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New methodology for assessing the environmental efficiency of transport: Application to the valorization of biomass from phytoremediation

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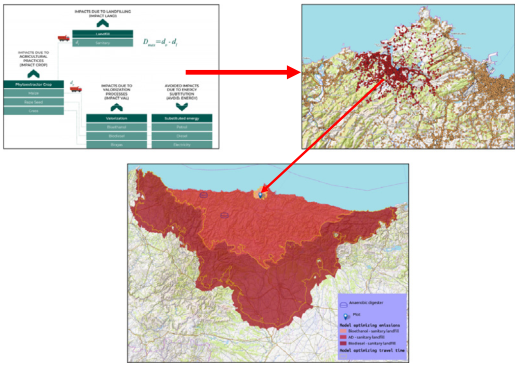
HIGHLIGHTS

- A new methodology is developed to compare the environmental burdens when designing transport routes for materials
- The methodology is applied to facilitate the selection of phytoextractor crops for the remediation of soils contaminated by heavy metals.
- The maximum distances at which the biomass from phytoextraction of heavy metals can be valorized are defined for a real case in Spain.

GRAPHICAL ABSTRACT



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ABSTRACT

It is known that any environmental remediation process must be approached as a system and that the transport of materials is key to determining its sustainability. The aim of this work is to establish how far it was possible to transport plant material from a phytoextraction process in such a way that the environmental gain of the remediation process is not compromised. In the absence of a general methodology to answer our question, a new methodology based on spatial analysis and the life cycle perspective is proposed to calculate, under different hypotheses and depending on the type of remediation, the maximum distance that a lorry can travel, taking as a limit the distance in which the environmental benefit would be equal to 0.

The results obtained show that there are significant differences depending on the type of optimisation proposed for the transport route as well as the type of valorization of the plant material to be carried out. Thus, in the case of bioethanol, biomass could be transported up to 25 km. For biodiesel, it can be shipped over distances between 255 and 415 km and finally, if it is valorized by anaerobic co-digestion, biodigesters up to 267 km away could be sought for the most favourable case.

1. Introduction

Large patches of contaminated soil with varying amounts of heavy metals are present throughout the world, which mainly come from industrial and agricultural activities. Unlike biodegradable organic substances, heavy metals are highly persistent and accumulate in the soil posing risks to the environment and human health when their concentration is above certain levels (Moreno-Jiménez et al., 2011).

To proceed with the decontamination of these soils, a technique known as phytoextraction has emerged, which is a variant of phytoremediation that takes advantage of the capacity of certain plants to absorb pollutants present in the soil when they are in ionic and available form. Phytoextractor plants use transmembrane transporters located in the root cells that are able to insert them into the cytosol and then translocate them to the aerial parts

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of the plant (Chibuike and Obiora, 2014; Socha and Guerinot, 2014). Therefore, the concentration of metals in the soil decreases as the biomass is harvested (Ali et al., 2013). The plant species employed for phytoextraction usually fall into the category of hyperaccumulators, which are species capable of accumulating unusual amounts of metals, or energy crops as the absolute accumulation of metals in their tissues is proportional to the biomass produced. The latter are the most used, as they potentially allow economic returns to be obtained (Vangronsveld et al., 2009; Meers et al., 2010). This technique has notable advantages over traditional technologies originated in civil engineering given that its environmental burden and economic costs are notably lower (Glass, 2000; Masciandaro et al., 2014), and it does not destroy the edaphic properties, which allows the subsequent use of the soil for food production (Vangronsveld and Cunningham, 1998).

However, phytoextraction is not a technique without disadvantages, especially due to the long periods of time required to achieve the recovery of a contaminated soil (Dickinson et al., 2009; Fumagalli et al., 2014). Moreover, although phytoremediation is generally perceived as a sustainable technology, like all agricultural activities it can cause numerous environmental impacts due for instance to harvesting activities (von Blottnitz and Curran, 2007), the application of fertilizers and pesticides and their associated direct emissions (Suer and Andersson-Sköld, 2011). The management of the metal-rich biomass generated is of special importance, since once harvested it has to be removed and managed in some way to prevent the metals from being incorporated back into the soil (Quarshie et al., 2021). Therefore, the biomass is required to be either stored off-site or processed through some type of technology (Yang et al., 2019). To this end, the most common options are landfill disposal, composting, or energy valorization (Kovacs and Szemmelveisz, 2017). However, none of the existing management options are exempt from technical problems in their application, and can lead to significant environmental burdens due to the release of pollutants back into the environment in different forms such as metal-rich leachates during composting processes or particle emissions to the atmosphere and soil contamination caused by the disposal of solid burning residuals from incineration or combustion (Sas-Nowosielska et al., 2004; Kovacs et al., 2013; Dilks et al., 2016; Chen et al., 2018). On the other hand, the most likely alternative, landfilling without treatment, would not be desirable either, since it also could cause environmental problems as there is the risk of just shifting the contaminant from one place to another, and it is banned in several contexts (Šyc et al., 2012; Kovacs et al., 2013).

It is clear that the management of biomass from phytoextraction is a very important factor, often unresolved (Shah and Daverey, 2020). The valorization of the biomass is the preferred option both from an economic and an environmental point of view. On the one hand, it allows obtaining some type of financial return (Gerhardt et al., 2017). On the other hand, the valorization of the biomass might bring environmental benefits through the production of usable energy in a cleaner way. Moreover, in (Vigil et al., 2015) it was established through a Life Cycle Assessment that the environmental sustainability of phytoremediation is questioned if the biomass is not valorised somehow. Similarly, in (Vocciante et al., 2019) the same phytoremediation scenario was formulated with two biomass management options: biomass valorization and landfilling; finding that the first option had a lower carbon footprint.

Over the past decades, sustainability management and evaluation methodologies have evolved towards a life cycle perspective, where instead of only analysing the environmental performance of the process under study, all the impacts both upstream and downstream are considered. Waste management, including agricultural residue and biomass are frequently supported by Life Cycle Assessment (LCA) methodology. For instance, (Dastjerdi et al., 2021) provides an extensive examination of 101 LCA studies between the years 1981 to 2019 on the energy valuation of waste. More recently, (Mulya et al., 2022) reviews 240 papers from 2009 to 2020 focusing on the different LCA methodologies for Solid Waste Management and 77.1 % of the studies included in this review consider transportation somehow.

In this way, it is possible to have a comprehensive perspective and a guarantee that the improvements that can be achieved do not induce more significant impacts in other steps of the value chain. Therefore, the consideration of the environmental component in phytoextraction projects involves adopting a holistic perspective that considers not only the benefits of decontamination and the impacts of cultivation, but also takes into account all the downstream implications after planting or sowing. Thus, we consider that it is more correct to replace the common-used concept of phytoextractor crop, with the new concept of *phytoextractor system*, understanding this as the set of all the activities necessary for the phytoremediation of the soil throughout the entire life cycle of the intervention, from the cultivation of the phytoremediator plant to the final management of the produced biomass. Our proposal defines this *phytoextractor system* as a 3-tuple *cultivation-transport-management of biomass*, which allows a more informed decision-making from the conception phases of this type of projects, since the selection of the plant will restrict the subsequent management of its biomass and vice versa.

In addition, it is highly unlikely that the construction of specific valorization facilities for the phytoremediation of a particular plot would be economically feasible, except in the case of the remediation of very vast extensions included in a regional scale planning with a long-term perspective. Therefore, the selection of a phytoextraction technology for the decontamination of a specific plot must necessarily begin by studying the recovery/management possibilities that its biomass has in its geographical area. This approach has already been used for the Rejuvenate decision support tool (Andersson-Sköld et al., 2014) that looks for a market outlet in the site's vicinity before selecting the right energy crop for a marginal land. However, it must be considered the fact that the biomass transportation will also entail extra environmental burdens directly proportional to the distance to travel.

Consequently, the transport of biomass is an important issue when the sustainability of phytoextraction projects is assessed as its environmental burden and economic costs could exceed the benefits obtained. To the best of the authors´ knowledge, the only published study that specifically addresses this topic is (Voets et al., 2013), that intended to find the optimum location for a new power plant dedicated to valorizing willow biomass grown on contaminated land. However, as previously stated, this approach represents a very limited amount of the possible cases. (Abbasi et al., 2020) studied the environmental burden of production and transport of Paulownia cultivation in Iran using a hybrid Geographical Information System (GIS) and mathematical model. Also, (Hiloidhari et al., 2017) included a review of several research in the interrelated methods of GIS and LCA for optimal energy power plant locations and (Roni et al., 2017) proposed a model that optimizes the CO_2 emissions due to transportation along the whole biofuel supply chain. Other recent studies that optimize the location of biomass and waste management facilities can be found in (Hiloidhari et al., 2017; Laasasenaho et al., 2019; Jayarathna et al., 2022). Additionally, other reported studies reinforce the importance of biomass transportation when the sustainability of phytoextraction projects is assessed. (Manouchehrinejad et al., 2020) calculated the Global Warming Potential (GWP) of Napier grass grown on marginal land and valorized through the Combined-Heat-Power. It was found that the share of transport in the overall GWP was of 7 % when the biomass was transported to a facility 50 km away and up to 30 % when the biomass was sent to a facility located 150 km away. Also, the sustainability of a phytoextraction project was compromised when the biomass had to be transported distances over 200–300 km according to (Vigil et al., 2015). (Vocciante et al., 2019) reported that when the biomass is landfilled, transport contributed to the 25 % of the overall GWP. The literature review clearly shows that biomass transportation from phytoextraction remains poorly addressed by the academic domain. Given the influence implied by the distances between the contaminated plots and the centres of use or disposal, it is evident the need to deepen the implications of transport to guarantee the sustainability of the phytoremediation projects.

In a wider sense, the main objective of this research is to explore the implications that transport has over this type of projects. More specifically, we will establish the maximum distances to which the phytoextraction-originated biomass can be sent for three phytoextraction representative cases: bioethanol, anaerobic co-digestion and biodiesel**,** in order to guarantee that the environmental burdens of its transport do not exceed the benefits of the intervention. The accomplishment of the study's goals will allow to establish the maximum distance the biomass can be sent to for valorization and will serve to a better selection of the phytoextractor crop assuming the need for valorization in advance.

2. Materials & methods

To establish maximum distances over which biomass from phytoextraction can be sent, a life cycle perspective will be adopted considering all the stages of three phytoextractor systems, although the standard ISO 14040 (ISO/IEC ISO 14040:2006, 2006) is not formally followed. The systems are representative of the main types of phytoextractor crops and the main biomass valorization pathways are proposed.

- Maize cultivation (*Zea mais*), which will serve as a raw material for the production of bioethanol.
- Rapeseed cultivation (*Brassica napus* var. *oleifera*), which will be used for the production of biodiesel
- Grass (generic), which will be valorized as biogas through anaerobic co-digestion (AD)

Since it is necessary to remove the biomass generated from the plot after phytoextraction, it is assumed that the biomass is either valorized~~,~~ or sent to the nearest viable landfill. Therefore, landfilling to a so-called *sanitary landfill*~~,~~ is taken as a reference for comparison with the environmental characteristics of a urban waste landfill~~,~~ since the impacts derived from its disposal would be produced if is not valorized. The denomination of sanitary landfill corresponds to the used by the Ecoinvent Life Cycle Inventory (LCI) database (Doka, 2003).

The environmental impact corresponding to the valorization of each phytoextraction route is calculated. Biomass energy conversion produces sustainable energy in forms of bioethanol, biodiesel and biogas and the impact of the equivalent amounts of petrol, diesel and natural gas that was avoided is taken into account. Therefore, an environmental gain could be achieved if the following expression has a positive sign:

$$\begin{aligned}&\text{Environmental balance} =\\&(\text{Impact Avoided Energy} + \text{Impact Landfilling}) -\\&(\text{Impact Valorization } Activities + \text{ Impact } Crop\ Activities)\end{aligned}$$

The methodological approach is explained graphically in Fig. 1**.**

Finally, the environmental impact of transporting biomass to the valorization centre is assessed and the extent to which these impacts offset the benefit from the valorization is calculated, considering this as the maximum distance at which it is environmentally feasible to send phytoextraction biomass. This distance is understood to be the difference between the distance contaminated plot- valorization center and contaminated plot-nearest viable landfill according to the expression:

$$D_{max} = d_v - d_l$$

where

- D_{max} is the maximum environmentally viable distance
- d_v - Distance plot-center of valorization
- d_l - Distance plot-nearest viable landfill

2.1. Environmental impacts modelling

The modelling of the environmental effects of both the cultivation and harvesting of the plants, as well as the energy conversion and disposal to landfill is supported by the Ecoinvent v2.2 database (DB). This DB is used exclusively to guarantee consistency and ensure that all processes are comparable with each other since they have been modelled based on the same assumptions. Ecoinvent is the most used and accepted DB by the scientific community. This database has already been used in several similar studies (Perimenis et al., 2011; Suer and Andersson-Sköld, 2011; Yue et al., 2014; Vigil et al., 2015).

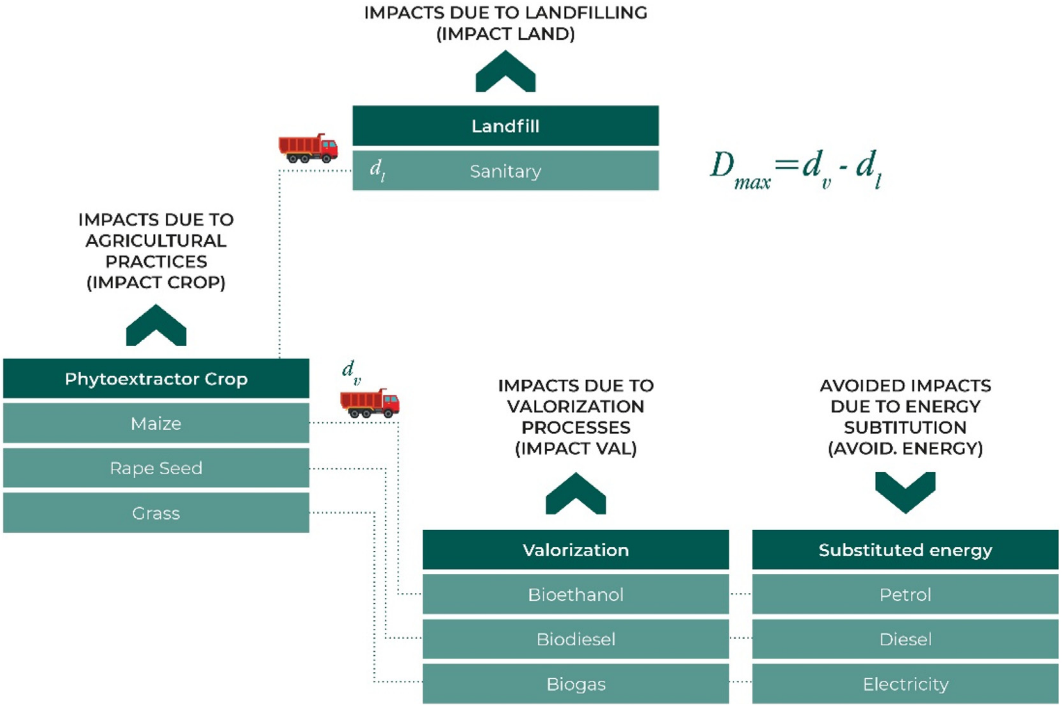

Fig. 1. Graphical representation of the methodological approach.

The outcome desired for this research is to estimate the environmental impact expressed in terms of Global Warming Potential (GWP) over a period of 100 years. This indicator has been chosen as it is usually considered a key concern for the environmental assessment of road transportation studies joint with the cumulative energy demand (CED) (Liljenström et al., 2021; Ternel et al., 2021; Xiong et al., 2021). For that purpose, the ReCiPe midpoint (H – Hierarchy perspective) methodology was chosen as it is widely used and updated (Huijbregts et al., 2017).

2.2. Description of the assessed phytoextraction systems

Three representative scenarios of the main phytoextractor systems are proposed.

Scenario 1: Corn cultivation-Transportation-Valorization as bioethanol / Landfill disposal. During the growth of corn plants, CO_2 is abated from the atmosphere. Once the biomass is harvested, it can be sent to a nearby landfill. When the organic waste is landfilled, it is usually covered with soil that leads to biological degradation in both aerobic and anaerobic conditions producing CO_2 and CH_4 respectively. In this case, it is considered that the generated CO_2 will reach sooner or later the atmosphere and that the generated CH_4 will be burnt in open flare before its emission, discharging a similar amount of the abated CO_2 back to the atmosphere, so the net carbon footprint is considered zero. Flaring is the most usual alternative for landfill gas treatment when no other energy recovery technologies are implemented (Sauve and van Acker, 2020). Alternatively, the biomass can be sent to a facility for its recovery as bioethanol, which will later be burned in combustion engine vehicles, returning the captured CO_2 to the atmosphere. The extraction and processing of an equivalent amount of gasoline would be avoided (system expansion).

Scenario 2: Rapeseed cultivation-Transportation-Valorization as biodiesel / Landfill disposal. Rapeseed is grown. After its harvest, it is either sent to a landfill or to a valorization plant for the production of biodiesel. Said biofuel is burned in combustion engine vehicles, returning the captured CO_2 to the atmosphere and the impacts of the production of an equivalent amount of conventional diesel are avoided.

Scenario 3: Grass cultivation-Valorization by anaerobic co-digestion / Landfill disposal. Grass (generic sp.) is grown. After its harvest, it is sent to a landfill or to an anaerobic digester where biogas will be produced. This biogas will be burned in an adjacent small (160 kW) heat and power co-generation unit that generates heat and electricity. The impacts of producing the same amount of electricity considering the European energy mix are avoided. The process also generates digestate as a by-product that replaces the manufacture of a nitrogen equivalent amount of mineral fertilizer. Its application in the soil also implies that a part of the CO_2 captured during plant growth is incorporated in the form of mineral carbon into the soil, so not all carbon is returned to the atmosphere and is subtracted from the balance.

2.3. Functional unit

Due to the differences in biomass yield per hectare of the 3 raised crops, a truck trip at 100 % capacity is taken as a functional unit in order to establish a comparable framework for all crops and uses, regardless of the area remediated to achieve said production. Likewise, the return of the empty truck to the point of departure is considered. The amount of both corn and rapeseed to be transported is 15.75 t, while only 14 t are moved for grass due to its lower density.

2.4. Exemplary case

The three representative phytoextractor systems will be modelled as applied at a real slightly contaminated soil with Pb in its top layer (153.33 mg / kg DM) located next to an industrial estate in the north of Spain, which was used in 2010 for a phytoremediation pilot experience. Its geographical location is shown in Fig. 2. Further details of the plot can be referred in (Vigil et al., 2015).

The plot has a sanitary landfill owned by the regional authority located 16.7 km away, where the biomass could be landfilled.

In all cases, it is considered that the biomass is going to be transported to the recovery centre or to the landfill by a 32-40 t truck manufactured to comply with the EURO IV emission regulations, reflecting the most likely conditions for transportation of this harvested biomass.

Transportation modelling is based on the Ecoinvent process *Transport, lorry > 32 t, EURO4*. This process considers the impacts derived from the manufacture, use, maintenance and disposal of the vehicle and the wear and tear of the road. Afterwards, it was modified to exclude the generic average greenhouse gas (GHG) emissions and truck's diesel consumption. GHG emissions and diesel consumption are modelled instead for each road section more accurately by using the EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook (EMEP/EEA air pollutant emission inventory guidebookEMEP/EEA air pollutant emission inventory guidebook — European Environment Agency, n.d.), a Tier 3 level methodology for the calculation of exhaust emissions. It covers hot and cold-start exhaust emissions from passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles. It is based on vehicle statistical calculations and provides for each type of vehicle

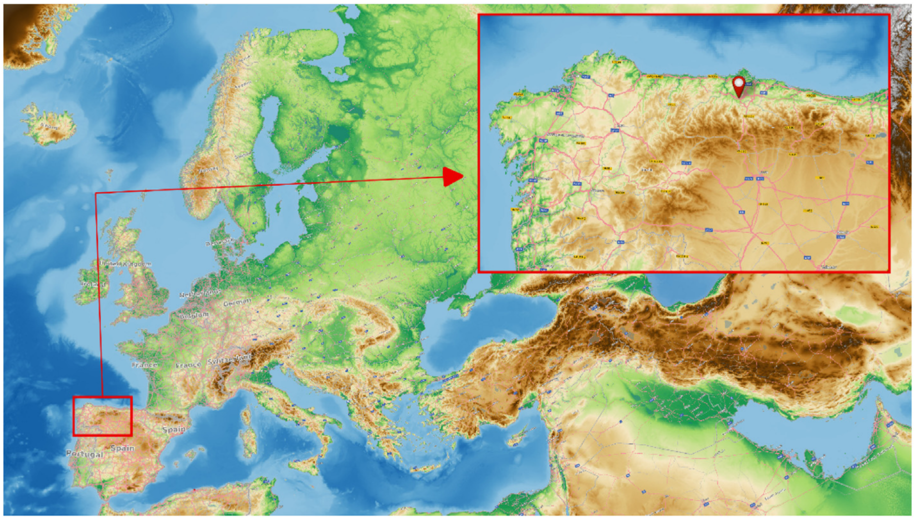

Fig. 2. Geographical location of the case study.

consumption results per km based on speed, slope, load and type of road (Highway, Rural or Urban).

The model was implemented in an object-relational database management system (ORDBMS) PostgreSQL v12.6 equipped with the Postgis spatial extension v3.1.2 (Group, 2020) and the extension for route calculation pgRouting v3.1 (Projects, 2020). The Postgis spatial extension allows the storage of GIS objects in the database, as well as providing them with their analysis and processing functions. pgRouting adds to Postgis and PostgreSQL optimal routes and network analysis functions and algorithms such as Dijikstra, Shooting A * and Shooting * (Zhang and He, 2012), and is capable of handling large volumes of data more efficiently than other database systems of graph data (Miler et al., 2014).

Data and cartography of the Spanish road network were obtained through Openstreetmap (Foundation, 2020). This cartography was processed to eliminate those road sections that were topologically invalid or formed isolated networks. To obtain the slopes of each section, the nodes of the network were crossed with the heights obtained from the Shuttle Radar Topography Mission 1-arc sec Global (Rodríguez et al., 2006) that provides height data with a resolution of approximately 30 m.

The model traverses all possible routes through the road network starting from the contaminated plots and stops when the surplus of GHG emissions to each phytoextractor system is reached. In order to avoid illogical or impossible itineraries, routes were optimised through the Dijkstra algorithm (Dijkstra, 1959) following two criteria: a) Optimising GHG emissions; b) Optimising travel time.

3. Results

Fig. 3 shows the total length in km of the road sections considered in the model, characterising each road in terms of slope and road type (rural, urban or highway).

As it can be seen in Fig. 3, most of the sections are on rural roads and the gradients are mostly flat. The length of sections between 0 and ± 6 % are almost equivalent since the return trips mostly use the same roads.

The results of the environmental models, excluding the transport to the valorization centres, regarding the near sanitary landfill are shown in Table 1.

In the case biomass is used to produce biodiesel in a facility located on the plot itself, 433 kg CO_2-eq would be saved. Therefore, if it were decided to use another facility further away, it would have to be at a distance where the associated emissions would not exceed that amount in order to ensure the carbon neutrality of the remediation. The valorization as bioethanol barely compensates environmentally, as only saves 28 kg of CO_2-eq. Finally, it is noted that if valorization through anaerobic co-digestion for electricity production is considered, installations could be sought within a radius whose transport emissions would not exceed 304 kg CO_2-eq.

Once the maximum emissions that can be associated with the transport of biomass are known, all possible routes from the plot are run using the emissions model described in Section 2.4 until the maximum acceptable emissions shown in the Table 1 are reached, whose maximum distance will depend on the type of road, the slope and the speed.

Tables 2 and 3 show the maximum distances where biomass can be sent to for valorization, named as "*break-even points*". Results are also shown in Fig. 4 to facilitate interpretation. Fig. 4 is a diagram named boxplot that represents all points in the simulation to which it is possible to transport biomass without incurring higher greenhouse emissions than those saved through recovery. The side limits of each box show the interquartile range-first (Q1) and third quartile (Q3)-and the inner line the median of the data set. The whiskers, or lines extending from the box, extend from Q1 and −/+ 1.5*interquartile range.

As it can be seen, when biomass is to be valorized as biodiesel, the maximum ranges are between 253 and 415 km with averages of 343 km (opt. emissions) and 334 km (opt. time); through anaerobic co-digestion between 144 and 267 km with averages of 219 km (opt. emissions) and

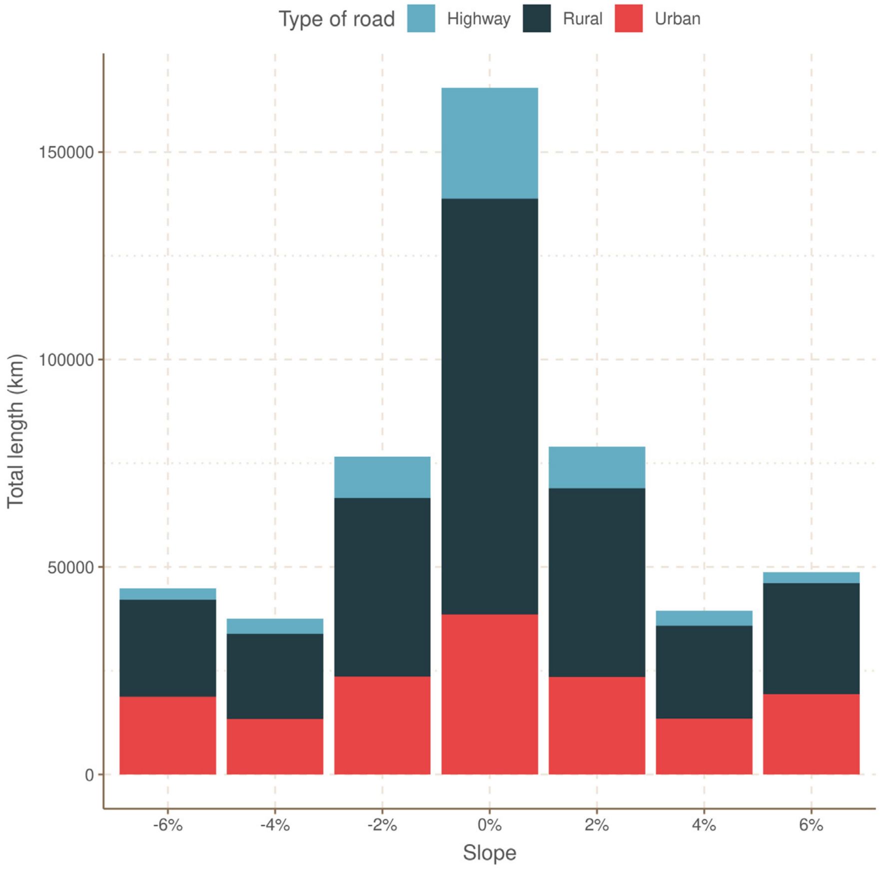

Fig. 3. Distribution of road length according to road type and slope group.

Table 1
Results of environmental models excluding transport to valorisation centres in kg CO_2-eq (ReCiPe H/H).

	Biodiesel	Bioethanol	Anaerobic co-digestion
Kg CO_2-eq savings due to valorization	213.144	−166.734	105.120
Kg CO_2-eq emissions due to sanitary landfill disposal	192.528	192.528	171.136
Kg CO_2-eq emissions due to transport to sanitary landfill (opt. emissions)	27.975	27.975	27.975
Kg CO_2-eq emissions due to transport to sanitary landfill (opt. Travel time)	28.227	28.227	28.227
Kg CO_2-eq surplus when biomass is sent to sanitary landfill (opt. time)	433.899	54.021	304.483
Kg CO_2-eq surplus when biomass is sent to sanitary landfill (opt. emissions)	433.647	53.769	304.231

210 km (opt. time). Also, in this case biomass could be transported to be valorized as bioethanol at a distance up to between 0.1 and 28 km with averages of 11 km optimising the routes in terms of both emissions and time.

Finally, the routes obtained were plotted to show on the ground the possible locations up to which the search for valorization facilities could be considered (Fig. 5). The map shows semi-concentric shapes representing the limit to where it is environmentally feasible to send biomass for a specific valorisation. The yellow lines show the limits obtained when travel time is optimised, while the coloured lines show the limits when emissions are optimised. The narrower shade (in pale cream) refers to the locations up to which it is environmentally feasible to pursue a bioethanol production facility. At the opposite extreme, the dark maroon colour shows the plot boundary to where biodiesel production facilities could be pursued. The large differences in distances for the same system are mainly explained by the regional orography. When following the coastline, the distances from the plot to the east are similar to those to the west as it is more or less flat. However, when the routes go inland there are large variations due to the presence of mountain formations.

For the exemplary case, in Fig. 5 it can be seen that within the eligible areas there is no plant for valorisation as bioethanol or biodiesel. However, two feasible biodigesters do fall within it, one 65 km away in a village called Tineo and another one 79 km away in another one named Navia.

Therefore, if the GWP is used as the indicator to measure the environmental sustainability of the phytoremediation project, it can be said that the only valid option would be the use of an herbaceous plant with phytoextractive capacity for the metal of interest, in this case Pb, thus limiting the range of candidate species to be used.

4. Discussion

This research proposes a methodology that facilitates the decision-making process for the design of heavy metal phytoextraction projects, as it ensures the carbon neutrality of the proposal from the beginning of the project design, making it a key aspect of this kind of projects.

As highlighted by (Aalto et al., 2019) the computational power and the integration of different methodologies for both environmental and spatial analysis constitute a present and future tool for the search of both location and transport solutions for plant material. Our work would be integrated in those that combine LCA/Carbon footprint and network analysis with GIS, an emerging area of work for environmentally and economically sustainable management in bioenergy planning (Hiloidhari et al., 2017). A significant number of these works have focused on the search for optimal locations (Sánchez-García et al., 2017; Santibanez-Aguilar et al., 2018), on the elaboration of networks or supply chains (Kesharwani et al., 2018) or on the impact of alternative transport fuels (Ashtineh and Pishvaee, 2019). In parallel, the existing literature also deals with production capacity and its sustainable use (Singlitico et al., 2018), emissions from the transport of plant material (Jäppinen et al., 2012, Jäppinen et al., 2014) and how to optimize the spatial distribution of production and consumption or processing sites (Zhang et al., 2016). All the aforementioned works have been developed and validated in specific regions or countries and it is their orographic characteristics, transport infrastructures and location of production and processing areas that determine the results obtained.

Our work provides a new methodology to establish the real maximum distance that plant material can be transported to be valorized in a carbon neutral way under real conditions, in line with the same concept of accessibility present in (Bertolini et al., 2005). Our results show the remarkable differences in distance to be travelled between the different ways of plant material valorisation under equal transport conditions, which is novel in relation to the scientific literature that usually focuses the analysis on the different existing transport alternatives in case studies (Jäppinen et al., 2012, Jäppinen et al., 2014; Santibanez-Aguilar et al., 2018). We consider that the replicability of our methodology will allow us to carry out the same simulation in other regional and national scenarios by simply changing the conditions of the transport infrastructure and/or the consumption conditions of the chosen means of transport. In addition, this methodology can be extended to include other impact indicators commonly used in LCA, such as cumulative energy demand, acidification potential and eutrophication potential, to consider environmental sustainability from a broader perspective than just climate change, a limitation of the current approach.

Moreover, a recent reference validates our results by trying to solve different problems in similar contexts. (Venanzi et al., 2018) also uses the break-even point concept for the design of Agri-food waste management logistics chains through anaerobic co-digestion, finding distances between 131.5 and 286.1 km, a result very similar to ours (between 144.2 and 267.1 km for grass valorization through Anaerobic co-digestion).

Finally, the distances obtained between the same origin and destination nodes were compared when routes are optimised by minimising GHG emissions against the ones obtained when the fastest route is sought. As expected, there is a certain difference between both optimisations so when optimising emissions at the expense of time, a slightly greater distance can be travelled. Fig. 6 shows the difference between the emissions when optimising travel time and when optimising GHG emissions, corroborating the positive difference when using the fastest route. In order to test whether these differences are statistically significant, we applied the *Paired t-test* (testing the difference of emissions by type of optimization (mean of the differences = 8.89). The results show that the effect is positive, statistically significant, and large (difference = 8.89, 95 % CI [8.92, 8.86], t(167170) = 622.43, $p < .001$; Cohen's d = 1.52, 95 % CI [1.64, 1.52]).

Although statistically the difference is significant according to Cohen's (Cohen, 1988) criterion, it is important to determine quantitatively whether in practical terms it is worth optimising routes by emissions at the expense of time, which a priori implies higher costs for logistics operators as they require the truck and driver to work longer for the same load.

Table 2
Maximum environmentally viable distances in km "break-even points" (opt. travel time).

	Mean (km)	SD	Min (km)	Median (km)	Max (km)
Biodiesel - sanitary landfill	342.9	24.2	270.5	346.0	397.4
AD - sanitary landfill	219.2	18.9	158.9	219.0	267.1
Bioethanol - sanitary landfill	10.8	5.9	0.1	9.6	27.8

Table 3
Maximum environmentally viable distances in km "break-even points" (opt. emissions).

	Mean (km)	SD	Min (km)	Median (km)	Max (km)
Biodiesel - sanitary landfill	333.9	28.4	253.1	337.1	415.4
AD - sanitary landfill	209.6	18.5	144.2	210.6	257.2
Bioethanol - sanitary landfill	10.8	5.6	0.1	9.9	25.0

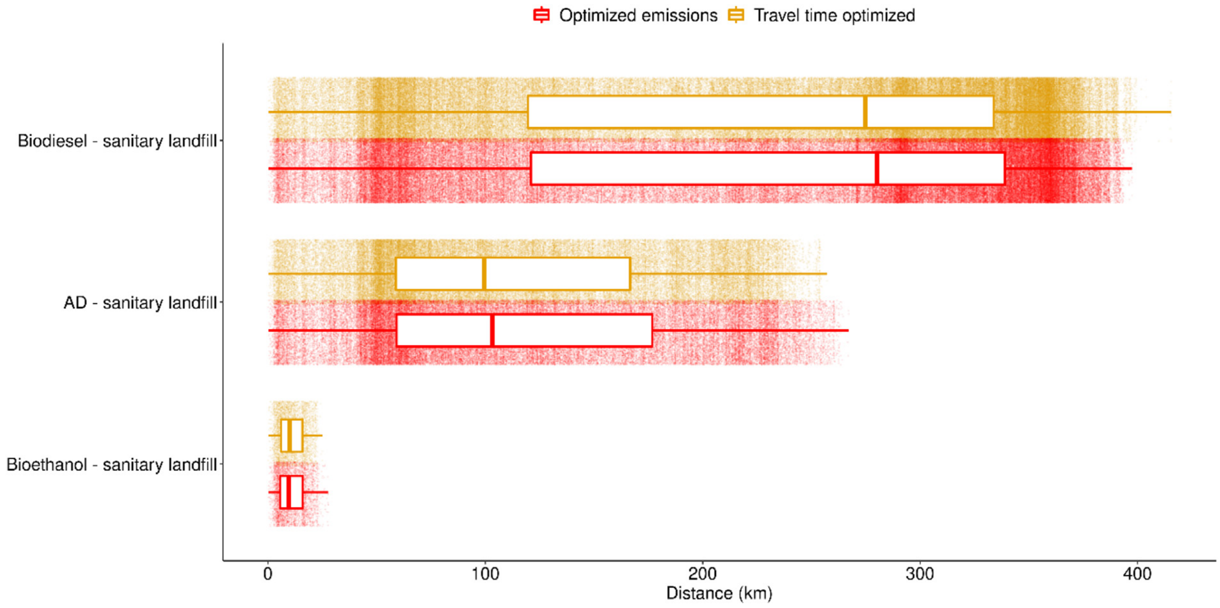

Fig. 4. Break-even data points representation.

For this purpose, a 2D histogram with hexagonal cells was plotted (Fig. 7) which, similarly to a heatmap, paints each cell in a different colour depending on how many points fall into it. The X-axis shows the linear distance to the origin and the Y-axis shows the difference in length travelled in km for all trips between the same two origin and destination nodes with both optimisations.

Fig. 7 shows that for the shortest routes there are no major differences between the two types of optimisations. When we move away from the origin the variability raises, due to the increase in the number of alternative routes available to reach the same point. This fact starts to intensify from distances about 40 km. Therefore, in practical terms prioritising lower emission routes over faster ones would not be justified for shorter distances if the latter is more expensive. As the distance to be travelled increases, it might be appropriate to study in more detail the type of optimisation to be applied to routing design due to the accumulation of the small differentiating effect. At around 110 km from the origin, a peak of difference is generated corresponding to the previously mentioned mountainous areas. It is important to note that these conclusions are only applicable in the context under study and for territories with similar orography and predominant road types.

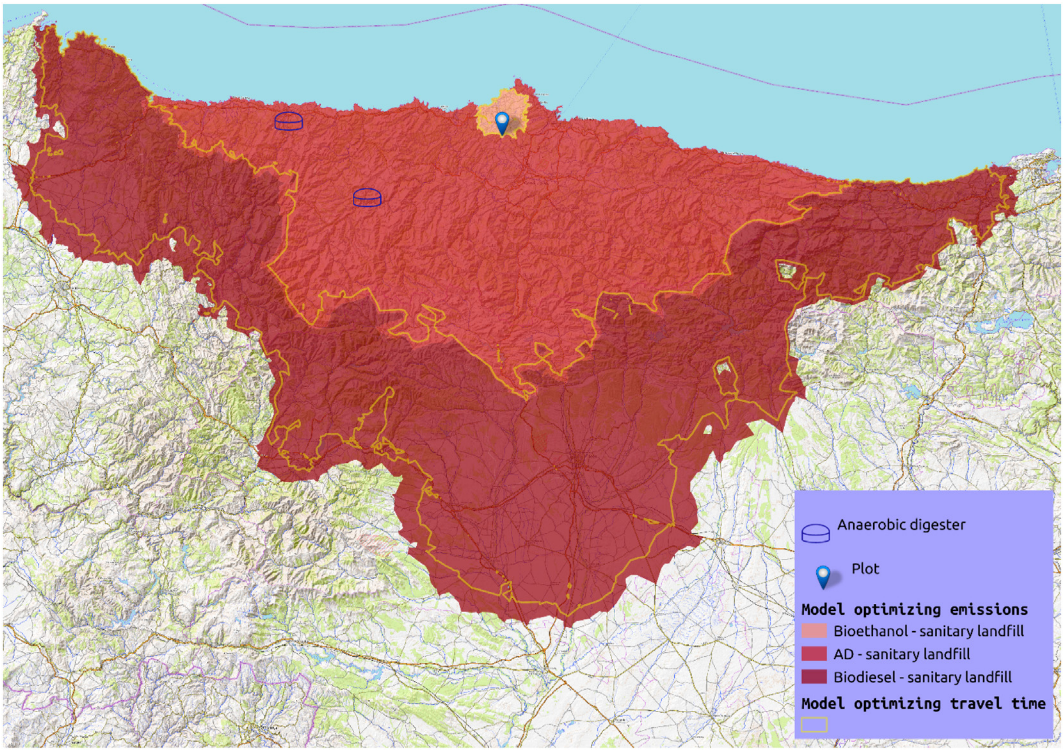

Fig. 5. Geospatial representation of environmentally viable boundaries for phytoextraction biomass management.

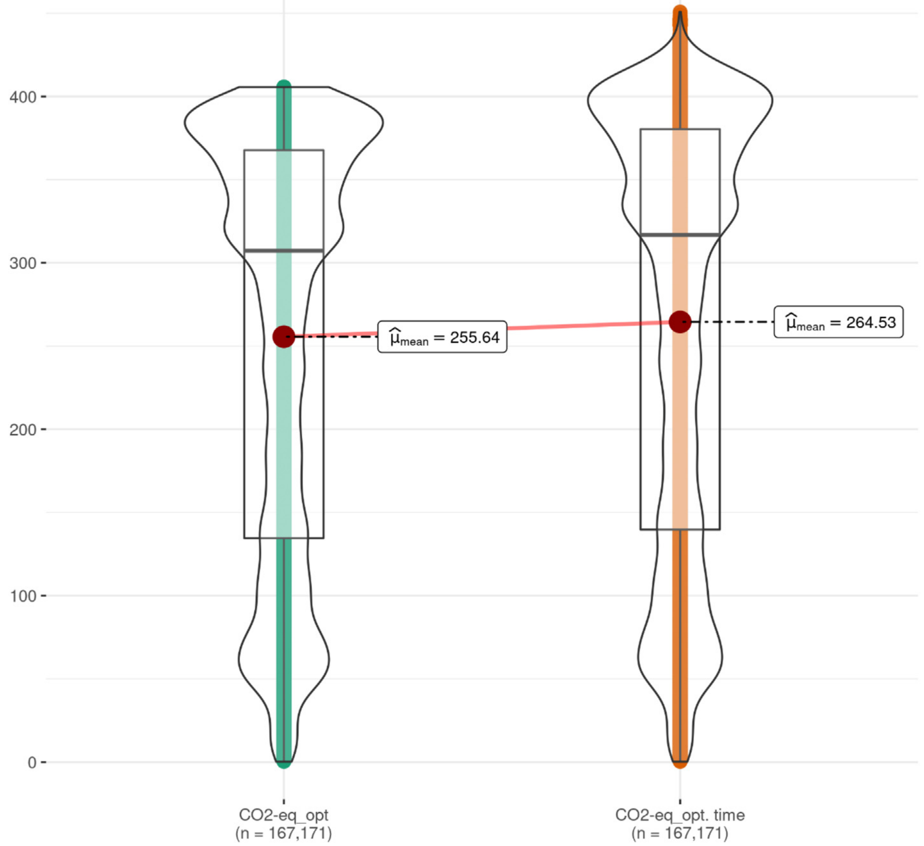

Fig. 6. Comparison of route emissions according to route optimization model.

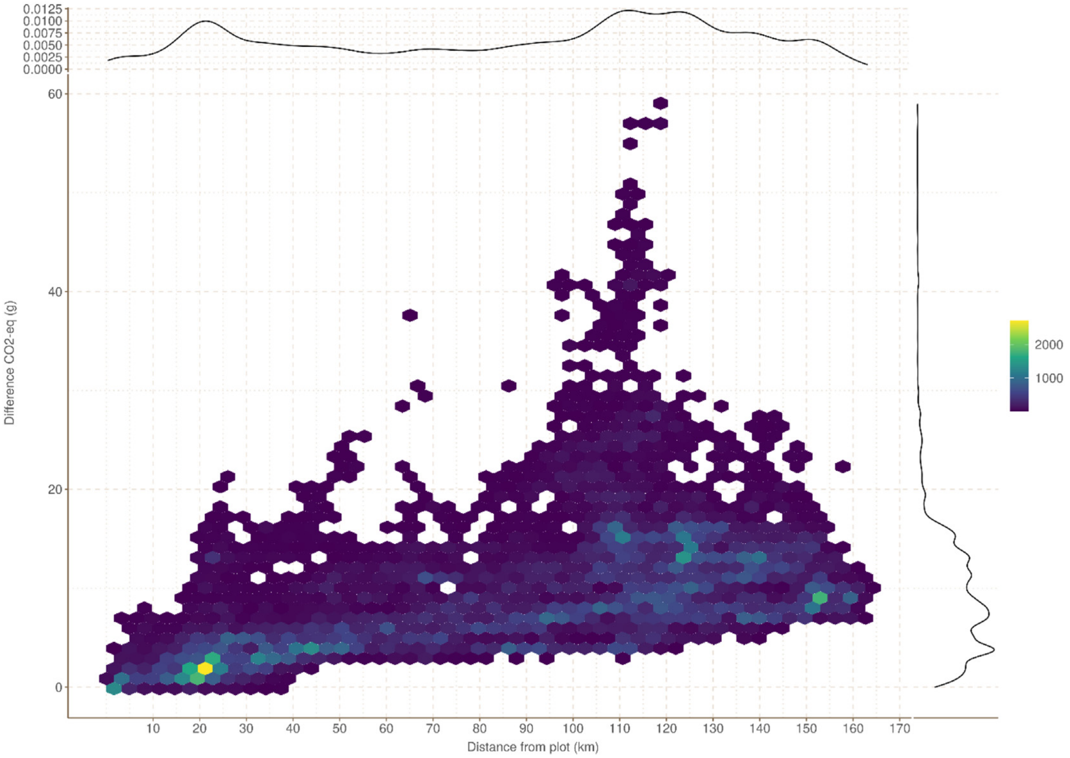

Fig. 7. Hexagonal heatmap illustrating the relationship between distance from plot and difference in CO2 eq. emissions for time optimisation against emissions optimisation.

5. Conclusions

This study has addressed the importance of transport for the design of phytoextraction projects, given that the sustainability of the intervention requires a rigorous approach to the a posteriori management of metal-rich biomass, so that the choice of the species to be used depends both on the metals to be extracted and on the existing possibilities for their valorization.

This research establishes through a case study in northern Spain up to what distance it is environmentally viable to send biomass for 3 representative systems of valorization: bioethanol, biodiesel and anaerobic co-digestion. The results are obtained through a Carbon Footprint and GIS-based model that analyses the GHG emissions for all possible routes starting from the remediation plot. The results show that the break-even points for valorisation as biodiesel are between 226 and 343 km and by anaerobic co-digestion between 19 and 210 km. On the other hand, valorization as bioethanol is only feasible when the recovery plant is no further away than 28 km.

Although these results have been obtained for a specific case, the routes follow a highly varied orography, so the ranges obtained using our methodology represent a good starting point for other situations. This methodology can be applied to different geographical contexts and can even be extended to other valorization techniques such as pyrolysis and incineration, and even to other types of bioremediations, such as the use of microalgae for the remediation of contaminated water, whose biomass must also be managed in some way.

CRediT authorship contribution statement

Miguel Vigil: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Visualization **Franco-Vazquez, L.**: Software, Formal analysis, Writing - Review & Editing, Visualization **Marey-Pérez, M. F.**: Methodology, Formal analysis, Resources, Writing - Review & Editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Research data for this article: https://github.com/luisfrancoinv/acv

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References

Aalto, M., et al., 2019. Modeling of biomass supply system by combining computational methods – a review article. Appl. Energy 243, 145–154. https://doi.org/10.1016/J.APENERGY.2019.03.201.

Abbasi, M., Pishvaee, M.S., Bairamzadeh, S., 2020. Land suitability assessment for paulownia cultivation using combined GIS and Z-number DEA: a case study. Comput. Electron. Agric. 176, 105666. https://doi.org/10.1016/J.COMPAG.2020.105666.

Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—concepts and applications. Chemosphere 91 (7), 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075.

Andersson-Sköld, Y., et al., 2014. Developing and validating a practical decision support tool (DST) for biomass selection on marginal land. J. Environ. Manag. 145, 113–121. https://doi.org/10.1016/j.jenvman.2014.06.012.

Ashtineh, H., Pishvaee, M.S., 2019. Alternative fuel vehicle-routing problem: a life cycle analysis of transportation fuels. J. Clean. Prod. 219, 166–182. https://doi.org/10.1016/J.JCLEPRO.2019.01.343.

Bertolini, L., le Clercq, F., Kapoen, L., 2005. Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. Transp. Policy 12 (3), 207–220. https://doi.org/10.1016/J.TRANPOL.2005.01.006.

von Blottnitz, H., Curran, M.A., 2007. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J. Clean. Prod. 15 (7), 607–619. https://doi.org/10.1016/j.jclepro.2006.03.002.

Chen, Y., et al., 2018. Structural development and assembly patterns of the root-associated microbiomes during phytoremediation. Sci. Total Environ. 644, 1591–1601. https://doi.org/10.1016/J.SCITOTENV.2018.07.095.

Chibuike, G.U., Obiora, S.C., 2014. Heavy metal polluted soils: effect on plants and bioremediation methods. Appl.Environ.Soil Sci. 2014. https://doi.org/10.1155/2014/752708.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences. 2nd ed. Routledge https://doi.org/10.4324/9780203771587.

Dastjerdi, B., et al., 2021. A systematic review on life cycle assessment of different waste to energy valorization technologies. J. Clean. Prod. 290, 125747. https://doi.org/10.1016/j.jclepro.2020.125747.

Dickinson, N.M., et al., 2009. Phytoremediation of inorganics: realism and synergies. Int.J. Phytoremediat. 11 (2), 97–114. https://doi.org/10.1080/15226510802378368.

Dijkstra, E.W., 1959. A note on two problems in connexion with graphs. Numer. Math. 1 (1), 269–271. https://doi.org/10.1007/BF01386390 1959 1:1.

Dilks, R.T., Monette, F., Glaus, M., 2016. The major parameters on biomass pyrolysis for hyperaccumulative plants - a review. Chemosphere, 385–395 https://doi.org/10.1016/j.chemosphere.2015.12.062 Elsevier Ltd.

Doka, G., 2003. Swiss Centre for Life Cycle Inventories A Joint Initiative of the ETH Domain and Swiss Federal Offices Life Cycle Inventories of Waste Treatment Services.

EMEP/EEA air pollutant emission inventory guidebookEMEP/EEA air pollutant emission inventory guidebook — European Environment Agency, Available at https://www.eea.europa.eu/themes/air/air-pollution-sources-1/emep-eea-air-pollutant-emission-inventory-guidebook (Accessed: February 11, 2021).

Foundation, O., 2020. OpenStreetMap. Available at: https://www.openstreetmap.org.

Fumagalli, P., et al., 2014. The rotation of white lupin (Lupinus albus L.) with metal-accumulating plant crops: a strategy to increase the benefits of soil phytoremediation. J. Environ. Manag. 145, 35–42. https://doi.org/10.1016/j.jenvman.2014.06.001.

Gerhardt, K.E., Gerwing, P.D., Greenberg, B.M., 2017. Opinion: taking phytoremediation from proven technology to accepted practice. Plant Sci., 170–185 https://doi.org/10.1016/j.plantsci.2016.11.016 Elsevier Ireland Ltd.

Glass, J.D., 2000. Economic potential of phytoremediation. Available at:Phytoremediation of Toxic Metals, 15–31. https://ci.nii.ac.jp/naid/10010559418.

Group, T.P.D., 2020. "PostGIS 3.1.2dev Manual," Postgis Docs [Preprint]. Available at: https://postgis.net/docs/manual-3.1/.

Hiloidhari, M., et al., 2017. Emerging role of geographical information system (GIS), life cycle assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. Bioresour. Technol. 242, 218–226. https://doi.org/10.1016/J.BIORTECH.2017.03.079.

Huijbregts, M.A.J., et al., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22 (2), 138–147. https://doi.org/10.1007/s11367-016-1246-y.

ISO/IEC ISO 14040:2006, 2006. Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization (ISO), Genève, Switzerland.

Jäppinen, E., Korpinen, O.J., Ranta, T., 2012. The effects of local biomass availability and possibilities for truck and train transportation on the greenhouse gas emissions of a small-diameter energy wood supply chain. BioEnergy Res. 6 (1), 166–177. https://doi.org/10.1007/S12155-012-9244-9 2012 6:1.

Jäppinen, E., Korpinen, O.J., Ranta, T., 2014. GHG emissions of forest-biomass supply chains to commercial-scale liquid-biofuel production plants in Finland. GCB Bioenergy 6 (3), 290–299. https://doi.org/10.1111/GCBB.12048.

Jayarathna, L., et al., 2022. Geographical information system based fuzzy multi criteria analysis for sustainability assessment of biomass energy plant siting: a case study in Queensland, Australia. Land Use Policy 114, 105986. https://doi.org/10.1016/J.LANDUSEPOL.2022.105986.

Kesharwani, R., Sun, Z., Dagli, C., 2018. Biofuel supply chain optimal design considering economic, environmental, and societal aspects towards sustainability. Int. J. Energy Res. 42 (6), 2169–2198. https://doi.org/10.1002/ER.4006.

Kovacs, H., Szemmelveisz, K., 2017. Disposal options for polluted plants grown on heavy metal contaminated brownfield lands – a review. Chemosphere, 8–20 https://doi.org/10.1016/j.chemosphere.2016.09.076 Elsevier Ltd.

Kovacs, H., Szemmelveisz, K., Palotas, A.B., 2013. Solubility analysis and disposal options of combustion residues from plants grown on contaminated mining area. Environ. Sci. Pollut. Res. 20 (11), 7917–7925. https://doi.org/10.1007/s11356-013-1673-2.

Laasasenaho, K., et al., 2019. GIS-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas. Sustain.Energy Technol.Assess. 32, 47–57. https://doi.org/10.1016/J.SETA.2019.01.006.

Liljenström, C., et al., 2021. Life cycle assessment as decision-support in choice of road corridor: case study and stakeholder perspectives. Int. J. Sustain. Transp. 15 (9), 678–695. https://doi.org/10.1080/15568318.2020.1788679.

Manouchehrinejad, M., et al., 2020. Economic and environmental impact assessments of a stand-alone napier grass-fired combined heat and power generation system in the southeastern US. Int. J. Life Cycle Assess. 25 (1), 89–104. https://doi.org/10.1007/s11367-019-01667-x.

Masciandaro, G., et al., 2014. Phytoremediation of dredged marine sediment: monitoring of chemical and biochemical processes contributing to sediment reclamation. J. Environ. Manag. 134, 166–174. https://doi.org/10.1016/j.jenvman.2013.12.028.

Meers, E., et al., 2010. The use of bio-energy crops (Zea mays) for 'phytoattenuation' of heavy metals on moderately contaminated soils: a field experiment. Chemosphere 78 (1), 35–41. https://doi.org/10.1016/j.chemosphere.2009.08.015.

Miler, M., Medak, D., Odobašić, D., 2014. The shortest path algorithm performance comparison in graph and relational database on a transportation network. Promet-Traffic Transp. 26 (1), 75–82.

Moreno-Jiménez, E., et al., 2011. Using Mediterranean shrubs for the phytoremediation of a soil impacted by pyritic wastes in Southern Spain: a field experiment. J. Environ. Manag. 92 (6), 1584–1590. https://doi.org/10.1016/j.jenvman.2011.01.022.

Mulya, K.S., et al., 2022. A systematic review of life cycle assessment of solid waste management: methodological trends and prospects. Sci. Total Environ. 831 (November 2021), 154903. https://doi.org/10.1016/j.scitotenv.2022.154903.

Perimenis, A., et al., 2011. Development of a decision support tool for the assessment of biofuels. Energy Policy 39 (3), 1782–1793. https://doi.org/10.1016/j.enpol.2011.01.011.

Projects, Osg.C, 2020. pgRouting. Available at: https://pgrouting.org/.

Quarshie, S.D.G., Xiao, X., Zhang, L., 2021. Enhanced phytoremediation of soil heavy metal pollution and commercial utilization of harvested plant biomass: a review. Water Air Soil Pollut. 232 (11), 1–28. https://doi.org/10.1007/S11270-021-05430-7 2021 232:11.

Rodríguez, E., Morris, C.S., Belz, J.E., 2006. A global assessment of the SRTM performance. Photogramm. Eng. Remote. Sens. 72 (3), 249–260. https://doi.org/10.14358/PERS.72.3.249.

Roni, M.S., et al., 2017. A multi-objective, hub-and-spoke model to design and manage biofuel supply chains. Ann. Oper. Res. 249 (1–2), 351–380. https://doi.org/10.1007/S10479-015-2102-3/TABLES/9.

Sánchez-García, S., et al., 2017. A GIS methodology for optimal location of a wood-fired power plant: quantification of available woodfuel, supply chain costs and GHG emissions. J. Clean. Prod. 157, 201–212. https://doi.org/10.1016/J.JCLEPRO.2017.04.058.

Santibanez-Aguilar, J.E., et al., 2018. Facilities location for residual biomass production system using geographic information system under uncertainty. ACS Sustain.Chem.Eng. 6 (3), 3331–3348. https://doi.org/10.1021/ACSSUSCHEMENG.7B03303/SUPPL_FILE/SC7B03303_SI_002.PDF.

Sas-Nowosielska, A., et al., 2004. Phytoextraction crop disposal - an unsolved problem. Environ. Pollut. 128 (3), 373–379. https://doi.org/10.1016/j.envpol.2003.09.012.

Sauve, G., van Acker, K., 2020. The environmental impacts of municipal solid waste landfills in Europe: a life cycle assessment of proper reference cases to support decision making. J. Environ. Manag. 261, 110216. https://doi.org/10.1016/J.JENVMAN.2020.110216.

Shah, V., Daverey, A., 2020. Phytoremediation: a multidisciplinary approach to clean up heavy metal contaminated soil. Environ. Technol. Innov., 100774 https://doi.org/10.1016/j.eti.2020.100774 Elsevier B.V.

Singlitico, A., Goggins, J., Monaghan, R.F.D., 2018. Evaluation of the potential and geospatial distribution of waste and residues for bio-SNG production: a case study for the Republic of Ireland. Renew. Sust. Energ. Rev. 98, 288–301. https://doi.org/10.1016/J.RSER.2018.09.032.

Socha, A.L., Guerinot, M.Lou, 2014. Mn-euvering manganese: the role of transporter gene family members in manganese uptake and mobilization in plants. Front. Plant Sci. 5 (APR). https://doi.org/10.3389/FPLS.2014.00106.

Suer, P., Andersson-Sköld, Y., 2011. Biofuel or excavation? - life cycle assessment (LCA) of soil remediation options. Biomass Bioenergy 35 (2), 969–981. https://doi.org/10.1016/j.biombioe.2010.11.022.

Šyc, M., et al., 2012. Willow trees from heavy metals phytoextraction as energy crops. Biomass Bioenergy 37, 106–113. https://doi.org/10.1016/j.biombioe.2011.12.025.

Ternel, C., Bouter, A., Melgar, J., 2021. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. Transp. Res. Part D: Transp. Environ. 97, 102897. https://doi.org/10.1016/J.TRD.2021.102897.

Vangronsveld, J., Cunningham, S.D., 1998. Metal-contaminated Soils: In Situ Inactivation and Phytorestoration. Springer.

Vangronsveld, J., et al., 2009. Phytoremediation of contaminated soils and groundwater: lessons from the field. Environ. Sci. Pollut. Res. 16 (7), 765–794. https://doi.org/10.1007/s11356-009-0213-6.

Venanzi, S., et al., 2018. Use of agricultural by-products in the development of an agro-energy chain: a case study from the Umbria region. Sci. Total Environ. 627, 494–505. https://doi.org/10.1016/j.scitotenv.2018.01.176.

Vigil, M., et al., 2015. Is phytoremediation without biomass valorization sustainable? - comparative LCA of landfilling vs. anaerobic co-digestion. Sci. Total Environ. 505, 844–850. https://doi.org/10.1016/j.scitotenv.2014.10.047.

Vocciante, M., et al., 2019. Enhancements in phytoremediation technology: environmental assessment including different options of biomass disposal and comparison with a consolidated approach. J. Environ. Manage. 237 (November 2018), 560–568. https://doi.org/10.1016/j.jenvman.2019.02.104.

Voets, T., et al., 2013. GIS-BASED location optimization of a biomass conversion plant on contaminated willow in the campine region (Belgium). Biomass Bioenergy 55, 339–349. https://doi.org/10.1016/j.biombioe.2013.02.037.

Xiong, S., et al., 2021. A hybrid life cycle assessment of the large-scale application of electric vehicles. Energy 216, 119314. https://doi.org/10.1016/J.ENERGY.2020.119314.

Yang, Y., et al., 2019. Phytoextraction of Cd from a contaminated soil by tobacco and safe use of its metal-enriched biomass. J. Hazard. Mater. 363, 385–393. https://doi.org/10.1016/j.jhazmat.2018.09.093.

Yue, D., You, F., Snyder, S.W., 2014. Biomass-to-bioenergy and biofuel supply chain optimization: overview, key issues and challenges. Comput. Chem. Eng. 66, 36–56. https://doi.org/10.1016/j.compchemeng.2013.11.016.

Zhang, L., He, X., 2012. Route search base on pgRouting. Adv. Intell. Soft Comput. 115 AISC (VOL. 2), 1003–1007. https://doi.org/10.1007/978-3-642-25349-2_133/COVER/.

Zhang, X., Luo, K., Tan, Q., 2016. A feedstock supply model integrating the official organization for China's biomass generation plants. Energy Policy 97, 276–290. https://doi.org/10.1016/J.ENPOL.2016.07.027.