ReGeo
ISSN: 2177-3246

USE OF BIOFERTILIZERS AS AN AGRICULTURAL PRACTICE AIMED AT INCREASING RESILIENCE AND CLIMATE ADAPTATION IN FAMILY FARMING SYSTEMS: AN ANALYSIS BASED ON SCIENCE, BRAZILIAN PUBLIC POLICIES, AND THE IPCC FRAMEWORK FOR CLIMATE JUSTICE AND JUST TRANSITION

USO DE BIOFERTILIZANTES COMO PRÁTICA AGRÍCOLA VISANDO AUMENTAR A RESILIÊNCIA E A ADAPTAÇÃO CLIMÁTICA EM SISTEMAS DE AGRICULTURA FAMILIAR: UMA ANÁLISE BASEADA NA CIÊNCIA, NAS POLÍTICAS PÚBLICAS BRASILEIRAS E NO MARCO DO IPCC PARA JUSTIÇA CLIMÁTICA E TRANSIÇÃO JUSTA

USO DE BIOFERTILIZANTES COMO PRÁCTICA AGRÍCOLA PARA AUMENTAR LA RESILIENCIA Y LA ADAPTACIÓN CLIMÁTICA EN SISTEMAS AGRÍCOLAS FAMILIARES: UN ANÁLISIS BASADO EN LA CIENCIA, LAS POLÍTICAS PÚBLICAS BRASILEÑAS Y EL MARCO DEL IPCC PARA LA JUSTICIA CLIMÁTICA Y LA TRANSICIÓN JUSTA

10.56238/revgeov16n5-011

Mariana Rodrigues Fontenelle[1], Catharine Abreu Bomfim[2], Lucimeire Pilon[3], Francisco Vilela Resende[4], Daniel Basílio Zandonadi[5], Ilvan Medeiros Lustosa Júnior[6], Carlos Eduardo Pacheco Lima[7]

ABSTRACT

The objective of this study is to present a systematic review of the literature addressing the use of biofertilizers in family farming as a strategy for increasing resilience and climate adaptation, its relationship with Brazilian public policies, and with the Intergovernmental Panel on Climate Change's benchmarks for climate justice and just transition. To this end, the PRISMA method was used, which is state of the art for studies that aim to systematically review the literature on a given topic, and a case study on the non-commercial biofertilizer Hortbio®. It was possible to verify the need to migrate from the conventional model of food production to regenerative agriculture, including the use of bio-inputs as a strategy. Bio-inputs contain a series of microorganisms capable of producing compounds similar to plant growth-promoting hormones that can increase the tolerance of agricultural crops to abiotic stresses.

---

[1] Dr. in Agricultural Microbiology. Embrapa Hortaliças. Brasília, Brazil. E-mail: mariana.fontenelle@embrapa.br Orcid: 0000-0001-8318-5933

[2] Dr. in Microbial Biology. IPMP Bioinsumos LTDA. Brasília, Brazil. E-mail: catharineabreu@gmail.com Orcid: 0000-0002-0896-8062

[3] Dr. in Science. Embrapa Hortaliças. Brasília, Brazil. E-mail: lucimeire.pilon@embrapa.br Orcid: 0000-0002-0896-8062

[4] Dr. in Crop Science. Embrapa Hortaliças. Brasília, Brazil. E-mail: francisco.resende@embrapa.br Orcid: 0000-0002-6354-4828

[5] Dr. in Life Sciences and Technology. Universidade Federal do Rio de Janeiro. Rio de Janeiro, Brazil. E-mail: danielzandonadi@gmail.com Orcid: 0000-0003-3347-4600

[6] Dr. in Forest Sciences. Universidade de Brasília. Brasília, Brazil. E-mail: ilvan.junior@ifb.edu.br Orcid: 0000-0002-3873-737X

[7] Dr. in Soils and Plant Nutrition. Embrapa Hortaliças. Brasília, Brazil. E-mail: carlos.pacheco-lima@embrapa.br Orcid: 0000-0002-6975-8560

Hortbio® fits into this context, with great microbial diversity, auxin production, and proven ability to increase heat tolerance in lettuce. Its open formula and non-commercial nature make it a potential solution that meets the IPCC's climate justice and just transition frameworks.

Keywords: Climate Change. Climate Emergency. Bio-Inputs. IPCC Referential. Brazilian National Public Policies. Hortbio®.

RESUMO

O objetivo do presente trabalho é apresentar uma revisão sistemática de literatura que aborde o tema uso de biofertilizantes na agricultura familiar como estratégia de aumento da resiliência e adaptação climática, sua relação com políticas públicas brasileiras e com os referenciais do Painel Intergovernamental sobre Mudanças Climáticas de justiça climática e transição justa. Para tal, foi utilizado o método PRISMA, estado da arte para trabalhos que visam revisar sistematicamente a literatura sobre um determinado tema, e um estudo de caso sobre o biofertilizante não comercial Hortbio®. Foi possível constatar a necessidade de migração do modelo convencional de se produzir alimentos para a agricultura regenerativa, incluindo o uso de bioinsumos como estratégia. Os bioinsumos apresentam em sua composição uma série de microrganismos capazes de produzir compostos semelhantes a hormônios promotores de crescimento vegetal que são capazes de aumentar a tolerância dos cultivos agrícolas a estresses abióticos. O Hortbio® se enquadra nesse contexto, com grande diversidade microbiana, produção de auxina e capacidade comprovada de aumentar a tolerância ao calor em alface. Sua fórmula aberta e seu caráter não comercial o potencializam como solução que atende aos referenciais de justiça climática e transição justa do IPCC.

Palavras-chave: Mudanças Climáticas. Emergência Climática. Bioinsumos. Referenciais do IPCC. Políticas Públicas Nacionais Brasileiras. Hortbio®.

RESUMEN

El objetivo de este trabajo es presentar una revisión sistemática de la literatura sobre el uso de biofertilizantes en la agricultura familiar como estrategia para aumentar la resiliencia y la adaptación climática, su relación con las políticas públicas brasileñas y el marco del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) para la justicia climática y la transición justa. Para ello, se empleó el método PRISMA, un método de vanguardia para la revisión sistemática de la literatura sobre un tema específico, así como un estudio de caso sobre el biofertilizante no comercial Hortbio®. El estudio demostró la necesidad de cambiar del modelo convencional de producción de alimentos a la agricultura regenerativa, incluyendo el uso de bioinsumos como estrategia. Los bioinsumos contienen una serie de microorganismos capaces de producir compuestos similares a hormonas que promueven el crecimiento vegetal y aumentan la tolerancia de los cultivos a estreses abióticos. Hortbio® se enmarca en este contexto, con una importante diversidad microbiana, producción de auxinas y una capacidad demostrada para aumentar la tolerancia al calor en la lechuga. Su fórmula abierta y su naturaleza no comercial lo convierten en una solución potencial que cumple con los criterios de justicia climática y transición justa del IPCC.

Palabras clave: Cambio Climático. Emergencia Climática. Bioinsumos. Referencias del IPCC. Políticas Públicas Nacionales Brasileñas. Hortbio®.

ISSN: 2177-3246

1 INTRODUCTION

Human activities are undoubtedly the main cause of global warming (GW) observed in recent decades. This rise in average air temperature is mainly due to the increase in atmospheric emissions of greenhouse gases (GHGs) observed since the industrial revolution (IPCC, 2023). The increase in global average temperature (GAT) observed between 2011 and 2020, when compared to the period from 1850 to 1900 (pre-industrial), was 1.1 °C (IPCC, 2023). It is worth remembering that the limit established by the Paris Agreement was 1.5 °C (IPCC, 2018), with a view to preventing a collapse of the climate system. However, 2024 was the first year to exceed this initial limit, reaching 1.6 °C (Copernicus, 2025a), raising concerns about a possible loss of this window of opportunity. January 2025 was the warmest month on record to date, with temperatures 1.75°C higher than the average temperature recorded in the pre-industrial period (Copernicus, 2025b).

There is high confidence that the global average temperature since 1970 has increased faster than in any previous 50-year period in the last 2000 years. There is unequivocally a strong relationship between the increase in atmospheric GHG concentrations and human activities, with atmospheric CO_2 concentrations reaching a peak of 410 ppm in 2019, and there is high confidence that this value is higher than any other observed in the last 2 million years. CH_4 and N_2O levels, in turn, reached values of 1866 ppb and 332 ppb in the same year, which represent, with a very high level of confidence, values higher than those observed in the last 800,000 years (IPCC, 2021).

Among the projected impacts of Global Climate Change (GCM), many stem from the occurrence of widespread extreme phenomena in ecosystems, people, populations, and infrastructure, and their frequency and intensity have increased over the last few decades, such as heat waves on land and in the oceans, intense rainfall, droughts, and fires, with it becoming increasingly clear that the origin of this increase can be attributed to human action (IPCC, 2021).

IPCC (2021) also shows that GCC has reduced food and water security, hampering efforts to achieve the Sustainable Development Goals (SDGs). Global agricultural productivity, for example, has slowed over the last 50 years worldwide, hindering actions such as the fight against hunger. The concentration of the negative impacts of GCC has been observed mainly in low and mid-latitudes, exposing millions of people to food, nutritional, and water insecurity, with the greatest impacts observed in regions of Asia, Africa, Central America, and South America. The loss of productive potential associated with the decline in dietary diversity has increased malnutrition in communities such as indigenous peoples, as well as small-scale food producers and their low-income households, affecting mainly children, the elderly, and pregnant women. About half of the world's population already experiences severe water shortages in at least part of the year, hampering their own survival and food production. Obviously, economic damage resulting from agricultural activities has also been observed in these regions (IPCC, 2023).

This article aims to analyze the role of biofertilizers as an agricultural practice for building resilient family farming systems that are adapted to climate change based on a systematic literature review and a case study of Hortbio® biofertilizer. It also aims to convince Brazilian public policy makers and implementers of the importance of investing in this area.

2 MATERIAL AND METHODS

2.1 SYSTEMATIC REVIEW OF LITERATURE

The objective of the systematic literature review was to highlight the impacts of GCC on Brazilian family farming, the need to increase resilience and climate adaptation, and to describe regenerative agriculture as a strategy in this scenario, focusing on the use of bio-inputs and based on a case study of the Hortbio® biofertilizer. To this end, the principles established by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol were followed to ensure transparency, reproducibility, and technical and scientific rigor.

2.2 INCLUSION AND EXCLUSION CRITERIA

Only scientific articles published in indexed journals, official documents from the Brazilian federal government, and technical and scientific materials produced by Embrapa were used. We sought to restrict the period to a maximum of 10 years to maintain the state of the art on the subject. A few exceptions were made to classic materials related to the topic that were widely cited.

2.3 SEARCH STRATEGY

Search was conducted in the Capes Periodicals Portal and complemented with queries in Perplexity.ai, a generative artificial intelligence tool that provides bibliographic references from indexed and peer-reviewed journals. To ensure search efficiency, prompt engineering and prompt chaining techniques were applied to structure the queries with clear instructions and specific indexing terms. Indexing terms included: global climate change, resilient agriculture, adaptation of agriculture to climate change, regenerative agricultural systems, conservationist agricultural systems, sustainable agricultural systems, family farming, impacts of climate change on Brazilian agriculture, climate justice, just transition, low carbon and adaptation Brazilian public policies, bio-inputs as adaptation strategy, bio-inputs to control abiotic stress, Hortbio®, among others. All references retrieved through the AI tool were subsequently verified for accuracy, traceability (DOI or link), and compliance with peer-review criteria before inclusionin the analysis.

3 SYSTEMATIC REVIEW

3.1 THE IMPORTANCE OF AGRICULTURE AND THE NEED TO TRANSITION TO SUSTAINABLE AND RESILIENT SYSTEMS

In recent decades, incredible increases in agricultural productivity have been observed. Although the world's population has doubled during this period, cereal production, for example, has tripled, using only 30% more land than in the past. This reflects the fundamental role of science, technology, and innovation in the sector, which resulted in what was then called the Green Revolution. Modern agriculture, following the green revolution, has been essential in providing food for a continuously expanding population, ensuring food and nutritional security for a significant portion of the world's population. However, its reliance on processes such as high soil turnover, high use of chemical inputs, and high consumption of water for irrigation has caused various problems, including environmental degradation (Pingali, 2012).

Pingali (2012) also points out that, although they have brought about important positive social impacts such as poverty reduction with the fall in real food prices, increased calorie availability, and improved protein consumption resulting in lower levels of malnutrition, negative impacts such as the persistence of social inequalities in rural areas and limited food diversification have also resulted from this process. Additionally, although it has saved land and forests due to increased productivity, negative environmental impacts such as soil degradation, contamination of water resources by chemical inputs, and overuse of these water resources have also been observed as negative environmental impacts. Also noteworthy are greenhouse gas emissions from agricultural systems and the need to mitigate them, as well as the influence of these systems on biodiversity loss. (Sela et al., 2024).

Zhang et al. (2018) analyzed global research trends on the environmental impacts of chemical inputs in agriculture in three different periods (1990-1999; 2000-2007; 2008-2016). The authors point out that the main contaminants from agriculture are pesticides and fertilizers, which mainly affect soil, water, and air. In general, the intensive use of fertilizers and pesticides is linked to high rates of environmental contamination due to their low efficiency of use, with the contribution of heavy metals, nitrates, and persistent organic compounds standing out. There is also growing concern about the transfer of these contaminants along food chains, affecting animals and human health, which can result in serious disorders in humans such as cancer and endocrine disruption, among other chronic problems. Among the environmental impacts, the potential for soil acidification and degradation, eutrophication of surface and groundwater bodies, accumulation of heavy metals and persistent organic residues, and air pollution stand out. These impacts result from processes such as leaching, surface runoff, and losses due to volatilization, among others. In recent years, there has been a trend toward intensified monitoring and assessment of environmental risk, as well as the replacement of conventional production systems with more sustainable ones. The authors also emphasize that the integration of research, development, and innovation (RD&I) with public policy is essential to changing this worrying scenario.

A paradigm shift is therefore necessary, where more sustainable, resilient, and regenerative systems become central to agricultural production. Practices such as organic fertilization, no-till farming, crop rotation, soil cover, integrated pest and disease management, irrigation, and optimized fertilization are essential for soil restoration, biodiversity recovery, and the mitigation of pollution and atmospheric greenhouse gas (GHG) emissions. In a case study in India, the application of a quantitative multi-criteria method called Analytical Hierarchy Process recommended the use of practices such as soil cover, waste management, and precision irrigation as priorities for a semi-arid climate region. Although the need to adopt regenerative practices has been technically proven, the lack of public policies is still an obstacle to the transition from conventional systems to the recommended systems. It is clear, therefore, that regenerative practices and systems are fundamental to reducing the environmental impacts of agricultural systems, but this requires abandoning the logic of short-term results alone and considering medium- and long-term results (Sela et al., 2024).

It is also necessary to remember that we are living in a delicate moment, where global climate change (GCC) has great potential to damage agricultural activities. Agriculture contributes to this phenomenon by emitting greenhouse gases (GHG), but it can act as a sink for these gases when managed regeneratively (Li et al., 2024). Assad & Assad (2024) highlight that the increase in average temperatures and rainfall variability is already observed and evident processes, with clear trends toward greater frequency and intensity of events such as droughts, heat waves, rains, and natural disasters. They also point out that plants with a C3 photosynthetic cycle are more susceptible to the effects of rising temperatures and water shortages than C4 plants. Examples of C3 plants include rice, beans, coffee, and most vegetables, while C4 plants include corn and sugarcane. Many of these crops are also used by family farms, so it is important that their production systems become more resilient and adapted to new climatic conditions. Phenomena such as rising temperatures, associated with reduced precipitation levels and increased evapotranspiration, threaten food and nutritional security in Brazil, where approximately 70% of the food consumed by Brazilians comes from family farming (IBGE, 2017). Therefore, it is essential to identify practices that can potentially increase resilience and climate adaptation for Brazilian family farming.

3.2 FAMILY FARMING AND ITS CHALLENGES IN THE FACE OF CLIMATE CHANGE

In Brazil, the term family farming is defined by Law 11.326/2006, referring to rural activities carried out on a small area of land and managed by the producer and their family members, predominantly using their own labor and obtaining at least 50% of the family income from the establishment's agricultural activities. This concept is broad, encompassing farmers, extractivists, aquaculturists, foresters, artisanal fishermen, indigenous peoples, quilombolas, and other traditional communities.

Brazilian family farming is among the economic activities most vulnerable to climate change, as it constantly faces difficulties in accessing credit, the scrapping of rural extension structures, less prepared infrastructure, and greater difficulty in accessing scientific and technological results. The concentration of water resource use by large economic activities directly impacts this sector, especially in regions that already face water scarcity, such as the Brazilian semi-arid region. In addition, the low capacity to raise financial resources, low income, and other socioeconomic limitations has led to the use of often inadequate production systems, resulting in the depletion of natural resources, soil erosion, loss of biodiversity, rural exodus (mainly of the younger population), food insecurity, and, consequently, increased social inequalities (CONTAG & Observatório do Clima, 2025).

Table 1 summarizes the main impacts projected by GCC in different Brazilian regions, based on publications whose original studies used state-of-the-art climate models.

Table 1

Summary of expected climate change per Brazilian regions and potential effect on family farming

Region	Main impact	Potential effect on family farming
Brazil	Widespread increase in temperatures in all regions and increased frequency and intensity of extreme rainfall and drought events.	Damage to production, logistic and storage infrastructure, need to use practices such as protected cultivation, water conservation and reuse, loss of soil fertility due to erosion, increase in diseases and pests, loss of food quality, increase of production costs, dependence of irrigation. Higher risks must be observed for family farmers because they have more difficulty to access to new markets and credit lines, increasing water, food, and nutritional insecurity. Greater social inequality is likely to result. Less suitable for mild and cold climate dependent crops.
Northern	More intense, frequent, and prolonged droughts, temperatures potentially over 4°C until 2050, increased occurrence of forest fires, and intensified water stress.	Decline in productivity rates, migration of crops to more suitable areas, losses related to extractivism, food and nutritional insecurity, lower income, and increased social inequalities. Higher dependence on irrigated agriculture. Increased need for practices capable of reducing the temperature in the growing microclimate. Less suitable for mild and cold climate dependent crops.
Southeastern	Greater frequency and intensity of extreme rainfall events, causing floods, landslides, and risks to structures such as dams, increased heat waves, and potentially more intense and	Damage to production, logistic and storage infrastructure, need to use practices such as protected cultivation, water conservation and reuse, loss of soil fertility due to leaching and, mainly, surface runoff and water erosion, increase in diseases and pests, leading to loss of productivity and food quality and increased production costs. Increased need for practices capable of reducing the temperature in the growing microclimate. Less suitable for mild and cold climate dependent crops.

	longer-lasting dry periods.	
Northeastern	Reduction in precipitation levels, increase in the intensity, duration, and frequency of drought events, tendency toward desertification of part of the current semi-arid region, sharp increase in temperature.	Yield losses due to water stress, less suitable for mild and cold climate dependent crops, dependence on irrigated agriculture, need to use practices such, water conservation, reservation and reuse. Increased need for practices capable of reducing the temperature in the growing microclimate. The use of practices that significantly reduce the need for irrigation water, such as soil-less cultivation, is desirable.
Southern	Trend toward an increase in extreme rainfall events, causing floods and landslides, changes in the climate calendar such as delays in the onset of the rainy season, precipitation concentrated in short periods of time, probability of increased frost in higher elevations. Possible alternation between intensely rainy and intensely dry periods.	Damage to production, logistic and storage infrastructure, need to use practices such as protected cultivation, need to use water flow regulation infrastructure, loss of soil fertility due to leaching and, mainly, surface runoff and water erosion, increase in diseases and pests, leading to loss of productivity and food quality and increased production costs.
Midwest	Significant increase in average and maximum annual temperatures, which may exceed 4.5°C by the end of the century. Greater intensity, duration, and	Productivity losses, stress overload due to water deficit and excess, greater losses related to high temperatures, especially for crops better suited to cold and mild climates, the need for more adapted agricultural practices, increased food, nutritional, and water insecurity, the need to use practices such as treated effluent reuse, water and soil conservation, and water storage, greater dependence on irrigated

	frequency of heat waves. Trend toward a reduction in average annual precipitation, which, combined with the increase in temperature, is expected to lead to increased evapotranspiration, despite the considerable uncertainty that still exists among current model projections. More concentrated and irregular rainfall events, increased intensity, duration, and frequency of drought events. Concentrated rainfall events can lead to hydrological extremes, resulting in flooding and increased erosion. Increased occurrence of increasingly intense forest fires. Increased occurrence of strong winds causing damage to agricultural infrastructure and wind erosion.	agriculture, higher production costs, higher expenses for forest fire control, and increased social inequality.

Source: The authors based on articles by Ballarin et al. (2023), Flores et al. (2024), Kahana et al. (2024) and Marques et al. (2024).

Although many of the climate adaptation actions presented in Table 1 do not correspond to regenerative practices, the Intergovernmental Panel on Climate Change, as well as Brazilian public policies such as the Low Carbon Agriculture and Climate Change

ISSN: 2177-3246

Adaptation Plan (ABC+ Plan), advocate adaptation based on co-benefits (capable of promoting mitigation and adaptation at the same time) and nature-based strategies as the preferred ones. Regenerative agriculture falls within this context, and it is important to contextualize it, study and discuss the agricultural practices it adopts.

3.3 REGENERATIVE FAMILY FARMING AS PART OF THE SOLUTION

Draft Law Nº. 1787 of 2025, currently being debated in the Brazilian Senate, aims to establish a National Policy for the Promotion of Regenerative Agriculture (PNFAR), with the objective of promoting the adoption, development, and coordination of practices, knowledge, and technologies focused on the active regeneration of agricultural ecosystems, climate resilience, and food and nutritional security.

In Article 2, the Draft Law states that the PNFAR will be governed by the following principles: respect for ecological cycles and the evolutionary capacity of living systems; promotion of the biological, functional, and cultural diversity of agroecosystems; integration of scientific, traditional, and practical knowledge in soil and landscape management; recognition of the multifunctionality of agriculture and the diversity of social actors in the field; promotion of productive autonomy and continuous innovation in rural areas; and appreciation of regeneration as an active process of ecological and social restoration.

In turn, in Article 3, the draft presents the concept of regenerative agriculture as a "*systemic approach to agricultural management that aims to regenerate the health of soil, water, biodiversity, biogeochemical cycles, and socioeconomic relationships that sustain agroecosystems, integrating ecologically based, culturally contextualized, and adaptive practices*". Regenerative practices are understood as an "*open set of techniques and processes, recognized by science or participatory validation systems, that promote verifiable regeneration results, such as permanent soil cover, green manure, crop rotation and intercropping, crop-livestock-forest integration, agroforestry management, use of bio-inputs, polyculture, and recovery of degraded areas*".

It is clear, therefore, that the use of bio-input is one of the recommended practices when using regenerative agriculture, which, in turn, has among its objectives, increasing resilience and climate adaptation. This view becomes even more evident when analyzing the Brazilian ABC+ Plan, which encourages the adoption of sustainable agricultural production systems, practices, products, and processes, also known by the acronym SPS_{ABC}. Among the various alternatives for achieving sustainable, resilient, and adapted agriculture is the use of bio-inputs, recognized for their potential to mitigate atmospheric greenhouse gas emissions and increase climate resilience and adaptation due to their potential to mitigate the effects of abiotic stresses, as will be detailed in the next topic.

The use of bio-inputs is also encouraged by several other Brazilian public policies, such as the National Policy on Climate Change, the National Adaptation Plan, Non-Determined Contributions, the National Policy on Organic Agriculture and Agroecology, the National Bio-Inputs Program, and the National Urban and Peri-Urban Agriculture Program. It is also related to the international agenda on sustainability and climate change, such as Agenda 2030 and the IPCC reports, and is aligned with at least SDG 2, SDG 3, SDG 6, SDG 11, SDG 12, SDG 13, and SDG 15.

3.4 BIOFERTILIZERS AS KEY PRODUCTS FOR INCREASING CLIMATE RESILIENCE AND ADAPTATION

The demand for biofertilizers has been growing over the last few years. The reason for this, in addition to their agronomic benefits, is that these products are seen as fundamental to emerging issues such as GCC, sustainability, and unique health. They can reduce the negative effects of synthetic fertilizer use and improve soil health and the environmental conditions. As a result, there has been an increase in public policies that focus on incentives and regulations to expand their adoption (Kurniawati et al., 2023).

Although biofertilizers are often referred to as equal products, there are significant differences between them, each fulfilling specific functions. Bouhzam et al. (2025), assessing the environmental impacts of different biofertilizers, organic compounds, and biostimulants used in Europe through Life Cycle Assessment (LCA), concluded that the transition to a circular economy using biofertilizers depends on rational choices and specific situations, especially regarding the target nutrient, due to the wide variation in their contents. The products still differ in terms of their environmental impact and efficiency, and priority should be given to those that have a low impact and a high effect on agricultural productivity. A similar situation was shown by Cajamarca et al. (2019a), who, analyzing the chemical composition, agronomic potential, and heavy metal content of agro-industrial waste used in the manufacture of biofertilizers, found high variability in the composition with a direct impact on fertilization potential and environmental impact caused by potential heavy metal contamination. One of the key points for the widespread adoption of biofertilizers, therefore, is a minimum standardization of these products so that rural producers can be assured of maintaining productivity regardless of the batch of biological material used.

Biofertilizers not only could meet the nutritional needs of agricultural crops but are also important for increasing resilience and climate adaptation. Many studies have pointed to the potential of these products to fulfill these functions. This occurs mainly due to the presence of plant growth-promoting microorganisms (PGPM) (Bomfim et al., 2024), which can produce compounds similar to those that act in various plant development processes, increasing plant tolerance to abiotic stresses, such as auxins (IAA) (Santos et al., 2020). IAA are recognized participant of various processes linked to plant development, such as rooting, apical dominance, plant growth, geotropism, phototropism and fruit development (Alatzas, 2013).

Biofertilizers based on arbuscular mycorrhizal fungi (AMF) have shown potential to mitigate the negative effects of high temperatures on soybean crops, improving their development and productivity (Junrami et al., 2022). The authors point to mechanisms such as improved nutrient absorption capacity, optimization of photosynthetic processes, improved osmotic adjustment, promotion of superior antioxidant activity, and improved reproductive capacity as the reasons for these results. Biofertilizers with other classes of microorganisms in their composition, such as plant growth-promoting rhizobacteria and endophytic microorganisms, for example, have also shown potential for mitigating the adverse effects of abiotic stresses, and are therefore an important strategy for adapting to extreme environmental events. Tang et al. (2022) recognized the role of AMF as playing a critical role in increasing crop tolerance to abiotic stresses such as drought, salinity, nutrient deficiency, and heat. These authors highlight that AMF establish symbiotic relationships with the roots of more than 80% of terrestrial plants, making them extremely important in the composition of biofertilizers. They agree with the mechanisms cited by Junrami et al. (2022) and cite the following compounds as responsible for hormonal regulation, influenced by microorganisms: abscisic acid, auxins, gibberellins, jasmonates, and strigolactones, which act to promote stress tolerance by adjusting root growth and stomatal closure.

However, the role in increasing tolerance to abiotic stress in cultivated plants is not restricted to AMF. Other endophytic microorganisms, such as plant growth-promoting rhizobacteria (PGPR), also play a central role. Among the mechanisms of action that promote this increase in tolerance are colonization and symbiotic relationships, hormonal regulation and release of phytochemicals, antioxidant activity, ionic homeostasis and regulation of water balance, gene expression and molecular signaling, phytoprotection and biocontrol, and phytoremediation. The authors also conclude that endophytic microorganisms are essential for the development of sustainable biotechnology-based technologies aimed at increasing the resilience of agricultural crops under different environmental stress conditions, including those related to GCC. Pérez-Bernal et al. (2025), when evaluating the combination of biofertilizers composed of AMF and PGPR with intercropping production systems, observed improvements in yield and increased land use efficiency, proving to be strategic for sustainable agriculture in areas with water and mineral input restrictions, resulting in agronomic and environmental benefits.

The strategy for adapting Brazilian agriculture to climate change is based on structural actions involving RD&I, rural technical assistance (RTA), sectoral public policies, and market integration. Products, practices, and processes such as genetic improvement, the adoption of products that increase resilience and climate adaptation, the use of conservationist/regenerative and integrated management systems, climate forecasting and risk zoning tools, financing instruments, ATER strategies, and public policies are essential. The use of bio-input fits into this context, being one of the main strategic elements, increasing sustainability and, additionally, reducing dependence on external inputs. Among the objectives of using biofertilizers are the replacement of nitrogen fertilizers, the promotion of soil conservation and biodiversity, the promotion of RD&I actions for the decentralized use of bio-inputs, and the induction of the use of bio-inputs in the National Fertilizer Plan 2050 (MAPA, 2023).

In the next section, we will discuss a case study covering a wide range of results from various publications, as well as unpublished results, on the potential of the open formula biofertilizer Hortbio®, developed by Embrapa Vegetables, as a strategy for increasing resilience and climate adaptation, as well as agricultural sustainability.

3.5 HORTBIO® OPEN FORMULA BIOFERTILIZER AS A CASE STUDY

Hortbio® is an organic biofertilizer, with free use and formula, registered by Embrapa Hortaliças. For every 100 L, it consists of 1 kg of blood meal, 4 kg of rice or cotton bran, 1 kg of castor bean meal, 2 kg of bone meal, 1 kg of crushed legume grains or seeds, 1 kg of ash, 0.5 kg of brown sugar or raw sugar, 0.5 kg of cornmeal or cassava flour, and 88 L of non-chlorinated water (Embrapa Vegetables, 2012). Efficient microorganisms are added to this mixture (EM) - 2 L. These are collected using a cooked rice trap (a tray filled with unseasoned rice and covered with shade cloth) buried in soil in preserved areas, such as an area with

Cerradão-type vegetation in Embrapa Vegetables' Organic Agriculture sector. Before adding and after removing the soil, the dark microbial colonies are discarded, using only the lighter ones. The biofertilizer is then aerated for 15 minutes every hour, using an air compressor, for 10 days. The final product should be used in a concentration of 5% and is valid for 30 days.

Microbiological characterization of Hortbio® was performed by Bomfim et al. (2024), who found high microbial diversity, totaling 217 isolates of microorganisms. Of these, 120 were bacteria (including actinomycetes), 61 were yeasts, and 36 were filamentous fungi. Genetic sequencing showed that the main bacterial groups present were Firmicutes, Proteobacteria, Actinomycetes, and Bacteroidetes, with a predominance of *Bacillus*, *Klebsiella*, *Kurthia*, *Enterococcus*, *Staphylococcus*, and *Pseudomonas*. The most prominent fungal genera were *Galactomyces*, *Penicillium*, *Mucor*, *Aspergillus*, *Cladosporium*, and *Trichoderma*, while the main yeast genera were *Candida* and *Pichia*. The greatest microbial diversity occurred 10 days after inoculation with EM, a period in which the highest concentration of IAA was also found, suggesting a possible relationship between these two factors. Thus, the 10-day maturation period would, in theory, be ideal for application in crops when there is a need to mitigate abiotic stresses potentiated by GCC.

Among the microorganisms present in Hortbio®, isolates of *Bacillus*, *Pseudomonas*, *Enterobacter*, *Klebsiella*, and *Streptomyces* are recognized as promoters of growth and increased tolerance to water, heat, and salt stress through the synthesis of phytohormones, osmolytes, and the activation of antioxidant enzymes. Among fungi, *Galactomyces candidum* is recognized for its resistance to nutritional stress conditions and is reported as an endophytic microorganism naturally found in cultivated plants. *Trichoderma harzianum* can enhance the systemic tolerance of plants by inducing mechanisms of tolerance to drought, heat, and salinity through processes such as auxin production, nutrient solubilization, and antioxidant system activation. Finally, yeasts of the genus *Pichia* are described as potential phosphate solubilizers and phytohormone producers, which aid in the nutrition, growth, and resilience of plants, especially in tropical soils such as oxidic Latosols, which have a high phosphorus adsorption capacity (Bomfim et al., 2024). The chemical and physicochemical characteristics of Hortbio® should also be highlighted and can be seen in Table 2.

As previously mentioned, the heterogeneity of biofertilizer formulations is clear, which has been a problem for the mass adoption of this type of product and is not exclusive to Hortbio®, as clearly demonstrated by Cajamarca et al. (2019a). Greater predictability of the formula used, nutrient concentrations and balance, as well as its effects on crops, is essential for such adoption and should be the next step in the development of biofertilizers.

Despite their potential to increase resilience and climate adaptation, certain precautions must be taken when using biofertilizers in general and, in this case, with a focus on Hortbio®. As demonstrated by Cajamarca et al. (2019a), there is great heterogeneity in samples of the raw materials used for production, which can result in products with different chemical, physicochemical, and microbiological compositions. There is also a risk of heavy metal contamination, depending on the batch of agro-industrial waste used. In addition, processes such as the capture of microorganisms in the soil can vary depending on several factors, such as soil type, vegetation, the state of conservation/preservation of the area, and climatic characteristics, among others. The results obtained by Pilon et al. (2019) also point to the need to adopt sanitary precautions during the production of biofertilizer to prevent microbiological contamination by potentially pathogenic microorganisms such as *E. coli* and *Salmonella* spp.

Table 2

Chemical and physicochemical characteristics of Hortbio biofertilizer determined in different studies.

Study	pH	EC	C	N	C/N	P	K	S	Ca	Mg	Fe	B	Mn	Na	Cu	Zn	Cd	Pb	Cr	Hg	Ni
			dag/L	g/L		mg/L															
Ludke (2009)	5.2	5.9	0.9*	1.5	6.0	170.5	1861.4	82.3	984.5	495.6	12.5	89.2	9.0	---	0.6	1.4	<0.01	<0.01	0.3	<0.01	0.2
Embrapa Hortaliças (2012)	---	---	---	1.5	---	200.0	1800.0	82.3	1000.0	500.0	12.5	89.2	1.4	---	0.6	1.4	---	---	---	---	---
Cajamarca et al. (2019a)	6.0	5.9	$20.3^{\#}$	4.5	4.5	810.0	2930.0	460.0	3910.0	1000.0	121.15	---	---	---	---	8.8	0.1	---	---	---	---

*Organic Carbon; $^{\#}$Total Carbon determined by CHNS
Source: The authors modified from studies cited.

*Organic Carbon; Total Carbon determined by CHNS
Source: The authors modified from studies cited.

Legend:
pH - hydrogen ion potentialEC – Electrical Conductivity
C – Carbon; N – Nitrogen; C/N – Carbon-Nitrogen rate; P – Phosphorus; K – Potassium; S – Sulfur; Ca – Calcium; Mg – Magnesium; Fe – Iron; B – Borum; Mn – Manganese; Na – Sodium; Cu – Cooper; Zn – Zinc; Cd – Cadmium; Pb – Lead; Cr – Chromium; Hg – Mercury; Ni - Nickel

Regarding the productivity and quality of fertilized products such as Hortbio®, Cajamarca et al. (2019b) and Bomfim et al. (2023) evaluated its effect under experimental conditions (pot cultivation and greenhouses). The former authors evaluated the production of three curly lettuce cultivars using Hortbio® as a nutrient source, while the latter evaluated the use of this product to produce three different types of lettuce (curly, American, and romaine). In both cases, it was possible to see that its use for the same plant but with different genetic material must be adapted. For example, for two cultivars, Cajamarca et al. (2019b) found better productivity when Hortbio® was diluted to 5%, while for the other cultivar, the optimal dosage was 10%. Bomfim et al. (2023) found good results for curly and American lettuce, which showed good development with lower doses of Hortbio®, while romaine lettuce showed poor results, regardless of the dose used. In both cases, the optimal dose of biofertilizer was between 50 kg N/ha and 150 kg N/ha. Higher doses caused morphophysiological damage associated with soil salinization, as well as characteristics of the soils used with results compatible with this process. Used at the correct dose, Hortbio® was able to improve soil quality and produce IAA concentrations compatible with those necessary to mitigate the negative effects of abiotic stresses.

As a non-commercial, low-cost product linked to the circular economy through the reuse of agricultural waste, and applicable to the production of crops predominantly linked to family farming (vegetables), Hortbio® emerges as a solution for increasing resilience and climate adaptation that fits within the IPCC's climate justice and just transition frameworks. These concepts will be discussed in more detail in the next topic.

3.5 IPCC’S CLIMATE JUSTICE AND JUST TRANSITION FRAMEWORKS CONCEPT

The term climate justice stems from the recognition that the global impacts of climate change are unevenly distributed, disproportionately affecting low-income populations, rural communities, and small farmers, who contribute less to the increase in atmospheric GHG concentrations. For these populations, actions such as technological development compatible with their profile, differentiated sources of financing, and the existence of public policies for climate inclusion are necessary. These actions are closely linked to the concept of a just transition, which refers to the need for social inclusion and equitable benefits as the shift toward low-carbon and climate-resilient production models occurs (IPCC, 2023).

In the Brazilian rural context, these references apply mainly to family farming, whose farmers are mostly low-income and sometimes socioeconomically vulnerable. They also face conditions such as difficulties in accessing financing, less technologically advanced agricultural systems, low levels of basic sanitation, and limited access to technical information that supports the adoption of mitigation, resilience, and adaptation practices. It is also not uncommon for family farmers to have their production areas located in fragile environments with various factors that hinder agricultural production, such as extreme temperatures, irregular rainfall, degraded soils, and mountainous terrain. To mitigate this condition, it is essential to adopt regenerative practices and systems, including the use of biofertilizers as an agent to increase tolerance to abiotic stresses.

Hortbio®, as an open-source and non-commercial biofertilizer, plays a role in promoting climate justice and a just transition, democratizing the adoption of strategies to increase resilience and climate adaptation, while maintaining or increasing the sustainability of family farming systems. In this context, it has been proven that this biofertilizer has the potential to mitigate the negative effects of high temperatures caused by GCC, as demonstrated by Lima et al. (2024) who, simulating the average temperature regime projected for Brazil in pessimistic climate change scenarios, observed positive effects from the use of Hortbio compared to mineral fertilization for morpho-agronomic attributes such as premature bolting, lower incidence of tipburn and chlorosis, making it a low-cost and highly accessible solution for family farming adaptation.

4 CONCLUSIONS AND FINAL CONSIDERATIONS

1. Use of biofertilizers represents an important strategy for promoting sustainable and resilient family farming.
2. Several national public policies and international agendas recognize the role of these products in increasing resilience and climate adaptation.
3. Science also proves this fact by pointing to the presence of microorganisms such as AMF and PGPR capable of producing plant growth-promoting compounds such as various hormones, which have the potential to mitigate the negative impacts of abiotic stresses.
4. The Hortbio® biofertilizer stands out for being an open-formula, non-commercial product with a proven ability to maintain productivity and reduce the vulnerability of lettuce production to heat.

5. In addition, Hortbio® contributes to the circular economy by being produced using agricultural and agro-industrial waste as raw material, reducing its environmental footprint.
6. Although there are public policies to encourage the use of bio-inputs in Brazil, these are still of limited reach for family farmers, making it necessary to expand services to this audience as a strategy for climate justice and just transition.
7. Science-based standardization of biofertilizers can increase safety, reproducibility, scalability, and maintenance of production rates, reinforcing their use by family farmers.
8. Climate adaptation is essential for maintaining the food and nutritional security of the Brazilian population.

ACKNOWLEDGEMENTS

We would like to thank the Federal District Research Support Foundation (FAP-DF) and the Brazilian Agricultural Research Corporation (Embrapa) for funding the research, and the National Council for Scientific and Technological Development (CNPq) for awarding the Productivity Grant in Technological Development and Innovative Extension to co-author Carlos Eduardo Pacheco Lima (Process number: 313563/2025-0).

REFERENCES

Alatzas, A. (2013). Histones and plant hormones: New evidence for an interesting interplay. Botanical Review, 79, 317–341. https://doi.org/10.1007/s12229-013-9119-6

Anand, U., Pal, T., Yadav, N., et al. (2023). Current scenario and future prospects of endophytic microbes: Promising candidates for abiotic and biotic stress management for agricultural and environmental sustainability. Microbial Ecology, 86, 1455–1486. https://doi.org/10.1007/s00248-023-02190-1

Assad, E. D., & Assad, M. L. R. C. L. (2024). Mudanças do clima e agropecuária: impactos, mitigação e adaptação. Estudos Avançados, 38(112), 271–292. https://doi.org/10.1590/s0103-4014.202438112.015

Ballarin, A. S., Sone, J. S., Gesualdo, G. C., Schwamback, D., Reis, A., Almagro, A., & Wendland, E. C. (2023). CLIMBra - Climate change dataset for Brazil. Scientific Data, 10, 36. https://doi.org/10.1038/s41597-023-01956-z

Bomfim, C. A., do Vale, H. M. M., Lima, C. E. P., da Silva, J., Zandonadi, D. B., & Fontenelle, M. R. (2024). Microbiological characterization and functional evaluation in formulation made on farm at different times of production. Revista Caderno Pedagógico, 21(6), 1–23. https://doi.org/10.54033/cadpedv21n6-155

Bomfim, C. A., Fontenelle, M. R., Braga, M. B., Zandonadi, D. B., Silva, J. da, Guedes, I. M. R., Vale, H. M. M., & Lima, C. E. P. (2023). Lettuce types development and substrate fertility attributes in response to doses of an aerobic biofertilizer. Journal of Agricultural Sciences Research, 3(10), e9733102313079. https://doi.org/10.22533/at.ed.9733102313079

Bouhzam, I., Azarkamand, S., Puig, R., Bala, A., Fullana-i-Palmer, P., Sazdovski, I., Mazurenko, B., Mir, S., Sani, M. N. H., Lopes, I. G., Maievska, T., Raksha, N., Savchuk, O., Ghaley, B. B., Yong, J. W. H., & Tonkha, O. (2025). Assessing environmental impacts of various biofertilizers in Europe: A step toward circular economy transition. Sustainable Production and Consumption, 56, 460–476. https://doi.org/10.1016/j.spc.2025.04.012

Cajamarca, S. M. N., Lima, C. E. P., Silva, J. da, Guedes, I. M. R., Braga, M. B., Fontenelle, M. R., & Figueiredo, C. C. (2019b). Curly lettuce development, nutrient absorption and salinization tolerance in response to an aerobic biofertilizer produced from agro-industrial residues. Australian Journal of Crop Science, 13(10), 1659-1667. https://doi.org/10.21475/ajcs.19.13.10.p1893

Cajamarca, S. M. N., Martins, D., da Silva, J., Fontenelle, M. R., Guedes, Í. M. R., de Figueiredo, C. C., & Lima, C. E. P. (2019a). Heterogeneity in the chemical composition of biofertilizers, potential agronomic use, and heavy metal contents of different agro-industrial wastes. Sustainability, 11(7), 1995. https://doi.org/10.3390/su11071995

CONTAG, Observatório do Clima. (2025). Family farming and food systems: Carbon removal and just transition. (Eds. C. E. P. Lima, F. B. P. L. Rubinstein, J. B. Amaral, L. S. Leal, R. Zoche, S. P. Bonetti). Seven Publications Ltda. https://doi.org/10.56238/livrosindi202507-002

COPERNICUS. (2025a, January 10). Copernicus Global Climate Report 2024 confirms last year as the warmest on record, first ever above 1.5°C annual average temperature. Copernicus. https://www.copernicus.eu/en/news/news/copernicus-global-climate-report-2024-confirms-last-year-warmest-record-first-ever-above

COPERNICUS. (2025b, February 6). Surface air temperature for January 2025. Copernicus Climate Change Service. https://climate.copernicus.eu/surface-air-temperature-january-2025

Embrapa Hortaliças. (2012). Hortbio®: Biofertilizante líquido para produção de hortaliças. Folder técnico. Brasília, DF: Embrapa Hortaliças. Recuperado de https://www.infoteca.cnptia.embrapa.br/bitstream/doc/946012/1/folder20hortbio.pdfEmbrapa

Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., ... & Hirota, M. (2024). Critical transitions in the Amazon forest system. Nature, 626(7995), 555–562. https://doi.org/10.1038/s41586-023-06970-0

Instituto Brasileiro de Geografia e Estatística (IBGE). (2017). Censo Agropecuário 2017: Agricultura Familiar. Governo Federal do Brasil.

Intergovernmental Panel on Climate Change (IPCC). (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change (IPCC). (2021). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani et al. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 3–32). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

Intergovernmental Panel on Climate Change (IPCC). (2023). Summary for Policymakers. In A. Reisinger, R. Slade, J. Skea et al. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 3–36). IPCC. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Kahana, R., Halladay, K., Alves, L. M., Chadwick, R., & Hartley, A. J. (2024). Future precipitation projections for Brazil and tropical South America from a convection-permitting climate simulation. Frontiers in Climate, 6, 1419704. https://doi.org/10.3389/fclim.2024.1419704
Kurniawati, A., Stankovics, P., Hilmi, Y. S., Toth, G., Smol, M., & Toth, Z. (2023). Understanding the future of bio-based fertilisers: The EU's policy and implementation. Sustainable Chemistry for Climate Action, 3, Article 100033. https://doi.org/10.1016/j.scca.2023.100033

Li, L., Awada, T., Shi, Y., Jin, V. L., & Kaiser, M. (2025). Global Greenhouse Gas Emissions From Agriculture: Pathways to Sustainable Reductions. Global Change Biology, 31(1), e70015. https://doi.org/10.1111/gcb.70015

Marques, M. T. A., Kovalski, M. L., Perez, G. M. P., Martin, T. C. M., Barbosa, E. L. S. Y., Ribeiro, P. A. S. M., & Valdes, R. H. (2024). Data-driven discovery of mechanisms underlying present and near-future precipitation changes and variability in Brazil. EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2024-48

Ministério da Agricultura e Pecuária. Secretaria de Inovação, Desenvolvimento Sustentável, Irrigação e Cooperativismo. (2023). Estratégia de adaptação à mudança do clima para a agropecuária brasileira. Brasília: MAPA/SDI. ISBN 978-85-7991-214-6.

Pérez-Bernal, S., Sekar, J., Prabavathy, V. R., Mathimaran, N., Thimmegowda, M. N., Bagyaraj, D. J., & Kahmen, A. (2025). Biofertilizers enhance land-use efficiency in intercropping across crop mixtures and spatial arrangements. Frontiers in Agronomy, 7, 1562589. https://doi.org/10.3389/fagro.2025.1562589

Pilon, L., Ginani, V. C., Fontenelle, M. R., Lima, C. E. P., Braga, M. B., & Zandonadi, D. B. (2019). Qualidade microbiológica de alface fertirrigada por gotejamento com fertilizantes orgânicos ou mineral (Boletim de Pesquisa e Desenvolvimento 179). Embrapa Hortaliças.

Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences, 109(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109

Santos, M. P., Zandonadi, D. B., de Sá, A. F. L., Costa, E. P., de Oliveira, C. J. L., Perez, L. E. P., Façanha, A. R., & Bressan-Smith, R. (2020). Abscisic acid-nitric oxide and auxin interaction modulates salt stress response in tomato roots. Theoretical and Experimental Plant Physiology, 32, 301–313. https://doi.org/10.1007/s40626-020-00187-6

Sela, S., Dobermann, A., Cerri, C. E., Svoray, T., van-Es, H., Amsili, J., Biradar, S., Luzon, U., & Katz, S. (2024). Towards a unified approach to prioritization of regenerative agricultural practices across cropping systems. npj Sustainable Agriculture, 2(24), Article 224. https://doi.org/10.1038/s44264-024-00031-3

Tang, H., Hassan, M. U., Feng, L., Nawaz, M., Shah, A. N., Qari, S. H., Liu, Y., & Miao, J. (2022). The critical role of arbuscular mycorrhizal fungi to improve drought tolerance and nitrogen use efficiency in crops. Frontiers in Plant Science, 13, 919166. https://doi.org/10.3389/fpls.2022.919166

Zhang, L., Yan, C., Guo, Q., Zhang, J., & Ruiz-Menjivar, J. (2018). The impact of agricultural chemical inputs on environment: Global evidence from informetrics analysis and visualization. International Journal of Low-Carbon Technologies, 13(3), 338–352. https://doi.org/10.1093/ijlct/cty039