, Meteorología y Estudios Ambientales (2015). *Informe nacional Generación y Manejo de Residuos Peligrosos* (Colombia 2014 2015). Retrieved from: http://documentacion.ideam.gov.co/openbiblio/bvirtual/023638/Inf_Nac_gen_manejo_residuos_desechos%20peligrosos.pdf

Instituto de Hidrología, Meteorología y Estudios Ambientales (2016). *Informe nacional Generación y Manejo de Residuos Peligrosos en Colombia* (Año 2016). Retrieved from: http://www.andi.com.co/Uploads/RESPEL_2016_636567285350504800.pdf

Korhonen, Jouni; Honkasalo, Antero; Seppälä, Jyri (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041

LaGrega, Michael; Buckingham, Phillip; Evans, Jeffrey (1994.). *Environmental Resources Management. Hazardous Waste Management.* McGraw-Hill: New York.

Lett, Lina (2014). Las amenazas globales, el reciclaje de residuos y el concepto de economía circular. *Revista Argentina de Microbiología*, *46*(1), 1–2. https://doi.org/10.1016/S0325-7541(14)70039-2

Loaiza, Alexandra; Cifuentes, Sergio; Colorado, Henry (2017). Asphalt modified with superfine electric arc furnace steel dust (EAF dust) with high zinc oxide content. *Construction and Building Materials*, *145*, 538–547. https://doi.org/10.1016/j.conbuildmat.2017.04.050

Loaiza, Alexandra; Colorado, Henry (2018). Marshall stability and flow tests for asphalt concrete containing electric arc furnace dust waste with high ZnO contents from the steel making process. *Construction and Building Materials*, *166*, 769–778. https://doi.org/10.1016/j.conbuildmat.2018.02.012

Loaiza, Alexandra; Garcia, Edwin; Colorado, Henry (2018). Evaluation of asphalt binder blended with coconut coir dust and residual coconut fibers for structural applications. *Revista de La Construcción. Journal of Construction*, *17*(3), 542–554. https://doi.org/10.7764/RDLC.17.3.542

Ministerio de Ambiente, Vivienda y Desarrollo Territorial (30 de diciembre de 2005a). *Por el cual se reglamenta parcialmente la prevención y el manejo de los residuos o desechos peligrosos generados en el marco de la gestión integral.* [Decreto 4741 de 2005]. DO: 46.137. Retrieved from: http://www.corpocaldas.gov.co/publicaciones/1524/02-28/Decreto4741de2005.pdf

Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2005b). *Política ambiental para la gestión integral de residuos o desechos peligrosos.* Retrieved from: http://www.minambiente.gov.co/images/AsuntosambientalesySectorialyUrbana/pdf/Polit%C3%ACcas_de_la_Direcci%C3%B3n/Pol%C3%ADtica_Ambiental_para_la_Gesti%C3%B3n_Integral_de_Residuos_o_Desechos_Peligrosos.pdf

Ministerio de Ambiente, Vivienda y Desarrollo Territorial. (2007a). Gestión Integral de Residuos o Desechos Peligrosos Bases Conceptuales. *Dirección de Desarrollo Sectorial Sostenible*, *1*(24), 186. Retrieved from: https://www.minsalud.gov.co/sites/rid/Lists/BibliotecaDigital/RIDE/IA/INS/manual-gestion-integral-residuos.pdf

Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2 de agosto de 2007b). *Por la cual se establecen los requisitos y el procedimiento para el Registro de Generadores de Residuos o Desechos Peligrosos, a que hacen referencia los artículos 27 y 28 del Decreto 4741 del 30 de diciembre de 2005.* [Resolución 1362 de 2007]. Retrieved from: https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=26053

Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2017). *Política nacional. Gestión integral de residuos de aparatos eléctricos y electrónicos.* Retrieved from: http://www.minambiente.gov.co/images/AsuntosambientalesySectorialyUrbana/pdf/e-book_rae_/Politica_RAEE.pdf

Nema, Arvind; Gupta, S. K. (1999). Optimization of regional hazardous waste management systems: an improved formulation. *Waste Management*, *19*(7–8), 441–451. https://doi.org/10.1016/S0956-053X(99)00241-X

Ness, David (2008). Sustainable urban infrastructure in China: Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems. *International Journal of Sustainable Development & World Ecology*, *15*(4), 288–301.

Orloff, Kenneth; Falk, Henry (2003). An international perspective on hazardous waste practices. *International Journal of Hygiene and Environmental Health*, *206*(4), 291–302. https://doi.org/10.1078/1438-4639-00225

Pearce, David; Turner, Kerry (1990). *Economics of natural resources and the environment*. JHU Press.

Presidencia de la República (18 de diciembre de 1974). *Por el cual se dicta el Código Nacional de Recursos Naturales Renovables y de Protección al Medio Ambiente*. [Decreto 2811 de 1974]. DO: 34.243. Retrieved from: http://www.secretariasenado.gov.co/senado/basedoc/decreto_2811_1974.html

Presidencia de la República (31 de Julio de 2002). *Por el cual se reglamenta el manejo y transporte terrestre automotor de mercancías peligrosas por carretera.* [Decreto 1609 de 2002]. Retrieved from: http://www.minambiente.gov.co/images/BosquesBiodiversidadyServiciosEcosistemicos/pdf/Normativa/Decretos/dec_1609_310702.pdf

Presidencia de la República (26 de mayo de 2015). *Por medio del cual se expide el Decreto Único Reglamentario del Sector Ambiente y Desarrollo Sostenible.* [Decreto 1076 de 2015]. Retrieved from: https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=62511

Quan, Jonathan; Colorado, Henry A.; Yeh, Po-Ching; Yang, Jenn-Ming (2016). Hybridized ZnO nanostructures on carbon-fiber through combustion synthesis induced by joule heating. *Ceramics International*, *42*(11), 13053–13060. https://doi.org/10.1016/j.ceramint.2016.05.085

Requier-Desjardins, Denis. (Noviembre de 1999). Agro-industria rural y sistemas agroalimentarios localizados: ¿Cuáles puestas. En *X Aniversario de PRODAR*, Quito, Ecuador.

Restrepo, Jose; Colorado, Henry A. (2018). Additive Manufacturing of Epoxy Resin Matrix Reinforced with Magnetic Particles. In *TMS Annual Meeting & Exhibition* (Eds.). (pp. 619–624). TMS 2018 147th Annual Meeting & Exhibition Supplemental Proceedings. TMS 2018. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-319-72526-0_58

Revelo, Carlos; Colorado, Henry A. (2018). 3D printing of kaolinite clay ceramics using the Direct Ink Writing (DIW) technique. *Ceramics International*, *44*(5), 5673–5682. https://doi.org/10.1016/j.ceramint.2017.12.219

Sáez, Alejandrina; Urdaneta, Joheni (2014). Manejo de residuos sólidos en América Latina y el Caribe. *Omnia*, *20*(3), 121-135.

U.S. Energy Information Administration. (2015). *Short-term energy outlook: Global liquid fuels. Retrieved February 5, 2016.* Retrieved from: https://www.eia.gov/outlooks/steo/report/global_oil.php

Unión Europea. (2018). *Directiva (UE) 2018/851 del Parlamento Europeo y del Consejo, de 30 de mayo de 2018 sobre los residuos*. Retrieved from: https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32018L0851&from=EN

Vergara, Sintana; Damgaard, Anders; Gomez, Daniel (2016). The efficiency of informality: quantifying greenhouse gas reductions from informal recycling in Bogotá, Colombia. *Journal of Industrial Ecology*, *20*(1), 107–119. https://doi.org/10.1111/jiec.12257

Yong, Ren (2007). The circular economy in China. *Journal of Material Cycles and Waste Management*, *9*(2), 121–129. https://doi.org/10.1007/s10163-007-0183-z

Yu, J. (2010). The effectiveness of extended producer responsibility in motivating eco-design changes: perspectives from China's electrical and electronics industry. *HKU Theses Online (HKUTO).*

Zhijun, Feng; Nailing, Yan (2007). Putting a circular economy into practice in China. *Sustainability Science*, *2*(1), 95–101. https://doi.org/10.1007/s11625-006-0018-1

Zhu, J., Gu, H., Guo, J., Chen, M., Wei, H., Luo, Z., Ho, T. C. (2014). Mesoporous magnetic carbon nanocomposite fabrics for highly efficient Cr (VI) removal. *Journal of Materials Chemistry A*, *2*(7), 2256–2265. https://doi.org/10.1039/C3TA13957C