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 Urrao 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

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.

![Location of the roads and cross section.](a) (b)

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).
These regions soils have clay (Urrao) and sandy-clay (La Paz) characteristics. Table 1 characterises the soils under study.

| Type of soil                  | Standard  | Urrao   | La Paz   |
|-------------------------------|-----------|---------|----------|
| Unified Soil Classification   |           |         |          |
| System (USCS)                 | MH 1 SC 2 |         |          |
| AASHTO classification         | INV E 3-122 | A-7-5 | A-6      |
| Natural humidity (%)          | 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/m³)       | INV E-142 | 14.8    | 19.5     |
| Optimal humidity (%)          | 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.

![Cross section](image)

**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/m³) | Quantity of Soil for Stabilisation Urrao (t/m³) | Quantity of Material for La Paz (t/m³) | Quantity of Soil for Stabilisation La Paz (t/m³) |
|---------------------------|--------------------------------------|-----------------------------------------------|--------------------------------------|-----------------------------------------------|
| Fly ash                   | 97.4                                 | 997.6                                         | 155                                  | 1272.8                                        |
| Lime (Fly ash)            | 65                                   |                                               | 51.8                                 | 1272.8                                        |
| Brick dust                | 113                                  |                                               | 162                                  | 1272.8                                        |
| Lime (brick dust)         | 534                                  | 1049.2                                        | 45.6                                 | 1272.8                                        |
| 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), 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 sta-
  bilisation 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/cm$^3$, 94 g/mol (en) from Germany;
  - Propylene glycol; via Propylene oxide (PO)-hydrogenation; single route, at plant; 1.04 g/cm$^3$, 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/cm$^3$ (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/cm$^3$, 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/cm$^3$, 134 g/mol (en);
  - Dipropylene glycol by product propylene glycol via PO hydrogenation; hydration of propylene oxide; single route, at plant; 1.02 g/cm$^3$, 134 g/mol (en) from the U.S.;
- Polycarbonate–acrylonitrile–butadiene–styrene compound (80% PC, 20% ABS); mixing, pelleting 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/cm$^3$, 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 Distance (km) | Urrao Time (h) | La Paz Distance (km) | La Paz 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/m$^3$, 18 g/mol from the U.S.).

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

| Activity           | 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          | 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.

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.

Figure 4. Environmental impacts for each stabiliser applied in Urrao.
Table 9. Environmental impacts for liquid stabilisers at each life cycle stage for the Urrao system.

| Impact Categories | Material Production | Preliminaries Activities | Stabilisation | Total | Material Production | Preliminaries Activities | Stabilisation | Total |
|-------------------|---------------------|--------------------------|---------------|-------|---------------------|--------------------------|---------------|-------|
| ADP elements 4 kg Sb-Equiv. | 0.362 | $7.21 \times 10^{-5}$ | 24,100 | 0.362 | 0.00565 | $6.10 \times 10^{-7}$ | 9.76 $\times 10^{-5}$ | 0.00575 |
| ADP fossil 5 MJ | $3.41 \times 10^{6}$ | 5930 | $7.30 \times 10^{6}$ | 1.07 $\times 10^{7}$ | $1.64 \times 10^{8}$ | 50.2 | 2.92 $\times 10^{6}$ | 1.67 $\times 10^{8}$ |
| 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 $\times 10^{-4}$ | 29.3 | 4910 |
| FAETP 8 kg DCB-Equiv. | 822 | 3.54 | 163,000 | 1.63 $\times 10^{5}$ | $3.69 \times 10^{6}$ | 0.0299 | 65,000 | 3.76 $\times 10^{6}$ |
| GWP 100 years 9 kg CO2-Equiv. | $1.50 \times 10^{5}$ | 53.0 | 78,000 | 2.28 $\times 10^{5}$ | $1.32 \times 10^{7}$ | 0.448 | 31,300 | 1.32 $\times 10^{7}$ |
| HTP 10 kg DCB-Equiv. | 7650 | 44.7 | 459,000 | 4.66 $\times 10^{5}$ | $1.19 \times 10^{7}$ | 0.379 | 1.84 $\times 10^{5}$ | 1.21 $\times 10^{7}$ |
| MAETP 11 kg DCB-Equiv. | $3.63 \times 10^{6}$ | 6720 | $6.16 \times 10^{8}$ | 6.20 $\times 10^{8}$ | $1.40 \times 10^{10}$ | 56.9 | 2.47 $\times 10^{8}$ | 1.42 $\times 10^{10}$ |
| ODP 12 kg R11-Equiv. | $1.35 \times 10^{-5}$ | $2.73 \times 10^{-9}$ | $2.18 \times 10^{-5}$ | $3.53 \times 10^{-5}$ | $4.92 \times 10^{-4}$ | $2.31 \times 10^{-11}$ | 8.72 $\times 10^{-6}$ | 5.01 $\times 10^{-4}$ |
| POCP 13 kg Ethene-Equiv. | 34.6 | 0.0474 | 170 | 204 | 5490 | 4.01 $\times 10^{-4}$ | 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, 9 HTP: Human Toxicity Potential, 10 MAETP: Marine Aquatic Ecotoxicity, 11 ODP: Ozone Layer Depletion Potential, 12 POCP: Photochemical Ozone Creation Potential, 13 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 × 10⁶ | 5.34 × 10⁶ | 15.5 | 19,000 | 9.48 × 10⁶ | 9.50 × 10⁶ |
| 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 × 10⁸ | 4.49 × 10⁸ | 135 | 21,500 | 8.00 × 10⁸ | 8.00 × 10⁸ |
| 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, 9 HTP: Human Toxicity Potential, 10 MAETP: Marine Aquatic Ecotoxicity, 11 ODP: Ozone Layer Depletion Potential, 12 POCP: Photochemical Ozone Creation Potential, 13 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 | \(2.25 \times 10^{-5}\) | \(1.34 \times 10^{-4}\) | 0.542 | 0.0150 | \(6.31 \times 10^{-6}\) | \(2.41 \times 10^{-4}\) | 0.0152 |
| ADP fossil \(5\) MJ | \(5.11 \times 10^{6}\) | 1850 | \(4.04 \times 10^{6}\) | \(9.15 \times 10^{6}\) | \(4.36 \times 10^{8}\) | 518 | \(7.12 \times 10^{6}\) | \(4.43 \times 10^{8}\) |
| 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 | \(9.78 \times 10^{6}\) | 0.309 | 159,000 | \(9.94 \times 10^{6}\) |
| GWP 100 years \(9\) kg CO2-Equiv. | 225,000 | 16.5 | 43,200 | 268,000 | \(3.51 \times 10^{7}\) | 4.63 | 76,200 | \(3.52 \times 10^{7}\) |
| HTP \(10\) kg DCB-Equiv. | 11,500 | 14.0 | 254,000 | 266,000 | \(3.16 \times 10^{7}\) | 3.91 | 448,000 | \(3.20 \times 10^{7}\) |
| MAETP \(11\) kg DCB-Equiv. | \(5.45 \times 10^{6}\) | 2100 | \(3.42 \times 10^{8}\) | \(3.47 \times 10^{8}\) | \(3.73 \times 10^{10}\) | 587 | \(6.02 \times 10^{8}\) | \(3.79 \times 10^{10}\) |
| ODP \(12\) kg R11-Equiv. | \(2.03 \times 10^{-5}\) | \(8.54 \times 10^{-10}\) | \(1.21 \times 10^{-5}\) | \(3.24 \times 10^{-5}\) | 0.0013 | \(2.38 \times 10^{-10}\) | \(2.13 \times 10^{-5}\) | 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. | $6.44 \times 10^{-7}$ | $7.26 \times 10^{-4}$ | $1.49 \times 10^{-4}$ | $8.76 \times 10^{-4}$ | $6.44 \times 10^{-7}$ | $5.32 \times 10^{-4}$ | $1.33 \times 10^{-4}$ | $6.65 \times 10^{-4}$ |
| ADP fossil 5 MJ | $15.5$ | $59,800$ | $4.48 \times 10^{6}$ | $4.54 \times 10^{6}$ | $15.5$ | $43,700$ | $3.98 \times 10^{6}$ | $4.03 \times 10^{6}$ |
| AP 6 kg SO2-Equiv. | $0.000429$ | $2.13$ | $651$ | $653$ | $0.00429$ | $1.56$ | $578$ | $580$ |
| EP 7 kg Phosphate-Equiv. | $9.90 \times 10^{-4}$ | $0.710$ | $45.0$ | $45.7$ | $9.90 \times 10^{-4}$ | $0.520$ | $40.0$ | $40.5$ |
| 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. | $135$ | $67,700$ | $3.78 \times 10^{8}$ | $3.78 \times 10^{8}$ | $135$ | $49,500$ | $3.36 \times 10^{8}$ | $3.36 \times 10^{8}$ |
| ODP 12 kg R11-Equiv. | $5.41 \times 10^{-12}$ | $2.75 \times 10^{-8}$ | $1.34 \times 10^{-5}$ | $1.34 \times 10^{-5}$ | $5.41 \times 10^{-12}$ | $2.02 \times 10^{-8}$ | $1.19 \times 10^{-5}$ | $1.19 \times 10^{-5}$ |
| POCP 13 kg Ethene-Equiv. | $3.79 \times 10^{-4}$ | $0.478$ | $104$ | $105$ | $3.79 \times 10^{-4}$ | $0.349$ | $92.8$ | $93.1$ |
| 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, 9 HTP: Human Toxicity Potential, 10 MAETP: Marine Aquatic Ecotoxicity, 11 ODP: Ozone Layer Depletion Potential, 12 POCP: Photochemical Ozone Creation Potential, 13 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.

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