ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.2, e274674, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n2e274674 Review

Bibliometric and multicriteria analysis for selection of amendments potentiators of compost from municipal biowaste[1]

Análise bibliométrica e multicritério para seleção de aditivos potencializadores de compostagem de biorresíduos municipais

Victor A. L. Sandoval[2*], Johan S. T. Corredor[3], Sahra N. R. Rincón[3] & Kimberly P. Montañez-Medina[4]

[1] Research developed at San Gil University Foundation, Yopal, Casanare, Colombia
[2] Sergio Arboleda University/Faculty of Natural Sciences and Engineering/Environment and Sustainability Research Group, Bogotá D.C., Colombia
[3] San Gil University Foundation/Faculty of Natural Sciences and Engineering/TERRANARE Research Group, Yopal, Casanare, Colombia
[4] Lund University/Department of Physical Geography and Ecosystem Science, Lund, Skane, Sweden

HIGHLIGHTS:

Relevant topics such as municipal waste, industrial demand, and economic contribution set trends in research.
Availability and cost logistics affect the quality of nutrient and carbon amendment for municipal biowaste composting.
Analytic hierarchy process: economic tool to decide how to improve municipal biowaste compost quality in a specific region.

ABSTRACT: Municipal biowaste has a high potential for agricultural use. However, it requires an additional amendment to increase the nutritional content used during the composting process. The purpose of this study was to investigate the selection of compost-enhancing amendments from municipal biowaste using bibliometric and multicriteria analysis. The municipality of Yopal (Casanare, Colombia) was chosen as a case study. Using a search equation in the Scopus and Web of Science databases over five years (2018-2022), 53 publications were discovered, from which 25 were chosen for a full review to identify alternatives for amendment. Ashes, rice husks, sawdust, sugarcane bagasse, tree pruning waste, and alfalfa hay were assessed as amendment substitutes. Criteria such as financial cost, accessibility to acquire the amendment, nitrogen, phosphorus, and carbon contribution were used in the analysis of hierarchical processes. Tree pruning waste was the best option based on the criteria chosen because it is easily accessible and contributes with carbon and nitrogen (C/N: 13) to composting. Factors such as cost and affordability influence the physical and chemical characteristics that an amendment brings to the composting of municipal biowaste.

Key words: organic waste, amendment alternatives, composting, analytical hierarchy process

RESUMO: Os biorresíduos municipais têm um elevado potencial para utilização agrícola. No entanto, requer uma alteração adicional para aumentar o conteúdo nutricional utilizado durante o processo de compostagem. O objetivo deste estudo foi investigar a seleção de aditivos melhoradores de compostagem a partir de resíduos biológicos municipais, utilizando análise bibliométrica e multicritério. O município de Yopal (Casanare, Colômbia) foi escolhido como estudo de caso. Utilizando uma equação de busca nas bases de dados Scopus e Web of Science ao longo de cinco anos (2018-2022), foram descobertas 53 publicações, das quais 25 foram escolhidas para uma revisão completa para identificar alternativas de alteração. Cinzas, cascas de arroz, serragem, bagaço de cana-de-açúcar, podas de árvores e feno de alfafa foram testados como substitutos de emendas. Critérios como custo financeiro, acessibilidade para aquisição do aditivo, aporte de nitrogênio, fósforo e carbono foram utilizados na análise dos processos hierárquicos. A poda de árvores foi a melhor opção pelos critérios escolhidos por ser de fácil acesso e contribuir com carbono e nitrogênio (C/N: 13) para a compostagem. Fatores como custo e acessibilidade influenciam as características físicas e químicas que uma alteração traz para a compostagem de biorresíduos municipais.

Palavras-chave: resíduos orgânicos, alternativas de emenda, compostagem, processo de hierarquização analítica

• Ref. 274674 – Received 31 May, 2023
* Corresponding author - E-mail: valizcanos@gmail.com
• Accepted 28 Oct, 2023 • Published 24 Nov, 2023
Editors: Ítalo Herbet Lucena Cavalcante & Carlos Alberto Vieira de Azevedo

Introduction

The production of municipal solid waste (MSW) is a global environmental concern that implies economic, political, and social challenges for a growing population and demand for natural resources. MSW is classified into two types: biodegradable and non-biodegradable. Municipal biowaste (MBW) falls into the first category; these are renewable resources capable of being converted into energy and other raw materials (Nanda & Berruti, 2021). The conversion of MBW into compost produces humus, which can be used as a fertilizer (Kozlov et al., 2020). Compost is a source of carbon, nitrogen, phosphorus, and potassium, and it can improve aggregate stability, cation exchange capacity, and microbial dynamics in soils. It also aids in water retention in soils with a high sand concentration, increasing the amount of water available to plants (Nanda & Berruti, 2021).

However, some organic residues used for composting have low carbon or nutrient contents, which limits the nutritional needs of the microorganisms in charge of the process (Götze et al., 2016). For this reason, amendments or co-substrates are frequently used to help close this nutritional gap and increase the benefits of compost. Finding an ideal amendment to compost MBW is a time-consuming process because factors such as the nutritional contribution of this type of waste must be considered, as its availability for use in a specific geographical area (Sayara et al., 2020).

Since there is a wide variety of amendments to improve compost properties from MBW, this study aimed to investigate the selection of compost-enhancing amendments from municipal biowaste using bibliometric and multicriteria analysis. The city of Yopal (Colombia) was selected as the case study region for this research.

Material and Methods

VOSviewer (v. 1.6.18) was used as technology watch software to scan the global literature related to MBW composting and the use of supporting amendments. Only articles and reviews published in the last five years (2018-2022) in Web of Science (WoS) and Scopus databases were considered.

In the technological surveillance process, the following keywords and operators were the primary focus of the search equation: "municipal biowaste" AND "composting" AND "amendment" AND "soil". Duplicate results from each database, non-indexed and in-press scientific articles, were excluded from the analysis of the search engine results. Each shortlisted manuscript was evaluated to identify the types of amendments associated with MBW composting.

The amendment to complement the MBW composting in this study region (Yopal City, Casanare, Colombia) was selected using the analytic hierarchy process (AHP). Through bibliometric analysis, different amendment alternatives were selected and prioritized for evaluation according to the following criteria: economic cost (C_1), accessibility of the amendment in the study area (C_2), supply of nutrients like nitrogen and phosphorus (C_3), and carbon contribution (C_4).

Each alternative (A_m) and criterion (C_n) was paired and scored using the numerical ratings shown in Table 1. Each assigned score was organized in a matrix (S) forming reciprocal comparisons (Eq. 1). The reciprocity of the matrix S satisfies that $S_{i,j} = 1/S_{j,i}$, for each i row and j column. The matrix S is denoted as $S_{n,n}$ for n criteria and $S_{m,m}$ for m alternatives. Every paired comparison between alternatives was made in $S_{m,m}$ considering each criterion.

Given the S matrix, each element ($S_{i,j}$) was divided by the total sum of its columns (ΣS_j) to obtain the normalized comparison matrix ($S_{i,j}$ Normalized) (Eq. 2). The importance weights (W_i) for each criterion and alternative, was calculated from the average values of each normalized comparison matrix (Eq. 3). N corresponds to the total number of criteria or alternatives evaluated.

$$S = \left[S_{ij}\right] = \left[\left(1,\ldots,S_{1,j}\right),\ldots,\left(S_{i,1} = \frac{1}{S_{1,j}},\ldots,1\right)\right] \quad (1)$$

$$S_{i,j}\ \text{Normalized} = \frac{S_{i,j}}{\sum S_j} \quad (2)$$

$$W_i = \frac{\sum S_{i,j}\ \text{Normalized}}{N} \quad (3)$$

Global priorities (P_{gi}) were estimated to select the amendment alternative (m) that best fits each of the previously established criteria (n). The alternative weights estimated by criterion ($W_{m,n}$) were multiplied by the column vector of criteria weights (W_n) (Eq. 4). The maximum value of the resulting matrix (P_{gi}) corresponded to the alternative with the highest priority of the established hierarchical order.

$$P_{gi} = W_{m,n} \times W_n \quad (4)$$

Finally, the consistency ratio (CR) was calculated to determine whether the consistency level of the ratings assigned to the criteria and alternatives is acceptable (Eqs. 5, 6, and 7). CI, RI, N, and λ_{max}, are the consistency index, random consistency index, the number of alternatives evaluated, and the maximum eigenvalue, estimated as $\lambda max = \Sigma(S_{i,j} \times w_i)$.

$$CR = \frac{CI}{RI} \quad (5)$$

Table 1. Pairwise comparison between criteria and alternatives

Verbal preference declaration	Numerical rating
Highly preferred	9
Between very strongly preferable and highly preferred	8
Very strongly preferable	7
Between very strongly preferable and strongly preferable	6
Strongly preferable	5
Between moderately preferred and strongly preferable	4
Moderately preferred	3
Between slightly preferred and moderately preferred	2
Slightly preferred	1

$$CI = \frac{(\lambda_{max} - N)}{N - 1} \quad (6)$$

$$RI = \frac{1.98 \times (N - 2)}{N} \quad (7)$$

If the value of CR ≤ 0.10, the consistency is reasonable; otherwise, it is inconsistent, leading to reconsidering and modifying the original values of the matrix of paired comparisons (Table 1) until a consistent ratio is obtained.

Results and Discussion

The process performed with VOSviewer v.1.6.18 identified 24 keywords, the most popular being compost, manure, and organic waste. In the review of the scientific material, 67 documents were found, but 14 were eliminated for not meeting the bounds mentioned in the search equation item. From 53 publications discovered, only 25 were chosen for a full review to identify alternatives for amendment.

In the final revision process, 14 articles were considered because they included the relationship between substrate amendment and the improvement of physical, chemical, and biological characteristics in the composting process. These manuscripts were then grouped according to the authors' criteria into five thematic axes that were titled to represent the grouped words (Figures 1A and B and Table 2).

In Figure 1A, the cluster-based grouping, each color represents a different thematic axis, and the largest and closest words correspond to the most citations and the shortest Euclidean distances, respectively. In Figure 1B, the cluster-

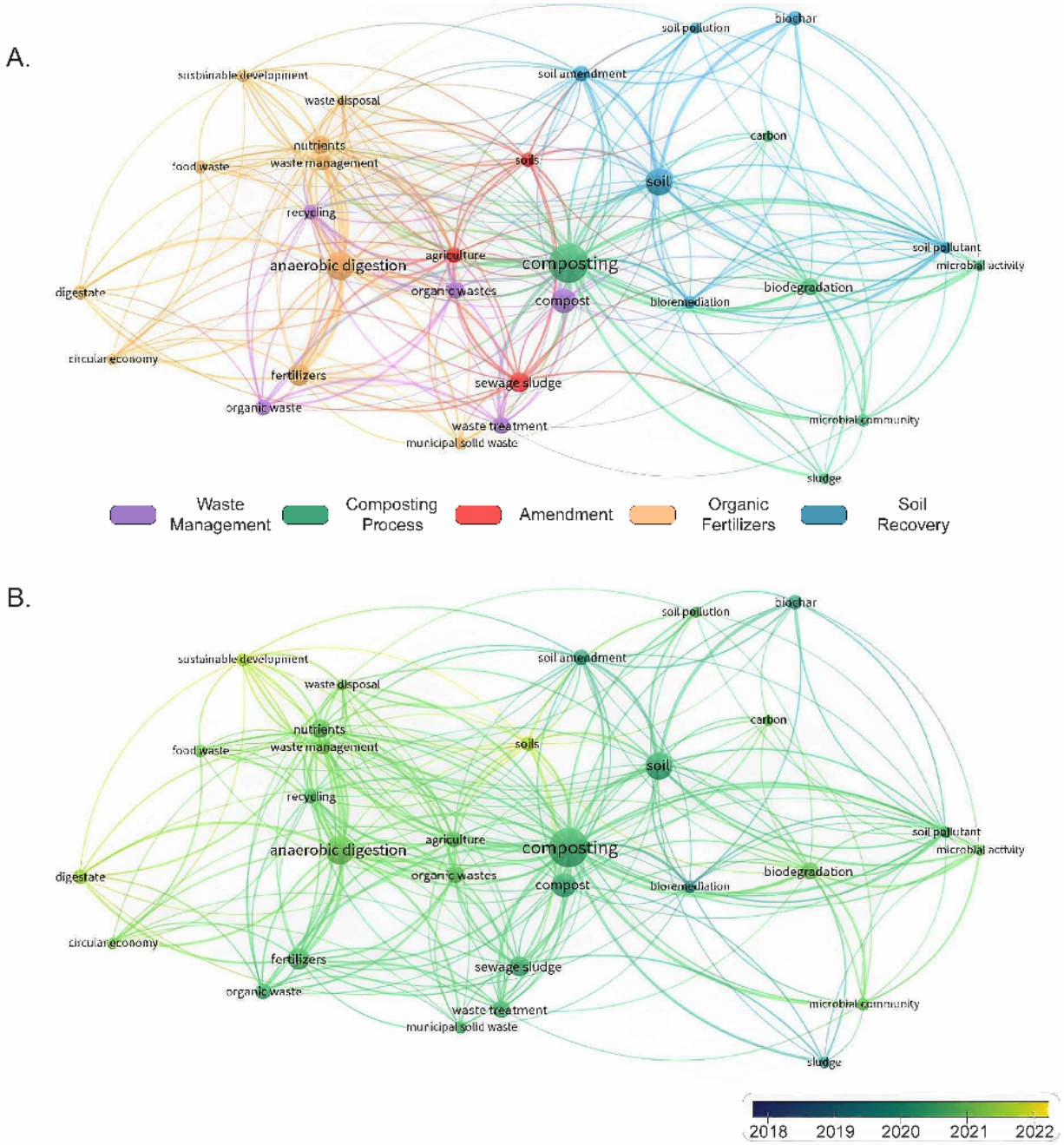


Figure 1. Maps of keywords co-occurrence in the selected articles (A) and chronological map with the most popular topics published between 2018 and 2022 (B)

Table 2. Research trends by thematic axis

	Thematic axis	Subjects
1	Waste management	Compost, organic waste, recycling, waste treatment
2	Composting process	Biodegradation, sawdust, composting, microbial activity, microbial community
3	Amendment	Agriculture, medical stone, sewage sludge, soils
4	Organic fertilizers	Sugarcane filter cake, digestate, fertilizers, municipal biowaste, nutrients
5	Soil recovery	Biochar, bioremediation, soil, soil amendment

based grouping, each color represents the most popular topics published between 2018 and 2022 based on the frequency and semantic proximity of the research topics consulted.

Research trends by thematic axis

The first thematic axis is related to waste management and the different options for its treatment (Figure 1A). Some problems related to the poor disposal of municipal solid waste correspond to water contamination and the emission of gases into the atmosphere. In Latin American countries such as Colombia, solid waste treatment is associated with disposal practices or open burning. Authors such as Bonoli et al. (2019) found that composting domestic organic waste mixing with ash allows recycling of 60% of the organic fraction of household waste, and local farmers purchase the compost produced. The second thematic axis (Figure 1A) depicts some composting processes and stages, such as biodegradation and microbial activity. Liu et al. (2021) provide an example of the importance of microbial community in composting by using pig manure, mushroom residues, and sawdust at a ratio of 3:1:1.7. The researchers followed the process for 36 days, improving NO^{3-}-N fixation and reducing N_2O emissions. The use of sawdust as an amendment improved the nitrogen conversion and increased the activity of denitrifying microorganisms.

The third thematic axis (Figure 1A) denotes amendments like sewage sludge that can be incorporated into the soil for agriculture. Madrid et al. (2020) used biodegradable extractants like some cyclodextrins (CDs), β-cyclodextrin (BCD), hydroxypropyl-β-cyclodextrin (HPBCD), randomly methylated-β-cyclodextrin (RAMEB), and a biosurfactant (rhamnolipid, RL) for the removal of organic contaminants such as pyrene (PYR), phenanthrene (PHE), and nonylphenol (NP) from several biosolids samples to improve their subsequent biodegradation before agricultural application. HPBCD, RAMEB, and RL were the most effective in extracting PHE and PYR from biosolids. This study was the first step to obtaining composted biosolids by increasing the bioavailability of extractants in sewage sludge samples and their later degradation by microorganisms during sewage sludge stabilization treatments. Other authors, such as Awasthi et al. (2018), studied the feasibility of medical stone (MS) amendment for dewatered fresh sewage sludge (DFSS) co-composting. The researchers performed five treatments with four different MS percentages (2, 4, 6, and 10%) and a 1:1 dry-weight mixture of DFSS and wheat straw (WS) as a bulking agent. The results show that the treatments with 6 and 10% MS improved the decomposition of organic matter and the activity of the dehydrogenase enzyme, as well as the increase in the formation of soluble nutrients in water like dissolved organic carbon, dissolved organic nitrogen, phosphorus, and NO^{3-}-N.

The fourth axis (Figure 1A) refers to substrates used as raw materials for compost production. In the Colombian region of Valle del Cauca, Soto-Paz et al. (2020) performed the composting process with municipal biowaste (MBW) collected from a composting facility. This waste is distinguished by its heterogeneous physical composition, high humidity, the concentration of salts, and deficiency of certain nutrients, including total organic carbon and phosphorus. They employed sugarcane filter cake (SFC) as an amendment to improve the compost's physicochemical properties. The mixing ratio of the biowaste and the sugarcane filter cake at ratios of 90:10, 80:20, and 70:30, as well as the turning frequency of 1, 2, and 3 turns per week, are among the experimental parameters considered to maximize parameters such as C/N ratio.

This thematic axis also deals with anaerobic digestion (AD) as a process for the treatment of organic waste. This process involves the oxidative deterioration of organic matter (OM) to produce methane and carbon dioxide. Regarding the publications whose focus was anaerobic digestion, these were eliminated because this project is based on the use of municipal solid waste through aerobic methods.

The fifth thematic axis shows some amendments used to recover contaminated soils (Figure 1A). Authors such as Aborisade et al. (2022) synthesized eggshell-biochar modified with nanoscale zerovalent iron/activated carbon (ESB-nZVI/AC) via carbothermal reduction to immobilize contaminants such as lead and cadmium in the soil. This process caused an increase in surface area, pore volume, and oxygen-bearing functional groups in the ESB modified with nZVI/AC, leading to higher immobilization efficiency of the synthesized adsorbents on toxic metals in soil. This treatment improved the quality and health of the soil, reducing electrical conductivity (EC) and regulating the pH. Since 2018, research related to the use of biochar in creating sustainable agricultural systems has been developing. Biochar reduces contamination of surface and groundwater bodies, as well as the absorption and leaching of chemicals from agrochemicals (Medyńska-Juraszek et al., 2020; Aborisade et al., 2022).

Regarding multitemporal research analysis, the number of publications in the last five years has increased, with 30% of the articles published in 2021-2022. Since 2020, research has focused on topics related to the sustainable management of organic solid waste and obtaining nutrients or fertilizers from it (Figure 2B) (Bonoli et al., 2019; Soto-Paz et al. al., 2020; Liu et al., 2021). This trend reveals the interest of academics in researching issues related to the use of municipal solid waste. Although, the variation in the number and frequency of publications may be related to the rise of major global economic issues. Given the time and effort required to publish new knowledge in an indexed journal, this "momentary" interest is reflected in the bibliometric activity of the following eras.

Using substrates from biowaste to prepare compost and adding amendments to improve the quality and productivity of soil and crops is not a new idea. Still, due to the double advantage that its implementation represents, it is becoming more relevant every day. For example, Asquer et al. (2017) conducted studies that aimed to correlate trends in the use of biowaste of municipal origin to produce energy and address the growing problem of this waste.

The study areas around MBW and their utilization have generally changed during the last five years. Compost and composting were popular keywords in articles from 2019 and 2020. However, there was a study supported by modern technology. Soto-Paz et al. (2020) used an artificial neural network (ANN) to optimize the composting procedure in this study. Due to its ability to adapt to any local context and circumstances, the rise of artificial intelligence has encouraged the development of new technologies related to the proper management of biowaste. This article offers a real-world example demonstrating the tool's value as a decision-making tool for selecting waste management system alternatives under various scenarios and priorities.

In recent publications, composting has been identified as a crucial recovery strategy in a circular economy approach; by 2022, there were co-occurrences with this keyword, whose purpose is the application of organic waste to improve the physicochemical properties of soils. However, MBW contains contaminants that represent a danger to the environment but can be treated by pre- and post-processing to create a highly beneficial fertilizer; this is the case of Ingrando et al. (2022), who carried out microwave-assisted extraction and determination by gas chromatography of thirty priority micropollutants in the fraction of biowaste derived from urban solid waste for the recovery of materials in the circular economy approach.

Source of inputs, operating parameters, and outputs of the composting process

Controlled conditions for substrate degradation are proposed by several authors, including Jiang et al. (2020), Asquer et al. (2019), and Ray et al. (2017). They design field experiments with the relevant operating parameters kept within a specific range for this purpose. In contrast, other authors, such as Liu et al. (2021) and De Corato et al. (2018), perform field studies considering local climatic circumstances. In both cases, key operating parameters such as compost temperature (°C), humidity (%), turning frequency, mixing ratio (PM), radiation (MJ m^{-2}), and precipitation (mm) are regularly measured. The duration of the tests is between 48 and 120 days and changes depending on the authors' objectives and the conditions of the site where they are conducted.

Composting is a complex and dynamic phenomenon involving biological, chemical, and physical organic matter transformations. For hundreds of years has been used to boost agricultural soil output, but research related to the implications and benefits of this approach has only recently been discovered. This expansion of scientific studies has coincided with an increased demand for organic compost in numerous industries related to the diverse choices of input sources such as municipal, industrial, and agricultural wastes. Table 3 summarizes the input sources the authors consulted for this study used as substrates and amendments for composting.

Biomass ash is used to provide calcium, potassium, magnesium, and phosphorus, increase the humidification of organic matter, and improve pH and electrical conductivity. Asquer et al. (2019) used different proportions of biomass ash to achieve increased Ca, K, Mg, and P and optimize organic matter humidification, pH, and electrical conductivity.

Medyńska-Juraszek et al. (2020) treated leafy vegetables with biochar made from wheat straw to lessen their absorption of heavy metals. The reduction is achieved using higher doses in the compost in mixture proportions no greater than 10% substrate and amendment and 90% deteriorated soils. Soto-Paz et al. (2020) used sugarcane filter cake (SFC) as it is a by-product of the industry with high levels of organic matter (> 40%) and P (> 1%). Ratios between biowaste (BW) and amendments (AM) at a ratio between 25 and 30 or 20 and 35 with turning frequencies between one and six times per week are necessary for C/N-based mix ratios for substrate mixing. Additional qualities that were enhanced by the inclusion of amendments are listed in Table 4.

Table 3. Material sources to use as substrate and amendment in compost

Authors	Substrate	Amendment
Dědina et al. (2022)	Biodegradable waste Separated digestate	Ash from biomass wood chips and straw admixture
Medyńska-Juraszek et al. (2020)	Municipal green waste	Wheat straw biochar
Asquer et al. (2017)	Municipal organic waste	Biomass ashes
Karnchanawong et al. (2017)	Green waste	Fly ash
Duan et al. (2021)	Cow manure	Rice husk
Liu et al. (2021)	Pig manure	Sawdust
Jiang et al. (2020)	Pig manure	Sawdust
Soto-Paz et al. (2020)	Biowaste	Sugarcane filter cake (liquor)
Fascella et al. (2021)	Municipal biowaste	Gardening residues
De Corato et al. (2018)	Municipal solid waste Cow manure-household waste	Agro-industrial residues Plant green waste Fuel ethanol co-products
Ai et al. (2020)	Sewage sludge	Alfalfa Ryegrass Tall fescue
Ray et al. (2017)	Dairy products or manure Dairy waste Manure with antibiotics	Alfalfa hay Pine bark mulch Sawdust

Table 4. Characteristics that are improved with the addition of amendments in the MWB composting process

Authors	Amendment	Enhanced Features
Karnchanawong et al. (2017)	Fly ash	pH buffering. Bad odors reduction. Addition of minerals for plant growth. Neutralization of acids in soils.
Duan et al. (2021)	Rice Husk	Increment of air content. Water and nutrient retention.
Liu et al. (2021)	Sawdust	Rapid growth of the bacterial community. Reduction of N_2O emissions. Increased carbon content.
Xu et al. (2022)	Sugarcane bagasse Escarole waste Sawdust	pH reduction. Improvement of the C/N ratio. Moisture and water retention.
Maucieri et al. (2019)	Green cuttings	Contribution of nutrients to the soil for the use of plants
Ai et al. (2020)	Alfalfa	Improves the richness of the bacterial community. Moisture and water retention.

Selection of the amendment through the analytical hierarchy process

Six amendment alternatives were chosen from the bibliometric analysis: MBW ashes (A_1), rice husks (A_2), sawdust (A_3), sugarcane bagasse and filter cake (A_4), tree pruning waste (A_5), and alfalfa hay (A_6). The following comparisons were made using these data and the specifications of each alternative:

C_1: $A_4 > A_1 > A_6 > A_5 > A_3 > A_2$; for the costs of each alternative ordered from the highest to the lowest.

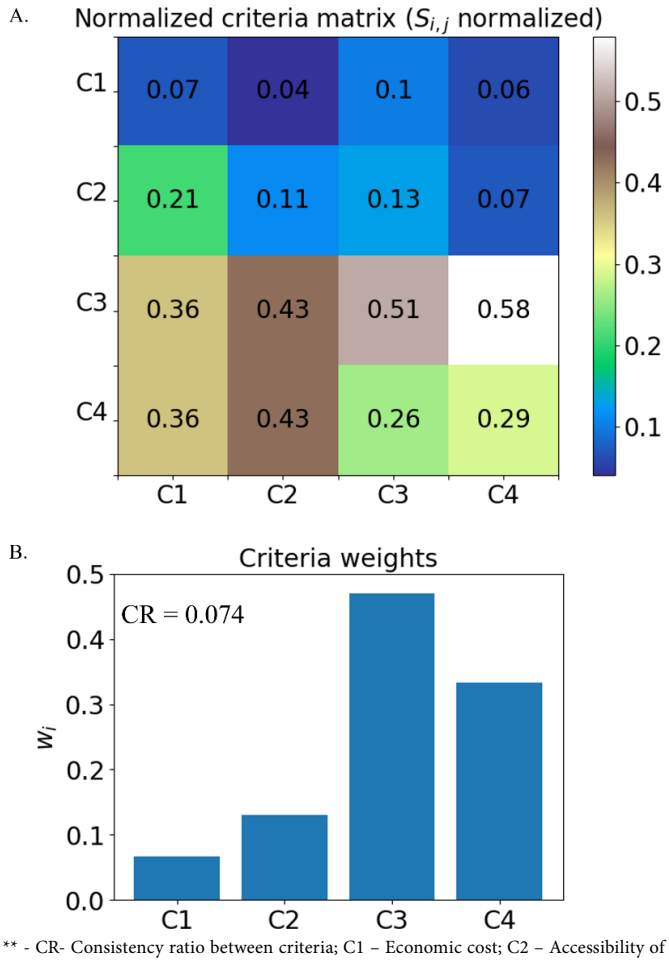
C_2: $A_2 > A_5 > A_3 > A_6 > A_1 > A_4$; for the orderly availability of each alternative.

C_3: $A_1 > A_6 > A_5 > A_4 > A_3 > A_2$; for ordered comparisons of nutrient content (%N and %P) in each amendment.

C_4: $A_1 > A_5 > A_2 > A_4 > A_3 > A_6$; for ordered comparisons of carbon content (%C) in each amendment.

Based on the normalized paired comparison of criteria (Figure 2A), nutrients (C_3) and carbon content (C_4) revealed the importance of 47% (w_i = 0.470) and 33% (w_i = 0.330) concerning the quality of MBW compost (Figure 2B). According to Soto-Paz et al. (2020), C_3 and C_4 help increase compost's chemical properties, improving its uses in sectors such as agriculture. Nutrients (%N and %P) and carbon (%C) contributions listed in Table 5 were used to support the numerical preferences assigned. On the other hand, the cost (C_1) (w_i = 0.067) and the availability (C_2) (w_i = 0.131) showed a second order of importance concerning the amendment features (C_1 and C_2). C_3 and C_4 referred to the process of acquiring a certain amendment based on its availability and cost. Based on research and publications by Lagos-Burbano (2019), the criteria assigned in this research prioritized the availability of amendments in the study area over those that implied high transportation costs from other territories.

Figure 3A summarizes the weights (w_i) among alternatives based on each criterion. Rice husk was 39% more important than the other options in terms of C_1 since Yopal City is located in one of Colombia's most productive rice regions, accounting for 37% of total national rice production (Figure 3B). Alternatives made from sugarcane (bagasse and filter cake) and MBW biomass ashes were the most expensive. For example, MBW ashes production requires prior treatments

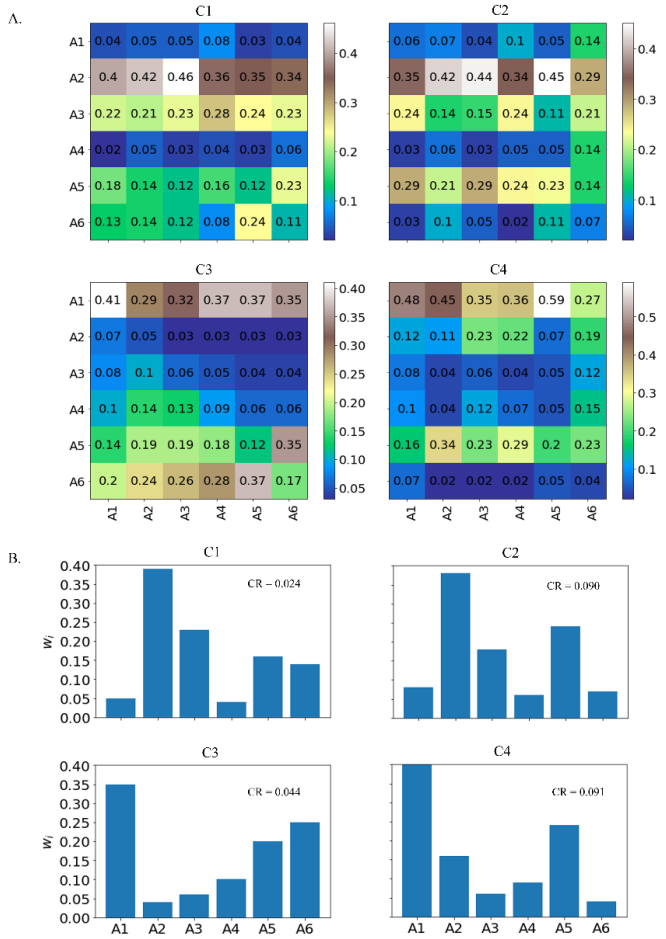


** - CR- Consistency ratio between criteria; C1 – Economic cost; C2 – Accessibility of the amendment in the study area; C3 – Supply of nutrients like nitrogen and phosphorus; C4 – Carbon contribution

Figure 2. Paired comparison among criteria, considering normalized comparison matrix ($S_{i,j}$ Normalized) (A) and weights among criteria (B)

Table 5. Nutrient and carbon content (%W/W) of the amendment alternatives considered (A_1, A_2, A_3, A_4, A_5, and A_6)

Alternatives	%N	%P	%C	Authors
A_1	4.45	0.52 – 1.18	97.00	Symanowicz et al. (2018)
A_2	0.080 – 0.60	0.0027 – 0.055	46.60	Duan et al. (2021); Thind et al. (2017)
A_3	0.27	0.69 – 0.20	21.10 – 22.7	Liu et al. (2021)
A_4	0.60	0.30	39.00	Bravo et al. (2017)
A_5	1.00	0.50	17.49	Cestonaro et al. (2019); Li et al. (2022)
A_6	0.58	1.97 – 2.73	16.00	Ai et al. (2020)



** - CR – Consistency ratio; C1 – Economic cost; C2 – Accessibility of the amendment in the study area; C3 – Supply of nutrients like nitrogen and phosphorus; C4 – Carbon contribution; A1 – MBW ashes; A2 – Rice husk; A3 – Sawdust; A4 – Sugarcane bagasse and filter cake; A5 – Tree pruning waste; A6 – Alfalfa hay

Figure 3. Paired comparison of alternatives by criterion. Normalized comparison matrices ($S_{i,j}$ Normalized) (A) and weights among alternatives (B)

to remove products such as heavy metals, making it a costly option for MBW composting (Wong et al., 2020); meanwhile, sugarcane is produced in the southwest of the country, which would imply a high transportation cost (~1000 km).

Among the options considered in C_2, rice husk had the highest relative weight. Colombian regions like Casanare, Tolima, and Huila are the major rice producers, making it possible to quickly use and acquire agricultural waste such as rice husks (23% of the product's initial weight). Sugarcane bagasse and filter cake, alfalfa hay, and MBW ashes must be shipped from different regions within Colombia, limiting their availability. Regarding pruning waste, the times set by the municipal sanitation business for trimming front gardens and parks govern its acquisition.

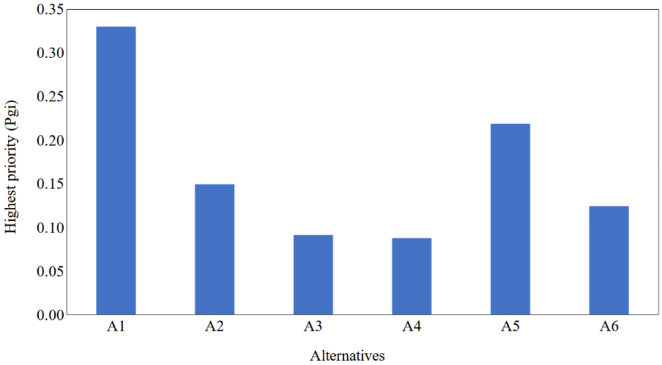
The comparison of alternatives based on C_3 (Figure 3B) shows that MBW ashes, alfalfa hay, and pruning waste are good alternatives to add more nutrients to the compost, as reported by the research conducted by the authors shown in Table 4. Only MBW ashes and pruning waste outperformed the other alternatives in C_4, with 42 and 24% relevance, respectively. The medium relevance that sawdust implied as a substitute for the substrate is an important point to emphasize because sawdust can come from different types of wood used in sawmill processes, varying their carbon contribution.

According to the AHP method results, MBW ashes and pruning waste are the amendment choices that best meet the set criteria due to their nutritional and carbon content (Figure 4). However, these are affected by costs and production frequency for the study area. The use of ashes as an amendment for MBW composting is a medium and long-term solution. According to Wong et al. (2020), research on the use of ash in municipal solid waste increased by 21 to 218 publications per year between 1994 and 2018, demonstrating positive benefits in the nutrient supply provided by this option. Authors like Asquer et al. (2019), Asquer et al. (2017), and Karnchanawong et al. (2017) show how the use of this type of ashes favors the increase in Ca, K, Mg, and P concentrations as well as the pH levels (allowing to buffer low pH levels in the soil) and electrical conductivity. The most difficult aspect of obtaining this raw material is finding reliable and affordable methods to measure contaminants such as polychlorinated dibenzo-p-dioxins and heavy metals such as Cd, Pb, Hg, Zn, and Cu, as well as coupling practical, affordable technologies to produce it.

Pruning waste, unlike ashes, is a readily available amendment. This alternative is limited by the pruning times performed by municipal service companies, as they would be the primary supplier of this raw material in the study area. Pruning waste, according to Maucieri et al. (2019), is an important source of organic carbon (250 g kg^{-1} dry matter) and nutrients (27 g kg^{-1} dry matter), with the main limitation being their high lignin content, which increases the time transformation or decomposition to simpler organic chains.

The importance of alfalfa hay, rice husks, sawdust, sugarcane bagasse, and the filter cake was medium (for the first two) and low (for the last two). According to the findings of Ray et al. (2017), while alfalfa hay reduces the concentrations of contaminants such as antibiotics and improves the C/N ratio in compost (25-30), it also has operational limitations, similar to the alternative of pruning waste, because the content of lignocellulosic material lengthens the composting process. According to Duan et al. (2021) and Thind et al. (2017), in their research, using rice residues can contribute to improving the physical properties of the soil due to its carbon and nitrogen content.

In the case of sawdust as an amendment alternative, the study found it 8.9% relevant to the evaluated criteria. The main



** - A1 - MBW ashes; A2 – Rice husk; A3 - Sawdust; A4 - Sugarcane bagasse and filter cake; A5 - Tree pruning waste; A6 – Alfalfa hay

Figure 4. Aggregate criteria weights of each alternative according to the highest priority considered (P_{gi}) in each alternative

disadvantage of using sawdust is that it contributes very little to microbial growth during composting. Regarding sugarcane products such as bagasse and filter cake, their use favors the increase in the concentrations of organic matter, phosphate, and nitrogen in the composting process. However, its transportation costs and low availability make it an unfeasible alternative for the study region (Soto-Paz et al., 2020).

It should be noted that in the industrial production of compost, factors such as cost, availability, and longer composting time (when using pruning waste) play a limiting technical and operational role. The weighting given to each set of options and the inclusion of additional criteria, such as their impact on composting time, influence how each of these alternatives is classified and chosen. The most practical possibilities for using an amendment to assist the MBW composting process would be to use rice husks and pruning waste due to their simplicity, low cost, and ease of purchase.

On the other hand, it is important to point out that MBW composting is a global challenge that requires finding suitable amendments that can improve this product's process and quality. Countries and regions have different availability and accessibility to amendments depending on their agricultural, industrial, and environmental conditions. Therefore, considering the local context improves the process of selecting an amendment because it considers each case's cultural and economic conditions.

Conclusions

1. Bibliometric tools, such as VOSviewer, offer a fast and efficient alternative to analyze and learn a specific research topic. In the selection of amendments for municipal biowaste, bibliometric analysis allowed for structuring and characterizing the aspects related to each criterion considered in this research.

2. The hierarchical process analysis technique is a valuable tool for selecting amendments for composting municipal biowaste. Its combination with bibliometric analysis offers a broader and deeper vision and greater objectivity and rigor in selecting the best alternative.

3. Ashes and pruning waste can be used as amendments for composting municipal biowaste in the studied region. These two alternatives can be profitable in the long term in small communities. However, other options, such as rice husks, are a suitable alternative because of their high production in Yopal City, low cost, and carbon contribution; their only limiting aspect is their low contribution of nutrients.

Literature Cited

Aborisade, M. A.; Feng, A.; Zheng, X.; Oba, B. T.; Kumar, A.; Battamo, A. Y., Kavwenje, S.; Liu, J.; Chen, D.; Okimiji, O. P.; Ojekunle, O. Z.; Yang, Y.; Sun, P.; Zhao, L. Carbothermal reduction synthesis of eggshell-biochar modified with nanoscale zerovalent iron/activated carbon for remediation of soil polluted with lead and cadmium. Environmental Nanotechnology, Monitoring & Management, v.18, p.1-10, 2022. https://doi.org/10.1016/j.enmm.2022.100726

Ai, Y. J.; Li, F. P.; Gu, H. H.; Chi, X. J.; Yuan, X. T.; Han, D. Y. Combined effects of green manure returning and addition of sewage sludge compost on plant growth and microorganism communities in gold tailings. Environmental Science and Pollution Research, v.27, p-31686–31698, 2020. https://doi.org/10.1007/s11356-020-09118-z

Asquer, C.; Cappai, G.; Gioannis, G. D.; Muntoni, A.; Piredda, M.; Spiga, D. Biomass ash reutilisation as an additive in the composting process of organic fraction of municipal solid waste. Waste Management, v.69, p.127–135, 2017. https://doi.org/10.1016/j.wasman.2017.08.009

Asquer, C.; Cappai, G.; Carucci, A.; Gioannis, G. D.; Muntoni, A.; Piredda, M.; Spiga, D. Biomass ash characterization for reuse as additive in composting process. Biomass and Bioenergy, v.123, p.186–194, 2019. https://doi.org/10.1016/j.biombioe.2019.03.001

Awasthi, M. K.; Wang, Q.; Awasthi, S. K.; Li, R.; Zhao, J.; Ren, X.; Wang, M.; Chen, H., Zhang, Z. Feasibility of medical stone amendment for sewage sludge co-composting and production of nutrient-rich compost. Journal of Environmental Management, v.216, p.49-61, 2018. https://doi.org/10.1016/j.jenvman.2018.01.032

Bonoli, A.; Zanni, S.; Awere, E. Organic waste composting and sustainability in low-income communities in Palestine: Lessons from a pilot project in the village of Al Jalameh, Jenin. International Journal of Recycling of Organic Waste in Agriculture, v.8, p.253–262, 2019. https://doi.org/10.1007/s40093-019-0264-8

De Corato, U.; Salimbeni, R.; De Pretis, A.; Patruno, L.; Avella, N.; Lacolla, G.; Cucci, G. Microbiota from 'next-generation green compost' improves suppressiveness of composted Municipal-Solid-Waste to soil-borne plant pathogens. Biological Control, v.124, p.1–17, 2018. https://doi.org/10.1016/j.biocontrol.2018.05.020

Dědina, M; Jarošíková, A.; Plíva, P.; Dubský, M. The effect of ash admixture on compost quality and availability of nutrients. Sustainability, v.14, p.1-7, 2022. https://doi.org/10.3390/su14031640

Duan, H.; Ji, M.; Chen, A.; Zhang, B.; Shi, J.; Liu, L.; Li, X.; Sun, J. Evaluating the impact of rice husk on successions of bacterial and fungal communities during cow manure composting. Environmental Technology & Innovation, v.24, p.1-15, 2021. https://doi.org/10.1016/j.eti.2021.102084

Fascella, G.; Montoneri, E.; Rouphael, Y. Biowaste-Derived Humic-like Substances Improve Growth and Quality of Orange Jasmine (*Murraya paniculata* L. Jacq.) Plants in Soilless Potted Culture. Resources, v.10, p.1-12, 2021. https://doi.org/10.3390/resources10080080

Götze, R.; Boldrin, A.; Scheutz, C.; Astrup, T. F. Physico-chemical characterisation of material fractions in household waste: Overview of data in literature. Waste Management, v.49, p.3-14, 2016. https://doi.org/10.1016/j.wasman.2016.01.008

Ingrando, I.; Rivoira, L.; Castiglioni, M.; Tumiatti, V.; Lenzi, F.; Pagliano, A.; Bruzzoniti, M. C. Microwave-assisted extraction and gas chromatographic determination of thirty priority micropollutants in biowaste fraction derived from municipal solid waste for material recovery in the circular-economy approach. Talanta, v.241, p.1-8, 2022. https://doi.org/10.1016/j.talanta.2022.123268

Jiang, J.; Wang, Y.; Guo, F.; Zhang, X.; Dong, W.; Zhang, X.; Zhang, X.; Zhang, C; Cheng, K.; Li, Y.; Zhu, G. Composting pig manure and sawdust with urease inhibitor: Succession of nitrogen functional genes and bacterial community. Environmental Science and Pollution Research, v.27, p.36160–36171, 2020. https://doi.org/10.1007/s11356-020-09696-y

Karnchanawong, S.; Mongkontep, T.; Praphunsri, K. Effect of green waste pretreatment by sodium hydroxide and biomass fly ash on composting process. Journal of Cleaner Production, v.146, p.14-19, 2017. https://doi.org/10.1016/j.jclepro.2016.07.126

Kozlov, G.; Pushkarev, M.; Danilovich, D.; Garabadzhiu, A. Technologically significant properties of municipal solid waste compost. E3S Web of Conferences, v.175, p.1-8, 2020. https://doi.org/10.1051/e3sconf/202017512015

Lagos-Burbano, E.; Castro-Rincón, E. Sugar cane and by-products of the sugar agro-industry in ruminant feeding: A review. Agronomía Mesoamericana, v.30, p.917-934, 2019. https://doi.org/10.15517/am.v30i3.34668

Li, M.; Li, F.; Zhou, J.; Yuan, Q.; Hu, N. Fallen leaves are superior to tree pruning as bulking agents in aerobic composting disposing kitchen waste. Bioresource Technology, v.346, p.1-9, 2022. https://doi.org/10.1016/j.biortech.2021.126374

Liu, C.; Yan, J.; Huang, Q.; Liu, H.; Qiao, C.; Li, R.; Shen, B.; Shen, Q. The addition of sawdust reduced the emission of nitrous oxide in pig manure composting by altering the bacterial community structure and functions. Environmental Science and Pollution Research, v.29, p.3733-3742, 2021. https://doi.org/10.1007/s11356-021-15786-2

Madrid, F.; Rubio-Bellido, M.; Morillo, E. Extraction of nonylphenol, pyrene and phenanthrene from sewage sludge and composted biosolids by cyclodextrins and rhamnolipids. Science of The Total Environment, v.715, p.1-8, 2020. https://doi.org/10.1016/j.scitotenv.2020.136986

Maucieri, C.; Barco, A.; Borin, M. Compost as a substitute for mineral N fertilization? effects on crops, soil and N leaching. Agronomy, v.9, p.1-16, 2020. https://doi.org/10.3390/agronomy9040193

Medyńska-Juraszek, A.; Bednik, M.; Chohura, P. Assessing the influence of compost and biochar amendments on the mobility and uptake of heavy metals by green leafy vegetables. International Journal of Environmental Research and Public Health, v.17, p.1-16, 2020. https://doi.org/10.3390/ijerph17217861

Nanda, S.; Berruti, F. Municipal solid waste management and landfilling technologies: A review. Environmental Chemistry Letters, v.19, p.1433-1456, 2021. https://doi.org/10.1007/s10311-020-01100-y

Ray, P.; Chen, C.; Knowlton, K. F.; Pruden, A.; Xia, K. Fate and effect of antibiotics in beef and dairy manure during static and turned composting. Journal of Environmental Quality, v.46, p.45-54, 2017. https://doi.org/10.2134/jeq2016.07.0269

Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of organic wastes through composting: process performance and compost application in agriculture. Agronomy, v.10, p.1-23, 2020. https://doi.org/10.3390/agronomy10111838

Soto-Paz, J.; Alfonso-Morales, W.; Caicedo-Bravo, E.; Oviedo-Ocaña, E. R.; Torres-Lozada, P.; Manyoma, P. C.; Sanchez, A.; Komilis, D. A new approach for the optimization of biowaste composting using artificial neural networks and particle swarm optimization. Waste and Biomass Valorization, v.11, p.3937-3951, 2020. https://doi.org/10.1007/s12649-019-00716-8

Symanowicz, B.; Becher, M.; Jaremko, D.; Skwarek, K. Possibilities for the Use of Wood Ashes in Agriculture. Journal of Ecological Engineering, v.19, p.191-196, 2018. https://doi.org/10.12911/22998993%2F86156

Thind, H. S.; Yadvinder-Singh; Sharma, S.; Varinderpal-Singh; Sram, H. S.; Bijat-Singh. Phosphorus fertilizing potential of bagasse ash and rice husk ash in wheat–rice system on alkaline loamy sand soil. The Journal of Agricultural Science, v.155, p.465-474, 2017. https://doi.org/10.1017/S0021859616000484

Wong, S.; Mah, A. X. Y.; Nordin, A. H.; Nyakuma, B. B.; Ngadi, N.; Mat, R.; Amin, N. A. S.; Ho, W. S.; Lee, T. H. Emerging trends in municipal solid waste incineration ashes research: A bibliometric analysis from 1994 to 2018. Environmental Science and Pollution Research, v.27, p.7757-778, 2020. https://doi.org/10.1007/s11356-020-07933-y

Xu, N.; Bhadha, J. H.; Rabbany, A.; Swanson, S.; Mccray, J. M.; Li, Y.; Strauss, S. L.; Mylavarapu, R. Sugarcane bagasse amendment mitigates nutrient leaching from a mineral soil under tropical conditions. Pedosphere, v.32, p.876–883, 2022. https://doi.org/10.1016/j.pedsph.2022.06.020