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ARTIFICIAL INTELLIGENCE AND DIGITALIZATION OF THE MADERUS METHODOLOGY: A BIBLIOMETRIC REVIEW ON THE OPEN TOOL FOR SUSTAINABLE RURAL DEVELOPMENT

Inteligência artificial e digitalização da metodologia MADERUS: uma revisão bibliométrica sobre a ferramenta aberta para o desenvolvimento rural sustentável

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Abstract: Family farming faces persistent challenges in accessing sustainability assessment tools that are both scientifically robust and operationally accessible. The Methodology for Assessing Sustainable Rural Development (MADERUS), proposed by Hein (2019) within the Graduate Program in Sustainable Rural Development (PPGDRS/UNIOESTE), represents a consolidated multidimensional instrument in this field; however, its application remains predominantly manual, limiting its accessibility and dissemination. This article presents a bibliometric review combined with content analysis of scientific production related to MADERUS, the digitalization of sustainability assessment tools, and the application of artificial intelligence in family farming. The search was conducted in the CAPES Journals Portal, the Brazilian Digital Library of Theses and Dissertations (BDTD), the UNIOESTE Institutional Repository, Scopus, Web of Science, and Google Scholar, using combined search terms in Portuguese and English for the period from 2008 to 2026. After systematic screening, 36 studies were selected for the final corpus, comprising 20 studies previously indicated by the advisor and 16 studies identified through the systematic search. The keyword co-occurrence analysis performed using VOSviewer, based on combined metadata from Scopus and Web of Science, generated a network with 148 connected items and 18 clusters, revealing three main thematic groupings: rural development and digital inclusion; digital technologies and artificial intelligence; and remote sensing and computer vision, with few connections between the first grouping and the others. The results support the feasibility and scientific relevance of a responsive web platform for digitalizing MADERUS with the support of generative artificial intelligence, making it more accessible to farmers, technicians, and public managers, while contributing to Sustainable Development Goals (SDGs) 2, 9, and 17.

Keywords: MADERUS; family farming; artificial intelligence; digitalization; sustainable rural development; bibliometrics.

Resumo: *A agricultura familiar enfrenta desafios persistentes de acesso a ferramentas de avaliação de sustentabilidade que sejam ao mesmo tempo cientificamente robustas e operacionalmente acessíveis. A Metodologia de Avaliação do Desenvolvimento Rural Sustentável (MADERUS), proposta por Hein (2019) no âmbito do PPGDRS/UNIOESTE, representa um instrumento multidimensional consolidado nesse campo, mas sua aplicação permanece predominantemente manual, limitando sua acessibilidade e difusão. Este artigo apresenta uma revisão bibliométrica com análise de conteúdo sobre a produção científica relacionada à MADERUS, à digitalização de ferramentas de avaliação de sustentabilidade e à aplicação de inteligência artificial na agricultura familiar. A busca foi realizada no Portal de Periódicos CAPES, na Biblioteca Digital Brasileira de Teses e Dissertações (BDTD), no Repositório Institucional da UNIOESTE, no Scopus, no Web of Science e no Google Scholar, com termos combinados*

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em português e inglês para o período de 2008 a 2026. Após triagem sistemática, foram selecionados 36 trabalhos para o corpus final, composto por 20 trabalhos previamente indicados pelo orientador e 16 trabalhos identificados pela busca sistemática. A análise de coocorrência de palavras-chave realizada no VOSviewer, com metadados combinados do Scopus e Web of Science, gerou uma rede com 148 itens conectados e 18 clusters, evidenciando três agrupamentos temáticos principais: desenvolvimento rural e inclusão digital; tecnologias digitais e inteligência artificial; e sensoriamento remoto e visão computacional, com poucas conexões entre o primeiro agrupamento e os demais.. Os resultados fundamentam a viabilidade e a relevância científica de uma plataforma web responsiva que digitalize a MADERUS com suporte de inteligência artificial generativa, tornando-a mais acessível para agricultores, técnicos e gestores públicos, contribuindo para os Objetivos de Desenvolvimento Sustentável (ODS) 2, 9 e 17.

Palavras-chave: *MADERUS; agricultura familiar; inteligência artificial; digitalização; desenvolvimento rural sustentável; bibliometria.*

INTRODUCTION

Family farming is one of the pillars of Brazil's agricultural production structure. The 2017 Agricultural Census reported that family farms account for 77% of all agricultural establishments in the country, contribute substantially to food production for the domestic market, and occupy 23% of Brazil's total agricultural area (IBGE, 2019). Despite their significant role, these farms continue to face persistent challenges related to management, access to resources, and the assessment of the sustainability of their production practices.

Assessing sustainability on family farms requires tools that integrate economic, social, and environmental dimensions in a coordinated manner. Sachs (2007) argues that any approach that fails to address these three dimensions simultaneously tends to produce incomplete assessments and, consequently, insufficient policies. Gliessman (2002) reinforces this perspective by emphasizing that conventional agriculture, driven by short-term productivity, compromises the ecological foundations that sustain future production, making it increasingly urgent to adopt methodologies capable of assessing the systemic viability of agroecosystems.

Within this context, the Methodology for the Assessment of Sustainable Rural Development (MADERUS), proposed by Hein (2019) within the Graduate Program in Sustainable Rural Development (PPGDRS) at the Western Paraná State University (UNIOESTE), stands out as a multidimensional assessment tool specifically designed for the realities of Brazilian family farming. Comprising 33 variables distributed across social, economic, and environmental dimensions, MADERUS was designed around the principles of participatory application, ease of use, and educational feedback for rural families. However, its application remains predominantly manual, relying on data collection and analytical procedures that require specialized technical expertise and consequently limit its reach precisely in the settings where it could be most valuable—among farmers, extension professionals, and municipal administrators.

Against this background, the following research question emerges: What does the existing scientific literature on MADERUS, the digitalization of sustainability assessment tools, and the application of artificial intelligence in family farming reveal about the gaps and opportunities for developing a responsive web platform that makes the methodology more accessible and easier to use?

The overall objective of this article is to map the state of scientific knowledge at

the intersections of MADERUS, the digitalization of rural sustainability assessment tools, and the application of artificial intelligence in family farming through a bibliometric review combined with content analysis. To achieve this objective, the following specific objectives were established: (a) to identify the temporal and thematic distribution of scientific publications on these topics in major national and international databases; (b) to analyze keyword co-occurrence networks using VOSviewer based on metadata exported from Scopus and Web of Science; and (c) to identify gaps in the literature that support the proposed digitalization of MADERUS through the integration of generative artificial intelligence as an open-access tool for sustainable rural development.

The rationale for this research is grounded in three complementary dimensions. From a scientific perspective, MADERUS is an empirically established methodology within PPGDRS/UNIOESTE, yet it is virtually absent from international databases—a condition that, as demonstrated by the findings of this review, stems from accessibility barriers associated with its manual application rather than from methodological limitations. From a technological perspective, generative artificial intelligence has reached a level of maturity that enables its integration with sustainability assessment tools, as documented in recent scientific literature (BARBEDO, 2023; MYSORE, 2024). From a social perspective, the proposal for an open, responsive, and user-friendly tool directly addresses the need to democratize access to rural diagnostic and assessment instruments. It is also aligned with SDG 2 – Zero Hunger and Sustainable Agriculture, SDG 9 – Industry, Innovation and Infrastructure, and SDG 17 – Partnerships for the Goals of the United Nations 2030 Agenda (UN, 2015). Schneider (2003) had already emphasized that family farming systems require analytical tools capable of addressing their complexity without imposing a disproportionate technical burden on users—an argument that remains relevant and that this study seeks to address.

The remainder of this article is organized as follows. Following this introduction, the methodology adopted for the bibliometric review is presented. The quantitative and qualitative results of the analysis are then reported, followed by an in-depth discussion of the identified thematic areas. Finally, the conclusions are presented in relation to the research question and the objectives established in this study.

METHODOLOGY

Bibliometrics, defined by Pritchard (1969) as the application of mathematical and statistical methods to the analysis of scientific literature, has become a key approach for mapping expanding fields of knowledge. Araújo (2006) complements this definition by emphasizing that bibliometric analysis enables the objective and replicable identification of publication patterns, co-authorship relationships, core journals, and temporal trends—characteristics that make it particularly suitable for the purpose of this study, which is to map an interdisciplinary field that is still emerging.

Zupic and Čater (2015) argue that bibliometric reviews should be combined with qualitative content analysis so that quantitative results—such as the number of publications, temporal distribution, and keyword networks—can be interpreted in light of what the studies actually address. Following this approach, the present study adopts

content analysis based on the principles proposed by Bardin (2011), which involve organizing the *corpus* into thematic categories through systematic reading and progressive coding of the texts. This approach prioritizes methodological rigor and transparency while avoiding a purely statistical interpretation of the analyzed literature.

Databases and Search Protocol

The literature search was conducted using the following databases and repositories:

- CAPES Journal Portal (www.periodicos.capes.gov.br) — the main aggregator of scientific literature available to Brazilian graduate programs, accessed through the CAFé academic network via UNIOESTE; time frame: 2009–2026 (platform limit);
- UNIOESTE Digital Library of Theses and Dissertations (tede.unioeste.br) — used to retrieve academic research produced within PPGDRS; no time frame was specified by the platform;
- Brazilian Digital Library of Theses and Dissertations (BDTD/IBICT — bdtd.ibict.br) — used to map national research produced by Brazilian graduate programs; time frame: 2008–2026;
- Scopus (Elsevier) — used to identify international scientific literature and generate metadata for keyword co-occurrence analysis; time frame: 2008–2026;
- Web of Science (Clarivate) — used as a complementary database to Scopus for international scientific literature; time frame: 2008–2026; the platform limited exports to 50 records per search;
- Google Scholar — used as a complementary source for open-access publications and gray literature; time frame: 2008–2026.

The search terms were organized into three thematic axes and combined using the Boolean operators AND and OR, as shown in Table 1.

Table 1 – Search-term protocol by thematic axis

Thematic Axis	Search Terms in Portuguese	Search Terms in English (Scopus and WoS)
Axis 1 – Rural Sustainability Assessment	"MADERUS"; "avaliação de sustentabilidade" AND "agricultura familiar"; "desenvolvimento rural sustentável" AND "metodologia"	"MADERUS"; "avaliação de sustentabilidade" AND "agricultura familiar"; "desenvolvimento rural sustentável" AND "metodologia"
Axis 2 – Digitalization and Technology in Agriculture	"digitalização" *AND* "agricultura"; "plataforma web" *AND* "rural"; "inclusão digital" *AND* "agricultor familiar"	"digitalização" *AND* "agricultura"; "plataforma web" *AND* "rural"; "inclusão digital" *AND* "agricultor familiar"
Axis 3 – Artificial Intelligence in Agriculture	"inteligência artificial" *AND* "agricultura"; "IA" *AND* "agricultura familiar"	"inteligência artificial" *AND* "agricultura"; "IA" *AND* "agricultura familiar"

Source: Prepared by the authors (2026).

As summarized in Table 1, the search strategy was structured around three

thematic axes: rural sustainability assessment, digitalization and technologies in agriculture, and artificial intelligence in agriculture, using specific search terms in Portuguese and English. The use of both languages reflects the characteristics of the databases consulted: while the CAPES Journal Portal, BDTD, and Google Scholar predominantly index Portuguese-language scientific literature in the context examined, Scopus and Web of Science searches were conducted using English-language terms to retrieve international publications. The searches were conducted between June 15 and 18, 2026.

Inclusion and Exclusion Criteria and Corpus Selection

The following inclusion criteria were adopted: publications in Portuguese, English, or Spanish; publication period from 2008 to 2026 (except for the CAPES Journal Portal, whose system allows searches only from 2009 onward); studies addressing at least one of the three defined thematic axes; and doctoral theses, master's dissertations, peer-reviewed scientific articles, academic book chapters, and technical reports published by recognized research institutions. The exclusion criteria comprised undergraduate and specialization-level final papers; publications without identifiable authorship or verifiable institutional affiliation; exclusively journalistic or popular science texts without scientific references; and studies focused on large-scale agriculture with no connection to sustainable rural development or family farming.

Data collection was conducted from June 15 to 18, 2026. Searches were performed on the following dates: CAPES Journal Portal and UNIOESTE Digital Library of Theses and Dissertations (June 15); Brazilian Digital Library of Theses and Dissertations (June 16); Scopus (June 16–17); Web of Science (June 17); and Google Scholar (June 18).

The initial searches retrieved a substantial number of records from the international databases, particularly for Axes 2 and 3. To make the screening process manageable, subject-area filters were applied before export. In Scopus, Axis 2 was filtered by the subject areas *Agricultural and Biological Sciences* and *Social Sciences* (310 → 192 records), while Axis 3 was filtered by *Agricultural and Biological Sciences*, *Social Sciences*, and *Computer Science*, with the 200 most-cited records exported (3,179 → 200). In Web of Science, records for Axes 1 and 2 were exported in accordance with the platform's available export capacity (11 and 50 records, respectively; Axis 2 returned 167 results, but the system limited exports to 50 records per search). For Axis 3, the 200 most-cited records were selected (1,102 → 200). Overall, 1,057 records were effectively exported and subjected to screening, as shown in Table 2.

Table 2 – Records by database, filters applied, and corpus selection process

Database / Search	Database / Search	Database / Search	Database / Search
Scopus — Axis 1	14	14	No additional filter
Scopus — Axis 2	310	192	Filter: Agricultural and Biological Sciences and Social Sciences
Scopus — Axis 3	3,179	200	Filter: Agricultural and Biological Sciences, Social Sciences, and Computer Science; 200

			most-cited records
Web of Science — Axis 1	11	11	No additional filter
Web of Science — Axis 2	167	50	Platform export limit of 50 records per search
Web of Science — Axis 3	1,102	200	200 most-cited records
CAPES Journal Portal — MADERUS	4	4	2009–2026 time frame (platform limit)
CAPES Journal Portal — broader topic	116	116	"desenvolvimento rural sustentável" AND "agricultura familiar"
UNIOESTE Digital Library — MADERUS	8	8	No predefined time frame
Brazilian Digital Library of Theses and Dissertations — MADERUS	8	8	2008–2026 time frame
Google Scholar — MADERUS + "agricultura familiar"	21	21	2008–2026 time frame
Google Scholar — three combined topics	233	233	2008–2026 time frame
Total exported for screening	—	1,057	Records subjected to systematic screening
Selected for full-text review	—	89	After title and abstract screening
Final corpus	—	36	Fully met the eligibility criteria

Source: Prepared by the authors (2026).

The final corpus consisted of 36 studies from two distinct sources: (i) 20 studies previously recommended by the research advisor as key references for the study, encompassing the theoretical foundations of MADERUS, sustainability assessment, and family farming; and (ii) 16 studies retrieved through the systematic search strategy described above that met all inclusion criteria after title and abstract screening and full-text review.

Analysis Procedures

The bibliometric analysis was conducted in two complementary stages: a quantitative approach based on scientific production indicators and co-occurrence networks, and a qualitative approach based on thematic content analysis.

The first stage, quantitative in nature, comprised three procedures. First, the temporal distribution of publications was examined using the 667 records exported from Scopus and Web of Science—the only databases included in this study that provided structured metadata containing a publication-year field—allowing the identification of growth trends and inflection points in scientific production on the topics investigated. Second, the final corpus of 36 studies was characterized according to publication type and institutional affiliation. The studies were classified by type of publication (doctoral theses, master's dissertations, articles, books/book chapters, and

technical reports) and institution of origin in order to map the main centers of knowledge production in the field.

Finally, keyword co-occurrence analysis was performed using VOSviewer version 1.6.19, developed by Van Eck and Waltman (2010), based on the combined import of files exported from Scopus (CSV format) and Web of Science (tab-delimited format). The following parameters were adopted: (a) the *full counting* method, which considers all occurrences of terms across the documents; (b) an inclusion threshold of at least two keyword occurrences; (c) clustering with the default resolution parameter of 1.00, automatically applied by the software; (d) weighting by relevance (*relevance score*), assigning greater weight to terms considered more representative of the analyzed dataset; and (e) manual merging of synonymous terms and spelling variants by the authors, based on the preliminary reading of abstracts and keywords.

After these parameters were applied, VOSviewer identified 149 items with at least two occurrences, one of which was automatically excluded because it was disconnected from the main network—a standard software procedure intended to ensure that the map represents only documented relationships among connected items. The final network therefore comprised 148 connected items organized into 18 clusters, with 1,090 co-occurrence links and a total link strength of 1,600. Based on these data, network visualization and temporal overlay visualization maps were generated.

The second stage, qualitative in nature, consisted of thematic content analysis based on the principles proposed by Bardin (2011), involving the full-text reading and systematic categorization of all 36 studies included in the corpus. The coding process comprised the following steps: (i) definition of the units of analysis—each study in the corpus was treated as a single unit of analysis and read in full; (ii) establishment of thematic categories—a mixed approach was adopted: the general categories (*rural sustainability assessment*, *digitalization and digital inclusion*, and *artificial intelligence applied to agriculture*) were defined *a priori* based on the three search axes that guided data collection, while subcategories and specific thematic dimensions emerged inductively from the data during the systematic reading of the texts; (iii) coding—conducted by a single researcher under continuous supervision and periodic validation by the research advisor, who served as an independent reviewer to verify the consistency of the classifications; (iv) systematic data recording—for each study, the following information was extracted and organized in a structured Microsoft Excel spreadsheet: author(s), year of publication, type of publication, institution of origin, database in which the study was identified, predominant thematic axis, main findings, and contributions to the research; and (v) interpretive synthesis—the coded material was subjected to cross-study analysis to identify patterns, convergences, divergences, and gaps in the literature, which informed the discussion presented in Section 4.

As a methodological limitation, the coding was conducted by a single researcher. Although the process was supervised and periodically reviewed, this approach may introduce interpretive bias. This limitation is acknowledged and further discussed in the study limitations section.

BIBLIOMETRIC RESULTS

Temporal Distribution of Publications

The analysis of the temporal distribution was based on the 667 records exported from Scopus and Web of Science—the only databases that provided structured metadata with a publication-year field compatible with quantitative analysis. The results reveal substantial and accelerated growth in scientific production on the topics investigated, with a clear shift in publication volume beginning in 2019.

Between 2010 and 2018, the exported publications totaled 47 records, with relatively modest annual variation, and no single year exceeding eight records. The year 2019 marked the beginning of a consistent upward trajectory, with 25 records published that year. This number nearly doubled to 46 in 2020 and continued to increase substantially in subsequent years, reaching 64 in 2021, 89 in 2022, 105 in 2023, and 145 in 2024, the highest annual volume observed during the entire period analyzed. In 2025, 115 publications were recorded, while 2026, which was still ongoing at the time of data collection (June 2026), had already accumulated 46 records. Table 3 presents the complete annual distribution.

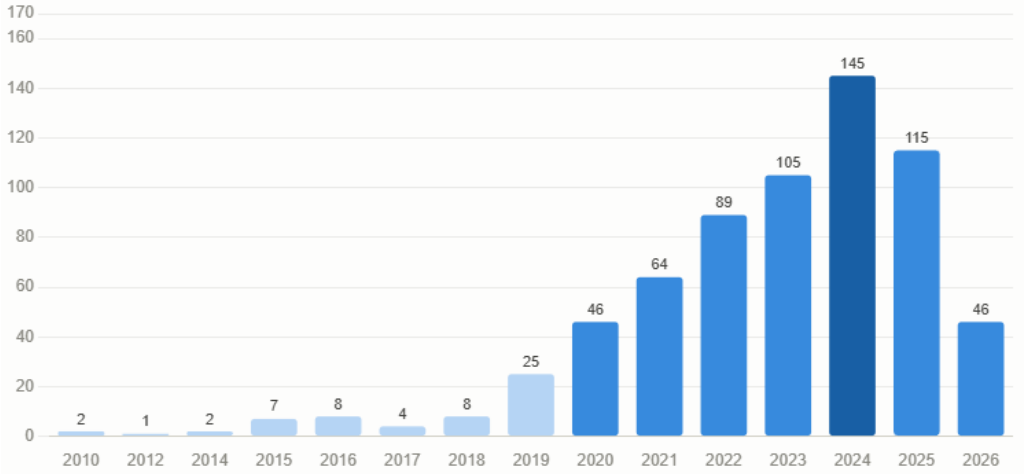
Table 3 – Annual distribution of records exported from Scopus and Web of Science (2010–2026)

Year	Records	Year	Records
2010	2	2019	25
2012	1	2020	46
2014	2	2021	64
2015	7	2022	89
2016	8	2023	105
2017	4	2024	145
2018	8	2025	115
		2026*	46
Total	**667**		

Source: Prepared by the authors (2026).

The inflection point observed in 2019 coincides with two relevant developments: the systematization of MADERUS by Hein (2019), which consolidated an applied research line within PPGDRS, and the publication of the report by Bolfe *et al.* (2020) on digital agriculture trends in Brazil.

Figure 1 – Annual distribution of records exported from Scopus and Web of Science (2010–2026)



Source: Prepared by the authors (2026).

The sustained growth observed in subsequent years reflects the simultaneous

expansion of two fields: the empirical consolidation of MADERUS across new municipalities and contexts, and the rapid international growth of research on artificial intelligence and agricultural digitalization. Figure 1 illustrates this annual publication trajectory.

Publication Types and Institutional Origin

The final corpus of 36 studies comprises 14 doctoral theses and master's dissertations (38.9%), 13 scientific articles published in peer-reviewed journals (36.1%), 7 books or book chapters (19.4%), and 2 institutional technical reports (5.6%). The predominance of theses and dissertations over journal articles reflects the still-emerging nature of the intersection between MADERUS and digital technologies. Research on the methodology remains concentrated in Brazilian institutional repositories: searches for MADERUS returned only 8 records in the UNIOESTE Digital Library of Theses and Dissertations, 8 in the Brazilian Digital Library of Theses and Dissertations, and 4 articles in the CAPES Journal Portal. In the international Scopus and Web of Science databases, MADERUS did not appear as the central focus of any records retrieved under Axis 1.

This distribution does not necessarily indicate scientific weakness in MADERUS; rather, it suggests that barriers related to accessibility and the usability of its manual application may constrain its dissemination beyond the academic environment of PPGDRS. Digitalization combined with artificial intelligence offers a potential means of addressing this barrier: by making the methodology more accessible and intuitive for different user profiles, it may create conditions for broader adoption and, consequently, greater scientific visibility.

In terms of institutional origin, PPGDRS/UNIOESTE stands out with 9 studies directly related to MADERUS. Other institutions contributing research on related topics include the Federal University of the São Francisco Valley (LOIOLA, 2024), the Federal Rural University of Rio de Janeiro (SILVA, 2025), and the Federal University for Latin American Integration (MESSIAS, 2024).

Table 4 – Thematic characterization of the final corpus by analytical focus

Predominant Thematic Focus	Representative Works in the Corpus
Theoretical foundations: sustainability, agroecology, and family farming	Sachs (2007); Gliessman (2002); Miranda (2008); Masera *et al.* (2000); Schneider (2003); Veiga, Abramovay, and Ehlers (2003)
Rural digital inclusion, agricultural technology, and early agricultural applications	Bauermann (2016); Bernardes *et al.* (2015); Rosário (2015); Basso *et al.* (2019); Messias (2024); Santos (2024)
Development, consolidation, and empirical applications of MADERUS	Hein (2019); Freitag (2020); Hahn (2022); Dalbello *et al.* (2021); Feitosa Filho (2023); Hansel (2024); Pérez (2024); Richart *et al.* (2026)

Digital agriculture, agricultural AI, and rural digital transformation	Bolfe *et al.* (2020); Barbedo (2023); Guilherme, Silva, and Florian (2024); Mysore (2024); Cruz Neto *et al.* (2025); Santos *et al.* (2025); Souza (2024); Silva (2025)
Sustainable rural development: innovation and public policies	Nunes (2024); Ribeiro (2025); Loiola (2024); Saraiva (2024)

Source: Elaborado pelos autores (2026).

Table 4 presents the thematic characterization of the final corpus, organized according to the thematic focuses identified through content analysis and the representative works associated with each category.

Keywords and Thematic Networks

Keyword co-occurrence analysis was performed using VOSviewer based on the combined import of files exported from Scopus (CSV format) and Web of Science (tab-delimited format), encompassing all three search axes from each database. The software identified 149 items with at least two occurrences. One item was automatically excluded because it was disconnected from the main network, a standard procedure that ensures that the map represents only effectively documented relationships. The resulting network comprised 148 connected items, 18 clusters, and 1,090 co-occurrence links, with a total link strength of 1,600.

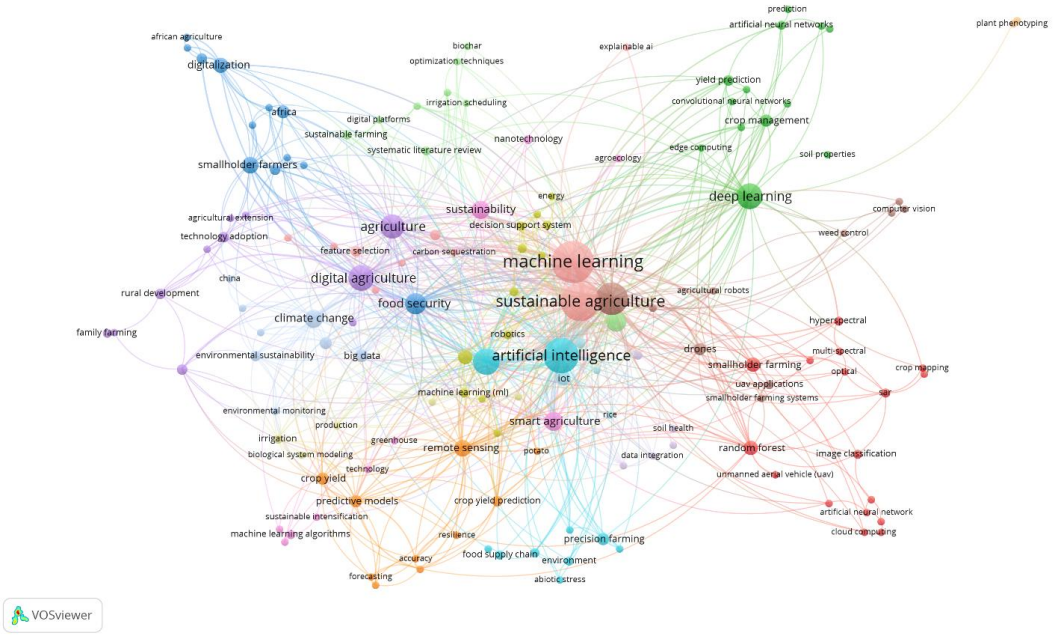
The central terms in the map, as indicated by node size, were sustainable agriculture, machine learning, artificial intelligence, digital agriculture, smart agriculture, and remote sensing. These terms form the core of the network and account for a substantial proportion of its connections, indicating that agricultural sustainability and emerging digital technologies constitute the dominant conceptual axes in the international scientific literature covered by the analysis.

Cluster analysis reveals three broader thematic groupings. The first, located on the left side of the map, brings together terms related to rural development and digital inclusion, including rural development, smallholder farmers, digital agriculture, technology adoption, family farming, and digitalization. The second, located in the central and center-right portions of the map, comprises terms associated with the technological frontier of agricultural production, including machine learning, artificial intelligence, sustainable agriculture, smart agriculture, deep learning, and food security. The third, located on the right side of the map, concentrates terms associated with remote sensing and computer vision, including remote sensing, drones, UAV applications, convolutional neural networks, and crop management.

The most relevant bibliometric finding is the weak connectivity between the first cluster—rural development and family farming—and the other two technological groupings. Terms such as family farming and rural development display relatively few and weak connections with artificial intelligence and machine learning in the network. MADERUS does not appear as a visible node, further demonstrating its absence from the international databases analyzed. This separation among thematic groupings

provides quantitative evidence of the research gap addressed in this article: scientific research integrating methodological tools for rural sustainability assessment with emerging digital technologies remains incipient.

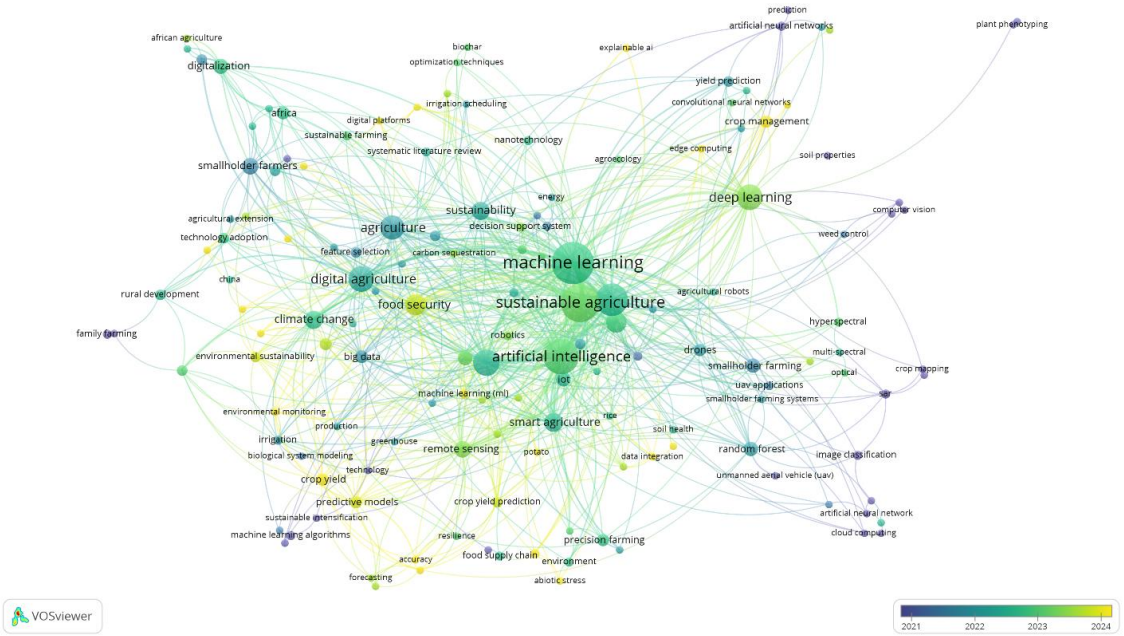
Figure 2 – Keyword Co-occurrence Map (Network Visualization — VOSviewer)



Source: Prepared by the authors (2026).

Figure 2 presents the keyword co-occurrence map generated using VOSviewer (Network Visualization). Figure 3 subsequently provides a temporal perspective of the same network through the Overlay Visualization.

Figure 3 – Temporal Overlay Map (Overlay Visualization — VOSviewer)



Source: Prepared by the authors (2026).

The temporal overlay visualization presented in Figure 3 shows the average publication year associated with each term on a scale ranging from 2021 to 2024. The most recent terms, represented in yellow and light green, are primarily associated with the technological frontier, including smart farming, machine learning, deep learning, and remote sensing. In contrast, the more established terms, represented in blue and purple, are associated with sustainable rural and agricultural development, including sustainable agriculture, food security, and digital agriculture. This temporal distribution indicates that the thematic fields identified in the network are at different stages of scientific development and reinforces the relevance of research aimed at integrating them through an accessible digital platform.

RESULTS AND DISCUSSION

MADERUS: Methodological Consolidation and Accessibility Barriers

MADERUS was proposed by Hein (2019) in response to the need for a sustainability assessment tool specifically designed for the context of Brazilian family farming. Unlike methodologies developed in broader international contexts, such as MESMIS, developed by Masera, Astier, and López-Ridaura (2000) for Latin American production systems, MADERUS is based on a set of 33 variables calibrated to the landholding, productive, and social conditions of family farming in southern Brazil, incorporating principles of participatory application and educational feedback for farming families.

Freitag (2020) conducted the only direct comparison between MADERUS and MESMIS identified in the literature analyzed in this study, concluding that both methodologies produce analytically consistent assessments, while MADERUS provides an application protocol that is more accessible to rural technicians and extension professionals without specialized training in systems assessment. This finding is particularly relevant to understanding the methodology as a candidate for digitalization: a tool designed for practical application in rural settings requires technological support that is equally adapted to the needs and capabilities of its intended users.

Empirical applications demonstrate the adaptability of MADERUS across different contexts. Hahn (2022) advanced its application by using it as an educational tool in rural extension processes. Feitosa Filho (2023) took a step toward digitalization by proposing a "sustainability calculator" based on MADERUS indicators. This initiative anticipated the rationale underlying the platform proposed in the present study, although it did not incorporate artificial intelligence or a responsive interface optimized for mobile devices.

Hansel (2024) applied MADERUS to 24 family farms in Quatro Pontes, Paraná, obtaining an average sustainability index of 75.11%. Based on this context, Richart *et al.* (2026) investigated female-managed farms in the same municipality and found an average index of 74.61%, a difference of only 0.50 percentage points. The proximity of these results suggests consistency in the application of MADERUS across different

analytical subsets within the same local context. Pérez (2024) further extended its empirical application by using MADERUS in Foz do Iguaçu, Paraná, providing additional evidence of its applicability across different settings in Western Paraná.

Taken together, these findings indicate that MADERUS has undergone substantial methodological development and empirical application. Its absence from the international bibliometric maps analyzed in this study should not, by itself, be interpreted as evidence of scientific weakness. Rather, the findings suggest that limitations related to the accessibility and usability of its predominantly manual application may contribute to restricting its dissemination beyond a specific academic environment. In this context, digitalization combined with artificial intelligence represents a potential pathway for expanding its reach among farmers, extension professionals, public administrators, and researchers.

Rural Digitalization: Opportunities and Constraints

Bauermann (2016) investigated the digital inclusion of family farmers in municipalities in Western Paraná and found that digital exclusion extends beyond access to devices or internet connectivity. It also encompasses digital literacy, trust in technology, and the suitability of interfaces for actual contexts of use. A platform that is neither intuitive nor context-sensitive may therefore reproduce, in digital form, many of the barriers previously associated with analog exclusion.

Bernardes *et al.* (2015) demonstrated that digital rural communication tools, when designed according to farmers' needs, can enhance organizational capacity and access to information among rural families. Rosário (2015) argues that the development of cross-platform applications optimized for mobile devices represents an effective strategy for reaching geographically dispersed populations whose internet access occurs predominantly through mobile connections. Messias (2024) further indicates that interface accessibility is a determining factor in the effective adoption of digital tools by family farmers.

The rural development and digital inclusion cluster identified in the VOSviewer map—which includes smallholder farmers, digital agriculture, technology adoption, and digitalization—indicates an internationally established research agenda. Silva (2025) concluded that family farmers who adopt digital technologies with appropriate guidance experience improvements in productivity, market access, and planning capacity. Loiola (2024) demonstrated that the digitalization of assessment methodologies not only facilitates their application but can also enhance farmers' engagement in the diagnostic process.

Bolfe *et al.* (2020) identify a persistent paradox: although Brazil is one of the world's leading agricultural producers, the adoption of digital technologies in family farming remains below its potential. The authors argue that overcoming this gap requires tools specifically designed for small-scale agriculture—simpler and more context-sensitive than solutions developed primarily for large-scale agribusiness. Santos (2024) supports this assessment by documenting, in Southwestern Paraná, that digital connectivity accompanied by appropriate technological tools can improve

market access and the quality of life of rural families.

Artificial Intelligence in Agriculture: Potential and Responsibility

The central cluster of the VOSviewer map—which brings together *machine learning*, *artificial intelligence*, *sustainable agriculture*, *deep learning*, and *food security* and displays some of the densest connections in the network—reflects the rapid expansion of AI applications in agriculture. With 3,179 raw records identified in Scopus and 1,102 in Web of Science for Axis 3, this thematic axis generated the largest initial search volume among the three investigated. The temporal distribution also demonstrates the recent expansion of the broader literature analyzed, with 145 of the 667 exported Scopus and Web of Science records published in 2024 alone.

Barbedo (2023) identifies data quality, implementation costs, and the lack of accessible interfaces as major barriers to AI adoption in family farming. Guilherme, Silva, and Florian (2024) conclude that generating personalized assessments in accessible language is among the applications with substantial potential to contribute to agricultural sustainability. Saraiva (2024) indicates that large language models have the capacity to translate technical data into language that is more understandable to non-specialist users.

Cruz Neto *et al.* (2025) argue that social inclusion should be incorporated as a design criterion from the earliest stages of developing agricultural technological solutions. Mysore (2024) presents use cases of the Gemini model for agricultural productivity, including management recommendations and the generation of contextualized reports in accessible language. Integrating this type of model into a MADERUS-based platform could enable the sustainability indices generated by the methodology to be translated into understandable assessments accompanied by practical recommendations, thereby addressing challenges related to accessibility and ease of use.

Santos *et al.* (2025) caution that the governance of data generated by farmers is a critical and frequently overlooked issue. Transparency regarding the processing of data collected during the application of MADERUS, as well as the protection of rural families' privacy, should therefore be incorporated into the system architecture from the design stage. Souza (2024) further emphasizes that integrating technologies into a digital agricultural ecosystem requires careful user-experience planning to prevent technical complexity from becoming a new barrier to access.

Proposta Identified Research Gaps and Positioning of the Proposed Research

The bibliometric and content analyses revealed three main research gaps that support the research proposal presented in this article.

The first gap concerns the absence of a digital platform specifically designed for MADERUS. Searches for MADERUS in the international databases retrieved no studies addressing the digitalization of the methodology. Feitosa Filho (2023) advanced in this

direction by developing a "sustainability calculator"; however, this initiative does not incorporate a responsive interface optimized for mobile devices or artificial intelligence integration. The proposed research therefore addresses the gap between the existing form of the methodology and the technological possibilities for making its application more accessible, intuitive, and scalable.

The second gap concerns the integration of methodological tools for rural sustainability assessment with generative artificial intelligence. The VOSviewer map revealed weak connections between terms such as *family farming* and *sustainability assessment* and terms such as *artificial intelligence* and *machine learning*, while no connections were identified with terms such as *generative AI* or *large language models*. Within the corpus analyzed, no studies were identified that applied large language models to interpret rural sustainability indicators and generate contextualized reports for farmers. This finding indicates an emerging research opportunity at the intersection of sustainability assessment, family farming, and generative AI.

The third gap concerns technological openness and accessibility. Most of the digital solutions identified in the review are proprietary or involve relatively high implementation costs. Nunes (2024) and Ribeiro (2025) argue that sustainable rural development requires tools that enable farmers themselves to understand their circumstances and make informed decisions. The proposal for an open and freely accessible web-based tool, available through a browser on different devices and designed with an emphasis on ease of use, responds to this demand while aligning with the principles of sustainable rural development and technological sovereignty.

CONCLUSION

This bibliometric review combined with content analysis was conducted to map the state of scientific knowledge at the intersections of MADERUS, the digitalization of rural sustainability assessment tools, and the application of artificial intelligence in family farming, while identifying research gaps that support the proposal for a responsive web platform integrating generative AI. From 1,057 records exported from six databases through a systematic search protocol, 36 studies were included in the final corpus: 20 studies previously recommended by the research advisor and 16 retrieved through the systematic search. These studies were subsequently subjected to bibliometric and content analyses.

In response to the research question, the findings reveal a substantial structural gap in the existing scientific literature. Although MADERUS has undergone methodological development and has been empirically applied in different contexts in Western Paraná, it remains virtually absent from the international databases analyzed. Keyword co-occurrence analysis using VOSviewer, comprising 148 connected items, 18 clusters, and 1,090 co-occurrence links, showed that sustainable rural development and digital technologies and AI are organized into thematic groupings with relatively weak connections between them. This finding indicates that the integration of methodological tools for rural sustainability assessment with emerging digital technologies remains incipient in the literature analyzed. This separation, together with

the limited presence of MADERUS in the retrieved literature, provides the central bibliometric evidence supporting the research problem: there is a documented gap at the intersection of MADERUS, rural sustainability assessment, digitalization, and emerging AI technologies, creating a relevant research opportunity for the proposed digitalization initiative.

The specific objectives were also addressed. The temporal distribution of the 667 records exported from Scopus and Web of Science showed accelerated growth beginning in 2019, reaching a peak of 145 records in 2024. This trend demonstrates the expansion of research related to agricultural AI, digitalization, and sustainability, although the thematic network suggests that these fields remain only partially interconnected. The co-occurrence analysis identified three major thematic groupings: rural development and digital inclusion; AI and machine-learning technologies; and remote sensing and computer vision. MADERUS did not emerge as a visible node in these networks. Three main research gaps were consequently identified: the absence of a dedicated digital platform for MADERUS, the limited integration of generative AI with rural sustainability assessment tools, and the scarcity of open and accessible technological solutions designed for this target audience. Together, these gaps provide a scientific basis for the proposed research.

The findings also support the three dimensions of the rationale presented in the Introduction. From a scientific perspective, the review indicates that accessibility and usability constraints associated with the predominantly manual application of MADERUS may contribute to its limited dissemination beyond its current academic context. From a technological perspective, the rapid growth of research on AI applications in agriculture, particularly since 2021, demonstrates an expanding scientific and technological environment for investigating the proposed integration. From a social perspective, the development of an open, accessible, and user-friendly tool responds to the broader objective of democratizing access to scientific knowledge and sustainability assessment in rural contexts, while contributing to the principles underlying SDG 2, SDG 9, and SDG 17 of the 2030 Agenda (UN, 2015).

This study has several limitations that should be considered when interpreting its findings. First, the hybrid composition of the final corpus—with 20 studies previously recommended by the research advisor and only 16 retrieved through the systematic search—prevents the entire corpus from being characterized exclusively as the outcome of a systematic review. Although this strategy was adopted to ensure the inclusion of key theoretical and methodological references, it introduces selection bias and limits the full reproducibility of the study. Second, the content analysis was coded by a single researcher, which may introduce interpretive bias despite advisor supervision and the use of systematic data-recording procedures. Third, the inclusion of appropriately classified and justified gray literature as complementary material represents a departure from a strict peer-reviewed-only criterion. Fourth, the co-occurrence analysis was based exclusively on metadata from Scopus and Web of Science, which provide only partial coverage of Brazilian scientific production, particularly publications in Portuguese and journals with more limited international indexing. Finally, and most importantly, the proposed digitalization of MADERUS through generative AI has not yet undergone empirical validation with actual users. Its usability, technical feasibility, effectiveness, and practical value therefore remain to be

established through future empirical research.

The findings of this review point to an applied research agenda encompassing: (a) the technical development of the proposed responsive web platform, integrating generative AI to support the interpretation of MADERUS inputs, indicators, and outputs; (b) participatory usability assessment involving family farmers, rural extension professionals, and public administrators to validate the tool under real-world conditions; (c) investigation of rural digital literacy and the factors influencing technology adoption among different farmer profiles; (d) examination of agricultural data governance, privacy, transparency, and the ethical implications of using generative AI in rural sustainability assessment; and (e) longitudinal monitoring of the platform's potential effects on farm management decisions and sustainability indicators. These research directions demonstrate that the contribution of this study extends beyond bibliometric mapping by establishing a theoretical and empirical foundation for an interdisciplinary research agenda with potential applications to family farming in Western Paraná and other Brazilian contexts. Future studies should also expand the search to additional databases, particularly SciELO and Redalyc, and consider systematic reviews following PRISMA guidelines or, where methodological and data conditions permit, meta-analytical approaches to further investigate the relationships identified in this study.

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