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Plants used for soil decontamination in Colombia: A systematic review
Plantas utilizadas en la descontaminación de suelos en Colombia: una revisión sistemática

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KEYWORDS
Colombia, phytoremediation, soil conservation; wildlife
Colombia, conservación del suelo, fitorremediación, fauna silvestre

ABSTRACT: Soil is the habitat of different kinds of vegetation and wildlife, as well as being used for various anthropogenic activities, such as the extraction of fossil fuels, agriculture, and mining, among others, which can contaminate the soil. The use of plants for soil decontamination has begun to be used as a bioremediation strategy to return the contaminated area to conditions similar to the original ones. In the following Systematic Review (SR) of scientific literature without a time limit, the plants used in Colombian soils are described. Four databases were used: ScienceDirect, SpringerLink, Scopus and Scielo through thirteen search paths. By evaluating various inclusion and exclusion criteria, the search retrieved a total of seven original articles. In the SR, it was found that the most studied contaminants in phytoremediation in Colombian soils are heavy metals and hydrocarbons. It was concluded that the implementation of plants in the soil allows a considerable reduction in contamination.

RESUMEN: El suelo es el hábitat de muchas especies de flora y fauna, además de ser utilizado para diversas actividades antropogénicas como son la extracción de combustibles fósiles, agricultura, minería entre otras, las cuales pueden llegar a contaminar el suelo. El uso de plantas para la descontaminación de suelos se ha utilizado como una estrategia de biorremediación, con el objetivo de retornar la zona contaminada a unas condiciones similares a las originales. En la siguiente revisión sistemática (RS) de literatura científica sin límite de tiempo, se describen las plantas utilizadas en suelos colombianos. Se usaron cuatro bases de datos: ScienceDirect, SpringerLink, Scopus y Scielo mediante trece rutas de búsqueda. Al evaluar diversos criterios de inclusión y exclusión, la búsqueda arrojó un total de siete artículos originales. En la RS se encontró que los contaminantes más estudiados en la fitorremediación de suelos colombianos son los metales pesados e hidrocarburos y se concluye que la implementación de plantas en los suelos permite obtener una disminución considerable en la contaminación.

1. Introduction

Soil is an essential component of the environment in which life develops; it is vulnerable, difficult, and long to recover, and of limited extension, which is why it is considered a non-renewable natural resource[1]. Likewise, it is an essential resource on which the health of people, the species of macro and microorganisms, and plants that inhabit it depend[2].

The term "soil contamination" refers to the presence of a chemical or substance off-site and/or present in a higher concentration than normal that has adverse effects on any organism, soil contamination often cannot be directly evaluated or perceived visually, making it a hidden danger[3]. This can occur due to natural activities such as volcanic eruptions and the weathering of rocks, or due to anthropogenic activities such as rapid industrialization (mining, oil extraction, among others) and urbanization[4], [5].

The report presented in 2018 by the FAO (Food and Agriculture Organization of the United Nations) indicates that soil contamination has increased on an unprecedented scale. For example, it is estimated that Australia has 80,000 sites with contaminated soil. For China, 19% of its agricultural soils are contaminated and, finally, for the United States, there are 1,300 sites with a critical level of contamination[6], worsening the degradation of the ecological environment, increasing the demand for food and the earth's natural resources, decreasing or limiting its ecosystem services, and causing population displacement[7].

According to the Ministry of Environment and Sustainable Development (2016), in Colombia there are approximately 1,843 sites considered potentially contaminated, by a variety of economic sectors such as mining, petrochemicals, hazardous waste management, among others.[8] In gold mining, the amalgamation process has been studied mainly in the departments of Antioquia, Bolívar, Chocó, and Córdoba, finding high concentrations of mercury in different environmental matrices and living beings, with some values exceeding permissible limits[9], [10].

In Colombia between 2015 and 2022, approximately 2,133 incidents and hydrocarbon spills occurred, mainly in the departments of Santander with 41% of the cases, followed by Boyacá (12.8%) and Antioquia (10.5%), causing an alteration in quality of the landscape and the ecosystem services that ecosystems provide for the normal development of the life of human beings[11].

Phytoremediation is a suitable technique for stabilizing, degrading, transforming, or immobilizing organic and inorganic contaminants such as heavy metals, pesticides, explosives, among others[12], and improve soil and water quality because some plants can easily accumulate these contaminants through different physical and biochemical mechanisms in their roots, leaves, or stems[13], [14].

The removal of contaminants in soils using phytoremediation allows the use of different plants according to the conditions of the soil and the contaminant to be treated, as is the case of *Raphanus sp*. which reduces organic contaminants by up to 90% of the initial concentration[15]; of the *Amaranthus spinosus* plant, which has shown a high removal of metals such as copper (Cu), zinc (Zn), lead (Pb), and cadmium (Cd) from contaminated soils of a mechanical workshop and a landfill, obtaining for Cd the highest removal percentages between 48.60% and 72.47%, respectively[16]; and the herb *Brachiaria brizantha*, showed good removal of petroleum derivatives in Venezuelan soil[17], like legume trees such as *Acacia angustissima*, *Acacia auriculiformis*, decreased the concentration of hydrocarbons in Brazilian soil[18].

Plants used in phytoremediation can be managed as low-cost extraction and purification entities. Some degradation processes occur more quickly with plants than with microorganisms, and it is appropriate to decontaminate large surfaces or to complete the decontamination of restricted areas over long periods of time[11], [19].

Unlike the physical and chemical techniques used in soil recovery, phytoremediation is a great alternative for the elimination, decontamination, and primary isolation of toxic substances in soils because it does not strongly alter soil structure or fertility. In addition, it is more environmentally friendly since it does not always or very rarely generate the release of secondary pollutants, nor does it require high operating costs, specialized personnel, and high energy costs[7], [20], [21].

Phytoremediation is a little explored technique in Colombia, with dispersed information and satisfactory results for the recovery of contaminated soils. The present study aims to collect information through a systematic review (SR) of the scientific literature, without time limit, that describes the plants implemented in contaminated soils in Colombia for phytoremediation.

2. Materials and methods

2.1. Search strategy

Four bibliographic databases were consulted, which were: ScienceDirect, Springer, Scopus, and Scielo, with the Prisma Declaration as reference[22] for this type of studies. The sensitivity and specificity criteria were considered; sensitivity was executed with the AGROVOC and MESH descriptors, and specificity was executed with the use of Boolean operations and free terms defined according to the research question. Various search routes were used, as shown in the following table (Table 1).

Table 1. Search routes

Magazine	Search Path
ScienceDirect	Phytoremediation AND Colombia AND "soil pollutants"
	Phytoremediation AND Colombia
	(Phytoremediation OR Plant remediation) AND Colombia
Springer	Phytoremediation AND Colombia AND "soil pollutants"
	Phytoremediation AND Colombia
	(Phytoremediation OR "Plant remediation") AND Colombia
Scopus	Phytoremediation AND Colombia AND "soil pollutants"
	Phytoremediation AND Colombia
	(Phytoremediation OR "Plant remediation") AND Colombia
Scielo	Phytoremediation AND Colombia
	(Phytoremediation OR "Plant remediation") AND Colombia
	Phytoremediation AND Colombia
	(Phytoremediation OR "Plant remediation") AND Colombia

The Mendeley Desktop V.2.76.0 reference manager was used to eliminate duplicate articles. The results obtained, after elimination, were organized in Microsoft Excel, and a first review of the articles was performed based on reading the abstract.

2.2. Inclusion and exclusion criteria.

The following generic inclusion criteria were defined: original articles written in English or Spanish, published in indexed journals, and without a time limit. Subsequently, the articles were subjected to the first selection filter under the following inclusion criterion: "*phytoremediation evaluated in the soil matrix*." Finally, to make the search more exhaustive, "*phytoremediation carried out with contaminated non-Colombian soil*" was defined as an exclusion criterion.

With the final articles, a peer review was performed to reduce or eliminate any uncertainty, and differences were analyzed and resolved by mutual agreement.

The final 7 articles were analyzed based on the plant used, type of contaminant, geographical location of the study, and the percentages of removal or reduction of the concentration of contaminants.

3. Results and discussion:

After implementation of the established search protocol, 254 results were obtained (ScienceDirect 12, Springer 179, Scopus 49 and Scielo 14). Subsequently, a Mendeley search manager was implemented to eliminate the 147 duplicate files. In the database constructed, 77 publications were analyzed based on the title and content of the abstract, and 67 of these were discarded for not complying with the inclusion criteria related to the defined research question. Ten (10) full-text articles were analyzed, where 3 were eliminated for meeting the exclusion criteria. Therefore, the search protocol yielded a result of 7 articles for SR (Figure 1).

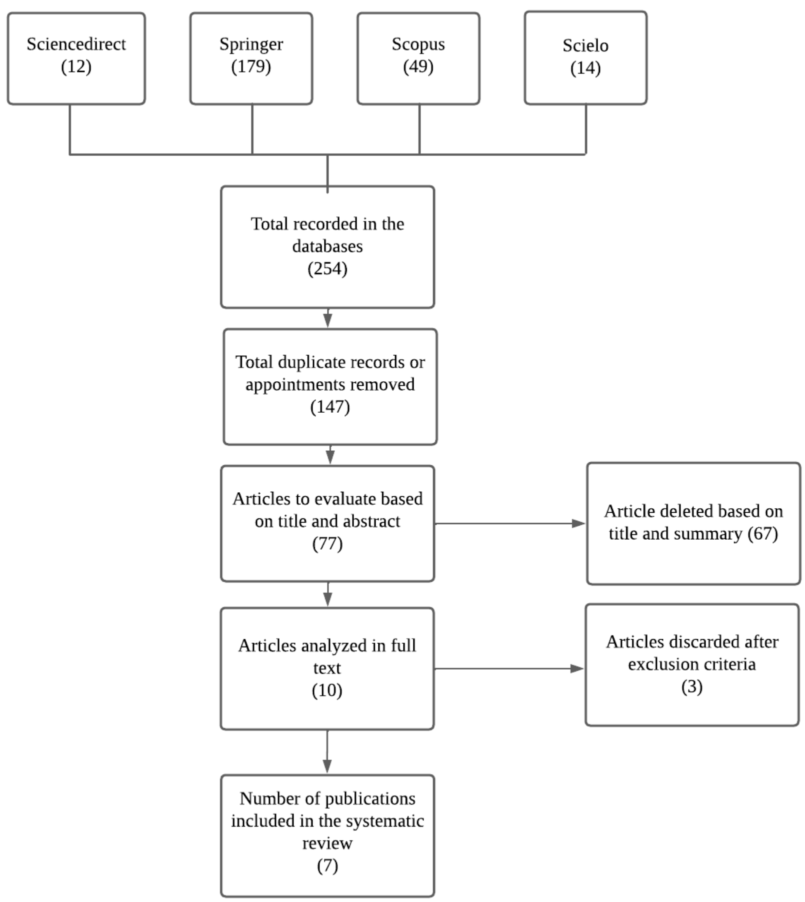

Figure 1. Search Strategy Flowchart

During the analysis of the 7 articles that entered the SR, a range of publications was identified that ranged from 2005 to 2022. Likewise, the geographical distribution of the departments or areas in Colombia in which the research was performed and the respective magazines where these were published (**¡Error! No se encuentra el origen de la referencia.**).

Table 2. Articles analyzed in the study.

Author	Magazine	Department or geographic area
[13]	Chemical Engineering Transactions	Bolivar
[23]	plants	North Colombia
[24]	Science of the Total Environment	Córdoba
[25]	International Journal of Environmental Science and Technology	Western Colombia
[26]	Water, Air, & Soil Pollution	Casanare
[27]	Colombian Biological Act	Antioquia
[28]	Chemosphere	Unspecified area

An analysis of the geographical location of Colombia where the RS phytoremediation processes were conducted showed that 73% of the plants were used in the department of Córdoba, followed by 12% in the department of Antioquia (Figure2). It can be stated that, as a consequence of the high legal and illegal mining activity in these two departments, there is high contamination by heavy metals in the soil, originating from different stages of the mining production process (extraction, transportation, among others), since in Colombia, the informality of Artisanal and Small Scale Mining (ASM) reached 87% of the Mining Production Units[29]. According to DANE statistics for 2021, the department of Córdoba in foreign trade contributes 72% in the export of nickel (Ni) and Antioquia contributes 60% in the export of gold (Au)[30], which generates mercury (Hg) pollution.

The contamination of heavy metals in soils, produced mainly by industrial activities such as mining, affects food and environmental safety and therefore human health, with the presence of these metals in the environment being one of the causes developing cancer[31]–[33]. The presence of mercury causes neurological health damage, hormonal alterations, kidney damage, infertility, among others[34].

Hydrocarbons cause damage to the central nervous system and increase the possibility of developing cancer, such as leukemia, and liver damage in humans[35].

The above shows the need to promote phytoremediation studies for the recovery of these soils and thus reduce the effects that these toxic compounds generate on health and the environment.

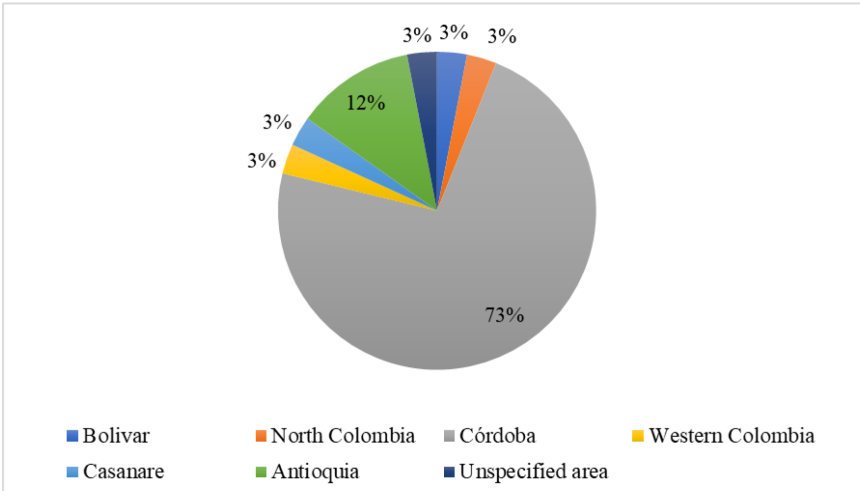

Figure2. Geographic distribution of plants used in phytoremediation processes in Colombia.

In the 7 articles analyzed from the SR, 33 plant species were identified and used to evaluate their potential in the phytoremediation of soil contaminants. Of these, the two most used species were *Helianthus annuus* and *Clidemia sp* in 2 investigations. The total number of plants evaluated are shown in (Figure 3).

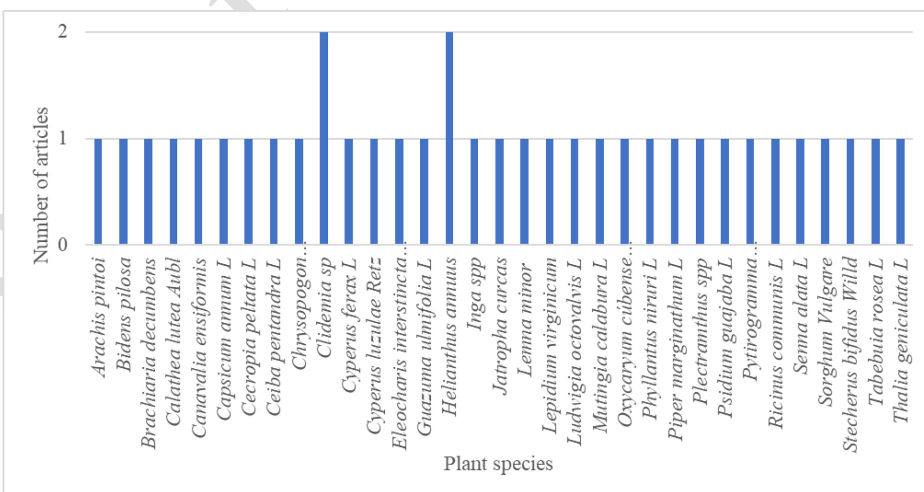

Figure 3. Genus of plants used for phytoremediation in the analyzed articles.

H. annuus is a herbaceous plant native to Central and North America. In Colombia, it is an introduced species and is found mainly in the Caribbean area[36], [37]; considered a plant with high tolerance to heavy metals[38]. Likewise, *H. annuus*, depending on the type of metal, can mobilize it to the roots, leaves and upper parts of the plant through various mechanisms.[39]. In the research of C. Turgut et al.[28] *H. annuus* is used to remove heavy metals such as Cd, Chromium (Cr) and Ni. Finding that this plant is the most efficient for the removal of Cr, followed by Ni and finally Cd with help of EDTA. EDTA at a concentration of 0.1 g kg-1 favored the absorption of Cr, while at a concentration of 0.3 g kg-1 it favored the absorption of Ni, and for Cd this was found below the detection limits.

Additionally, *H. annuus* has been used to remove copper (Cu) and it was determined that, with the help of bacteria, the development of plants is increased through an increase in the availability of nutrients, to improve the absorption capacity of the Cu; Furthermore, bacteria can bioaccumulate Cu, and most of them use aromatic hydrocarbons as a carbon source[13], [25], [26], [40]. Therefore, The combination of phytoremediation with other techniques increases the removal of contaminants, favoring the growth and absorption capacity of plants; They help the recovery of soils by increasing the bacterial community and dissipating and eliminating contaminants[40]–[42].

Other research has shown that *H. annuus* is useful for the removal of heavy metals such as Cd and Pb in soils, such as those in Australia[38]; as well as it has also been used in Perú for the removal of Cd[43], achieving that due to its high biomass, high growth rate and its absorption capacity, it allows the elimination of heavy metals, accumulating contaminants mainly in the roots. Additionally, the above accounts for their physiological plasticity to adapt to a multitude of ecosystems, which is mainly due to the fact that they can change their biochemical characteristics in response to external stimuli[38], [43].

Many studies have been performed on the benefit of using *H. annuus* in phytoremediation, because they can stabilize metals by storing them in leaf tissues and roots due to the presence of functional groups in the secretions of this[44].

The articles evaluated in the SR showed that the most studied contaminant is Cd (43%), and the least evaluated were Pb and Cu (14%), as shown below in (Figure 4).

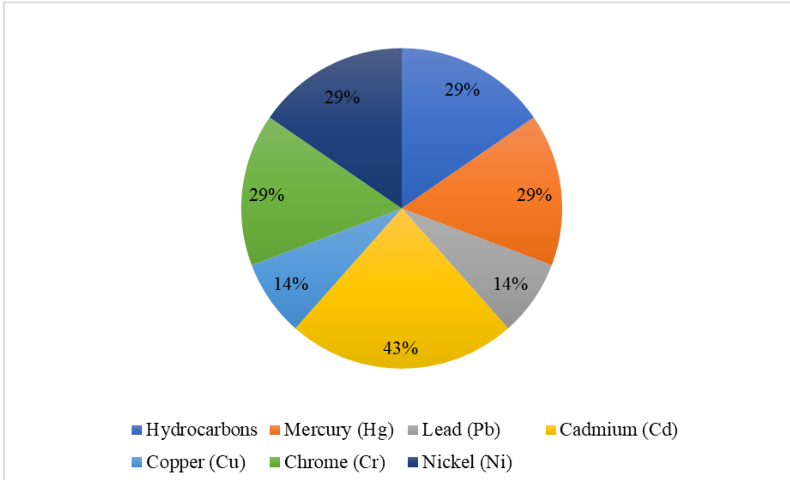

Figure 4. Pollutants evaluated in the RS

The (Figure 4) shows that the contaminants most treated in phytoremediation processes in Colombia are heavy metals with 71%, this is in accordance with the contamination associated with industrial activities, which generate the deterioration of the soil and its disqualification for any type of activity.[45]

In research performed with soils contaminated by heavy metals such as Cd, Cr, and Hg, extracted from gold mining areas in northern Colombia, the phytoremediation capacity of *Clidemia sericea D.*[23] Was evaluated and it was found that the highest concentrations of metals were present in the roots compared to the stems and leaves.

In soils contaminated with heavy metals such as Cd, Cr, and Ni, from the Moravia landfill[27], the phytoremediation potential of *Bidens pilosa*, *Lepidium virginicum*, *Brachiaria decumbens*, and *Arachis pinto* plants was evaluated, finding that they have good tolerance to high levels of heavy metals, as no significant symptoms of phytotoxicity were observed. The metals concentration was determined when the plants were planted for 60 and 105 days, where, according to the accumulation of metals in plants, their tissues showed the maximum bioconcentration values. Hence, the ecology and distribution of plants must be studied in relation to the physicochemical conditions of the environment and not in isolation.

On the other hand, Hg, a metal with high environmental impact due to its ability to bioaccumulate and exhibit high levels of toxicity, has also been detected in Colombian soils. In a publication by Marrugo-Negrete et al[24], where they focused on using plants that grew in the area near the Alacran Mine, whose site is contaminated with Hg, 24 different plants were found, of which three stood out: *Jatropha curcas, Thalia geniculata L., Piper marginathum,* being They are very common in mining areas of tropical regions without being from the same family due to their high resistance to these conditions, generating bioaccumulation percentages of 99%, 91%, and 91%, respectively.

In another investigation carried out by Marrugo-Negrete et al[46], *Jatropha curcas* was used to recover soils contaminated with Hg, finding that the greatest accumulation occurred in the roots and leaves, in addition to being a plant that easily adapts to soils eroded by mining activities, promoting conservation and restoration of these.

Additionally, at the time of carrying out the systematic review, more bibliographic material was found for phytoremediation in water sources than in soils, finding articles such as the case of *Limnocharis flava* [47] were used for the removal of Hg in wetlands in the department of Córdoba, showing a reduction in the concentration of this metal by 90%, with greater retention in the roots. On the other hand, the removal of heavy metals from the Bogotá River was evaluated using macrophytes such as *Polygonum punctatum*, *Eichhornia crassipes,* and *Myriophyllum aquaticum*, showing greater accumulation in areas that were submerged, such as rhizomes and roots.[48]

In the department of Cauca, Duckweed (*Lemna minor*) was used for treating wastewater originating from the washing of fique fiber (*Furcraea bedinghausii*). The phytoremediation capacity of this plant was evaluated by measuring physicochemical parameters such as chemical oxygen demand (COD) and biological oxygen demand (BOD5); The biggest advantage of treatments involving aquatic plants compared with conventional ones is that they require a lower cost of construction and maintenance.[49] Finally, in Cali, the phytoremediation capacity of twenty microalgae was evaluated for the elimination of pharmaceutical contaminants in domestic waste, showing reductions greater than 50%[50].

A complication that can arise when performing phytoremediation of Hg is that plants can phytovolatilize it and release it into the environment in its elemental form, Hg (0). When it comes into contact with the atmosphere, where species such as ozone (O_3) and sulfur dioxide (SO_2) are present, it can revert to the form Hg (II), which is the most reactive form of this compound, causing an even greater problem. Additionally, when deposited in the soil, it can transform into methylmercury, a highly toxic compound [51]. This occurs because, during phytovolatilization process, plants absorb contaminants from the soil and convert less volatile compounds into more volatile forms, releasing the contaminants into the atmosphere through volatilization[52].

Finally, phytoremediation has been mostly studied in areas with high soil contamination levels. For this reason, when conducting a process of this type, it is important to analyze the physicochemical characteristics of soils with the aim of selecting an appropriate plant, that can mitigate contamination and improve the physical conditions of humidity, texture, structure, and the rest. In addition to evaluating whether species released into the environment do not generate an effect of greater toxicity.

4. Conclusions

It is concluded that most phytoremediation studies on contaminated soils in Colombia have been carried out to remove heavy metals such as Cr, Cd, Pb, and Hg, among others. The location in the country where the greatest number of plants with bioremediation potential have been evaluated was in the department of Córdoba (24 different species), which can be attributed to mining activities in the area and the need to mitigate, in part, the adverse effects on ecosystems.

It was found that *H. annuus* is highly used for soil remeasurement through the phytoremediation technique, to stabilize metals by storing them in leaf tissues and roots.

During the search for information for the SR, it became evident that few studies have been carried out in the country to evaluate phytoremediation as a mechanism for the reduction and/or elimination of various contaminants in Colombian soils in comparison with water sources. However, it can be observed that it is a very promising technique for the recovery of contaminated soils due to its versatility and low costs.

5. Declaration of competing interests

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests , that interfere with the full and objective presentation of the work described in this manuscript.

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7. Author contributions

Led the conceptual and methodological phase of this type of scientific study that encompasses theoretical research: L. M. Múnera-Porras; developed the methodological phase, including the incorporation of studies in coherence with the PRISMA guidelines, the delineation by inclusion and exclusion criteria, and the analysis of information: M. F. Sarmiento-Gamero and M. V. Orozco

The researchers worked together to resolve any disagreements about which participants to include or exclude, and they made decisions by reaching a consensus among the three of them.

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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