

Article

Stabilising Rural Roads with Waste Streams in Colombia as an Environmental Strategy Based on a Life Cycle Assessment Methodology

Alejandra Balaguera ^{1,2,*} , Jaume Alberti ¹, Gloria I. Carvajal ^{2,*} and Pere Fullana-i-Palmer ^{1,*} 

¹ UNESCO Chair in Life Cycle and Climate Change ESCI-UPF, Pompeu Fabra University, Passeig Pujades 1, 08003 Barcelona, Spain; jaume.alberti@esci.upf.edu

² Facultad de Ingenierías, Universidad de Medellín, Medellín 050010, Colombia

* Correspondence: abalaguera@udem.edu.co (A.B.); gicarvajal@udem.edu.co (G.I.C.); pere.fullana@esci.upf.edu (P.F.-i.-P.)

Abstract: Roads with low traffic volume link rural settlements together and connect them with urban centres, mobilising goods and agricultural products, and facilitating the transportation of people. In Colombia, most of these roads are in poor conditions, causing social, economic, and environmental problems, and significantly affecting the mobility, security, and economic progress of the country and its inhabitants. Therefore, it is essential to implement strategies to improve such roads, keeping in mind technical, economic, and environmental criteria. This article shows the results of the application of the environmental life cycle assessment—LCA—to sections of two low-traffic roads located in two different sites in Colombia: one in the Urrea area (Antioquia), located in the centre of the country; and another in La Paz (Cesar), located in the northeast of the country. Each segment was stabilised with alternative materials such as brick dust, fly ash, sulfonated oil, and polymer. The analysis was carried out in three stages: the first was the manufacture of the stabiliser; the second included preliminary actions that ranged from the search for the material to its placement on site; and the third was the stabilisation process, which included the entire application process, from the stabiliser to the road. The environmental impacts are mainly found in the manufacture of stabilisers (60% of the total), for sulfonated oil or polymer, due to the different compounds used during production, before their use as stabilisers. The impact categories with the greatest influence were abiotic depletion potential (ADP), global warming potential (GWP) and terrestrial ecotoxicity potential (TETP). For the stabilisation stage (impact between 40% and 99%), ash and brick dust have the highest impacts. The impact categories most influenced in this stage were: acidification potential (AP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP) and photochemical ozone creation potential (POCP).

Keywords: life cycle assessment; waste management; circular economy; alternative materials; construction; road stabilisation



Citation: Balaguera, A.; Alberti, J.; Carvajal, G.I.; Fullana-i-Palmer, P. Stabilising Rural Roads with Waste Streams in Colombia as an Environmental Strategy Based on a Life Cycle Assessment Methodology. *Sustainability* **2021**, *13*, 2458. <https://doi.org/10.3390/su13052458>

Academic Editor: Edoardo Bocci

Received: 22 September 2020

Accepted: 16 December 2020

Published: 25 February 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

1.1. Low Traffic Roads in Colombia and Its Stabilisation

The Colombian road network has 204,855 km, of which approximately 70% corresponds to tertiary roads [1]. They are essential to facilitate the integration of rural areas with their respective urban headwaters, and boost the economy through the development of agricultural, mining and tourism activities [2]. About 96% of tertiary roads are in bad condition [3]. High levels of deterioration are found, consistent with the great topographic variability, soil susceptibility and hydrological regime to which they are exposed, hindering their proper functioning, especially in rainy seasons [4]. This fact, added to the financial impossibility of paving the entire tertiary network of the country, implies a need for reha-

bilitation and maintenance, implementing techniques that contribute to its stability and proper functioning.

In Colombia, the stabilisation of tertiary roads includes the use of materials such as lime, Portland cement, rock dust, colloidal transport materials, and organic bases, with procedures governed mainly by the Urban Development Institute of Bogotá (IDU), collected in its guide of design and construction of structural layers of pavements through chemical processes [5].

Traditionally, the implementation of soil stabilisation activities for roads includes the use of materials such as cement and lime. Some studies have found improvements in the mechanical properties of the soil under the addition of such materials [6–10].

The general specifications for road construction of the National Institute of Roads [11] also establish guidelines for road soil stabilisation, by using cement or lime as stabilising materials.

1.2. Assessing Environmental Impacts and Life Cycle Assessment (LCA)

The extensive use of traditional materials in roads stabilisation, such as natural aggregates, cement, and lime, is causing a gradual depletion of natural resources [12,13]. At the same time, the industry sector produces large quantities of different types of waste, which have to be managed, with the consequent environmental impacts [14]. Following the circular economy principles [15], some of this waste may become alternative materials to be reused in road stabilisation, as a means to (partially) solve both problems described above: resource depletion and environmental impacts.

Of course, there is a need to objectively quantify these improvements in terms of environmental impact. The LCA methodology is known as an objective assessment tool [16], and its results may facilitate the decision-making process [17–22]. In our case, LCA may allow builders and government decision-makers to measure the consumption and emissions generated during the life cycle of low traffic roads stabilised with alternative materials.

Since 2001, different applications have been developed for the use of the LCA methodology to assess the impacts of construction in general [23], to communicate them through environmental product declarations [24], and specifically to apply them for different materials in the construction of roads. Mroueh et al. [25] found that the use of fly ash, steel slag, and crushed concrete, as substitutes for natural aggregates in road construction in Finland, reduces the contributions for some impact categories. In the U.S., Rajendran & Gambatese [26] developed a life cycle-based comparative analysis of energy consumption and the generation of solid waste associated with concrete and asphalt pavements. Birgisdóttir et al. [27] analysed, in Denmark, the environmental impacts associated with road construction and the use of ash produced by municipal waste incineration. Chowdhury et al. [20], in the United States, compared by-products, such as fly ash and recycled asphalt (RAP), against natural aggregates by evaluating some impacts, such as energy consumption, acidification potential and toxicity potentials.

Celauro et al. [28] developed a study in Italy, in which different percentages of RAP were applied both to the asphalt and to the base layers, and the stabilisation of clay soil was performed with lime. They showed a reduction in energy consumption and emissions thanks to the avoided use and transport of traditional materials. In addition, the use of lime in the stabilisation and a greater amount of RAP lead to a significant reduction in CO₂ by 48.79%, CO by 41.11% and human toxicity potential (cancer) by 36.97%. Finally, in Paraguay, the environmental impacts of using clay–lime mixtures on soil stabilisation were analysed. They used different doses, which enabled the obtaining of different levels of stiffness and resistance. This guaranteed the desirable mechanical properties of the soil. In this study, lime production represented more than 75% of the total energy consumption, greenhouse gas emissions and photochemical oxidation for each of the analysed mixtures [12].

A literature review [29] has shown that not much research has been done related to LCA on low-traffic roads in developing countries, nor to stabilizing agents, nor to other more simplified life-cycle-based indicators that other sectors are using, such as the carbon footprint [30,31] or energy demand [32]. The aim of this paper is to present the results of

a pilot study in which different stabilising agents coming from waste streams have been technically tested in segments of low traffic roads in Colombia, and for which an LCA has been performed to compare their environmental impact and to show if they perform better than traditional virgin materials.

2. Materials and Methods

2.1. Roads Being Studied

The experimentation was performed in two different tertiary towns of Colombia. At the international level, roads that are known as tertiary in Colombia are associated with low traffic volumes and are called low volume roads (LVR). Low volume roads are characterised by not being paved and having an average daily traffic equivalent of fewer than 200 vehicles, as well as slow modes of travel that are mostly made up of pedestrians and non-motorised traffic [33].

The first town was Urrao, which is located in the southwest sub-region of Antioquia; and the second town was La Paz, which is located in Cesar region (between San José de Oriente and Filomachete region), in the northwest of Colombia (see Figure 1a), and close to the border with Venezuela (see Figure 1b). The reason to choose them was the relationship between those towns, their administrations, and their participation in the Red Innovial. The Red Innovial was a network that joined different public and private institutions in Colombia, such as universities and state organisations to investigate and perform new materials and constructive techniques for low traffic roads taking into account lower environmental impact and technical and economic viability.

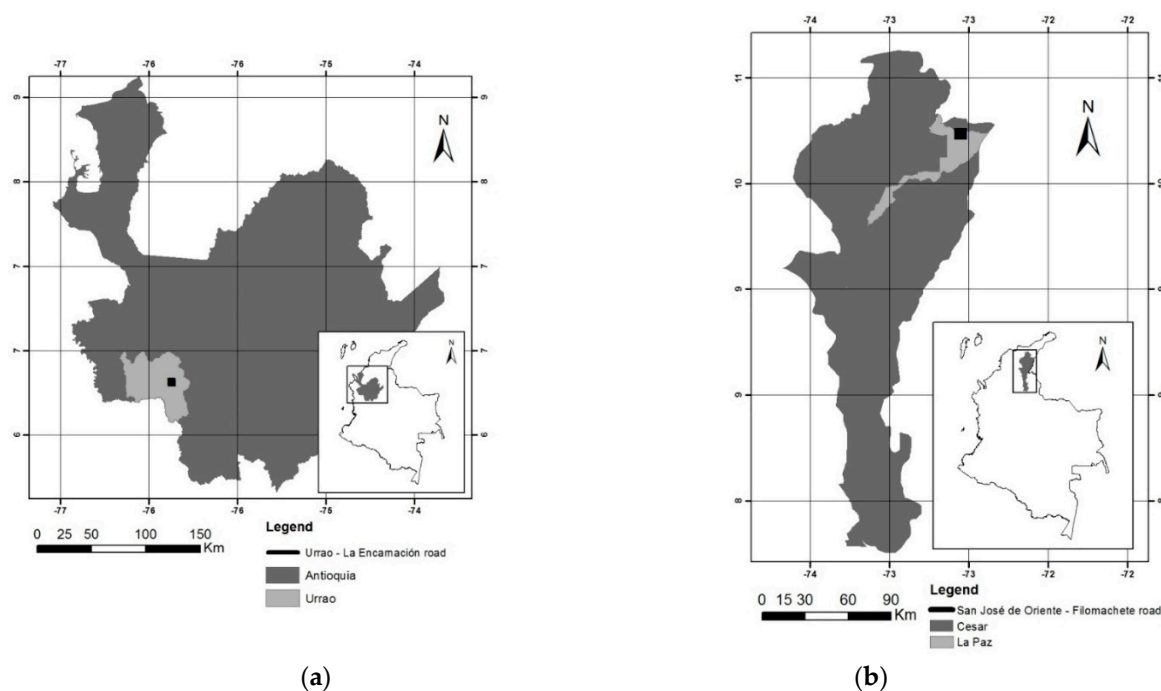


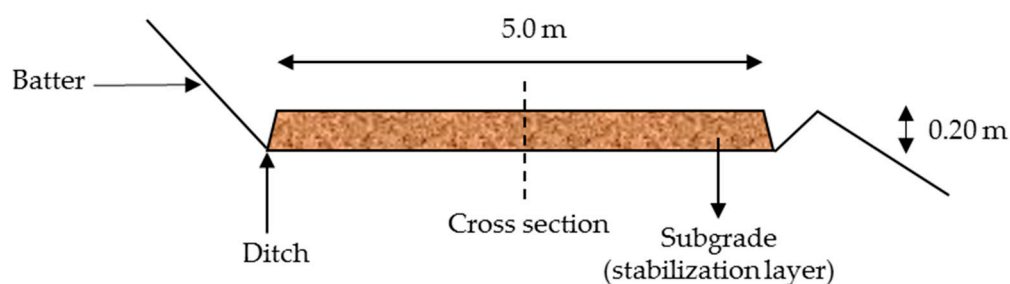
Figure 1. Location of the roads and cross section.

These regions soils have clay (Urrao) and sandy-clay (La Paz) characteristics. Table 1 provides an overview of the characteristics of the studied soils considering the standards defined by the National Institute of Roads in Colombia (INVIAS). The dimensions of each road were: width 5.0 m, length 1 km and thickness 0.20 m. The tests were performed by the authors within Red Innovial during 2016 (See Figure 2).

Table 1. Characterisation of the soils under study.

Properties	Standard	Urrao	La Paz
Type of soil		Lime	Sandy-clay
Unified Soil Classification System (USCS)		MH ¹	SC ²
AASHTO classification		A-7-5	A-6
Natural humidity (%)	INV E ³ -122	27	9
Specific gravity (Gs)	INV E-128	2.71	2.70
Liquid limit (%)	INV E-25	66	36
Plastic limit (%)	INV E-126	48	20
Plastic index (%)	INV E-126	18	16
Maximum size of particle (mm)		19	9.5
Clay (%)		23	14
Dry unit weight (kN/m ³)		14.8	19.5
Optimal humidity (%)	INV E-142	25.8	11.8

Source: INVIAS (2012). ¹ Unified Soil Classification System (USCS): MH means lime type; ² Unified Soil Classification System (USCS): MH means Sandy-clay type ³ INV E: Test Standard of the National Highway Institute (INVIAS) of Colombia.

**Figure 2.** Cross section.

The process of extraction of a soil sample in Urrao, the process of stabilisation, and the different testing methods descriptions may be found in the literature for different configurations of fly ash as stabilising material [34]. The methods used for the La Paz region were the same as those described for Urrao.

2.2. Stabilising Materials

As explained above, roads must be stabilised to correctly perform their function. This is required because of the characteristics of the current soil properties existing on the locations considered (see Table 1). This can be performed using natural aggregates or, as an alternative, some types of waste.

Four alternative waste materials have been tested, some of them needing a pre-treatment in order to be able to act as a stabilising agent (see Table 2). Before developing the LCA, laboratory tests were performed for each waste. Leaching potential was analysed; in the case of presenting any level of concentration in the soil it was discarded, being a decision criterion for application as stabilisers on the selected roads. Material 1 was fly ash waste from the combustion of coal in a thermoelectric process of a Colombian textile company located in Medellin city. The ash must follow an activation process with lime to become a stabilising agent. The description of this process and the testing methods are described in a previous paper [34].

Table 2. Design of the stabilising mixture.

Material	Quantity of Material for Urrao (t/m ³)	Quantity of Soil for Stabilisation Urrao (t/m ³)	Quantity of Material for La Paz (t/m ³)	Quantity of Soil for Stabilisation La Paz (t/m ³)
Fly ash	97.4	997.6	155	1272.8
Lime (Fly ash)	65		51.8	
Brick dust	113	1049.2	162	1272.8
Lime (brick dust)	534		45.6	
Sulphonated oil	0.426	1280	1.12	1480
Polymer	33.3	1280	50	1480

Material 2 was brick dust, which comes from the waste generated in the process of making bricks cooked at temperatures of 950 °C, and collected when emptying the storage wagons that are inside the brickyard. This material must follow, as described for the ash, an activation process with lime in order to become a stabilising agent [31].

Material 3 was a waste oil, which had a chemical transformation (a sulphonation process). This oil is a catalyst agent that produces ion exchange. Chemically, it is an organic compound derived from combined sulphides and acids. The most important function of this stabiliser is the reduction in the water contained between the soil particles, increasing the number of voids that allow the rearrangement of the particles, by attraction among them or by compaction [35]. The main effects of sulphonated oil on clay-clad soils are a reduction in interstitial spaces, reduction in permeability, increase in sedimentation, improvement of the response to compaction, and increase in the soil density. The studies carried out with sulphonated oils and the evidence obtained through field tests showed that the electrochemical stabilisation system is a competitive alternative to reduce the expansive potential of clay soils [36].

Finally, Material 4 was a polymer waste used as an emulsion. Polymer emulsions are a dispersed system in which the phases are immiscible or partially miscible liquids, one of which is dispersed in the other and whose structure is stabilised by a surfactant called an emulsifier.

2.3. LCA Methodology

The environmental assessment was made by using the LCA methodology following the ISO 14040 and ISO14044 standards [37,38] which involve four phases: “(i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation”. The software used was GaBi version 6.115 and most databases were also from thinkstep GaBi.

The scope of the study was restricted to cradle-to-gate, collecting data up to the stabilisers. This scope consideration is common in the construction sector, where environmental product declarations (EPDs) are widely used following the EN 15804 standard. In addition, because this is a first pilot scale study, technical environmental data collection is a challenge and data will have a high uncertainty. However, a simplified LCA is considered a better option than any other type of environmental assessment. ISO 14044 states that “The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.” Knowing the limitations in obtaining environmental information from this pilot system, it is not the intention of the study to advance further than a simplified LCA.

A complete LCA is not always needed to identify where the main impacts could be, and practice suggests different ways of applying the LCA methodology [39]. For instance, LCA is used to find the items (stages, processes, materials, etc.) which account for most of the impact in a system under an environmental product declaration programme [40] and it is recommended by the UNEP/SETAC life cycle initiative to help perform hot-spot analyses [41]. Depending on the goal of the environmental analysis, a simplified LCA

can be used and a selective assessment may be performed, taking into consideration only generic data and/or covering the life cycle in a restricted way (e.g., from cradle to gate), but without abandoning rigour [16,30]. The European Commission [42] introduced life cycle thinking (not only LCA) as essential to the sustainable use of resources. Some examples of this may be found in the literature [43].

The impact assessment method of CML [44], updated to 2016, was applied to evaluate the impacts, as recommended by the “Building Research Establishment Product Category Rules (PCR)” of construction products [12,44,45]. CML 2001 is an impact assessment method which restricts quantitative modelling to early stages in the cause–effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g., climate change) or commonly accepted groupings (e.g., ecotoxicity) [44]. It is recommended because it restricts quantitative modelling to the early stages of the cause–effect chain to reduce uncertainties. As in other studies [34,39,46–49] the analysed impact categories were: abiotic depletion potential (both ADP elements and ADP fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity (FAETP), global warming potential (GWP 100 years) excluding biogenic carbon, human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestrial ecotoxicity potential (TETP).

3. Life Cycle Assessment Methodology

3.1. Goal and Scope Definition

The functional unit was chosen as: “1 km of low traffic road”.

This functional unit enabled the assessment of environmental impact values and their comparison with other LCA studies applied to roads [28,50–52].

The scope of the study was defined as from cradle to gate. Therefore, according to CEN 15804 (2012) [45], a better naming might be “reference unit” instead of “functional unit”, but we will keep the latter, more commonly used. The scope included the following processes:

- The transformation of the polymer and sulphonated oil into stabilisers.
- The ash and brick dust taken as delivered by the industrial facility where they were produced as waste, without any additional processing of the material. Lime was used as an alkali activator in both cases, during stabilisation process.
- The preliminary activities stage included all the necessary processes before the stabilisation process. Among these activities, we included the transport of machinery and materials necessary for the stabilisation of the road, identifying its origin, time (in hours) and distances travelled (in km) from its origin to the study area.
- In the stabilisation process, the following activities are considered: scarification, stabiliser application, compaction, wetting, and curing depending on the case; as well as diesel consumption by each machine that was used in the process (see Figure 3).

Other processes were not included, considered as outside the limits of the system:

- Machinery manufacture, because the impact assigned to the time used for this system is very small in relation to the useful life of the machines.
- The maintenance stage, because it was beyond the scope of the Red Innovial, and is a stage that takes longer to be performed and evaluated than the duration of the project. As indicated above, this is an LCA from “cradle to gate” and, therefore, the use stage was not considered.
- The “end of life” stage, because no significant types or quantities of waste were generated during the whole process, as equally considered in previous studies [25,28].

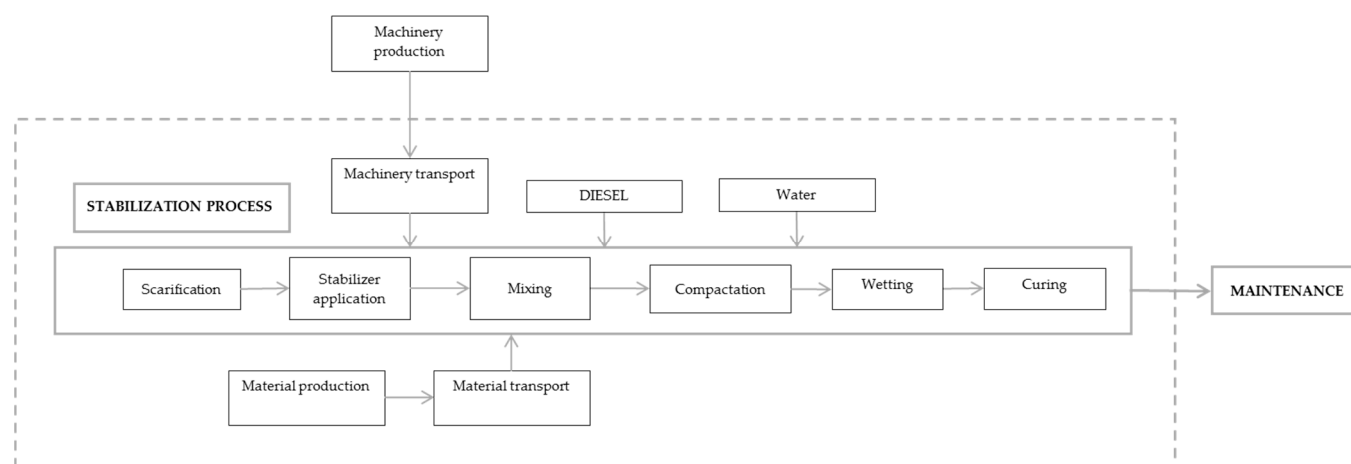


Figure 3. Flow chart of the stabilisation of the roads.

3.2. Inventory Analysis: Inputs and Outputs

3.2.1. Stabilisers

The following assumptions were taken:

- The “cut-off rule” [38] was applied and, therefore, wastes such as ash and brick dust entered the system with no environmental impact other than their transformation, if needed, and their transport to site.
- The polymer and the sulphonated oil were of waste origin, but they were mixed with virgin chemical compounds to be transformed into stabilisers. For instance, for the sulphonated oil manufacture, the following processes were used to model the substances used and obtained from the GaBi database. The needed amounts are presented in Table 3.
 - Silicone–resin plaster; technology mix; production mix, at plant; based on mineral fillers and a silicone bonding agent (en) from Germany; 100 mL;
 - Deionised water; highly pure, via ion exchange, from hydrochloric acid and caustic soda; single route, at plant from the U.S.; 1 kg/L (en);
 - Phenol; hock process, oxidation of cumene; single route, at plant; 1.07 g/cm³, 94 g/mol (en) from Germany;
 - Propylene glycol; via Propylene oxide (PO)-hydrogenation; single route, at plant; 1.04 g/cm³, 76.10 g/mol (en) from Germany;
 - Polyvinyl alcohol (from vinyl acetate) (PVAL); technology mix; production mix, at plant; without additives from the U.S.;
 - Antistatic agent (quaternary ammonium compound); technology mix; production mix, at plant; quaternary ammonium compound (en) Global;
 - Sulphuric acid aq. (96%); concentrated, sulphur dioxide route; single route, at plant; 96%, 1.84 g/cm³ (en) from the U.S.
- On the other hand, the environmental data for the chemical products added to the polymer were obtained from the GaBi database of the United States, and the processes for the compounds used in the production of the stabiliser are mentioned below (see Table 4 for quantities):
 - Acrylic acid (Propene); oxidation of propene; production mix, at plant; 1.05 g/cm³, 72.06 g/mol (en; Dipropylene glycol by product propylene glycol via PO hydrogenation; hydration of propylene oxide; single route, at plant; 1.02 g/cm³, 134 g/mol (en);
 - Dipropylene glycol by product propylene glycol via PO hydrogenation; hydration of propylene oxide; single route, at plant; 1.02 g/cm³, 134 g/mol (en) from the U.S.;

- Polycarbonate–acrylonitrile–butadiene–styrene compound (80% PC, 20% ABS); mixing, pelletising and compounding; single route, at plant; 80% polycarbonate, 20% acrylonitrile–butadiene–styrene (en);
 - Ethylene vinylacetate copolymer (E/VA) (72% ethylene, 28% vinylacetate); copolymerisation of ethylene and vinyl acetate; production mix, at plant; without additives, 72% ethylene, 28% vinyl acetate (en);
 - Sodium chloride (rock salt); salt mining and leaching; production mix, at plant; 2.17 g/cm³, 58.44 g/mol (en).
- For the alkaline activator (lime) model, the process used was: “Limestone flour (0.115 mm), production mix, at producer; grain size 0.115 mm”, from the GaBi database.

Table 3. Substances used for the production of kg of sulphonated oil.

Silicone–Resin Plaster (kg)	Deionised Water (kg)	Phenol (kg)	Propylene Glycol (kg)	Antistatic Agent (Quaternary Ammonium Compound) (kg)	Polyvinyl Alcohol (kg)	Sulphuric Acid Aq. (96%) (kg)
0.2	0.093	0.06	0.01	0.02	0.6	0.0004

Table 4. Substances used for the production of 1.0 kg of polymer.

Acrylic Acid (kg)	Dipropylene Glycol (kg)	Polycarbonate–Acrylonitrile–Butadiene–Styrene (kg)	Sodium Chloride (kg)	Ethylene Vinylacetate Copolymer (kg)
0.08	0.004	0.5	0.002	0.5

3.2.2. Material Transportation

To calculate consumptions related to materials transportation and their corresponding environmental impacts, the following data were used in the model:

- The distance travelled by each material from the production site to the corresponding road (Table 5);
- Material weight (Table 2), which depended on the type of soil at each road;
- In addition, for ash and brick dust, lime was used as an activator (Table 2);
- For any material transportation, the type of truck was chosen from the GaBi database, based on the amounts of materials needed to be transported: Truck-Heavy Heavy-duty Diesel Truck/53.333 lb payload-8b; Unit process, not pre-allocated; consumption mix;
- The weight of the motor grader (9844 kg), of the roller (7144.1 kg), and of each material used (see Table 2) was considered. The vehicle that transported the machinery was low-key, while the truck that transported the materials was a diesel-based truck (see Figure 3).

Table 5. Weights and distances travelled to transport the materials for each intervened road.

Material	Urrao		La Paz	
	Distance (km)	Time (h)	Distance (km)	Time (h)
Ash	159	3.5	234	5.9
Lime (ash)	159	3.5	25	0.7
Brick dust	159	3.5	322	8.1
Lime (brick dust)	159	3.5	25	0.7
Sulphonated oil	159	3.5	25	0.7
Polymer	159	3.5	25	0.7

3.2.3. Machinery Transportation

To calculate the consumptions of machinery transportation and their environmental impacts, the following data were used in the model:

- The distances for machinery acquisition were calculated based on the closer city to each stabilised road: 2 km for Urrao (Antioquia region) and 14 km for La Paz (Cesar region);
- The machines weights were [53,54]: 7144 kg for the roller and 9844 kg for the motor grader;
- The machinery was transported in a low bed truck, taken from GaBi database, and chosen based on the capacity to support the weight of each machine: "Flatbed, platform, etc./49,000 lb payload-8b; Unit process, not pre-allocated; consumption mix".

3.2.4. Stabilisation Stage

For the stabilisation stage, diesel machines were used. The consumptions were calculated taking into account functional unit; the calculations (Tables 6 and 7) considered the following conditions:

- Performances obtained from the manufacturers of: the motor grader (2080 L/h); the roller (1510 L/h); and the water tanker (3581 km/L);
- Distances used to perform each activity within the stabilisation stage (including scarification, application of stabiliser (depending on the case), wetting/curing and compaction): calculated based on the number of times the relevant machinery was to pass over each cell, multiplied by the length of the cell;
- The time to carry the materials to each place was calculated taking the distance travelled in km and the speed used by each type of transport, for each material or machinery;
- Amount of water in the mixtures of lime + ash and lime + brick powder, calculated according to the proportion of the material used in each of the sections (See Table 8);
- Environmental impacts of diesel production: calculated using the GaBi data set for the United States (USA), because no Colombian diesel data were available (Diesel at refinery; from crude oil; production mix, at refinery; 15 ppm sulphur);
- Water consumption, which was measured in the field, adding up the amounts used for the curing and wetting activities, which depended on each type of soil and its moisture requirements (Table 8);
- Environmental impacts of water production calculated using the U.S. GaBi dataset (Tap water from groundwater; filtration, disinfection, ion removal, etc.; production mix, at plant; 1000 kg/m³, 18 g/mol from the U.S.).

Table 6. Diesel consumption for the stabilisation stage in Urrao.

Activity	Diesel Consumption per Material (kg)			
	Sulphonated Oil	Polymer	Brick Dust	Ash
Scarification	12,300	67,700	49,100	106,000
Stabiliser application	4.08	14.6	*	*
Mixing	27,800	57,300	40,900	63,900
Compaction	16,700	16,900	13,300	15,000
Wetting/curing	2.04	1.36	6.12	8.16

Table 7. Diesel consumption for the stabilisation stage in La Paz.

Activity	Diesel Consumption per Material (kg)			
	Sulphonated Oil	Polymer	Brick Dust	Ash
Scarification	82,900	27,200	53,000	21,600
Stabiliser application	4.42	2.04	*	*
Mixing	29,200	10,300	19,200	45,800
Compaction	26,400	41,400	15,000	10,000
Wetting/curing	**	**	1.02	2.38

* These were applied manually, without a machine. ** Because of soil and material type, water addition was not needed.

Table 8. Water consumption during the stabilisation stage.

Material	Urrao kg	La Paz kg
Ash	57,000	15,400
Ash + lime	38,000	10,200
Brick dust	11,800	17,500
Brick dust + lime	5570	8220
Sulphonated oil	23,200	102,000
Polymer	20,300	50,300

* These were applied manually, without a machine.

3.3. Impact Assessment

This set of categories ensures the quantification of global impacts (ADP elements, ADP fossils, GWP, ODP), regional impacts (AP, EP), and local impacts (FAETP, HTP, MAETP, POCP, TETP). It also ensures the consideration of impacts on the terrestrial environment (ADP elements, ADP fossils, AP, EP, HTP, POCP, TETP), impacts on the aquatic environment (AP, EP, FAETP, MAETP), impacts on the air environment (GWP, ODP, POCP), and impacts on human health (HTP, ODP, POCP).

The reasoning for why to choose those categories is as follows. The global warming potential (or carbon footprint) generally has a more intense social perception than the other categories. A great interest in Colombia is focused on the impact on air quality due to the vehicle fleet and the industry [55]. On the other hand, supporting the circular economy and the need to save natural resources is of increasing interest worldwide. When emissions contributing to HTP and FAETP impact categories increase, they directly affect population health in the rural and urban areas. Finally, water consumption has been chosen because most of the Colombian water system is in the process of alteration, due to the detrimental effects caused by the transport of sediments, organic load, and toxic substances, with a high incidence in the industrial corridors located in the corresponding basins. In addition, the average consumption of urban households with drinking water service is 200 L/inhabitant per day, and 120 L/inhabitant per day for rural households. These figures exceed the minimum volume of 80 L necessary to guarantee life quality [56].

4. Results and Discussion

The results of the environmental impacts are presented in Tables 9–12, showing the differences of choosing the alternative materials used in the stabilisation process in the two road sections.

The stabilisation alternative which presented a higher environmental impact in all impact categories (with at least a difference of two orders of magnitude) was the sample using sulphonated oil. This difference is due to the need for significant additional resources for it to become a stabiliser [12]. If the environmental impact of the polymer (the second in the list) is normalised to 100%, for each road, the oil would have a contribution from 1500% up to 9500%, depending on the impact category.

If sulfonated oil, due to its high environmental impact, is discarded as a viable alternative for road stabilisation, the relative impacts of the other three options can be better analysed, without the interference of the high results produced by the oil. The results are presented below for the two roads studied.

4.1. Results for Urrao

For the soil of Urrao (see Tables 9 and 10 and Figure 4), the manufacture of the polymer and its application as a stabiliser were found to have greater impacts than the other two alternatives, which offer very similar results.

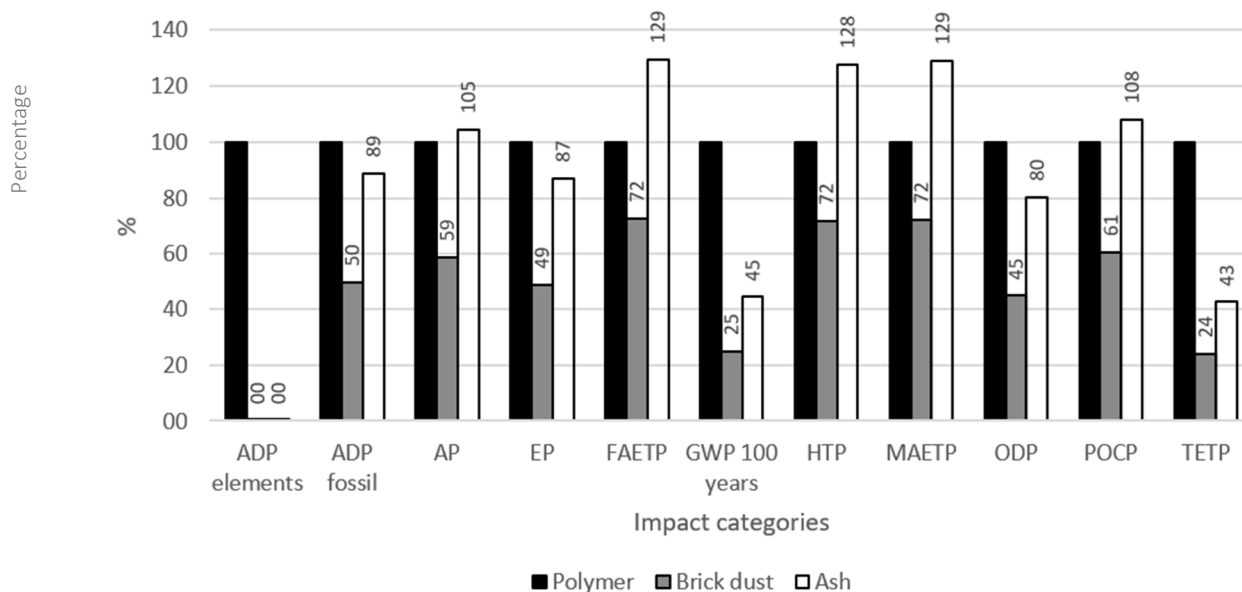


Figure 4. Environmental impacts for each stabiliser applied in Urrao.

Taking the polymer values (100%) as a reference, it was found that they presented higher impacts for the ADP elements, and GWP and TETP impact categories. This is due to the manufacture of the chemical compounds used during its transformation into a stabiliser. Some authors such as da Rocha et al.; Muench; and Siracusa et al.; [12,57,58] also found that, for the traditional materials such as natural aggregates and cement, the environmental impacts were generated during extraction and manufacturing.

For the other impact categories, the ash had the greatest impacts, because of the stabilisation stage: AP 104.5%, FAETP 129.4%; HTP 127.7%; MAETP 129.0%; and POCP 107.9%. Due to the type of soil in Urrao (clay soil), the machinery needed more time performing the processes of scarification, mixing, profiling, and wetting; therefore, more diesel consumption was needed. Larrea-Gallegos et al. [13] also found that stabilisation of soil had the highest impact due to fuel consumption. However, other authors Johnson et al.; Karavalakis et al.; Wu, Zhang, Lou, Li, & Chen [52,59,60] found that, for traditional materials, GWP was higher due to the combustion of fuels during the process of stabilisation.

Table 9. Environmental impacts for liquid stabilisers at each life cycle stage for the Urrao system.

Impact Categories	Polymer				Sulphonated Oil			
	Material Production	Preliminaries Activities	Stabilisation	Total	Material Production	Preliminaries Activities	Stabilisation	Total
ADP elements ⁴ kg Sb-Equiv.	0.362	7.21×10^{-5}	24,100	0.362	0.00565	6.10×10^{-7}	9.76×10^{-5}	0.00575
ADP fossil ⁵ MJ	3.41×10^6	5930	7.30×10^6	1.07×10^7	1.64×10^8	50.2	2.92×10^6	1.67×10^8
AP ⁶ kg SO2-Equiv.	259	0.212	1060	1320	58.000	0.00179	424	58.400
EP ⁷ kg Phosphate-Equiv.	36.2	0.0705	73.2	110	4880	5.96×10^{-4}	29.3	4910
FAETP ⁸ kg DCB-Equiv.	822	3.54	163,000	1.63×10^5	3.69×10^6	0.0299	65.000	3.76×10^6
GWP 100 years ⁹ kg CO2-Equiv.	1.50×10^5	53.0	78,000	2.28×10^5	1.32×10^7	0.448	31.300	1.32×10^7
HTP ¹⁰ kg DCB-Equiv.	7650	44.7	459,000	4.66×10^5	1.19×10^7	0.379	1.84×10^5	1.21×10^7
MAETP ¹¹ kg DCB-Equiv.	3.63×10^6	6720	6.16×10^8	6.20×10^8	1.40×10^{10}	56.9	2.47×10^8	1.42×10^{10}
ODP ¹² kg R11-Equiv.	1.35×10^{-5}	2.73×10^{-9}	2.18×10^{-5}	3.53×10^{-5}	4.92×10^{-4}	2.31×10^{-11}	8.72×10^{-6}	5.01×10^{-4}
POCP ¹³ kg Ethene-Equiv.	34.6	0.0474	170	204	5490	4.01×10^{-4}	68.0	5560
TETP ¹⁴ kg DCB-Equiv.	60.5	0.159	28.7	89.4	8430	0.00135	11.5	8440

⁴ ADP: Abiotic Depletion Potential, ⁵ AP: Acidification Potential, ⁶ EP: Eutrophication Potential, ⁷ FAETP: Freshwater Aquatic Ecotoxicity, ⁸ GWP: Global Warming Potential, ¹⁰ HTP: Human Toxicity Potential,

¹¹ MAETP: Marine Aquatic Ecotoxicity, ¹² ODP: Ozone Layer Depletion Potential, ¹³ POCP: Photochemical Ozone Creation Potential, ¹⁴ TETP: Terrestrial Ecotoxicity Potential.

Table 10. Environmental impacts for solid stabilisers at each life cycle stage for the Urrao system.

Impact Categories	Brick Dust + Lime				Ash + Lime			
	Material Production	Preliminaries Activities	Stabilisation	Total	Material Production	Preliminaries Activities	Stabilisation	Total
ADP elements ⁴ kg Sb-Equiv.	6.44×10^{-7}	2.31×10^{-4}	1.76×10^{-4}	4.07×10^{-4}	6.44×10^{-7}	2.31×10^{-4}	3.18×10^{-4}	5.49×10^{-4}
ADP fossil ⁵ MJ	15.5	19,000	5.32×10^6	5.34×10^6	15.5	19,000	9.48×10^6	9.50×10^6
AP ⁶ kg SO2-Equiv.	0.00429	0.676	773	773	0.00429	0.676	1380	1380
EP ⁷ kg Phosphate-Equiv.	9.90×10^{-4}	0.226	53.3	53.5	9.90×10^{-4}	0.226	95.2	95.4
FAETP ⁸ kg DCB-Equiv.	0.00415	11.3	118,000	118,000	0.00415	11.3	211,000	211,000
GWP 100 years ⁹ kg CO2-Equiv.	1.50	170	56,900	57,000	1.50	170	102,000	102,000
HTP ¹⁰ kg DCB-Equiv.	0.0624	143	334,000	334,000	0.0624	143	596,000	596,000
MAETP ¹¹ kg DCB-Equiv.	135	21,500	4.49×10^8	4.49×10^8	135	21,500	8.00×10^8	8.00×10^8
ODP ¹² kg R11-Equiv.	5.41×10^{-12}	8.74×10^{-9}	1.59×10^{-5}	1.59×10^{-5}	5.41×10^{-12}	8.74×10^{-9}	2.83×10^{-5}	2.83×10^{-5}
POCP ¹³ kg Ethene-Equiv.	3.79×10^{-4}	0.152	124	124	3.79×10^{-4}	0.152	221	221
TETP ¹⁴ kg DCB-Equiv.	0.00494	0.510	21.0	21.5	0.00494	0.510	37.5	38.0

⁴ ADP: Abiotic Depletion Potential, ⁵ AP: Acidification Potential, ⁶ EP: Eutrophication Potential, ⁷ FAETP: Freshwater Aquatic Ecotoxicity, ⁸ GWP: Global Warming Potential, ¹⁰ HTP: Human Toxicity Potential,

¹¹ MAETP: Marine Aquatic Ecotoxicity, ¹² ODP: Ozone Layer Depletion Potential, ¹³ POCP: Photochemical Ozone Creation Potential, ¹⁴ TETP: Terrestrial Ecotoxicity Potential

Table 11. Environmental impacts for liquid stabilisers at each life cycle stage for the La Paz system.

Impact Categories	Polymer				Sulphonated Oil			
	Material Production	Preliminaries Activities	Stabilisation	Total	Material Production	Preliminaries Activities	Stabilisation	Total
ADP elements ⁴ kg Sb-Equiv.	0.542	2.25×10^{-5}	1.34×10^{-4}	0.542	0.0150	6.31×10^{-6}	2.41×10^{-4}	0.0152
ADP fossil ⁵ MJ	5.11×10^6	1850	4.04×10^6	9.15×10^6	4.36×10^8	518	7.12×10^6	4.43×10^8
AP ⁶ kg SO2-Equiv.	389	0.0661	587	976	154,000	0.0185	1030	155,000
EP ⁷ kg Phosphate-Equiv.	54.4	0.0220	40.6	95.0	12,900	0.00616	71.5	13,000
FAETP ⁸ kg DCB-Equiv.	1230	1.11	90,000	91,300	9.78×10^6	0.309	159,000	9.94×10^6
GWP 100 years ⁹ kg CO2-Equiv.	225,000	16.5	43,200	268,000	3.51×10^7	4.63	76,200	3.52×10^7
HTP ¹⁰ kg DCB-Equiv.	11,500	14.0	254,000	266,000	3.16×10^7	3.91	448,000	3.20×10^7
MAETP ¹¹ kg DCB-Equiv.	5.45×10^6	2100	3.42×10^8	3.47×10^8	3.73×10^{10}	587	6.02×10^8	3.79×10^{10}
ODP ¹² kg R11-Equiv.	2.03×10^{-5}	8.54×10^{-10}	1.21×10^{-5}	3.24×10^{-5}	0.0013	2.38×10^{-10}	2.13×10^{-5}	0.00132
POCP ¹³ kg Ethene-Equiv.	51.8	0.0148	94.2	146	14,600	0.00414	166	14,800
TETP ¹⁴ kg DCB-Equiv.	90.8	0.0498	16.0	107	22,400	0.0139	28.2	22,400

⁴ ADP: Abiotic Depletion Potential, ⁵ AP: Acidification Potential, ⁶ EP: Eutrophication Potential, ⁷ FAETP: Freshwater Aquatic Ecotoxicity, ⁸ GWP: Global Warming Potential, ¹⁰ HTP: Human Toxicity Potential,

¹¹ MAETP: Marine Aquatic Ecotoxicity, ¹² ODP: Ozone Layer Depletion Potential, ¹³ POCP: Photochemical Ozone Creation Potential, ¹⁴ TETP: Terrestrial Ecotoxicity Potential.

Table 12. Environmental impacts for solid stabilisers at each life cycle stage for the La Paz system.

Impact Categories	Brick Dust + Lime				Ash + Lime			
	Material Production	Preliminaries Activities	Stabilisation	Total	Material Production	Preliminaries Activities	Stabilisation	Total
ADP elements ⁴ kg Sb-Equiv.	6.44×10^{-7}	7.26×10^{-4}	1.49×10^{-4}	8.76×10^{-4}	6.44×10^{-7}	5.32×10^{-4}	1.33×10^{-4}	6.65×10^{-4}
ADP fossil ⁵ MJ	15.5	59,800	4.48×10^6	4.54×10^6	15.5	43,700	3.98×10^6	4.03×10^6
AP ⁶ kg SO2-Equiv.	0.000429	2.13	651	653	0.00429	1.56	578	580
EP ⁷ kg Phosphate-Equiv.	9.90×10^{-4}	0.710	45.0	45.7	9.90×10^{-4}	0.520	40.0	40.5
FAETP ⁸ kg DCB-Equiv.	0.00415	35.6	99,800	99,900	0.00415	26.1	88,700	88,800
GWP 100 years ⁹ kg CO2-Equiv.	1.50	533	48,000	48,500	1.50	390	42,600	43,000
HTP ¹⁰ kg DCB-Equiv.	0.0624	451	282,000	282,000	0.0624	330	250,000	251,000
MAETP ¹¹ kg DCB-Equiv.	135	67,700	3.78×10^8	3.78×10^8	135	49,500	3.36×10^8	3.36×10^8
ODP ¹² kg R11-Equiv.	5.41×10^{-12}	2.75×10^{-8}	1.34×10^{-5}	1.34×10^{-5}	5.41×10^{-12}	2.02×10^{-8}	1.19×10^{-5}	1.19×10^{-5}
POCP ¹³ kg Ethene-Equiv.	3.79×10^{-4}	0.478	104	105	3.79×10^{-4}	0.349	92.8	93.1
TETP ¹⁴ kg DCB-Equiv.	0.00494	1.61	17.7	19.3	0.0494	1.17	15.7	16.9

⁴ ADP: Abiotic Depletion Potential, ⁵ AP: Acidification Potential, ⁶ EP: Eutrophication Potential, ⁷ FAETP: Freshwater Aquatic Ecotoxicity, ⁸ GWP: Global Warming Potential, ¹⁰ HTP: Human Toxicity Potential,

¹¹ MAETP: Marine Aquatic Ecotoxicity, ¹² ODP: Ozone Layer Depletion Potential, ¹³ POCP: Photochemical Ozone Creation Potential, ¹⁴ TETP: Terrestrial Ecotoxicity Potential

4.2. Results for La Paz

The environmental comparison was applied to the road in La Paz as well (see Tables 11 and 12 for absolute values, and Figure 5 for relative values). Results for the sulfonated oil are not presented in the figure, because its impacts exceeded the rest of the stabilisers by more than 1000%. The polymer results are taken as a reference value at 100%.

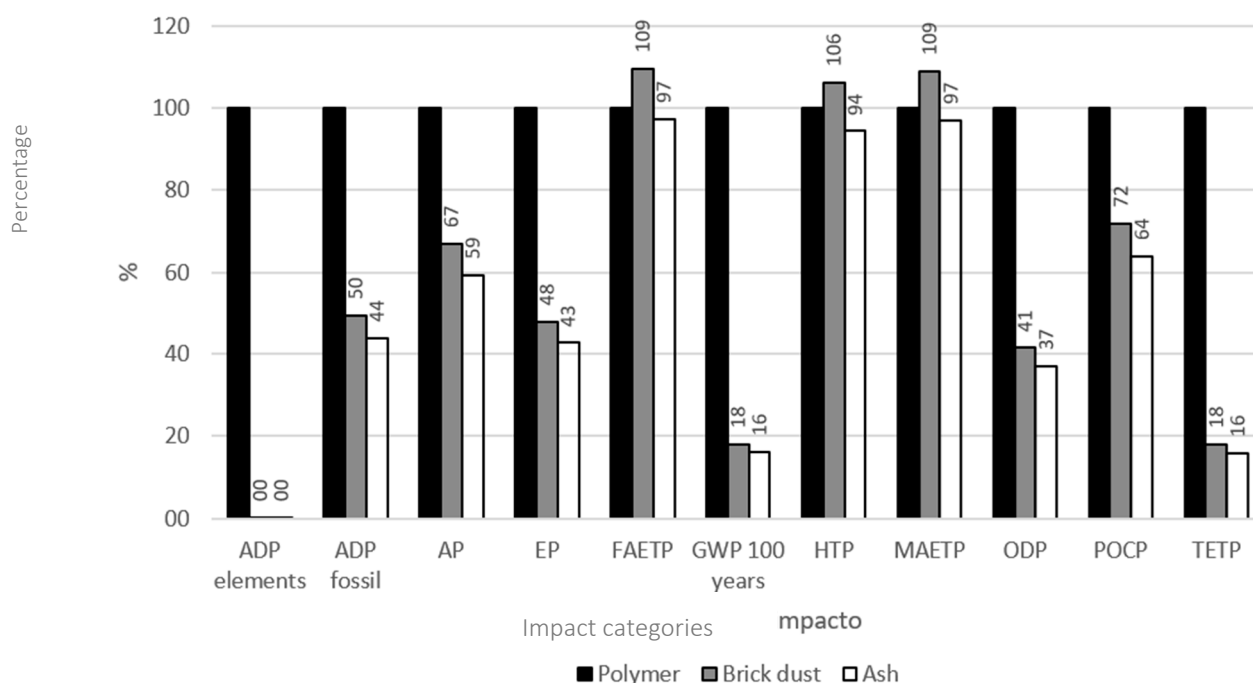


Figure 5. Environmental impacts for each stabiliser applied in La Paz.

For La Paz, the results obtained showed that the polymer impacts exceeded the rest of the stabilisers in even more impact categories than for Urrao (ADP elements, fossil ADP, AP, EP, GWP, ODP, POCP and TETP). For this road, the material that had the second place in impact was not the ash but the brick dust, because of the diesel consumption required for the stabilisation stage, offering greater impacts for three categories: FAETP (109.4%), HTP (106.2%) and MAETP (109.0%).

Some very significant data influencing the environmental results were obtained from processes included in databases corresponding to other countries (for example, the impacts associated with the generation of energy, the production of diesel and the manufacture of some raw materials), which may represent a significant uncertainty. During the project discussions, it was clearly acknowledged that a strong recommendation was to be sent to public authorities to start the construction of an environmental database of LCA data in Colombia, including energy, materials, and construction processes.

An extended analysis and comparison (obtaining environmental, social and economic information) with traditional materials used to stabilise soils, such as cement, lime and natural aggregates, would be very useful to produce policy changes in the sustainability direction.

Finally, although less common in Colombia, it would be also interesting to study roads with a high traffic volume, and promote environmental impact reduction in these more complex and exemplifying systems.

5. Conclusions

Due to the much higher environmental impact produced by the sulphonated oil for two types of soil, policy-makers may generally discard its use as stabiliser.

Regarding the three non-discarded stabilisation options (polymer, brick dust and ash), different results were obtained for the two tested roads, and even the order of priority

varied from one road to the other. The decision process on the stabiliser should consider the soil type and the impact categories considered relevant, together with economic and social variables, which have not been assessed in this study.

If the focus is how the different life cycle stages contribute to the total impact of each alternative material option, it can be concluded that, for both regions, the environmental impacts are mostly caused by the stabiliser manufacture (60% of the total). This is due to the production of different chemicals needed during this stage.

Within the most contributing life cycle stage, stabilisation, the percentages of the impacts ranged from 40% to 90%, depending on the type of stabiliser (solid or liquid). Solids (brick dust and ash) had the greatest impacts because of the processes required to perform this stage. For instance, its impact on climate change was due to fuel combustion. This stage is (by far) the most relevant.

As presented in the introduction, the most relevant categories for Colombia seem to be GWP, HTP, and MAETP. In this sense, the best alternative material found for the Urrao type of soil is brick dust, because its impact on GWP is 25% lower. The results for La Paz indicated that the best material is fly ash, with 18.1% of the impact in GWP impact category compared to the other options.

Having an alternative material instead of a conventional raw material can be a great advantage in environmental terms, because resources are kept in a more circular economy. Further research will be needed to compare those types of materials with traditional substances such as natural aggregates or cement. This is essential to ensure that the overall performance along the life cycle of the alternative stabilisers is better (and by how much) from an environmental point of view.

A more holistic sustainability assessment, taking into account social and economic indicators, would help improve sound decision-making by public authorities when choosing among road stabilising processes. To develop and test methodology on this matter is recommended, because tertiary roads highly influence the rural settlements and their economic systems, both during construction and use.

Author Contributions: Conceptualization, A.B. and G.I.C.; methodology, P.F.-i.-P.; software, J.A.; validation, P.F.-i.-P., G.I.C.; formal analysis, A.B.; investigation, A.B.; writing—original draft preparation, A.B.; J.A.; P.F.-i.-P.; G.I.C.; writing—review and editing A.B.; J.A.; P.F.-i.-P.; G.I.C.; supervision, P.F.-i.-P., G.I.C.; project administration, G.I.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by COLCIENCIAS and ESCI-UPF.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Thanks are given to Universidad de Medellín, Red Innovial and ESCI-UPF, for providing the funds of this research. One of the authors (A.B.) wishes to thank the UNESCO Chair in Life Cycle and Climate Change ESCI-UPF for hosting her during the 2016–2017 academic year, when research was carried out and this paper was started. The authors are responsible for the choice and presentation of information contained in this paper, as well as for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit this organisation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection.

References

1. DNP. *Política para la Gestión de la Red Terciaria: Presupuesto Informado por Resultados*; Departamento Nacional de Planeación: Bogotá, Colombia, 2017.
2. Muñoz, F.; Arias, Y.P.; Hidalgo, C. *Evaluación del polvo de ladrillo como estabilizante de suelo perteneciente a vías terciarias. Proceedings from: Simposio Colombiano Sobre Ingeniería de Pavimentos*; Santa Marta, Colombia, 2015; pp. 1–10.

3. La República. Del Total de la red vial terciaria con la que cuenta Colombia, 96% está en mal estado. 2017. Available online: <https://www.larepublica.co/infraestructura/del-total-de-la-red-vial-terciaria-con-la-que-cuenta-colombia-96-esta-en-mal-estado-2828335> (accessed on 27 September 2019).
4. Muñoz, F. *Evaluación de las Propiedades Hidráulicas de Suelos Estabilizados con Polvo de Ladrillo Utilizados en vías de Bajos Volúmenes de Tránsito*; Universidad de Medellín: Medellín, Colombia, 2016.
5. IDU. *Guía para el Diseño y la Construcción de Capas Estructurales de Pavimentos Estabilizados Mediante Procesos Químicos*; Instituto de Desarrollo Urbano: Bogotá, Colombia, 2005.
6. Cadavid, L.; Restrepo, F. *Evaluación del Efecto de la Erosión por Escorrentía Superficial en Suelos Residuales Arenosos Estabilizados con Cemento o cal*; Universidad de Medellín: Medellín, Colombia, 2007.
7. Cardona, C.; Ruiz, N. *Determinación de la Dosificación de cal para la Estabilización de Suelos Granulares de Dioritas, bajo Análisis de Pruebas Estadísticas*; Universidad de Medellín: Medellín, Colombia, 2005.
8. Echavarría, J.; Arroyave, N. *Diseño de Mezclas de Suelo-Cemento para Estructuras Ingenieriles, Utilizando Suelo Residual Proveniente de Diorite*; Universidad de Medellín: Medellín, Colombia, 2006.
9. Gómez, C.; Osorio, J. *Análisis del Comportamiento Estático de un Suelo Tipo Granular Adicionado con Cal*; Universidad de Medellín: Medellín, Colombia, 2004.
10. Ortiz, C.; Barreto, J. *Mejoramiento de Suelos con cal Fase III*; Universidad de Medellín: Medellín, Colombia, 2005.
11. INVIAS. *Especificaciones Generales de Construcción de Carreteras*; Instituto Nacional de Vías: Bogotá, Colombia, 2012.
12. Da Rocha, C.G.; Passuello, A.C.; Consoli, N.C.; Samaniego, R.A.Q.; Kanazawa, N.M. Life cycle assessment for soil stabilization dosages: A study for the Paraguayan Chaco. *J. Clean. Prod.* **2016**, *139*, 309–318. [\[CrossRef\]](#)
13. Larrea-Gallegos, G.; Vázquez-Rowe, I.; Gallice, G. Life cycle assessment of the construction of an unpaved road in an undisturbed tropical rainforest area in the vicinity of Manu National Park, Peru. *Int. J. Life Cycle Assess.* **2016**, *22*, 1109–1124. [\[CrossRef\]](#)
14. Kneese, A.V.; Ayres, R.U.; D'Arge, R.C. *Economics and the Environment: A Materials Balance Approach*; RFF Resources for the Future: New York, NY, USA, 2015.
15. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [\[CrossRef\]](#)
16. Fullana-i-Palmer, P.; Puig, R.; Bala, A.; Baquero, G.; Riba, J.; Rauegi, M. From Life Cycle Assessment to Life Cycle Management. *J. Ind. Ecol.* **2011**, *15*, 458–475. [\[CrossRef\]](#)
17. De Larriva, R.A.; Rodríguez, G.C.; López, J.M.C.; Rauegi, M.; I Palmer, P.F. A decision-making LCA for energy refurbishment of buildings: Conditions of comfort. *Energy Build.* **2014**, *70*, 333–342. [\[CrossRef\]](#)
18. Bloom, E.F.; Horstmeier, G.J.; Pakes Ahlman, A.; Edil, T.B.; Whited, G. Assessing the Life Cycle Benefits of Recycled Material in Road Construction. GeoChicago-Conference-Paper-I-94-and-Beltline-LCA. 2017. Available online: <http://rmrc.wisc.edu/wp-content/uploads/2017/05/GeoChicago-Conference-Paper-I-94-and-Beltline-LCA.pdf> (accessed on 30 December 2020).
19. Chiu, C.-T.; Hsu, T.-H.; Yang, W.-F. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resour. Conserv. Recycl.* **2008**, *52*, 545–556. [\[CrossRef\]](#)
20. Chowdhury, R.; Apul, D.; Fry, T. A life cycle based environmental impacts assessment of construction materials used in road construction. *Resour. Conserv. Recycl.* **2010**, *54*, 250–255. [\[CrossRef\]](#)
21. Hung, M.-L.; Ma, H.-W.; Chao, C.-W. Screening the Life Cycle Impact Assessment Methods and Modifying Environmental Impact Model to Determine Environmental Burdens. *J. Environ. Eng. Manag.* **2009**, *19*, 155–164. Available online: http://ser.cienve.org.tw/download/19-3/jeeam19-3_155-164.pdf (accessed on 30 December 2020).
22. Aldaco, R.; Margallo, M.; Fullana-i-Palmer, P.; Bala, A.; Gazulla, C.; Irabien, A.; Aldaco, R. Introducing life cycle thinking to define best available techniques for products: Application to the anchovy canning industry. *J. Clean. Prod.* **2017**, *155*, 139–150. [\[CrossRef\]](#)
23. Lasvaux, S.; Gantner, J.; Wittstock, B.; Bazzana, M.; Schiopu, N.; Saunders, T.; Gazulla, C.; Mundy, J.A.; Sjöström, C.; Fullana-i-Palmer, P.; et al. Achieving consistency in life cycle assessment practice within the European construction sector: The role of the EeBGuide InfoHub. *Int. J. Life Cycle Assess.* **2014**, *19*, 1783–1793. [\[CrossRef\]](#)
24. Benveniste, G.; Gazulla, C.; Fullana-i-Palmer, P.; Celades, I.; Ros, T.; Zaera, V.; Godes, B. Análisis de ciclo de vida y reglas de categoría de producto en la construcción. El caso de las baldosas cerámicas. *Informes de la Construcción* **2011**, *63*, 71–81. [\[CrossRef\]](#)
25. Mroueh, U.-M.; Eskola, P.; Laine-Ylijoki, J. Life-cycle impacts of the use of industrial by-products in road and earth construction. *Waste Manag.* **2001**, *21*, 271–277. [\[CrossRef\]](#)
26. Rajendran, S.; Gambatese, J. Solid Waste Generation in Asphalt and Reinforced Concrete Roadway Life Cycles. *J. Infrastruct. Syst.* **2007**, *13*, 88–96. [\[CrossRef\]](#)
27. Birgisdottir, H.; Bhandar, G.; Hauschild, M.; Christensen, T. Life cycle assessment of disposal of residues from municipal solid waste incineration: Recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. *Waste Manag.* **2007**, *27*, S75–S84. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Celauro, C.; Corriere, F.; Guerrieri, M.; Casto, B.L. Environmentally appraising different pavement and construction scenarios: A comparative analysis for a typical local road. *Transp. Res. Part D Transp. Environ.* **2015**, *34*, 41–51. [\[CrossRef\]](#)
29. Balaguera, A.; Carvajal, G.I.; Albertí, J.; Fullana-i-Palmer, P. Life cycle assessment of road construction alternative materials: A literature review. *Resour. Conserv. Recycl.* **2018**, *132*, 37–48. [\[CrossRef\]](#)
30. Bala, A.; Rauegi, M.; Benveniste, G.; Gazulla, C.; Fullana-i-Palmer, P.; Bala, A. Simplified tools for global warming potential evaluation: When ‘good enough’ is best. *Int. J. Life Cycle Assess.* **2010**, *15*, 489–498. [\[CrossRef\]](#)

31. Navarro, A.; Puig, R.; Fullana-I-Palmer, P. Product vs corporate carbon footprint: Some methodological issues. A case study and review on the wine sector. *Sci. Total Environ.* **2017**, *581–582*, 722–733. [CrossRef]
32. Puig, R.; Fullana-i-Palmer, P.; Baquero, G.; Riba, J.-R.; Bala, A. A Cumulative Energy Demand indicator (CED), life cycle based, for industrial waste management decision making. *Waste Manag.* **2013**, *33*, 2789–2797. [CrossRef]
33. Mackie, P.; Nellthorp, J.; Laird, J. Low Volume Rural Roads. 1 January 2005. pp. 1–9. Available online: <http://documentos.bancomundial.org/curated/es/286811468339867486/Low-volume-rural-roads> (accessed on 30 December 2020).
34. Balaguera, A.; Carvajal, G.I.; Jaramillo, Y.P.A.; Albertí, J.; Fullana-i-Palmer, P. Technical feasibility and life cycle assessment of an industrial waste as stabilizing product for unpaved roads, and influence of packaging. *Sci. Total. Environ.* **2018**, *651*, 1272–1282. [CrossRef]
35. Paez, D. Efectos de la estabilización electroquímica de suelos finos. *Rev. Ing. UPTC* **2005**, *18*, 83–96.
36. Camacho-Tauta, J.; Ortiz, O.J.R.; Mayorga, C. Efecto de la radiación UV en arcillas expansivas tratadas con aceite sulfonado. *Ingeniería y Competitividad* **2011**, *12*, 41–50. [CrossRef]
37. ISO. ISO 14044:2006(E)—Environmental management—Life cycle assessment—Requirements and guidelines. English, 2006. p. 42. Available online: <https://www.iso.org/standard/38498.html> (accessed on 28 January 2021).
38. ISO 14040. Environmental management—Life cycle assessment—Principles and framework. In *Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO: Geneva, Switzerland, 2006. [CrossRef]
39. Baitz, M.; Albrecht, S.; Brauner, E.; Broadbent, C.; Castellan, G.; Conrath, P.; Fava, J.; Finkbeiner, M.; Fischer, M.; I Palmer, P.F.; et al. LCA's theory and practice: Like ebony and ivory living in perfect harmony? *Int. J. Life Cycle Assess.* **2013**, *18*, 5–13. [CrossRef]
40. ISO. ISO 14025—Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. 2006. Available online: <https://www.normativa-iso-une-pdf.com/descarga/pdf/une-en-iso-140252010/> (accessed on 28 January 2021).
41. Barthel, M.; Fava, J.; James, K.; Khan, S. Hotspots Analysis an Overarching Methodological Framework and Guidance for Product and Sector Level Application. 2017. Available online: www.lifecycleinitiative.org (accessed on 30 December 2020).
42. Chomkham, K.; Wolf, M.-A.; Pant, R. International Reference Life Cycle Data System (ILCD) Handbook: Review Schemes for Life Cycle Assessment. In *Towards Life Cycle Sustainability Management*; Springer: Cham, Switzerland, 2011; pp. 107–117. [CrossRef]
43. Delgado-Aguilar, M.; Tarrés, Q.; Pèlach, M.À.; Mutjé, P.; Fullana-i-Palmer, P. Are Cellulose Nanofibers a Solution for a More Circular Economy of Paper Products? *Environ. Sci. Technol.* **2015**, *49*, 12206–12213. [CrossRef]
44. Guinée, J.B. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*; Kluwer Academic Publishers: New York, NY, USA, 2002.
45. BRE. Product Category Rules for Type III Environmental Product Declaration of Construction Products to EN 15804: 2012. 2013. Available online: http://www.bre.co.uk/filelibrary/materials/bre_en_15804_pcr.pn514.pdf (accessed on 30 December 2020).
46. Rashid, A.F.A.; Idris, J.; Sumiani, Y. Environmental Impact Analysis on Residential Building in Malaysia Using Life Cycle Assessment. *Sustainability* **2017**, *9*, 329. [CrossRef]
47. Quintero, A.B.; Cano, D.G.; Peláez, G.C.; Arias, Y.P. Technical and Environmental Assessment of an Alternative Binder for Low Traffic Roads with LCA Methodology. In *Proceedings of the 3rd Pan American Materials Congress*; Springer International Publishing: Cham, Switzerland, 2017.
48. Bueno, C.; Hauschild, M.Z.; Rossignolo, J.; Ometto, A.R.; Crespo-Mendes, N. Sensitivity analysis of the use of Life Cycle Impact Assessment methods: A case study on building materials. *J. Clean. Prod.* **2016**, *112*, 2208–2220. [CrossRef]
49. Huarachi, D.A.R.; Gonçalves, G.; De Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M. Life cycle assessment of traditional and alternative bricks: A review. *Environ. Impact Assess. Rev.* **2020**, *80*, 106335. [CrossRef]
50. Araújo, J.P.C.; Oliveira, J.R.; Da Silva, H.M.R.D. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. *Transp. Res. Part D Transp. Environ.* **2014**, *32*, 97–110. [CrossRef]
51. Santos, J.; Ferreira, A.; Flintsch, G.W. A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *Int. J. Pavement Eng.* **2014**, *16*, 315–336. [CrossRef]
52. Wu, D.; Zhang, F.; Lou, W.; Li, D.; Chen, J. Chemical characterization and toxicity assessment of fine particulate matters emitted from the combustion of petrol and diesel fuels. *Sci. Total Environ.* **2017**, *605–606*, 172–179. [CrossRef]
53. Ingersoll Rand. Ficha Técnica Vibrocompactador. 2015. Available online: <http://maquqam.com/tecnicas/carreteras-3337/ingersoll-rand/sd70d.html> (accessed on 30 December 2020).
54. John Deere. Ficha Técnica Motoniveladora. 2015. Available online: <http://maquqam.com/tecnicas/construccion-6735/john-deere/570b.html> (accessed on 30 December 2020).
55. Ministerio de Ambiente y Desarrollo Sostenible. Estrategia Nacional de Economía Circular 2018–2022. 2018. Available online: <https://id.presidencia.gov.co/Paginas/prensa/2019/190614-Presidente-Duque-Estrategia-Nacional-Economia-Circular-primera-politica-ambiental-de-este-tipo-en-America-Latina.aspx#:~:text=La%20Estrategia%20Nacional%20de%20Econom%C3%ADa%20Circular%20transformar%C3%A1%20las%20cadenas%20de,Am%C3%A9rica%20Latina%20para%20el%20203057> (accessed on 30 December 2020).
56. CEPAL. Agua para el siglo XXI para América del Sur. De la División a la Acción. 2016. Available online: <https://www.cepal.org/samta/noticias/documentosdetrabajo/5/23345/InCo00200.pdf> (accessed on 30 December 2020).
57. Siracusa, V.; Ingrao, C.; Giudice, A.L.; Mbohwa, C.; Rosa, M.D. Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach. *Food Res. Int.* **2014**, *62*, 151–161. [CrossRef]

-
58. Muench, S.T. Roadway Construction Sustainability Impacts. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2151*, 36–45. [[CrossRef](#)]
 59. Johnson, D.; Heltzel, R.; Nix, A.C.; Clark, N.; Darzi, M. Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development. *Appl. Energy* **2017**, *206*, 739–750. [[CrossRef](#)]
 60. Karavalakis, G.; Hajbabaie, M.; Jiang, Y.; Yang, J.; Johnson, K.C.; Cocker, D.R.; Durbin, T.D. Regulated, greenhouse gas, and particulate emissions from lean-burn and stoichiometric natural gas heavy-duty vehicles on different fuel compositions. *Fuel* **2016**, *175*, 146–156. [[CrossRef](#)]