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Research paper

Compost and vermicompost improve symbiotic nitrogen fixation, physiology and yield of the Rhizobium-legume symbiosis: A systematic review

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ABSTRACT

Compost and vermicompost are valuable sources of organic matter, nutrients and beneficial microorganisms for plants. Both improve the physical and chemical properties of soil and stimulate its biological processes, such as beneficial interactions between soil microorganisms and plants. One example is the symbiosis between legumes and rhizobia. A systematic review of the existing scientific literature was conducted to assess the effects of compost and vermicompost on symbiotic nitrogen fixation. The collected information and data were subsequently used for scientometrics and meta-analysis. Variance, effect size and percentage change from a control without compost or vermicompost were analysed. The scientometrics analysis revealed promising research areas including, the study of the effects of compost and vermicompost combined with rhizobia on plant physiology, nitrogen fixation, soil quality, economic benefits, microbial diversity and salinity stress. The combined use of compost and biochar emerged as the most recent research trend. Other relevant topics included the economic benefits, and environmental sustainability impacts of compost and legumes for improving soil quality and nitrogen availability. The meta-analysis showed that compost application, on average, increased nodule number by 66 %, nodule fresh weight by 52 %, plant biomass by 48 %, plant height by 21 % and yield by 20 %. Vermicompost application led to greater values in these parameters. Some scientific gaps have been addressed as: i) the effectiveness of compost at inducing nodule formation when inoculated with microbial inoculants, considering the legume species and the edaphoclimatic conditions of the experiment, ii) the effects of biochar and compost on nodulation improvement in legumes, and iii) the effect of the chemical and biological characteristics of compost (or vermicompost), especially nitrogen content or raw nitrogen-fixing bacteria present in compost in the Rhizobium-legume symbiosis. All these results confirm that using compost or vermicompost in the cultivation of legume crops is a valuable approach to increase soil fertility, crop productivity and agricultural sustainability.

1. Introduction

Soil is a non-renewable and fragile resource. Its conservation is essential to ensure food security and our sustainable future due to soil supporting a quarter of the planet's biodiversity (FAO and ITPS, 2015; Minasny et al., 2017). Soil fertility depends on its organic matter content which plays a key role in enhancing physical, chemical and biological properties while influencing various processes related to nutrient cycling, water retention and plant growth (Lehmann and Kleber, 2015; Wiesmeier et al., 2019). Organic wastes, by-products and crop surplus, which are generated in significant quantities by agricultural, livestock, forestry and food processing activities, serve as an important source of organic matter and plant nutrients (Alburquerque et al., 2004; Bustamante et al., 2008). Before being utilized, these wastes require biological stabilization to minimize any potential harmful effects on soils. Composting and vermicomposting are widely adopted and offer practical options for this purpose. Recycling organic wastes for agricultural application through composting and vermicomposting is a fundamental

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Table 1
An overview of the experimental framework applied in this study on based PSALSAR methodology (Mengist et al., 2020).

Steps	Title	Action	Results	
1	Definitions	Main question	Does compost (vermicompost) improve nodulation or SNF?	
		Specific questions: Are differences between…	… compost vs vermicompost? … compost (vermicompost) type? … compost (vermicompost) doses? … legume or endosymbiont?	
2	Keywords and combination	Compost (or vermicompost) AND nodule AND	Symbiosis: Nodulation, Legumes and Biological Nitrogen Fixation Inoculants: Inoculation, Symbiotic bacteria, PGPR and PGPB Legumes: *Glycine*, *Phaseolus*, *Pisum*, *Cicer*, *Vicia*, *Arachis*, *Medicago* and *Lotus* Endosimbionts: *Rhizobium*, *Ensifer*, *Mesorhizobium* and *Bradyrhizobium*	
3	Criteria	Inclusion	English, Primary research, Published in peer-reviewed journals, Control without compost (or vermicompost), data (mean and variance)	
		Exclusion	Duplicated, no compost (or vermicompost) information, no number of replicates	
4	Search in Scopus	Compost	Articles found with all combinations defined in Step 3	$N = 3141$
			Articles without duplications	$N = 170$
			Selected papers (after selection criteria of Step 3)	$N = 57$
		Vermicompost	Articles found with all combinations defined in Step 3	$N = 776$
			Articles without duplications	$N = 66$
			Selected papers (after selection criteria of Step 3)	$N = 26$
5	Definition of variables and co-variables	Main variables	- Nodule numbers (NN plant^{-1}) - Nodule biomass (mg DW plant^{-1}) - Plant biomass (g DW plant^{-1}) - Shoot biomass (g DW plant^{-1}) - Root biomass (g DW plant^{-1}) - Plant height (cm plant^{-1}) - Yield (g DW) - Total N (g kg^{-1})	
		Co-variables (explanatory variables)	- Legumes: *Phaseolus*, *Acacia*, *Prosopis*, *Glycine*, *Vigna*, *Cicer*, *Arachis*, *Sesbania*, *Neptunia*, *Pisum*, *Medicago*, *Vicia*, *Pithecellobium*, Others - Symbiont: Not added (raw soil), commercial rhizobia, *Bradyrhizobium*, *Rhizobium*, *Mesorhizobium*, *Ensifer*, Others - Compost (Vermicompost) type: Vegetal, Animal, Co-compost (Mix V + A), Bio-waste, Agro-industry or Other - Doses: $<$ 5, 5–20 and $>$ 20 t ha^{-1} - Experiment scale: Field or Greenhouse	
6	Extraction of data and construction of Meta-table	- Downloading articles in pdf format - Reading them carefully - Extraction of mean, absolute error and sample size	- Meta-table COMPOST.xlsx - Meta-table VERMICOMPOST.xlsx	
7	Data analysis	Scientometric analysis	- Co-occurrence analysis - Thematic categorization maps	
		Meta-analysis	- Effect size (Ln Response Ratio) - Random effect Variance - Publication bias - Bootstrap Mean Effect Size - Rosenberg Failsafe Calculation - Orwin Failsafe calculation - Forest Plot - Percentage of change (%)	
8	Results and Discussion	- Graphs and Tables elaboration - Description of data - Create a theory model - Conclusions		
9	Report	- PRISMA methodology - Journal article production		

principle of circular economy, which aims to create value by reducing raw material consumption while increasing waste recycling and reuse (Korhonen et al., 2018). This approach offers numerous environmental benefits, as organic wastes are an abundant and renewable resource that help to close the production loop (Ghisellini et al., 2016; Sharma et al., 2019).

Composting is a well-known biotechnology used for the treatment and revalorization of organic wastes (Bernal et al., 2009; Ayilara et al., 2020). It is a microbiological process involving the action of a diverse range of microorganisms that transform organic matter under controlled conditions (de Bertoldi et al., 1983; Duan et al., 2024; Angeles-De Paz et al., 2025; Salinas et al., 2025). This process leads to an increase in temperature, which serves as a selective factor for microbes, and contributes to waste sanitation by eliminating pathogens (Ryckeboer et al., 2003). Furthermore, composting is an aerobic process, indicating that microorganisms rely on oxygen to proliferate and convert organic matter (López-González et al., 2015a, 2015b). The final product of composting, known as compost, is a stable and agriculturally valuable material due to its content of organic matter, plant nutrient and beneficial microorganisms (Tortosa et al., 2012, 2023). Vermicomposting, on the other hand, closely resembles traditional composting, but involves the use of earthworms in addition to microorganisms for waste decomposition and occurs at mesophilic conditions (Benítez et al., 2002; Fernández-Gómez et al., 2010). Earthworms consume and transform organic waste into vermicompost, a nutrient-rich material that enhances soil quality (Van Groenigen et al., 2019; Blouin et al., 2019). Vermicomposting is utilized in agriculture as an eco-sustainable method of soil enrichment and is gaining global popularity due to its environmental and economic benefits (Rodriguez-Campos et al., 2014; Rehman et al., 2023).

Legumes crops are directly involved in the sustainability of the long-term production of agroecosystems (Voisin et al., 2014). Legumes can provide diverse ecosystem services, including: i) the improvement of human nutrition, health and livelihood security, ii) protection of soils from erosion and degradation, iii) enhancement of soil properties and associated processes such as soil carbon levels and phytoremediation of heavy-metal contaminated soils, and iv) assurance of climate resilience, in fields and socioeconomic conditions, among others (Voisin et al., 2014; Meena and Kumar, 2022 and the articles included in), which are directly related with Sustainable Developmental Goals (SDG) 2 (Zero Hunger), 13 (Climate Action) and 15 (Life on Land). On the other hand, legumes can establish symbiotic relationships with specific soil bacteria. These microorganisms are collectively known as rhizobia. They induce the formation of root organs called nodules. Inside these nodules, rhizobia transform atmospheric nitrogen (N_2) into a form readily assimilated by plants (NH_4^+) through the activity of one of the most important molecules in nature, the nitrogenase enzyme (Peix et al., 2015; Suzaki et al., 2015). This process is known as symbiotic nitrogen fixation (SNF) and nitrogenase chemical structure, biochemical and molecular mechanisms, genetic expression and regulation, and environmental relevance have been deeply studied for years (Poole et al., 2018; Rutten and Poole, 2019; Yang et al., 2022), making it a current hot topic for agronomic research (Burén and Rubio, 2018; Burén et al., 2020). Since the Green Revolution crop yields have increased significantly due to the development of high yielding semi-dwarf plant varieties along with the application of pesticides and mineral fertilizers (Phillips, 2014; Liu et al., 2022). Despite its relevance to food security, over-fertilization with nitrogen fertilizers has led to several environmental risks including soil and water nitrate contamination, eutrophication, soil acidification and salinization, greenhouse gas emissions, and accelerated biodiversity loss (Galloway et al., 2008; Tortosa et al., 2011; Morrissy et al., 2021). A promising alternative to mineral nitrogen fertilization is the natural process of SNF, especially associated with legumes crops, which can enhance soil fertility (Crews and Peoples, 2004; Peoples et al., 2009; Stagnari et al., 2017).

Some evidence supports that the application of compost or vermicompost to legumes can improve crop development, yield, and SNF. Mathenge et al. (2019) applied vermicompost in combination with a commercial rhizobia inoculant to soybeans. They assessed its effects in both greenhouse and field settings and found significant increases in nodulation, nodule occupancy, nitrogen uptake and grain yields. These results demonstrated that vermicompost can be used as an integrated soil fertility management for a sustainable intensification of smallholder agriculture. Ulzen et al. (2020) demonstrated that soybean response to rhizobia inoculants and P-fertilizers could be improved with the addition of compost, providing a viable N fertilization alternative for smallholder farmers in Ghana. Gupta et al. (2022) conducted a two-year field experiment of pigeon peas, which were fertilised with compost, vermicompost, *Rhizobium* spp. or other microbial inoculants. These treatments led to an improvement of soil microbiota, enzymatic and chemical properties, as well as plant development. More recently, it was demonstrated that compost derived from “alperujo”, the main organic waste from the olive oil industry, can enhance nodulation and SNF in soybean plants inoculated with *Bradyrhizobium diazoeffiens,* their natural endosymbiont (Tortosa et al., 2023). However, despite these promising results, the overall global effects of compost or vermicompost addition on legume crops remain unknown.

The main aim of this systematic review was to explore the research landscape and to synthesize the current knowledge of the effects of both organic amendments (compost and vermicompost), especially focusing on SNF, physiology and yield in the Rhizobium-legume symbiosis. To achieve this goal, both scientometric and meta-analysis methodologies were applied. Our hypothesis was that these organic amendments would increase nodule number and biomass, promote plant growth (shoot and roots) and development (height), improve seed yield and increase fixed nitrogen. Additionally, this study aimed to assess the effects of these amendments based on compost or vermicompost type, application dose, inoculated symbiont, legume species and experiment scale (greenhouse or field conditions).

2. Material and methods

2.1. Literature collection and data extraction

The experimental framework used in this research followed the PSALSAR methodology described by Mengist et al. (2020) with some key modifications (Table 1). The first step involved the definition of the main research question: “Does compost (and vermicompost) improve the nodulation or SNF?”. Additionally, complementary questions were also formulated: Are there differences between compost and vermicompost?, or between compost (or vermicompost) type?, or doses applied?, or the legume and its endosymbionts? In the second step, the main keywords and their combinations were defined before the scientific literature search. The terms “Compost” (or “vermicompost”) and “nodule” were individually combined with at least four groups of keywords related to: 1. symbiosis (nodulation, legumes and biological nitrogen fixation), 2. inoculants (inoculation, symbiotic bacteria, plant-growth promoting rhizobacteria or PGPR and plant-growth promoting bacteria or PGPB), 3. Legumes genera (*Glycine*, *Phaseolus*, *Pisum*, *Cicer*, *Vicia*, *Arachis*, *Medicago,* and *Lotus*), and 4. endosymbionts genera (*Rhizobium*, *Ensifer*, *Mesorhizobium* and *Bradyrhizobium*). The third step involved the quality check of criteria for both inclusion and exclusion of research documents (Table 1). The scientific literature search was performed in August 2023 using Scopus database (Elsevier). For compost, a total of 3.141 articles were found, which were narrowed down to 57 according to the selection criteria. For vermicompost, 776 articles were found and 26 were selected.

After reviewing and reading all these articles, data were extracted for the following main variables: nodules number (NN plant^{-1}), nodule biomass (mg dry weight [DW] plant^{-1}), plant biomass (g DW plant^{-1}), shoot biomass (g DW plant^{-1}), root biomass (g DW plant^{-1}), plant height (cm plant^{-1}), yield (g DW) and total nitrogen (N) (g kg^{-1}). Additionally, extracted data were clustered according to the following explanatory variables (co-variables):

- Compost (or vermicompost) type: Animal, Bio-waste, Co-compost (animal + vegetal), Other and Vegetal.
- Doses: < 5, 5–20 and > 20 t ha^{-1}.
- Symbiont: With inoculant (commercial rhizobia, *Bradyrhizobium*, *Rhizobium*, *Mesorhizobium*, *Ensifer*, and so forth) and without inoculant (not added or raw soil).
- Legumes: *Cicer, Glycine, Medicago, Phaseolus*, *Vicia, Vigna* and Others.
- Experiment scale: Field and Greenhouse.

Data were directly extracted from figures and tables included in each article, especially mean, absolute error and sample size (number of replicates). When standard error was not found (missing data), it was estimated as 5 % of the mean value. Two meta-tables were then prepared (one for compost and the other for vermicompost) containing all this information. These meta-tables were constructed by comparing control

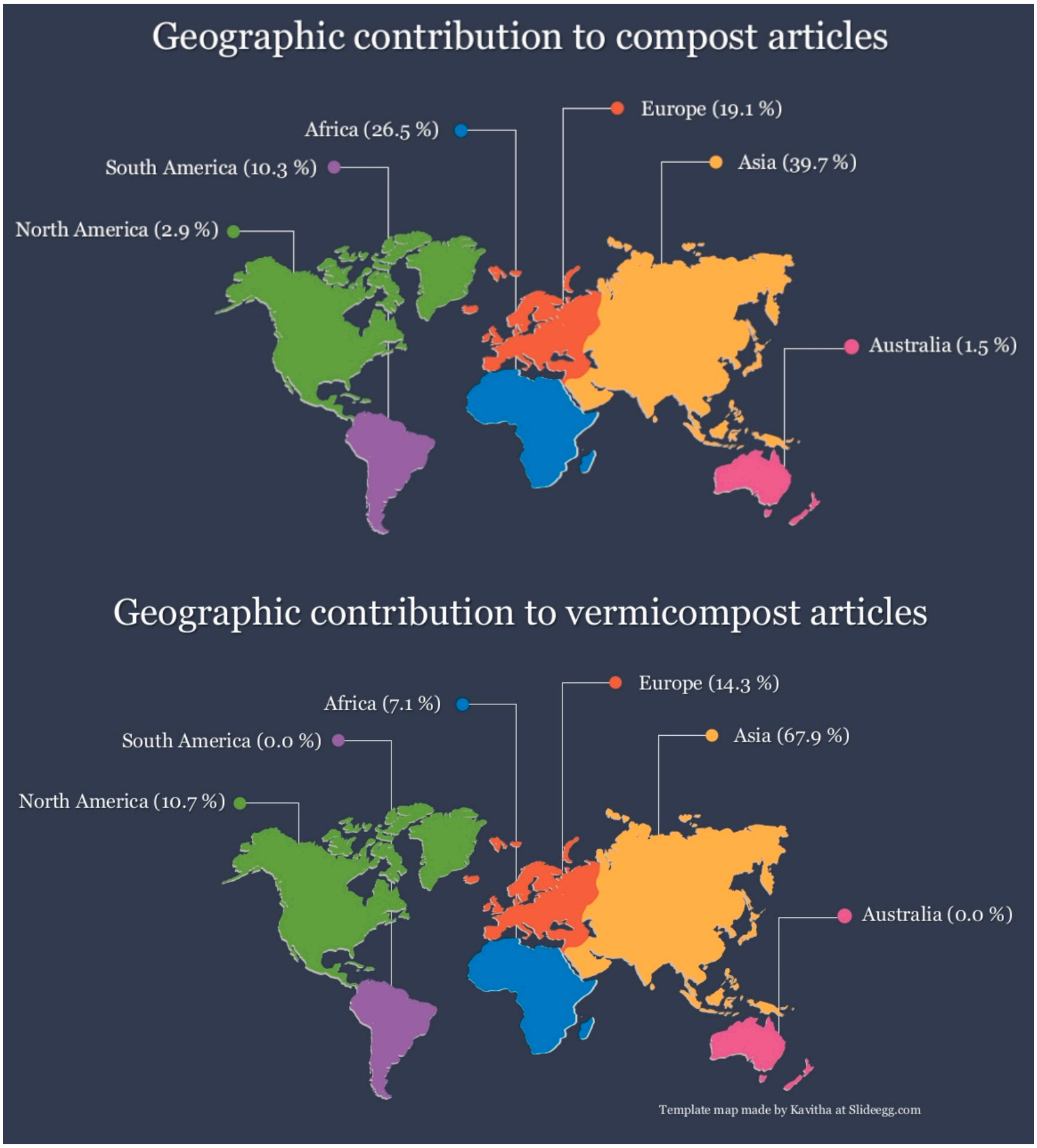

Fig. 1. Geographic distribution of the number of the articles of compost and vermicompost included in this meta-analysis. Data are expressed as percentage of the total articles of this meta-analysis.

treatments (without compost or vermicompost) vs treatments (compost or vermicompost addition). Both meta-tables can be downloaded from the Supplementary Material section (see Meta-table COMPOST.xlsx and Meta-table VERMICOMPOST.xlsx). Also, the total number of compost and vermicompost direct comparisons used in this study before data curing and their distribution by variables and co-variables can be consulted in Table S1 and S2, respectively.

2.2. *Scientometric analysis*

The scientometric study was performed with VOSviewer® software (van Eck and Waltman, 2010) by doing a co-occurrence analysis of words included in titles, abstracts and keywords of research articles, which were considered as the main research core of knowledge. In VOSviewer®, networks of interrelation were also constructed from specific meta-data structures of each article using data mining techniques and methods supported by social network visualization applications. The meta-data structures used included: i) keywords representing the scope of the research, thematic axes, areas of knowledge and general trends (Gerdsri and Kongthon, 2018), and ii) titles and abstracts. The former represents the research intent related to the study object and the work object, while the latter covers topics associated with the objective, methodology, results, and major conclusions of the research to map specific trends (Sohrabi et al., 2019). These meta-data structures were used to construct the key thematic co-occurrence network.

To define future research trends, the analysis incorporated the concepts of technology mining (Guo et al., 2012) and scientometrics (Mingers and Leydesdorff, 2015) and was executed in three distinct steps. Initially, a database was created and organized by extracting text segments from the findings and future work sections of the selected papers. Subsequently, this dataset was transferred to VOSviewer® and subjected to text co-occurrence analysis to discover patterns. Finally, the network of co-occurrences of future work was examined descriptively

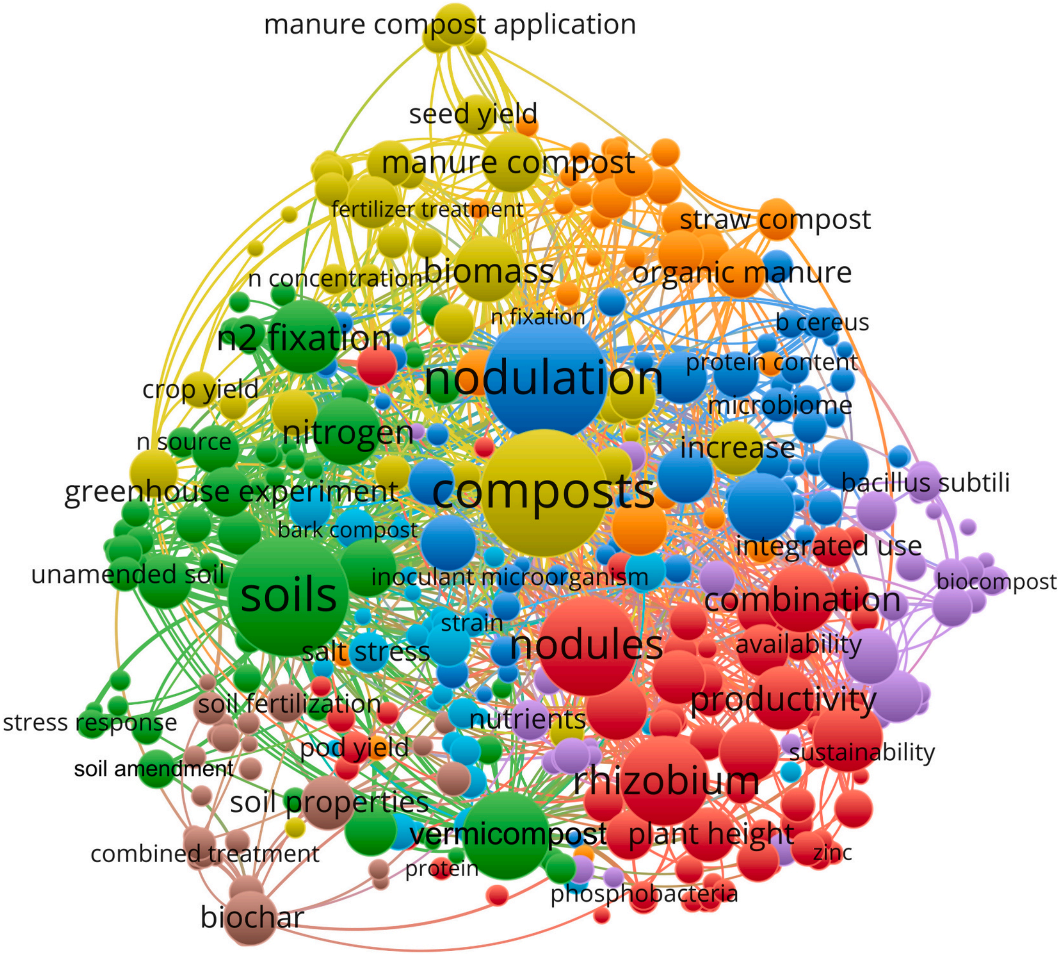

Fig. 2. Co-occurrence map illustrating general and specific research trends related to compost, vermicompost and legume nodulation. Node proximity indicates the relative connection between terms, while node size corresponds to the frequency of each keyword in the analysed manuscripts. Keywords, as well as words from titles and abstracts, are colour-coded to form clusters based on thematic similarity. The online version of this figure is available at https://tinyurl.com/24a69ccn.

and critically, allowing the description of immediate research short term actions supported by both qualitative (scientometrics) and quantitative (meta-analysis) data.

Additionally, Bibliometrix R-tool (https://www.bibliometrix.org) was used to create a thematic distribution map of the key trends identified (Aria and Cuccurullo, 2017). The thematic categorization map for research lines was constructed based on a two-dimensional distribution using the meta-data extracted from keywords, titles and abstracts (Callon et al., 1991; Cobo et al., 2011). The degree of relevance, also known as centrality, measures the interaction of each cluster with other clusters indicating the importance of the thematic cluster in the research field. The degree of development, also known as density, measures the internal strength of each thematic cluster based on the relationships among the topics it comprises showing the cluster's degree of development. Based on these two dimensions, clusters were categorized into the following four groups (Aria et al., 2022; Giannakos et al., 2020):

- Quadrant I: Niche Themes (low centrality and high density). Thematic clusters in this quadrant, often referred to as 'Ivory towers,' exhibit a high level of development but remain marginal to the research field. They may represent specialized areas or autonomous topics that contribute to subfields of research or are explored from other disciplines within the research field.
- Quadrant II: Motor Themes (high centrality and density). This quadrant comprises thematic clusters representing 'hot topics' or the mainstream of research. These clusters are well-developed and play a crucial role in structuring the research field.
- Quadrant III: Emerging or Declining Themes (low centrality and density). This quadrant identifies emerging themes ('new trends') with the potential to contribute to the research field, as well as themes that are losing importance ('disappearing'). These themes may signify evolving areas of research or declining interest within the field.
- Quadrant IV: Basic or Transversal Themes (high centrality and low density). Thematic clusters in this quadrant, known as 'Bandwagon' themes, are essential to the research field. However, their level of development suggests that they may represent past topics or those from other disciplines or contexts. They contribute to a deeper understanding of the research field.

2.3. Meta-analysis and publication bias

To evaluate the effect of compost or vermicompost in the nodulation and SNF of the Rhizobium-legume symbiosis, effect sizes (ln Response Ratio or RR) and effect size variances (v[ln RR]) were calculated according to Hedges et al. (1999): $lnRR = ln\frac{X_t}{X_c}$, where X_t and X_c are mean values of treatment and control, respectively; $v = \frac{SD_t^2}{n_t X_t^2} + \frac{SD_c^2}{n_c X_c^2}$, where SD_t, n_t, and SD_c and n_c were standard deviation and sample size of treatments and controls, respectively. We used a random effects model and the standard confidence intervals around means, which was based on normal distribution. Additionally, we used bootstrapping for confidence intervals (CI) around means (999 iterations), to achieve statistical significance when 95 % of the values did not overlap zero (Adams et al.,

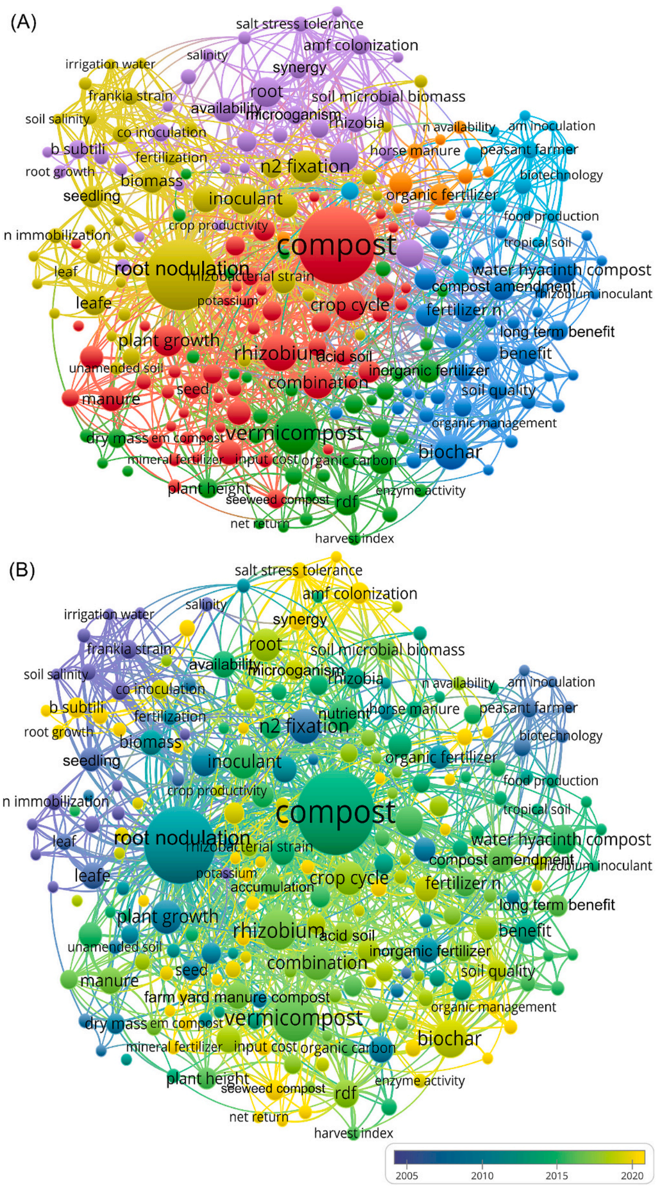

Fig. 3. Key text co-occurrence network and analysis of future research drivers on compost and legume nodulation. (A) Co-occurrence map based on words from the conclusions and future perspectives sections. The distance between nodes reflects their relative closeness, and node size represents the frequency of each word found. Keywords are colour-coded to form clusters based on thematic similarity. (B) Chronology of publications in the co-occurrence network based on words from the conclusions and future perspectives sections. Here, nodes represent words, and the colour of the connecting lines indicates their chronological order. Research topics published before 2020 are displayed in purple and dark green, and more recent topics from the past few years appear in light green and yellow. The online version of this figure is available at https://tinyurl.com/25bthdan.

1997; Dixon, 1993). To facilitate data interpretation, in RR data were transformed to percentage change according to the following formula: $\% \; change = \left(e^{lnRR} - 1\right) \times 100$. Heterogeneity, mean effect size and Rosenthal's and Orwin's fail-safe numbers to estimate the number of missing articles needed to achieve non-significant differences were calculated according to Rosenthal (1979), Orwin (1983), Hedges and Olkin (1985), Higgins and Thompson (2002) and Huedo-Medina et al. (2006). All calculations were performed using the open-source software Metawin v.3 (Rosenberg, 2024), available at https://www.metawinsoft.com/.

3. Results

3.1. Geographical description of the literature

The 57 articles included in the compost section were primarily performed in Asia (39.7 %), Africa (26.5 %), Europe (19.1 %) and South America (10.3 %). The less representative with a 2.9 and 1.5 % of the total number of articles were conducted in North America and Australia, respectively (Fig. 1). Among the countries, Pakistan (13.2 %), India (11.8 %), Brazil (8.8 %), Ethiopia (7.4 %), Indonesia (5.9 %) and Japan (5.9 %) were the most represented. Regarding vermicompost, most of the studies were carried out in Asia (67.9 %), Europe (14.3 %) and North America (10.7 %), particularly India and Mexico, which contributed 53.6 and 10.7 %, respectively, of the 26 articles included in this section (Fig. 1).

3.2. Scientometric analysis

The co-occurrence map in Fig. 2 was created using the most frequent words from the titles, abstracts and keywords of the 83 documents (57 of compost +26 of vermicompost), analysing their interconnections and frequency of occurrence. The map consisted of 440 words grouped into 8 clusters, each distinguished by a different colour. Each cluster highlights the main topics covered by the research articles. Cluster number 1, highlighted in red, is the largest group, comprising 83 words. It emphasizes research regarding the role of *Rhizobium* in nodule formation and its use as a biofertilizer to increase plant height, root length and biomass, resulting in increased crop yield and profitability. The second cluster, in green, is composed of 76 words. It reflects studies highlighting the most well-known benefits of compost and vermicompost as soil amendments. Additionally, it underscores the significance of these organic amendments in nitrogen fertilization, which is also likely related to the manuscripts included in this meta-analysis. Cluster number 3, in blue, consists of 71 words. It highlights research related to the influence of phosphorus and compost in the establishment of symbiosis. Some rhizobacteria known for their role as plant growth promoters and used as inoculants, such as *Mesorhizobium* sp., *Rhizobium leguminosarum*, and *Bacillus* sp., are included within this group. The fourth cluster, in yellow, comprises 56 words. It highlights investigations about the use of manure compost as an organic fertilizer, particularly in organic agriculture. Its role in SNF, nitrogen accumulation and its effects on increasing biomass, as well as nodule dry weight can also be observed within this group. Cluster number 5, shown in purple, consists of 44 words. It emphasizes complementing the benefits of compost with chemical fertilizers to enhance crop productivity. Clusters 6 to 8, in light blue, orange, and brown respectively, contain 38, 37, and 35 words, respectively. The main topics these clusters highlight include research related to the application of compost to reduce salt stress and its effect on soil pH, as well as the impact of poultry and cattle manure on increasing chlorophyll content, the presence and inoculation of mycorrhiza and biochar addition as combined treatment.

The co-occurrence network, built from the words in the conclusions and future research sections of the manuscripts included in the meta-analysis, consists of 230 words organized into 7 clusters composed of 53 (red), 38 (green), 41 (yellow), 39 (dark blue), 34 (purple), 14 (light blue), and 11 (orange) words (Fig. 3A). These findings outline future research perspectives on compost and legumes. One of the most promising areas of research that figure highlights is the study of the effects of combining compost or vermicompost with rhizobia, other plant growth-promoting bacteria, arbuscular mycorrhizal fungi, and mineral fertilizers on plant physiology—including root architecture and productivity—as well as on nitrogen fixation, soil quality, and economic benefits (represented by red, green, and dark blue clusters). How these combinations, or the application of compost or vermicompost alone, affect microbial diversity and salinity stress (purple cluster), while also enhancing legume nodulation, has also emerged as a topic of interest.

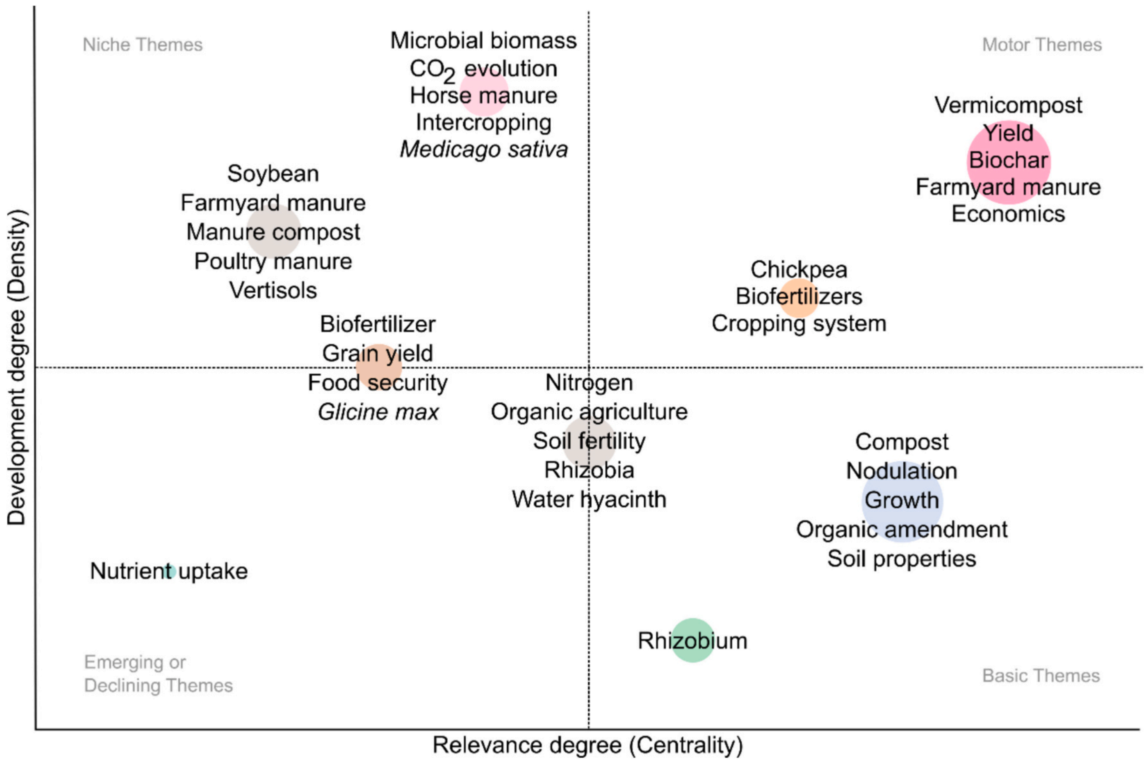

Fig. 4. Thematic map of research on compost, vermicompost, and legume nodulation. The four quadrants represent centrality and density, indicating the importance and development of research themes. This figure was generated using the Bibliometrix application and a BibTeX data file.

Relevant topics also include the economic benefits and impact on environmental sustainability that the use of compost and legumes can provide while improving soil quality and nitrogen availability (light blue cluster). Finally, yellow cluster comprises the mainstream of research for root nodulation improving nitrogen fixation and enhancement fertilization of key crops such as legumes.

A chronology overlay of publication is shown in Fig. 3B, where research topics published before 2020 are displayed in purple and dark green, and more recent topics from the past few years appear in light green and yellow. The map highlights that research on nitrogen fixation and root nodulation has been well-established over several years (purple nodes). More recent studies, represented in light green, focus on the use of straw compost, vermicompost, and inoculants based on rhizobia, other plant-growth-promoting bacteria, and mycorrhizal fungi. The combination of compost or vermicompost with biochar, aimed at improving the physical properties of soil, increasing organic matter content and reducing greenhouse gas emissions, has emerged as a recent research trend marked in yellow in Fig. 3B.

The thematic map in Fig. 4 illustrates field topic clusters. The only research topic within the quadrant with low relevance and a low degree of development refers to nutrient uptake, highlighting that the role of compost and vermicompost in plant nutrient improvement is well understood. Recent research builds on this understanding as a foundation for more specific themes. Similarly, as also observed in Figs. 2 and 3B, research related to compost as an organic amendment and its role in plant growth and nodulation, along with studies on Rhizobium, appear as basic topics (high relevance but low development). Themes related to organic agriculture are positioned in the middle of the lower quadrants with a higher degree of development, indicating that these fundamental topics have recently been explored for the implementation of this agricultural practice. Research with low relevance, but a high degree of development appeared related to manure compost, soybeans and food security, indicating that while these topics are considered important within the field, knowledge gaps remain regarding the use of this type of compost for legume fertilization and its potential to enable more people to meet their dietary needs. Finally, consistent with the findings in Fig. 3B, research on biochar, vermicompost, and the use of biofertilizers is underscored as a hot topic in the field, not only for yield improvement but also for the economic sustainability of production systems.

3.3. *Meta-analysis*

The effect of compost on several symbiotic, physiological, and productive parameters of the Rhizobium-legume symbiosis is shown in Fig. 5A. Based on percentage change, compost application increased nodule number and biomass by 66 and 52 %. Additionally, compost improved plant biomass, shoot and root weights and plant height by 48, 44, 22 and 22 %, respectively. The effect of compost on seed yield was less significant, with changes of 20 %. Total N was not statistically significant, as the bootstrap CIs overlapped with zero. Vermicompost showed similar results to compost, with even more remarkable effects but wider confidence intervals due to the smaller number of studies available (Fig. 5B). Consequently, these results should be considered with caution to prevent over-interpretation. Vermicompost increased nodule number and biomass by 126 and 53 %, plant biomass, shoot and root weights and plant height by 25, 61, 64 and 23 %, and seed yield and total N by 57 and 36 %.

Table 2 presents the number of direct comparisons for each measured variable. To address the ‘file drawer’ problem, both Rosenthal's Fail-Safe Number (FSN, $\alpha = 0.05$) and Orwin's FSN (minimal effect size = 0.200) were calculated. Rosenthal's FSN revealed the highest values for nodule numbers and shoot weight when compost was applied. In contrast, the remaining variables showed low FSN values, suggesting that additional studies are needed to conclusively rule out the file drawer effect. Although eight variables were analysed, only the number of nodules was reported in most of the compost and vermicompost articles included in this study. For compost, the minimum number of comparisons within groups was set at $n \geq 10$, and for vermicompost, at $n \geq 8$ (Table S1 and S2). Based on this, nodule number was selected as the representative variable to evaluate the effects of compost or vermicompost type,

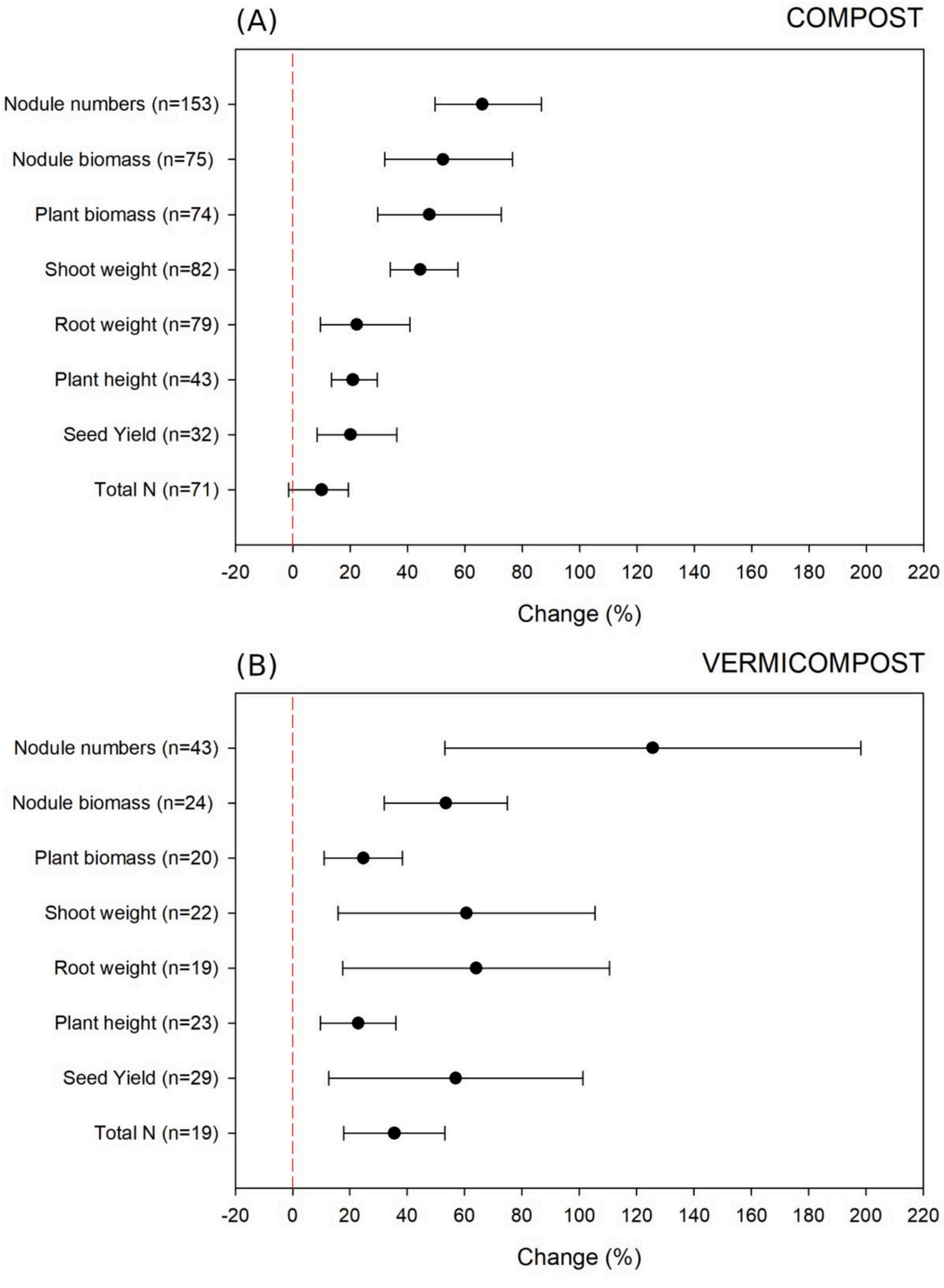

Fig. 5. Effect of compost (A) and vermicompost (B) application on nodules number, nodule biomass, plant biomass, shoot weight, root weight, plant height, seed yield and total N of legume crops. Data are expressed as percent change refer to controls without compost or vermicompost addition. Levels are considered statistically different when bootstrap CIs do not overlap. "n" means the number of compost or vermicompost direct comparisons used in this study before data curing.

dosage, symbiont, legume species and application scale on the Rhizobium-legume symbiosis. The analysis showed that compost increased nodule number, although this effect did not vary significantly by compost type (Fig. 6A). Compost derived from animal, bio-waste, co-compost, and other or plant-based materials increased nodule number by 50, 67, 179, 36, and 74 %, respectively. In contrast, plant-based vermicompost had a more pronounced effect in nodule number compared to other vermicompost types (Fig. 7A). Neither compost nor vermicompost application dosage significantly affected nodule number, with changes of 67, 67 and 45 % for compost rates of <5, 5–20 and > 20 t ha^{-1}, respectively (Fig. 6B), and changes of 129 and 120 % for vermicompost rates of <5 and 5–20 and > 20 t ha^{-1} (Fig. 7B). Regarding inoculation, the addition of compost or vermicompost to legume crops induced nodule formation (Fig. 6C and 7C). The percentage changes were 24 % when inoculants were previously added to the soil and 90 % when only compost was applied (Fig. 6C). Similarly, for vermicompost, the changes were of 210 % and 110 % (Fig. 7C). There is an apparent contradiction between compost and vermicompost effect when

Table 2

Total number of data included in the meta-analysis and number of articles that should be required to obtain non-significant difference based on Rosenthal's and Orwin's fail-safe numbers.

Compost			
Variables	Total number of direct comparisons	Rosenthal's Fail-safe Number	Orwin's Fail-safe Number
Nodule numbers	153	1996	235
Nodule biomass	75	667	83
Plant biomass	74	113	70
Shoot weight	82	1903	69
Root weight	79	253	0
Plant height	43	270	0
Seed yield	32	38	0
Total N	71	0	0

Vermicompost			
	Total number of direct comparisons	Rosenthal's Fail-safe Number	Orwin's Fail-safe Number
Nodule numbers	43	144	132
Nodule biomass	24	23	27
Plant biomass	20	67	2
Shoot weight	22	334	30
Root weight	19	132	28
Plant height	23	118	1
Seed yield	29	699	36
Total N	19	75	10

inoculants were initially added. May be, it can be explained with the number of direct comparisons found in vermicompost (only $n = 8$). Also, its wider confidence intervals were quite large and consequently, these results should be considered with caution to prevent over-interpretation.

Among legume species, *Medicago* (143 %), *Phaseolus* (158 %) and *Vicia* (58 %) appeared to be more responsive to compost addition, while *Cicer, Vigna* and *Glycine* showed lower responses, with changes of 34, 33 and 25 %, respectively (Fig. 6D). In contrast, *Glycine* was highly responsive to vermicompost addition, increasing nodule numbers (Fig. 7D). Finally, the effect of compost or vermicompost addition on nodule formation did not appear to be influenced by the experimental scale, with percentage changes of 61 and 70 % for compost (Fig. 6E) and 109 and 174 % for vermicompost on field and greenhouse scales, respectively (Fig. 7E).

4. Discussion

It is well known that soil organic matter (SOM) is related to soil fertility (Stevenson, 1994). However, intensive farming has led to a decrease in SOM and biodiversity worldwide (Tan et al., 2005; Tsiafouli et al., 2015). The overuse of mineral nitrogen fertilizers has caused several environmental issues, such as soil and water contamination, eutrophication, and an increase in the emission of greenhouse gases emissions, among others negative impacts (Vitousek et al., 1997; Galloway et al., 2008; Tortosa et al., 2011). According to FAO (2019), global demand for mineral nitrogen continues to rise. Nevertheless, the cost of nitrogen fertilizers has been increasing due to high and volatile energy prices, trade disruptions, elevated transportation costs, high crop prices (and thus high affordability) and political instability due to war (FAO, 2019; OECD-FAO., 2023). Organic amendments and fertilizers, such as compost and vermicompost and legume crops used as green manure applied to agricultural soils, are effective in mitigating this challenge by increasing soil organic carbon, plant nutrients as nitrogen and plant growth-promoting microorganisms (PGPRs) (Minasny et al., 2017; Tortosa et al., 2018; Blouin et al., 2019; Sharma et al., 2019). Also, the application of compost and vermicompost in legume cultivation can promote sustainable agricultural practices, contributing to SDG 2 (Zero Hunger) by enhancing crop yields, SDG 13 (Climate Action) through soil carbon sequestration and reduced greenhouse gas emissions, and SDG 15 (Life on Land) by supporting soil health and biodiversity. Several regions and countries have conducted research to evaluate sustainable strategies for reducing mineral nitrogen fertilization to address this issue. Fig. 1 summarises the geographical origin of the meta-analysis article authors. Asia, Africa and South America for compost, and Asia, Africa and North America for vermicompost, are the region's found to be more scientifically interested in applying compost or vermicompost to legume crops. This interest may be related to their nitrogen balance potential, defined as the relationship between the supply and the demand for fertilizers and other nitrogen-based applications (FAO, 2019). In recent years, in North America, Latin America and Caribbean, South Asia and Western Europe, this balance was negative, indicating that these regions were deficient in nitrogen fertilizers supplied relative to their agricultural demand (FAO, 2019). An exception was Africa, which had a positive nitrogen balance, but also, Africa had one of the lowest nitrogen fertilizers demands worldwide from 2016 to 2022, behind Oceania (FAO, 2019). Nonetheless, if the continent wants to achieve food self-sufficiency, nitrogen input in African agriculture will need to increase by 2050 (Elrys et al., 2020).

This study presents a comprehensive systematic review of research on compost, vermicompost, and their effects on legume nodulation (Fig. 8). It highlights research trends in this field and the benefits of using compost and vermicompost, with or without inoculants, to enhance nodule formation and promote plant growth. As was demonstrated, compost and vermicompost notably improve SNF, physiology and yield of the Rhizobium-legume symbiosis by increasing all parameters studied: nodule number (66 %), nodule fresh weight (52 %), plant biomass (48 %), plant height (21 %) and yield (20 %). The analysis of research trends highlights that recent studies have focused on investigating the effects of combining compost or vermicompost with inoculants containing rhizobia, other plant growth-promoting rhizobacteria, or mycorrhizae. While compost is known to increase microbial diversity, the specific rhizobial strains required by each legume are not always present in these communities. Moreover, the microorganisms within compost may not necessarily be the most competent strains for plant growth promotion (Amaya-Gómez et al., 2020). For these reasons, although compost enhances nodule formation, legumes sown in soils amended with compost or vermicompost have recently begun to be inoculated with commercial inoculants (Ben-Laouane et al., 2021; Mathenge et al., 2019; Salvador et al., 2022). For an inoculant to successfully induce nodule formation, several factors are important, including the selection of microbial strains capable of establishing interactions with the legume and surviving and persisting under specific soil conditions (O'Callaghan et al., 2022). None of their biological mechanisms were addressed in the investigations reviewed in this study, impeding a full understanding of how nodule formation is enhanced when compost or vermicompost is inoculated compared to when compost is used alone.

The major theme identified in yellow in Fig. 3B and within the motor themes in Fig. 4 was the use of the combination of biochar and compost or vermicompost. Biochar alone is recognized as a carbon-rich, solid organic material. Like compost, it is applied as a soil amendment. Its primary properties include increasing long-term carbon retention in the soil, enhancing physico-chemical characteristics (such as pH, water-holding capacity, and hydraulic conductivity), and promoting microbial diversity, favoring SNF and mycorrhizal abundance (Farhangi-Abriz, s. et al. 2021). Recent research has proven that the combination of vermicompost and biochar enhanced soil properties like pH and nutrient

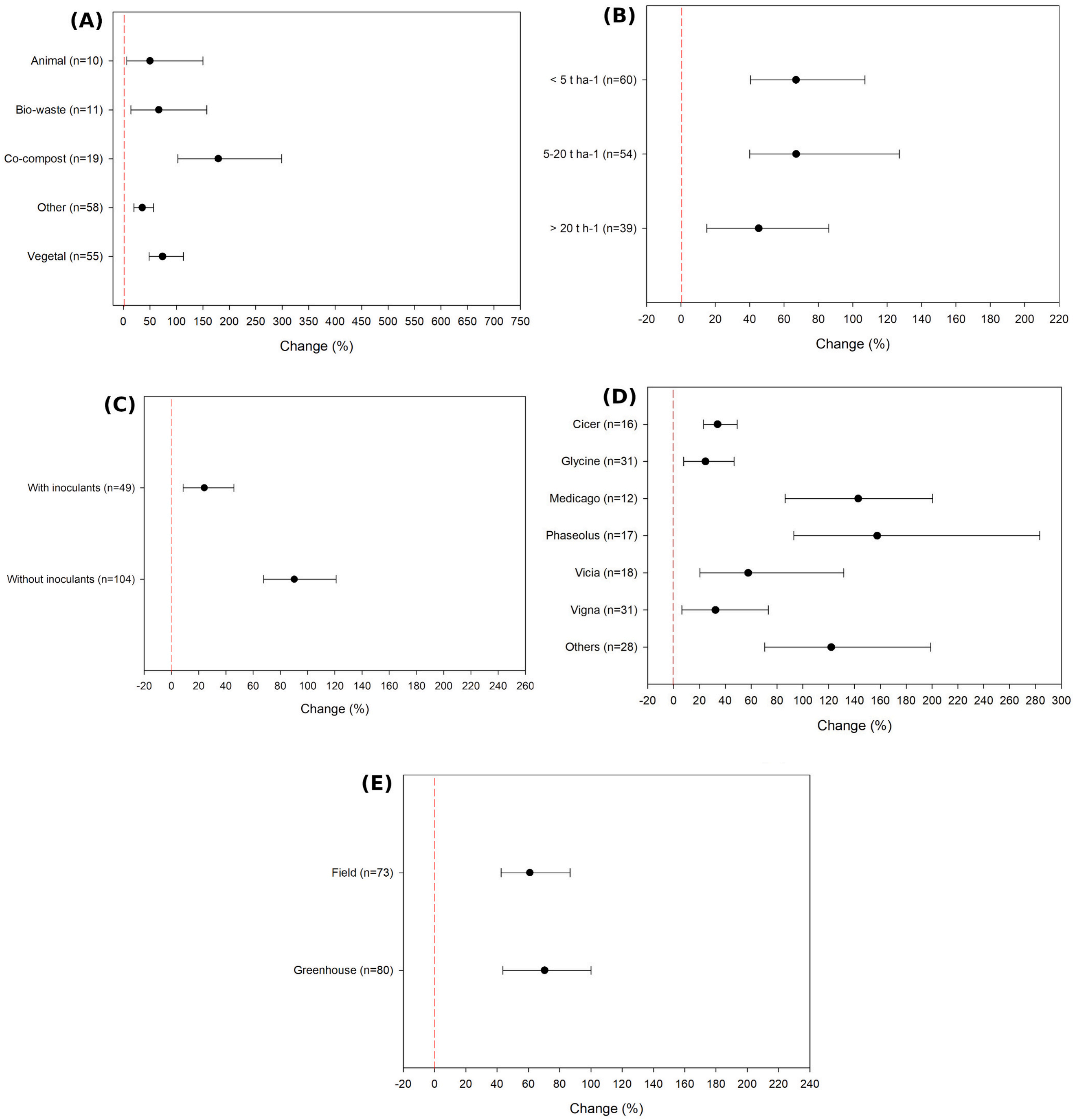

Fig. 6. Effect of the type (A), doses (B), inoculants (C), legumes (D) and experimental scale (E) of compost application on nodules number of legume crops. Data are expressed as percent change refer to controls without compost or vermicompost addition. Levels are considered statistically different when bootstrap CIs do not overlap. "n" means the number of compost direct comparisons used in this study before data curing.

content (C and K) and incremented the dry weight of cowpea plants, root nodule dry weight, and arbuscular mycorrhizal sporulation (Gopal et al., 2020). Purwaningsih et al. (2021) reported that seaweed compost and biochar significantly increased the growth rate of soybeans in sandy coastal soil. However, no significant changes were observed in nodule number, root length, or harvest index. A meta-analysis conducted by Farhangi-Abriz et al. (2021) on the effects of biochar on yield of cereal and legume crops highlights that the benefits of biochar are influenced by factors such as crop type, climate, soil pH and application rate. For legumes, the study concludes that the effect of biochar is limited, due to nitrogen availability, which may reduce nitrogen fixation, and also others factors such as irrigation strategies or soil type, among others (Haddad et al., 2022).

Finally, some scientific gaps have been addressed in this study. For instance, further research is needed to compare the effectiveness of compost or vermicompost inducing nodule formation when inoculated with microbial inoculants, considering the legume species and the edaphoclimatic conditions of the experiment. Such studies should also include a preliminary screening of candidate inoculants before assessing their effectiveness in combination with compost. Also, and due to

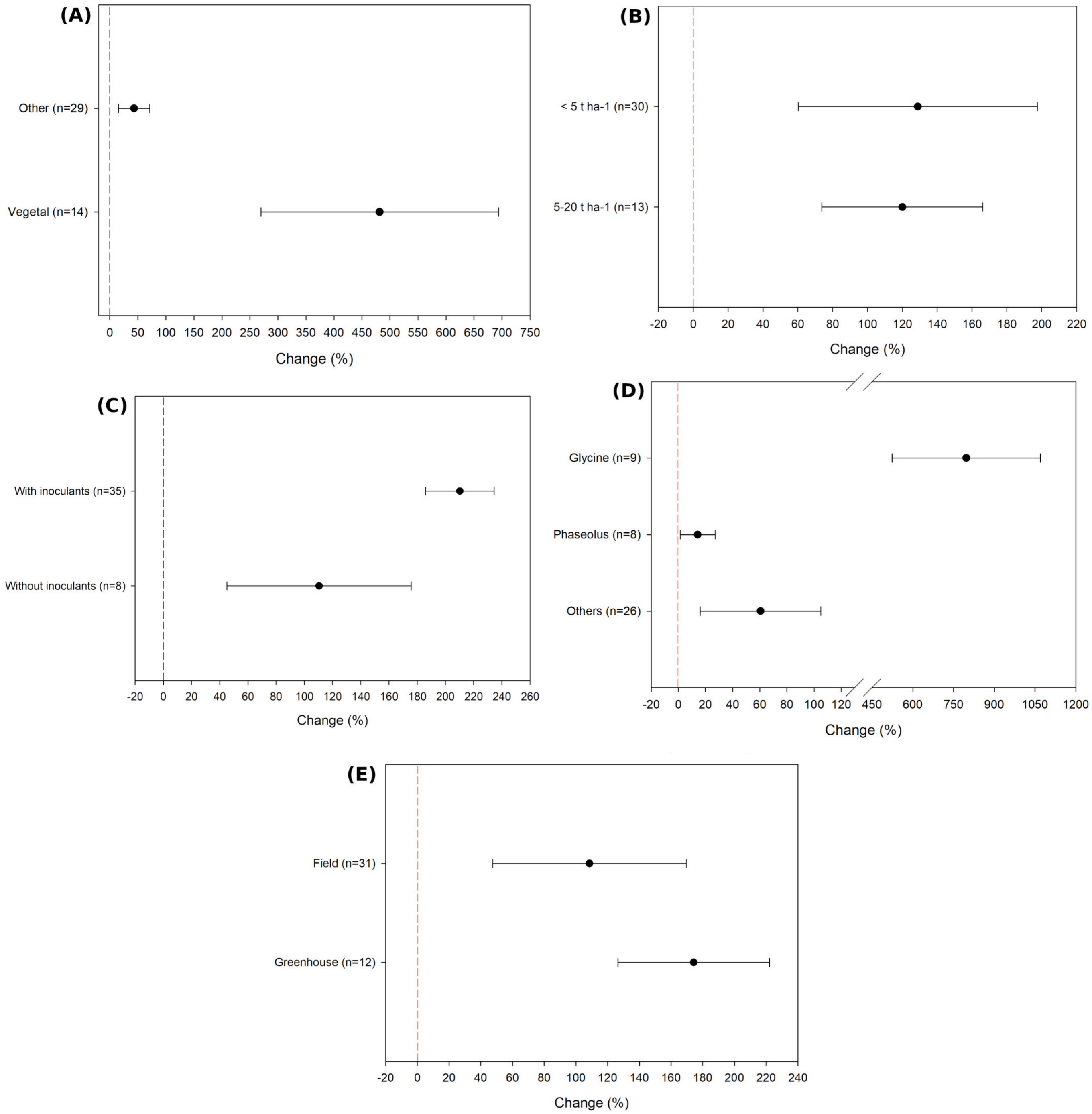

Fig. 7. Effect of the type (A), doses (B), inoculants (C), legumes (D) and experimental scale (E) of vermicompost application on nodules number of legume crops. Data are expressed as percent change refer to controls without compost or vermicompost addition. Levels are considered statistically different when bootstrap CIs do not overlap. "n" means the number of vermicompost direct comparisons used in this study before data curing.

limited data, it was not possible to compare the effects of biochar and compost on nodulation improvement in legumes.

As a future perspective, we recommend to carry out more research to evaluate, under the same conditions, the effects of these two soil amendments and how their combination with microbial inoculants influences legume nodulation. Additionally, as mentioned above, such investigations need to consider the use of appropriate inoculants tailored to the specific legume and soil environment. Added to that, the effect of compost (or vermicompost) chemical and biological characteristics, especially nitrogen content or raw nitrogen-fixing bacteria presented in compost, on SNF need to be thoroughly investigated. Finally, more studies including parameters such as acetylene reduction assay (ARA) as well as deciphering molecular mechanisms should be carried out.

5. Conclusions

Our results indicate that soil management using compost and vermicompost is beneficial for legume crops. Compost and vermicompost notably improve SNF, physiology and yield of the Rhizobium-legume symbiosis by increasing nodule number and biomass, plant biomass, plant height and seed yield. However, some research gaps highlighted

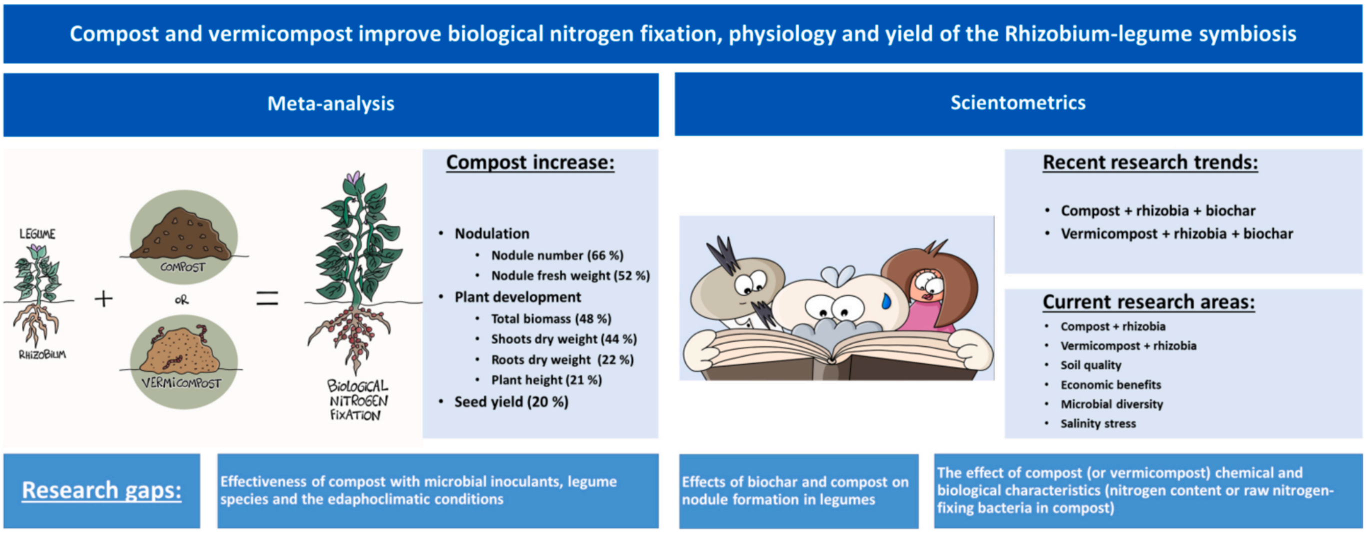

Fig. 8. An overview of the main effects of compost and vermicompost in Rhizobium-legume symbiosis.

by emerging trends need to be addressed, particularly regarding the use of inoculants and biochar. Our analyses have shown that supplementing compost with microbial inoculants did not enhance nodule formation as much as compost without inoculants. This finding requires further investigation to determine whether these results depend on the compost or vermicompost type or if specific rhizobia strains disrupt the compost's microbial community, leading to a smaller number of nodules. Additionally, exploring ways to mitigate any microbial imbalance, such as using microbial consortia, could be valuable in improving nodule formation. An additional step forward is to supplement compost with both microbial inoculants and biochar. The long-term effects of combining these practices on legume crop performance, nodule formation, carbon sequestration, greenhouse gas emissions and improvements in soil physicochemical properties remain inconclusive among researchers. However, there is consensus that these practices are well-suited for sustainable agriculture and organic farming.

CRediT authorship contribution statement

Carol V. Amaya-Gómez: Writing – review & editing, Visualization, Investigation, Data curation, Conceptualization. **Diego H. Flórez-Martínez:** Visualization, Methodology, Investigation, Data curation. **María Luz Cayuela:** Writing – review & editing, Methodology, Investigation. **Germán Tortosa:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2025.106051.

Data availability

The data that has been used is available at the Supplementary data section

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