

# Methods of soil recovery in quarries of arid and semiarid areas using different waste types

## AUTHORS

Peñaranda Barba  
M. A.<sup>1,\*</sup>  
marianpeba@gmail.com

Alarcón Martínez V.<sup>2</sup>

Gómez Lucas I.<sup>1</sup>

Navarro Pedreño J.<sup>1</sup>

\* Corresponding Author

<sup>1</sup>Departamento de Agroquímica y Medio Ambiente. Universidad Miguel Hernández de Elche. Edif. Alcudia. Avda. de la Universidad, s/n. 03202 Elche, Alicante, Spain.

<sup>2</sup>Departamento de Organización Industrial y Electrónica. Escuela de Ingeniería. Universidad Internacional de la Rioja. C/Almansa, 101. 28040, Madrid, Spain.

*Métodos de recuperación del medio edáfico en canteras de zonas áridas y semiáridas mediante el uso de residuos*

*Métodos de recuperação do solo em pedreiras de zonas áridas e semi-áridas usando diferentes tipos de resíduos*

Received: 17.01.2020 | Revised: 21.05.2020 | Accepted: 22.05.2020

## ABSTRACT

In the Region of Murcia, there are many abandoned quarries in which restoration processes have not been carried out, and there are others that have a restoration plan but soil rehabilitation has not been achieved. Open pit mining generates a great environmental impact in the area where the activity takes place since it alters the morphology of the earth's crust, pollutes the air, the surface and underground waters, eliminates the flora of the area and destroys the biotope, causing changes in the landscape and strong changes in ecosystems. There is an international concern to promote sustainable development and waste reuse. In the European Union and Spain there is a requirement to carry out a restoration plan for mining operations. Waste production is a big problem; ways of reusing waste without polluting the environment and reintroducing it into economic activity are sought. In this article, several techniques are compiled that have given satisfactory results in the restoration of mining spaces, mainly in the Region of Murcia (SE Spain), by using waste such as pig manure, marble debris, sewage sludge or compost of urban household waste. These wastes pose a problem due to their disposal if they are not reused, and their use to restore mining spaces is a good option against dumping, abandonment or incineration.

## RESUMEN

*En la Región de Murcia se encuentran abundantes explotaciones mineras abandonadas en las que no se ha llevado a cabo un proceso de restauración, y existen otras que disponen de un plan de restauración que no ha conseguido la adecuada rehabilitación del suelo. La minería a cielo abierto genera un gran impacto ambiental en la zona en que se desarrolla la actividad ya que altera la morfología de la corteza terrestre, contamina el aire y las aguas superficiales y subterráneas, elimina la flora de la zona y destruye el biotopo, causando modificaciones en el paisaje y fuertes cambios en los ecosistemas. Existe una preocupación internacional para promover el desarrollo sostenible, la reutilización de residuos y la exigencia en la Unión Europea y España para que se lleve a cabo un plan de restauración de las explotaciones mineras. La producción de residuos constituye un gran problema, se buscan maneras de reutilizarlos en las que no contaminen al medio ambiente y reintroducirlos en la actividad económica. En este artículo se recopila información sobre técnicas que han dado resultados satisfactorios en la restauración de espacios mineros, principalmente de la Región de Murcia (SE España), utilizando residuos como el purín de cerdo, restos de mármol, lodos de depuradoras o compost de residuos domésticos urbanos. Estos residuos suponen un problema por su eliminación si no se reutilizan y su uso para restaurar espacios mineros es una buena opción frente a los vertederos, abandonos o incineración de los mismos.*

## RESUMO

*Na Região de Múrcia, existem muitas explorações mineiras e pedreiras abandonadas, nas quais não foi realizado qualquer processo de restauração, e outras em que, embora possuindo um plano de restauração, a reabilitação do solo não foi alcançada. A exploração mineira a céu aberto gera um grande impacto ambiental na área onde se desenvolve a atividade, pois altera a morfologia da crosta terrestre, polui o ar e as águas superficiais e subterrâneas, elimina a flora da área e destrói o biótipo, causando alterações na paisagem e fortes mudanças nos ecossistemas. Existe uma preocupação internacional em promover o desenvolvimento sustentável e a reutilização de resíduos. Na União Europeia, incluindo em Espanha, há uma exigência para que se realizem planos de restauração das áreas onde ocorrem operações mineiras. A produção de resíduos é um grande problema; atualmente, procuram-se formas de reutilizar os resíduos sem poluir o ambiente e reintroduzi-los na atividade económica. Neste artigo, são compiladas técnicas que obtiveram resultados satisfatórios na restauração de espaços mineiros, principalmente na região de Múrcia (SE Espanha), utilizando resíduos como chorume de suínos, resíduos de mármore, lamas de ETAR ou composto de resíduos de sólidos urbanos. Estes resíduos representam um problema ambiental se não forem reutilizados. O seu uso para restaurar espaços de áreas mineiras é uma boa opção quando comparado com a sua inclusão em aterros, abandono ou incineração.*

## 1. Introduction

Open-pit mining generates a great environmental impact because it alters the morphology of the earth's crust, pollutes the air, surface and underground water, eliminates the existing flora in the area and destroys the biotope. This activity can also affect the health conditions of the surrounding inhabitants. By causing these modifications, negative visual impacts and strong ecological changes in the affected ecosystems are generated in the landscape (Gunn and Bailey 1993; Sheoran et al. 2010; Sort and Alcañiz 1996).

This article presents the important mining heritage that the Region of Murcia (SE Spain) has. The importance that this activity has had, especially in the Northwest of Murcia in the nineteenth and twentieth centuries, has left some mining spaces that should be the subject of an environmental policy.

The regional government is clearly committed to the mining industry, an economic activity that it plans to protect and promote through regulations that would have a validity of at least 25 years and that favors the exploitation of quarries over any other use of the territory. The analysis of the cartography included in the mining guidelines reveals that 59 population centers and 241 housing groups would be less than two kilometers from quarries. The Autonomous Community hardly poses restrictions on mining activity for environmental reasons: only in the case that industrial activity affects a protected natural area. Important steps have been taken but there is still not enough action to protect and enhance the vestiges left by this activity.

At present, the mining regulations require a restoration plan to be carried out before starting exploitation in order to prevent or reduce possible adverse effects on the environment and health caused by mining activity, and to establish the necessary preventive measures so that these impacts either do not occur, or affect the environment to a lesser extent. In addition, the land must be rehabilitated once the operation has been completed. Directive 2006/21/EC, on the management of waste from extractive industries requires the rehabilitation of areas where mining waste facilities have been located, as does the pre-existing Spanish mining legislation. This Directive is carried out, on a basic basis, by Spanish Royal Decree

### KEY WORDS

Circular economy, marble, mining, restoration, slurry.

### PALABRAS

#### CLAVE

Economía circular, mármol, minería, purines, restauración.

### PALAVRAS-

#### CHAVE

Atividade mineira, chorume, economia circular, mármore, restauração.

975/2009 of June 12 on the management of waste from extractive industries and the protection and rehabilitation of space affected by mining activities. Restoration and rehabilitation are among the most important measures, as it allows the exploited land to be integrated into its ecological and landscape environment, and to develop an alternative use to mining once its exploitation has ended (Escribano and Mataix 2007). With restoration, the aim is to return the original condition of the land, whereas with rehabilitation or recovery, a different use is achieved from that which the land had before being exploited.

In this article, the terms restoration and rehabilitation will be dealt with indistinctly, since the aim is to show that the soil must acquire such conditions that it is capable of serving as a biotope, allowing the development of living organisms, especially vegetation, regardless of the subsequent use to which the recovered space is destined.

Currently, there are abundant mining operations in which a restoration process has not been carried out and they have been abandoned, as in the case of the Region of Murcia. In addition, in other cases restoration plans have not achieved the correct rehabilitation of the soil. Thus, the objective of this review is to compile the most relevant information on the techniques used for the recovery of soils in open-pit mining spaces, which serve as a basis for future rehabilitation. Restoration in arid or semi-arid areas, as is the

case in the Region of Murcia, is much slower than in rainy areas due to the scarcity and torrential nature of the rainfall at certain times and the intense solar radiation in these areas contribute to desertification, which subjects the plants to severe water stress, contributing as a whole to increased soil erosion (Miralles et al. 2009).

## 2. State of the art 2000-2019

As a preliminary approximation, a bibliometric analysis was carried out based on the Scopus database, which allowed us to determine the interest of the scientific community in the restoration of open-pit mining spaces. In this sense, 446 documents were located for the period 2000-2019 using the “quarry restoration” search. Of these documents, only 338 corresponded to scientific articles.

Focusing our attention on these articles, the country with the highest number of publications on the subject was Spain (Figure 1). In the Spanish contributions, 35 of them were related to Murcia. In addition, in this group of countries with the greatest number of publications, the European countries stand out, indicative of the interest in solving an environmental problem such as restoration after mining activity.

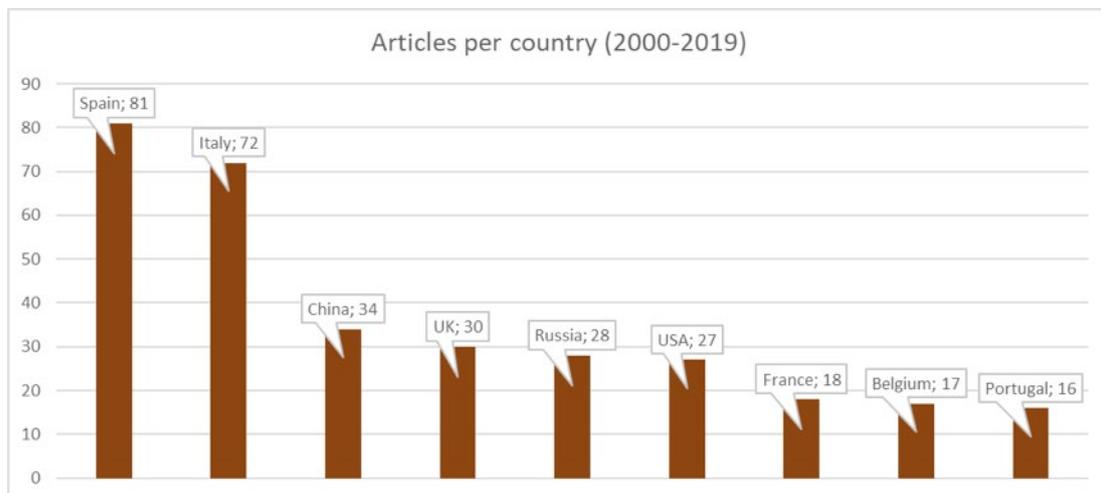
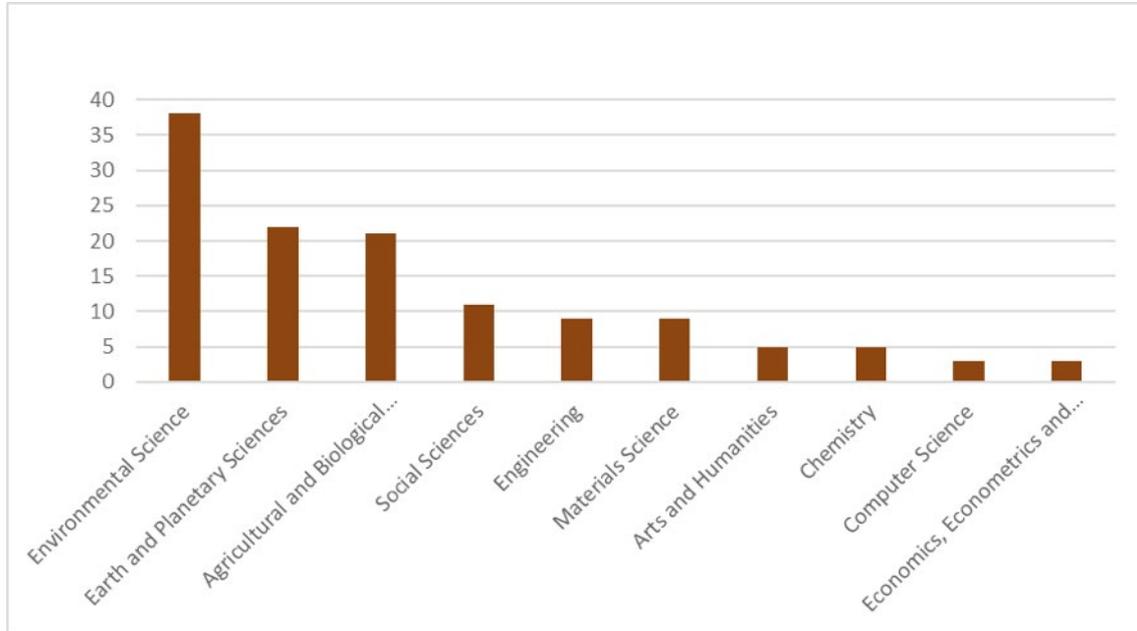


Figure 1. Number of published articles on quarry restoration published by country in the period 2000-2019 (own source).

In terms of the subdisciplines in which Scopus distributes the published articles, the one corresponding to "Environmental Science"

stands out above all others, followed by the publications in "Earth and Planetary Sciences", as shown in **Figure 2**.

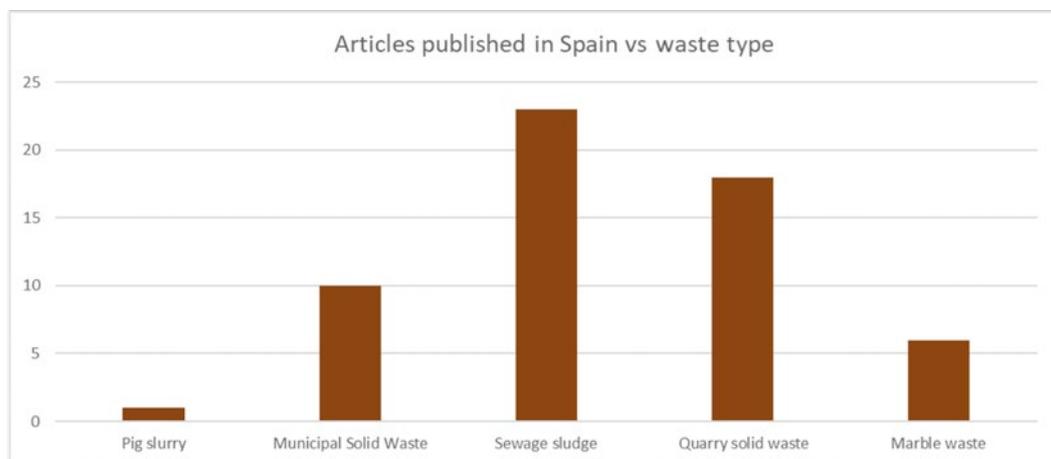


**Figure 2.** Subdisciplines where the articles published on quarry restoration in the Scopus database in the 2000-2019 period are grouped (own source).

In the studies with Spanish authors on waste used in mine restoration, those where sludge is used stand out, especially those that use sludge from wastewater treatment (**Figure 3**).

which the term "waste" is used are the following: (a) based on "pig slurry, municipal solid waste, marble waste", the publication of Castro-Gomes et al. (2012); (b) if we consider "sewage sludge, quarry solid waste", the most cited article is that of Luna et al. (2016a).

To conclude this preliminary analysis, the most frequently cited articles by Spanish authors in



**Figure 3.** Scopus publications by Spanish authors in the period 2000-2019 according to the type of waste used in quarry restorations (own source).

### 3. Situation in the Region of Murcia

Nowadays, in the Region of Murcia, there are a large number of abandoned quarries in which no restoration plan has been carried out, as in the rest of Spain. In the case of Murcia, most of them are located in the northwest of the Region. According to the latest data prepared by the Regional Directorate General of Industry, Energy and Mines, in 2006 there were 88 aggregate quarries in the Region of Murcia, of which 54 were active, and 144 ornamental rock quarries of which 83 were still active, giving a total 273 existing exploitations in the Region of Murcia of which 157 were active. The Region of Murcia is one of the areas with the greatest geological potential on a national scale, as it represents about 12.6% of the extraction of marble and limestone. Many areas are affected by metalliferous mining activities. These areas are located in Cartagena and La Unión, so for more than 2,500 years until 1991, Phoenicians, Romans, Arabs, Carthaginians and Spaniards have been extracting zinc, lead, copper, silver, manganese, iron and tin (Conesa and Faz 2009). Thus, all these mining activities have caused a large accumulation of heavy metals and generated acid drainage in the mines (Faz et al. 2008).

A high percentage of the mountains of the Region of Murcia are formed by limestones; predominant in the mountain ranges of Moratalla, Villafuertes, Gavilán, Cerezo, Los Alamos, Mojantes, Quipar, Oro, Ricote, Manzanete, Pila, Corque Place, Quibas, Espuña, Carrascoy, among others. The public administration today is faced with a large number of abandoned areas, with consequent landscape degradation (some of which are used as uncontrolled landfills), and with active exploitations, which should be restored in the future.

The limestones are the rocks that are currently most exploited in the region, their main use being gravels and concretes, or masonry stone and ornamental rocks, which are marketed both inside and outside the region. Some of the best-known varieties of ornamental rocks from quarries located in the region are: Caravaca red,

Cehégín red, Cehégín gray, Cehégín medium and Quipar red, which are Jurassic red nodular limestones; and the ivory cream of the Sierra de la Puerta, which is a Paleogene limestone. They are known as marbles, although from the geological point of view, they are sedimentary carbonate rocks.

The Region of Murcia has a Mediterranean climate with hot and dry summers and mild winters, although with frequent inland frosts, and rains in spring and autumn. The general characteristic of this climate is its scarcity of precipitation, concentrated over a few days of the year with a maximum in autumn. These rains, generally torrential, are produced when a mass of warm and humid air from the Mediterranean Sea rises over the coastal mountains, meets another mass of cold air and precipitates. These rains should be considered because of the high erosive power they can trigger when it comes to recovering mining spaces.

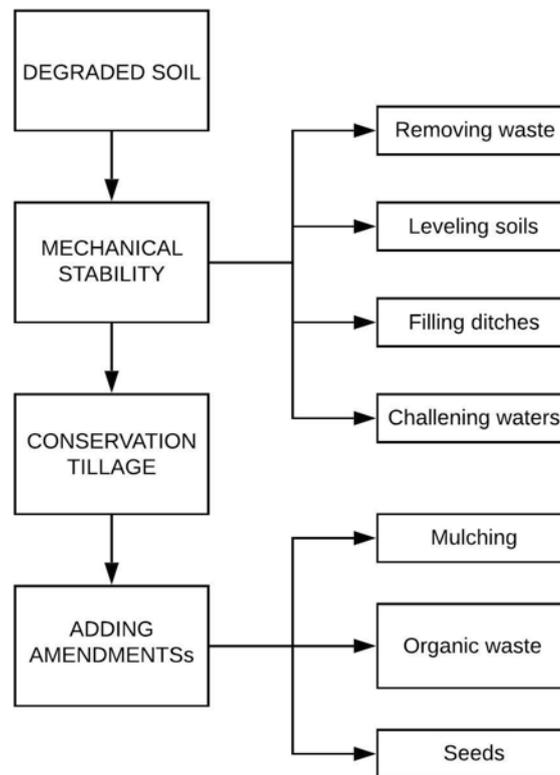
According to the Köppen climate classification, several climates are distinguished in the Region: semi-arid warm (BSh), semi-arid cold (BSk), and Mediterranean (Csa).

In the BSh climate the average annual temperature is above 18 °C and rainfall is scarce. Solar evaporation exceeds rainfall; it is a hot and dry climate. In the BSk climate, the average annual temperature is below 18 °C. Rainfall is also scarce and evaporation like in the BSh also exceeds rainfall; this climate is cold and dry. The Csa has an average temperature of the coldest month less than 18 °C and higher than -3 °C, and that of the warmest month is greater than 10 °C and the temperature of the warmest month exceeds 22 °C. Precipitation exceeds evaporation and there are seasonal rains. Summer is dry, so the minimum rainfall coincides with the period of higher temperatures. The rainiest season is not winter.

## 4. Keys for the recovery of the environment

The soil is the fundamental pillar for recovery of the open mining areas, and next to it, the vegetation that is a key factor for landscape

regeneration. If we add the need to reuse waste based on circular economy to these keys, we can conclude that the three basements in rehabilitation are soils, vegetation and the reuse of waste as the main source of organic matter. **Figure 4** shows the general restoration process of a quarry.



**Figure 4.** General restoration process of a quarry (own source).

The environmental properties affected by open-pit extractive activities are very diverse, altering both the morphology and the processes that affect the territory, changing them completely. If we focus on the example of the Region of Murcia, extrapolated to other arid and semi-arid Mediterranean areas, open pit limestone mining is particularly harmful due to the type of extraction (Luna et al. 2016b). In addition, these areas are susceptible to desertification and very sensitive to erosion due to the absence or scarcity of vegetation cover. Therefore, in order to restore an area without soils or with

highly degraded and often unstructured soils, a surface layer with adequate physical, chemical and biological properties should be prepared. The usual strategy in the restoration is therefore to re-establish the edaphic cover, but in many cases, to build a new edaphic environment - a Technosol (IUSS Working Group WRB 2015).

After mechanical stabilization of the environment, efforts should be directed towards improving the soil by adding organic materials (e.g. through waste) and then revegetation, in such a way that allows the landscape lost after mining to be returned to its previous state.

Before creating this layer of “new soil” or artificial soil created *ad hoc* (Technosol), it is necessary to clean the surface, removing materials or debris (artifacts) from the soil that are not useful for its recovery and leveling it to prevent erosion. It is crucial to adapt the hydrography for proper rehabilitation and so the gullies and trails must be covered and the waters must be channeled to prevent the material supplied from flowing and dragging (Zornoza et al. 2017).

Once mechanical stability is achieved, the soil is prepared using tillage techniques to reduce compaction and bulk density and increase the porosity of the arable layer, which in turn facilitates seed germination and seedling development (Kabas et al. 2012). It is also necessary to recover the fertility of the soil, incorporating or covering the surface with organic waste that in turn remedies the soil, fertilizes and protects it.

The strategy based on the increase of organic matter in the soil is essential to guarantee a real rehabilitation of the soils, since soil organic matter is a property closely related to soil structure (Tisdall and Oades 1982), aeration, water retention and circulation, reduction of erosion rates, stimulation of biological activity and the increase of fertility by nutrient release (Smith et al. 1993; Shafi et al. 2007). Soil organic matter is universally recognized as one of the most important factors responsible for soil fertility and protection against pollution, degradation, erosion and desertification, especially in semi-arid areas (Senesi et al. 2007). This new substrate must be transformed into a fertile soil in the short and medium term, which improves biological activity, activates biogeochemical cycles, and accelerates the regeneration of plant communities (Caravaca et al. 2002; Heneghan et al. 2008; Domene et al. 2010; Soliveres et al. 2012).

To achieve this, the incorporation of organic matter must allow the structure to be neither too loose nor too compact (Jorba et al. 2002), and it must achieve good water infiltration, be resistant to erosion and contain nutrients and microorganisms that allow vegetation to grow (Banning et al. 2011; Muñoz-Rojas et al. 2016).

## 5. Organic matter and soil properties

The improvement of soil properties by application of organic matter is a strategy linked to the roots of the history of agriculture. It was traditionally based on the application of organic residues and waste from animal origin. However, a wide variety of amendments from many different sources are currently applied. These are also used in the restoration of soils in mining operations.

Waste from activities such as slaughterhouses, forest management, livestock, agriculture, households, wastewater treatment (biosolids) or food industries can be considered as organic products or waste (Navarro-Pedreño et al. 1995). Organic waste must have a biological origin and composition and contain the so-called bioelements, to a greater extent carbon, hydrogen and oxygen (C, H and O) and to a lesser extent nitrogen, phosphorus and sulfur (N, P and S).

### 5.1. Increase in soil organic matter

The application of organic waste to the soil is a useful tool to maintain and increase the amounts of organic matter (Mondini et al. 2008; Jorba and Vallejo 2008; Kabas et al. 2014). Organic waste can be used as a source of nutrients, improving soil fertility and stimulating the formation of aggregates and the development of microbial populations (Ortiz et al. 2012; Ye et al. 2002; Zanuzzi et al. 2009). Effective recycling of organic waste in soil requires optimization of waste management to minimize CO<sub>2</sub> emissions and optimize the efficiency of soil C retention. Since the main objective after the application of organic amendments is the increase of organic matter, it is crucial to carry out an exhaustive study on the stability and mineralization of organic C (Zornoza et al. 2012). Therefore, amendments can be implemented with nutrients that are not mineralized so quickly that the organic matter disappears before the vegetation cover is properly developed. In addition, the implementation of these amendments could be beneficial to the environment, as it prevents their incineration or uncontrolled dumping, thereby helping to promote the circular economy.

These amendments improve soil C sequestration by replacing labile organic carbon from aggregates with more stable compounds (Ojeda et al. 2015), contributing to plant growth (Hemmat et al. 2010). With the application of organic amendments, in addition to total organic carbon (TOC) the total nitrogen (TN) also increases. These increases are associated with increases in basal respiration and dehydrogenase activity, which are accepted as indicators of total soil microbial activity (García et al. 1997; Bastida et al. 2006). The effect of organic amendments on soil TOC depends on the chemical composition of amendments (Tejada et al. 2009), which determines the rate of their mineralization by soil microorganisms (Hahn and Quideau 2013).

### 5.2. Biological activation

Soil biological activity is related to soil health and will act as an indicator of the effectiveness of recovery procedures (Epelde et al. 2009). In this sense, biochemical properties are considered potentially sensitive, early and effective indicators of soil health in contaminated soils (Clemente et al. 2007). There is a direct relationship between the addition of organic matter with the stimulation of growth and the activity of the microbial community of soils degraded by mining, resulting in the mineralization of nutrients for plants (Alvarenga et al. 2014) and the increase of fertility and soil quality (Diacono and Montemurro 2010).

Soil organic matter is a source of energy and carbon for soil microorganisms, which promote the formation of micro and macro-aggregates (Lehmann and Rillig 2015). There is clear evidence that microorganisms are involved in the aggregation process because microbial activity controls the production of exudates that act as binding agents in aggregates (De Gryze et al. 2005). In any soil where clay is present, interactions between polysaccharide exudates, organic colloids and other decomposition products promote stability (Dontsova and Bigham 2005).

A group of these microorganisms, arbuscular mycorrhizal fungi (AMF), produce a proteinaceous material called glomalin present in roots, soil and hyphae, and this protein has

the function of favouring the sequestration of C (Rillig 2004).

### 5.3. Structure and formation of aggregates

The application of organic waste, as indicated above, favors the formation of aggregates and thus the structure of the soil, so that it could lead to improved infiltration and water retention, making the soil more suitable for plant growth (Hueso-González et al. 2014). The stability of soil aggregates and the architecture of porous space affect water movement and storage, aeration, erosion, biological activity and plant growth (Bosch-Serra et al. 2017). At the same time, by achieving stable aggregates, the organic material is protected from microbial decomposition (Bronick and Lal 2005), erosion is reduced, root development is promoted (Tisdall and Oades 1982), soil structure degradation is prevented and water storage is favoured (Franzluebbers 2002). In short, organic matter amendments increase the stability of aggregates, contribute to the formation of new aggregates, increase porosity and water retention capacity, facilitate the development and establishment of vegetation and the formation of microbial communities and reduce erosion (Six et al. 2004).

In semi-arid environments, the presence of carbonates interferes with the relationship between clay minerals and soil aggregation, resulting in improved macro-aggregated stabilization in soils rich in carbonates, but with less porosity within macro-aggregates (Fernández-Ugalde et al. 2013). Moreover, the contribution of calcium carbonate in certain mining areas stabilizes the organic carbon added by organic amendments, minimizing losses of soil organic matter by mineralization (Zornoza et al. 2013).

### 5.4. Microbiota and enzyme activity

Soil microbiota helps the formation of soil structure, plant establishment and transformation of soil organic matter (Zink and Allen 1998). Many studies have demonstrated the importance of soil microbial communities for successful plant establishment and growth

(Kulmatiski et al. 2008; Epelde et al. 2010). However, extreme conditions caused by mining activities generally have a negative influence on soil biological activity (Asensio et al. 2013; Zornoza et al. 2013).

Not all organic waste produces the same effects on the soil microbiota. The microbial community responds faster to environmental changes than plants and is very sensitive (Harris 2009). However, many factors such as soil organic matter characteristics, soil moisture and soil temperature can affect biomass (Zhou et al. 2014) and soil microbial community structure (Hortal et al. 2015). The structure and activity of the soil microbial community may change in response to the quality of organic amendments. Therefore, soil processes mediated by microorganisms may also change depending on these changes in the microbial community (Lucas et al. 2014). In addition, since bacteria and fungi have different pH preferences (Rousk et al. 2009), the addition of alkaline amendments increases the pH of the soil, alters the balance between fungal/bacterial growth and the microbial structure of the community. This in turn can change the nature and magnitude of soil processes related to specific microbial groups (Zornoza et al. 2016). Changes in soil microbiota due to environmental factors should be reflected in the level of enzymatic activity of the soil (Kandeler et al. 1996). After the application of residues, there are changes in soil function that may indicate the evolution of microbial activity (Li et al. 2015). In general, organic amendments increase the enzymatic activities (b-glucosidase, alkaline phosphatase and urease) related to biogeochemical cycles of the elements in the soil (Pascual et al. 1997; Ros et al. 2003; Bastida et al. 2007; Tejada et al. 2009; Santos et al. 2014).

In semi-arid Mediterranean areas, indigenous microbial communities are well adapted to severe climatic conditions such as high temperatures and scarce rainfall, while new soil microbial communities from organic waste are more sensitive to water stress than native soil microbiota (Hueso et al. 2011). Organic amendments can also cause changes in the microbial populations of the native soil due to the diverse available substrates they provide (Luna et al. 2016b). Organic amendments have a strong effect on phospholipid contents,

stimulating bacterial and fungal proliferation, as demonstrated by several authors (Marschner et al. 2003; Bastida et al. 2008; García-Orenes et al. 2013; Lazcano et al. 2013; Luna et al. 2016b). The profiles obtained from the phospholipid analysis were positively correlated with the total carbon content (TOC), the total N content and the total P content.

## 6. Revegetation

In order to restore degraded arid and semi-arid areas with significant rates of erosion such as the Region of Murcia, it is necessary to establish a vegetation cover in addition to restoring the soil (Zornoza et al. 2017).

In arid and semi-arid regions, due to low rainfall, severe water stress is produced in plants. Normally the species used are seedlings or greenhouse plants, which experience post-transplant shock after sowing, associated with moisture or nutritional stress (Jacobs et al. 2005; Bateman et al. 2018). Therefore, it is necessary to use plant species adapted to water stress, the nutrients existing in the restored area and the climatology of the site, since these have developed morphological and physiological adaptations that allow them to survive and grow in difficult conditions (Clemente et al. 2004).

The use of native species for restoration is of special interest to maintain the equilibrium of the ecosystem. In addition, native plants adapt to climatic and soil conditions and provide the basis for natural ecological succession (Méndez et al. 2007). Native plants have greater possibilities of survival, growth and reproduction under conditions of environmental stress than plants introduced from other environments (Adriano 2001; Antonsiewicz et al. 2008). It is a very important and basic strategy in all mining operations to have a seed bank of the existing species prior to exploitation, or failing that, prepare one with the plants of the closest environment with the same conditions as those that were initially in the quarry. In this way, it will be possible to use species characteristic of

the area that can guarantee a better success in revegetation.

The beneficial effects of revegetation are very relevant from a soil and landscape point of view. Plants reduce water erosion by intercepting rain (Roundy et al. 2017; Tromble 1987), favor the increase of water infiltration (Huang et al. 2015; King et al. 2012; Piñol et al. 1991) and promote soil regeneration.

The application of organic matter inputs as a restoration technique increases the growth of plants due to the increase of available nutrients, mainly from organic amendments (Maisto et al. 2010; Moreno-Peñaranda et al. 2004). Thus, the appropriate combination of organic amendments and revegetation promotes the growth of plants (Caravaca et al. 2002) and, ultimately, the landscape recovery of the restored area.

## 7. Waste types applied as amendments

The European Commission (EC), during 2014 and 2015, made proposals focused on the circular economy and published an action plan that aims to “treat waste as a resource and convert Europe towards a circular economy”. The action plan suggests as an objective for 2030, among others, to prepare 65% of municipal waste for reuse and recycling.

In addition to environmental degradation, one of the main environmental problems in the world is the production and accumulation of waste, so the objectives established by the European Union (EU) must be taken into account. Waste generation together with the depletion of many resources, lead the EU towards a zero-waste strategy through the circular economy, in which the value of products, materials and resources is maintained in the economy for as long as possible and waste generation is reduced (Almendro-Candel et al. 2018). An essential part of the circular economy is the use of urban solid waste (MSW) in soils as a source of nutrients, mainly through prior composting (Almendro-Candel et al. 2019).

Given the need to integrate European zero-waste strategies and the adoption of the circular economy, the recovery of mining operations is an opportunity for the convenient use of organic waste that allows the recovery of soil and landscape of areas affected by extractive activities. Therefore, this section focuses on contrasting the use of different amendments that have been used in the rehabilitation of mining spaces and their results, based on those applied in the Region of Murcia. The accumulation of waste is a problem and for this reason it is important to look for ways to reuse them without polluting the environment. In the studies and examples analyzed, mulching with peat and other materials, sewage sludge, compost, pruning waste, pig slurry and inorganic marble waste are considered, as well as combinations between them.

These amendments have been studied because of their excess in the Region of Murcia, as they pose a problem for their elimination. It is very common for farmers to abandon pruning remains in wadis and wastelands or carry out uncontrolled incineration. Municipal solid waste is a problem due to its abandonment in uncontrolled dumps and sewage sludge would soon overtake us if we did not do anything with it. In the Region of Murcia, the pig sector is one of the most important in Spain, with a census of 2,145,408 heads producing more than 6.9% of the country's output (MAPA 2019). This generates a large amount of waste, about 6.5 hm<sup>3</sup> per year, and generates management problems for producers. In addition, in the Region, the marble natural stone extraction industry processes 147,000 m<sup>3</sup> of product per year, generating 128,120 t of inert waste, of which only 10% is recovered (Zornoza et al. 2017).

### 7.1. Mulching

One of the techniques used for the restoration of degraded mining soils is the application of mulch by using different types of peat. This acts by limiting water loss through evaporation, improving filtration and root growth, as well as establishing vegetation and reducing soil erosion (Shao et al. 2014; Hueso-González et al. 2015). In addition, the plant remains and the mulch increases the stability of soil aggregates (Wright and Upadhyaya 1998).

Along with mulching, there are other strategies associated with it such as the use of plastic, stones or wood chips, which are effective measures to prevent water loss (Bakker et al. 2012; Devine et al. 2007). At the same time as plant mulch reduces the evaporation of soil water (Laliberté et al. 2008), soil protection is favoured and mulching is efficient for improving the establishment of vegetation (Valdecantos et al. 2009).

However, it has been observed in some experiments that the use of a vegetable mulch does not produce significant effects on the survival rate of plants in arid environments where annual precipitation is very low and only little rain can reach the soil due to interception by the mulch cover (Grantz et al. 1998; Luna et al. 2016b). In addition, plant mulches can have a negative effect on the activity of certain enzymes such as glucosidase, suggesting that mulch can prevent the entry of plant debris and native organic matter caused by the barrier created by mulch itself (Qiu et al. 2014).

By applying pruning residues as a mulch, we prevent uncontrolled incineration of them as they form a focus of disease. Moreover, the process of optimal dehydration expels large amounts of CO<sub>2</sub> into the air. In addition, the abandonment of pruning residues in ramblas and wastelands constitutes a serious risk during torrential rains and contributes to the spread of pests and diseases. Mulching may not always provide the expected beneficial effects on soil microbial activity as in some cases the effects on alkaline phosphatase and urease activities are positive and in other negative (Luna et al. 2016b). Several authors have found a significant negative effect on enzymatic activities related to C and P (b-glucosidase and alkaline phosphatase, respectively), while microbial biomass was not significantly affected by the type of coverage. Therefore, since these enzymes are frequently immobilized in clay and humic fractions (Nannipieri 2006; Bastida et al. 2012), it can be suggested that mulch has a stronger impact on the extracellular environment than on microbial growth (Luna et al. 2016b).

The positive effect of mulch on vegetation is related to improvements in soil water content, which would provide benefits for plant

establishment, particularly in arid and semi-arid areas with severe water scarcity (Bautista et al. 2009).

Regarding the use of other surface materials, Luna et al. (2016b) did not observe clear positive effects with the use of gravel on the growth of plants and found a general negative effect using wood chips as mulch. Consistently, several authors found that wood chips could inhibit plant growth due to allelochemical compounds (Duryea et al. 1999; Rathinasabapathi et al. 2005). In addition, differences between plant species were found (Escós et al. 2000; Armas and Pugnaire 2005). Previous studies also reported negative effects (Kruse et al. 2004), no effects (Fernández et al. 2011; Santana et al. 2014) and positive effects (Badía and Martí 2000; Bautista et al. 2009). Contradictory effects have therefore been found in the case of mulch by using wood chips.

## 7.2. Compost from municipal solid waste

Composted material from municipal solid waste (MSW) mainly induces an increase in TOC and glomalin content in soil (Luna et al. 2016a). The increase in TOC content by compost is caused by the stable nature of the amendment (García et al. 1992; Ros et al. 2003; Dearden et al. 2006).

According to Luna et al. (2016b), composting increases electrical conductivity (EC) ( $P < 0.05$ ) the first few days of being applied, but soil salinity decreases over time. This initial increase in EC may result from the incorporation of low molecular weight organic compounds or the release of salts during the decomposition of organic substances (González-Ubierna et al. 2012; Mingorance et al. 2014; Pérez Gimeno et al. 2016). The decrease over time of the EC may be due to the leaching of ions by rain, which contributes to reduce soil salinity (González-Ubierna et al. 2012).

Regarding soil carbon metabolism, five years after the application of MSW compost in the work carried out by Luna et al. (2016b), basal soil respiration is only sensitive to the application of further amendment and is similar to that of the natural soil of reference.

Compost increases microbial biomass and alters the composition of the community towards a community dominated by fungi. Fungi are capable of degrading more recalcitrant organic material (Boer et al. 2005); therefore, an increase in fungal biomass in soils modified with compost could be attributed to the presence of stabilized substrates that give a competitive advantage to fungi. Moreover, the development of vegetation cover on soils treated with compost could contribute to the entry of cellulose and lignin into the soil. Fungi are able to degrade these C polymers through their enzymatic systems (Boer et al. 2005; Baldrian et al. 2010). According to the study of Luna et al. (2016b), bacterial PLFA and Gram+/Gram- ratios increase in treated plots, reaching values similar to those observed in undisturbed reference soils. Gram+ bacteria communities are more resistant to drying and re-wetting than Gram- bacteria because of their physiological characteristics, i.e. the presence of a strong, thick and interconnected peptidoglycan cell wall (Schimel et al. 2007). In fact, the Gram+/Gram- ratio has been suggested as an indicator of resistance to disturbances in microbial communities (De Vries and Shade 2013). A shift to a more dominant Gram+ microbial community (high Gram+/Gram- values) can be seen as a mechanism to adapt to a semi-arid climate.

### 7.3. Sewage sludge

Sludge, in general, has stood out in its results for the creation of greater stability of soil aggregates (García-Orenes et al. 2005). Some results, however, indicate that it is not much larger than the reference soil and reaches a lower TOC than unaltered natural soils (Luna et al. 2016b). The organic carbon fraction of the sludge from wastewater treatment is more biodegradable than that of this composted material and can be rapidly hydrolyzed by enzymatic activity (Cook and Allan 1992), which would explain the difference in the results in the use of this waste. In general, composted sewage sludge (biosolids, as several types of treated sewage sludge that can be used as soil conditioner are termed) is a preferential organic waste used in agriculture and environmental rehabilitation.

Soils treated with sludge also have higher concentrations of actinobacteria, which can

probably be attributed to the high content of these commonly found in wastewater treatment plants (Bitton 2005; Wang et al. 2014). However, the content and proportion of microbial biomass, both in restored and natural soils, responds over time to seasonal changes and vegetation development (Bastida et al. 2007; Baldrian et al. 2010).

### 7.4. Combination of MSW compost and sewage sludge

The combination of both residues apparently produces a sum of its positive properties in the soil. These affect enzyme activity, improve soil microbiological properties and improve soil respiration (Luna et al. 2016b).

The amendments of sewage and compost produce a positive correlation between enzymatic activities and the TOC and TN contents, favouring soil productivity and fertility (Luna et al. 2016b). This could be related to the higher organic matter content in plots modified with compost, as well as the stimulation of plant development that provides organic matter inputs to the soil (Bastida et al. 2008).

Compost and sludge contribute to increased plant growth, for example in the species *M. tenacissima*, *A. cytisoides* and *A. terniflora* (Valdecantos et al. 2011). However, opposite impacts on plant survival and growth have been observed. On the one hand, plant survival rates decrease slightly in the first months of planting, probably due to a high organic matter content, which increases soil salinity and the possible lack of nutrients associated with the increment of soil microbial activity. On the other hand, organic amendments are beneficial for plant growth in the following months, as they improve nutritional conditions (Luna et al. 2016a). In a semi-arid region under Mediterranean climate, the mean survival value of *M. tenacissima* of 92% was found four years after sowing. Values above 40-60% were noted by Valdecantos et al. (2011) and Oliet et al. (2012) for different species of plants in Mediterranean conditions. This was considerably above the value of 10% reported by Rokich (1999) in a Mediterranean mining restoration 2 years after sowing. The species that developed mechanisms to resist

water stress during the summer period are of great interest. *M. tenacissima* is best suited for successful recovery under the semi-arid Mediterranean climate in the short term (Luna et al. 2018).

#### 7.5. Sewage sludge, MSW compost and gravel

In addition to the properties commented on by the previous combination, the addition of inorganic, gravel-sized materials to these amendments introduces a noticeable physical change, favouring the creation of pores and spaces available for rapid infiltration and root development. This combination could be of great interest and application in certain environments where it is necessary to increase macroporosity and facilitate water infiltration and gas exchange.

From the point of view of the biological activity of soils, it should be pointed out that when this mixture of materials has been used, the detected dehydrogenase activity is much greater than if only organic amendments to MSW compost or sludge were applied. This may be correlated with an observed increase in vegetation cover with gravel (Masciandaro et al. 2004; Mukhopadhyay et al. 2016; Luna et al. 2016b), favored by changing physical conditions in the environment.

#### 7.6. Pig slurry

The use of slurry as an amendment can solve two problems: recovery of a by-product and rehabilitation of degraded mining areas.

Slurry has a high organic matter content and can affect soil structure in several ways. The slurry provides sodium, magnesium and calcium (Na, Mg and Ca, respectively) in addition to the three main nutrients, nitrogen, phosphorus and potassium (N, P and K). Interchangeable cations ( $K^+$ ,  $Na^+$ ,  $Mg^{2+}$  and  $Ca^{2+}$ ) affect soil aggregation. Sodium mainly causes dispersion of clay particles and destabilization of aggregates (Crescimanno et al. 1995). The dispersion of the aggregates generally leads to the formation of soil crusts, causing slow infiltration and high particle mobility by surface runoff. In calcareous soils, both  $Ca^{2+}$  and  $Mg^{2+}$  reduce clay dispersion (Amezketta and Aragüees 1995). In addition,

adsorbed  $K^+$  limits clay dispersion due to its hydration energy, which is equivalent to 72% of that of adsorbed  $Na^+$  (Levy and Torrento 1995). Carbonates probably prevent the decomposition of organic matter, which can be deduced from the evolution of the respiration rate during a growing season and from differences in the stability of aggregates when mineral and organic fertilizers are compared.

The introduction of pig slurry in fertilization strategies benefits porosity, mainly in the range area of 25-200  $\mu m$ , but this is a transitory effect. These pores are associated with capillary water movement, soil aeration, rapid water drainage and root growth (Bosch-Serra et al. 2017). The dose for pig slurry should be established through the thresholds imposed by legislation on the addition of total nitrogen to soil to avoid contamination by salinity and highly soluble and water-movable nitrates (Directiva del Consejo 91/676/EEC). The dose of pig slurry applied increases the initial salinity values significantly and if unsuitable doses are used, they can be limiting initially in the establishment of the plants (Bosch-Serra et al. 2000). Furthermore, according to Salazar et al. (2009), high doses of slurry have significantly more nitrates than low doses and the highest values of nitrates occur at the surface. The application of pig slurry contributes to the improvement of soil fertility by facilitating greater colonization of natural vegetation (Kabas et al. 2012).

Contrary to what is often observed for solid animal manure, the application of liquid pig manure does not always increase the C content in the soil (Plaza et al. 2005; Carter and Campbell 2006; Angers et al. 2010), partly because of its low C content and rapid mineralization (Rochette et al. 2000; Chantigny et al. 2001; Pardo et al. 2011). The organic matter fraction of pig manure is composed largely of fast-decomposing organic C that may not contribute significantly to stabilizing organic matter. In addition, its high labile C and available N and P contents could accelerate the decomposition of native soil C (Peu et al. 2007; Rochette et al. 2000). Therefore, the application of carbonates seems to be useful to stabilize fresh and very labile organic matter, as is the case with pig slurry.

On the other hand, due to the release of root exudates in the rhizosphere, the application of pig slurry increases TOC and TN, improves soil structure and provides nutrients for microbial populations, which are the basis for ensuring ecosystem recovery. In addition, pig slurry is a good fertilizer due to the large amount of nutrients provided, which are necessary to promote the development of vegetation. Therefore, the use of this waste to recover degraded soils is of great interest, although some procedures, such as liming, must be carried out to minimize the rapid mineralization of organic matter from this type of waste (Zornoza et al. 2012). An increase in soil organic matter content also favours an increase in soil cation exchange capacity (CEC) (Kabas et al. 2012). Zornoza et al. (2017) demonstrated that there was a significant increase in CEC after the application of pig slurry.

Nitrogen is an essential element for vegetation and microbial communities. The increase in N improves the nutritional conditions of the soil and helps the growth and development of the introduced plants. With the application of pig slurry, shortly after a year, production and the different extractions and losses of nitrogen tend to balance out their concentration (Salazar et al. 2002). However, this TN decreases with time, which could be due to plant absorption, and immobilization by microbial biomass. To prevent the lack of TN that could limit the development of vegetation, it would be interesting to include legumes among the species introduced in the revegetation, in order to increase the availability of this nutrient through biological fixation of atmospheric N (Zornoza et al. 2017).

The microbial population increases after the application of pig slurry due to the increase of soluble C. Availability of C should allow the possibility of growth of microorganisms (Pérez de Mora et al. 2005). In addition, pig slurry also contains microbial biomass that can be incorporated into the soil. However, with the depletion of the labile fraction of organic matter, microorganisms do not maintain their growth and return to initial values in about 25 days (Plaza et al. 2007; Pardo et al. 2011; Zornoza et al. 2013). The same trend was observed for b-galactosidase and b-glucosidase activities associated with soluble C dynamics (Zornoza et al. 2012). However, fungal growth is more

stable over time, indicating a progressive and continuous growth that depends not only on the most labile organic compounds but also on the total organic carbon content of the soil. Fungi are able to degrade more complex organic compounds (Griffith and Bardgett 2008), which may allow for more stable growth over time.

The addition of marble waste in combination with pig slurry produces an accumulated bacterial growth (Zornoza et al. 2016). Bacterial and fungal growth rates are dependent on the pH and soluble and labile fractions of organic matter. From pH 4 to pH 8, the growth of fungi to bacteria changes about 30 times. The fungi are favored by a lower pH. This trend towards the different effect of pH on bacteria and fungi has previously been observed (Rousk et al. 2009, 2010; Fernández-Calviño et al. 2011). Pig slurry promotes faster microbial growth probably due to the higher content of soluble labile organic compounds (Zornoza et al. 2016).

The use of pig slurry has positive effects on the rehabilitation of mining soils, improving soil properties and increasing germination (Pardo et al. 2011; Zornoza et al. 2017).

### 7.7. Pig manure

Pig manure is an environmentally attractive amendment to prevent the formation of acid drainage from metal mines due to its high pH and presence of lime. It can be incorporated as part of long-term remediation process in abandoned mines and areas affected by mining activity.

The basic characteristics of pig manure are 13.5% humidity, 57% of CaCO<sub>3</sub> and 28.1 g/kg of TN. The study consulted shows that pig manure increases pH and improves conditions for plant growth (Faz et al. 2008).

With the application of pig manure, studies have shown a preliminary increase in pH, TN, organic carbon and equivalent calcium carbonate content, and a reduction in Zn, Bp and Cd, as well as a decrease in EC. It has also been observed that the pH does not have the capacity to neutralise acid in the leachate in the short term when this waste is applied (Faz et al. 2008). Aggregate stability increases significantly with

the application of pig manure and in addition, it produces a large fungal growth in soils and increases the concentrations of the saturated PLFAs (Zornoza et al. 2016). Several studies show the ability of pig manure to efficiently adsorb metal, reducing their availability in soil (Beesley et al. 2011; Park et al. 2011; Kelly et al. 2014; Zornoza et al. 2016).

#### 7.8. Marble waste

Waste from these calcareous quarries usually has a high apparent density and a massive structure, which gives them low filtration rates, triggers soil erosion processes and increases runoff (Moreno de las Heras et al. 2008). Its combined use with organic materials can be positive since carbonates and clays stabilize organic carbon and make it more inaccessible for microbial attack (Bernal et al. 1991). Therefore, the application of marble reduces the degradability of organic compounds. This is of particular interest for improving the accumulation of C in regenerated soils from the point of view of C sequestration (Shrestha and Lal 2006). Studies have shown that the application of marble sludge leads to an increase in soil pH and favours the accumulation of soil organic matter (Zornoza et al. 2017). The presence of calcium from marble sludge can favour the bonds between clay minerals, and promote intermolecular interactions between organic and inorganic compounds, forming aggregates (Baldock and Skjemstad 2000; Clough and Skjemstad 2000).

According to Kabas et al. (2012), marble waste inhibits plant development, probably due to the presence of higher contents of salts and clays, whereas according to Risser and Baker (1990), these residues can be used to neutralize the acidity of many types of mining waste. This favours the establishment of vegetation and increases the availability of nutrients such as K, C, Mg, Mo or P, which are more mobile at pH about 6. The application of marble waste stabilizes organic matter, microorganisms and enzymes involved in the degradation of more complex molecules to degrade organic matter, such as arylsterase, which could be used as an indicator of organic matter stability. If only marble waste is used, the biochemical properties of the

soil do not increase, indicating that changes in these properties are mainly due to the organic matter provided, verified with the use of pig slurry (Zornoza et al. 2013). The application of marble sludge together with pig slurry increases the growth of native vegetation, increases vegetation cover and biodiversity (Kabas et al. 2012).

#### 7.9. Pig manure with marble waste

This waste combination, as mentioned previously, offers aspects that should be considered. It was observed that this combination can reduce the available water but also improves the establishment of vegetation. It appears that the application of lime or alkaline materials together with the use of double doses of pig manure is a reasonable alternative for remediation of soils in acidic mining areas. However, it has been indicated that salinity should be considered with medium- and long-term monitoring (Faz et al. 2008).

## 8. Conclusions

In the XXI century, the mining industry stands out as one of the most important sectors when providing essential materials for economic development. However, great effort needs to be made to improve the economic, social and environmental aspects of this industry. This includes the need to rehabilitate the affected areas taking into account all the social agents involved in its development (administration, neighborhoods, town halls, etc.).

This review works on the importance of organic matter in the restoration of soils in areas affected by mining, in particular by open-pit extractive activities. It aims to highlight the great possibilities presented through the research and work generated in the last 20 years. The use of organic waste of many different kinds is feasible; however, not only the positive aspects have to be considered, but also the negative ones such as possible pollutants that are emitted as a

result of the quarrying activity. It should be noted that most of these are expected to be gases (CO<sub>2</sub>) from the combustion of the engines of the machines and the trucks used to transport the quarry materials and the waste. As a preventive measure in this regard, it would be advisable to have the ISO 14,000 standard and to have an environmental management system that establishes periodic maintenance of vehicles and/or equipment in general. This maintenance contributes to improving combustion and making it as efficient as possible, generating the least amount of carbon dioxide. In short, pollution is a limiting factor for the use of waste.

The major conclusions are that the increase of soil organic matter, the improvement in revegetation and the increase in water retention capacity are the most noteworthy aspects in a semi-arid environment such as the Murcia region.

As mentioned above, waste production is a crucial problem. Therefore, different ways of reusing waste that do not pollute the environment and can be reintroduced into economic activity in the frame of circular economy are sought.

## 9. Future actions

Future lines of research, complementing soil and vegetation aspects, are proposed. The first could be the improvement of habitat conditions for wildlife and the use of wildlife as an indicator, although the wildlife colonization of a restored quarry does not occur immediately because there is no habitat to support it. The main improvement for the fauna, in the beginning, is the restoration of vegetation and recovery of the original habitat. Except for some species of birds and mammals quite elusive to human presence, wildlife may be present in the early stages of the exploitation if restoration is initiated from the early stages (favouring the landscape evolution and habitat). The diversification of the flora species used in plant restoration results in a significant improvement in the landscape. Even more importantly, it supports a greater number

of wildlife species and increases the stability of the system. For this reason, a non-homogenous restoration is important. Other actions that can specifically help wildlife are sowings on debris or other altered spaces in which cereals and other cultivated plants are planted as a first-rate food source for many birds and mammals, as evidenced by numerous small plots used in hunting.

In line with the above, a high biodiversity footprint remains a key area of work. This includes both efforts to minimize the potential negative impact on biodiversity and to seek opportunities to increase it. Achieving a net positive impact (NPI) is a challenge for the future.

To achieve the target, it is proposed to work with major building materials companies to help actively reverse the trend of declining global biodiversity. As a proposal for future lines of work, it could be agreed to work within the following objectives:

- Reduce the ecological footprint on climate change through improved energy efficiency of installations, the use of renewable energy and special low carbon footprint cements.
- Improving knowledge and control of persistent organic pollutants, through systematic measurements, development and implementation of best practices, reporting on progress made.
- Reduce water consumption in operations and aim to improve knowledge of water flows by developing practices for their control.
- Analyze the potential of biodiversity in our quarries to study and develop biodiversity management programs; and aim to reduce the impact of quarries on biodiversity.

In conclusion, the general objective, is to achieve a positive net balance in nature after mining activities.

The second future line is the creation of artificial lagoons in the quarry and gravel exploitation sites that collect rainwater, thus creating lake spaces of great ecological value. These would serve as a refuge for many aquatic species and

allow the development of some amphibians and invertebrates. Instead of generating a large single lagoon, it is preferable to build several small lagoons with different ecological slope conditions, etc., because the possibilities for different types of fauna are greatly increased. Once space and spatial distribution are known, it will be necessary to generate the gaps in the lagoon in which rainwater will be deposited. In this type of design, there should be at least two depths, one more shallow to allow amphibian spawning and larval growth, and a deeper one for temporary maintenance of adults and other wildlife species that need more time in its development like some dragonflies, beetles, etc.



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