



## **ELECTRIC TRACTORS AND SUSTAINABILITY: EMERGING TECHNOLOGICAL TRENDS AND RESEARCH GAP**

Autores: Marcus Vinícius Gomes de Lima<sup>1</sup>, Flávia L. Consoni<sup>2</sup>

<sup>1</sup>IFMG campus Congonhas – [marcus.lima@ifmg.edu.br](mailto:marcus.lima@ifmg.edu.br); <sup>2</sup>Unicamp – [fconsoni@unicamp.br](mailto:fconsoni@unicamp.br)

### **ABSTRACT**

The tractor is the primary machine used in agriculture, performing essential tasks such as soil preparation, crop management, spraying, and the transportation of agricultural products. Mostly powered by diesel-fueled internal combustion engines (ICEs), a dominant technology that has several drawbacks: it produces significant noise pollution, contributes to soil contamination and atmospheric pollution, and emits greenhouse gases (GHGs) through the combustion of fossil fuels. Moreover, diesel tractors operate with low energy efficiency; up to 60% of the fuel's energy content is lost as waste heat rather than converted into useful work. Electric tractors (ETs) have emerged as a promising alternative to address these issues. By using electricity (ideally from renewable sources) to power high-efficiency electric motors, ETs can reduce emissions and energy losses while transmitting power more effectively to the tractor's working interfaces (wheels, power take-off (PTO), hydraulic pumps, etc.). Several commercial ET models are now available, although this technology remains relatively new to the market. This study aims to map the scientific literature on ETs with a focus on sustainability, using bibliometric analysis to identify research trends, key authors, prevalent keywords, contributing countries, and leading institutions. It also highlights emerging versus declining research themes and identifies gaps to understand how the academic community is approaching this new technology. The results indicate that recent research has focused on topics such as fuel-cell-powered tractors, automation and robotics, real-time data analysis, and data mining. The countries contributing the most publications on this topic include China (55 publications), Italy (45), Germany (18), Iran (18), Austria (12), Romania (8), the United States (8), and Brazil (7). Overall, studies consistently position ETs as a viable solution to mitigate the negative externalities of conventional diesel tractors, particularly by reducing or eliminating the use of fossil fuels.

*Keywords: tractor electrification; energy transition; scientometrics*

### **1 INTRODUCTION**

The tractor is the primary source of power for agricultural work, responsible for pulling, pushing, and transporting loads, as well as providing energy to operate implements (ISO, 2013). The dominant tractor technology – diesel-fueled internal combustion engines (ICEs) – has several drawbacks, including significant greenhouse gas (GHG) emissions, noise pollution, and soil contamination (Pascuzzi *et al.*, 2024; Scolaro *et al.*, 2021). Furthermore, ICEs exhibit low energy conversion efficiency. Friction losses alone can account for 10–15% of the energy generated by the engine (Pascuzzi *et al.*, 2024), and overall roughly 60% of the fuel's energy content is lost as unrecovered heat (Mocera *et al.*, 2023).

Tractor electrification has emerged as a viable alternative to enhance agricultural production while reducing the sector's negative externalities; it is also considered the fastest route to decrease emissions and dependence on fossil fuels (Lagnelöv *et al.*, 2021). Electric tractors (ETs) are powered by onboard battery systems that store electrical energy and feed it to electric motors, which



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convert electricity into the mechanical work required for tractor operation. However, several challenges hinder the adoption of ETs, including high initial purchase costs, socio-technical resistance to replacing the traditional ICE-based system, limited charging infrastructure, and other practical constraints.

An important factor supporting the adoption of ETs is the growing on-farm generation of renewable energy (e.g., solar power and biogas), which facilitates recharging of electric machinery, simplifies operations, reduces costs, and increases energy security (Gorjian *et al.*, 2021; Götz *et al.*, 2025; Schneider *et al.*, 2023; Xue, 2013). Thus, ETs represent a viable and accessible solution: by using renewable electricity for operation, more efficiently converting energy into work, and transmitting power more effectively to the tractor's interfaces (wheels, power take-off (PTO), hydraulic pumps, etc.) (Mocera *et al.*, 2023; Moreda *et al.*, 2016), they can significantly improve environmental performance, reduce dependence on fossil fuels, and mitigate the negative impacts of agriculture on nature.

In this context, the central question of this research is how the literature on ETs is characterized, particularly in terms of publication metrics. The primary objective is to map scientific publications on electric tractors with an emphasis on sustainability using a bibliometric analysis. Bibliometric methods apply mathematical and statistical techniques to investigate and quantify communication processes (Guedes; Borschiver, 2005), which helps identify the main themes in a given research area. Accordingly, this mapping examines the evolution of research on ETs, highlighting the leading authors, most frequent keywords, key contributing countries, and the institutions that have driven scientific advancements in the field.

Finally, this bibliometric analysis identifies the prominent themes in current and emerging studies, as well as topics that appear to be in decline. Investigating areas with remaining research gaps is necessary for a complete understanding of the factors influencing the socio-technical transition from ICE-based tractors to ETs, thereby reducing uncertainties and increasing confidence in this new technology.

## 2 MATERIALS AND METHODS

For this bibliometric analysis, the Scopus and Web of Science (WOS) databases were used, as they provide high-quality metadata (Pranckutė, 2021; Passas, 2024). Combining these two databases broadens the coverage of relevant literature and improves the reliability of bibliometric indicators in this field (Bakkalbasi *et al.*, 2006).

The search strategy was applied to titles, abstracts, and keywords in both databases using the following query: "(electric tractor\* OR electrified tractor\* OR electrification tractor\* OR electrification of agricultur\*) AND (agricultur\* OR farm\* OR agr\*) AND (sustainab\* OR renewable energy OR zero emission\* OR clean energy OR CO2 reduction)". Results were limited to journal articles and review articles. Additional filters included all publication years up to the search date (April 8, 2025), all subject areas, and all languages. The truncation wildcard (\*) was used in the search string to capture variations in terminology (e.g., tractor, tractors, tractores, etc.).

The search returned 51 documents from Scopus and 52 from WOS. These results were exported in BibTeX format and then merged into a single dataset using RStudio (version 4.3.1) with the Bibliometrix package (Aria; Cuccurullo, 2017). After removing 32 duplicate entries, a final set of 71 unique documents was obtained for analysis. This consolidated dataset was exported to Excel (XLSX format) and analyzed using the Biblioshiny application, a web interface of the Bibliometrix package.



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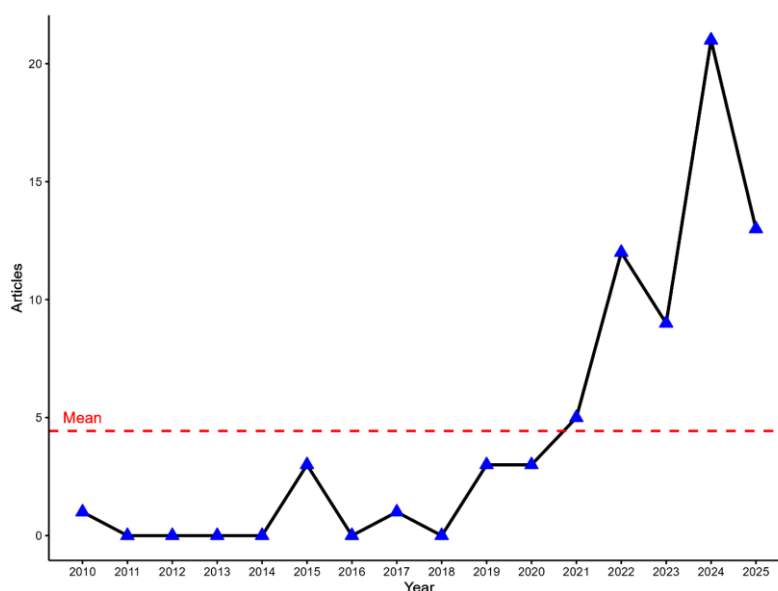
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These procedures enabled the mapping of various bibliometric dimensions: the annual publication output, the top journals, the leading authors and contributing countries, the most frequent keywords, as well as the central themes and emerging research trends. The entire process was conducted in accordance with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page *et al.*, 2021), using specific inclusion criteria and a checklist-based approach to ensure transparency in the systematic review and interpretation of results.

## 3 RESULTS AND DISCUSSION

Figure 1 shows the number of publications per year on electric tractors and sustainability. The marked rise in publications over the period indicates the growing attention that ETs are receiving from the scientific community.

Figure 1 – Annual production of articles on electric tractors and sustainability



Source: Author's elaboration

This trend can be attributed to a convergence of technical, economic, environmental, and political factors. Key developments include advances in battery technology (yielding higher energy densities and lower production costs per kWh) (IEA, 2025; Mauler *et al.*, 2021); the introduction of public policies and government incentives in certain countries to encourage ET adoption (Gul *et al.*, 2024); and the implementation of stricter environmental regulations along with a growing demand for precision agriculture technologies (Ghobadpour *et al.*, 2022; Sok; Hoestra, 2023).

A closer examination of the literature highlights several advantages of ETs, including low operating costs, reduced maintenance requirements, and zero exhaust emissions (Götz *et al.*, 2025; Mocera *et al.*, 2023; Pascuzzi *et al.*, 2024; Scolaro *et al.*, 2021). These benefits are important for farmers, as they help lower overall production costs. However, studies also report persistent



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barriers to ET adoption, such as high upfront purchase costs, limited battery capacity and range, socio-technical resistance to changing from conventional tractors, and insufficient charging infrastructure (Gul *et al.*, 2024).

The publications analyzed were spread across a variety of scientific journals. Table 1 presents the top ten journals (ranked by H-index) along with their key bibliometric indicators. Publications in journals such as *Energies* and *Biosystems Engineering* tend to emphasize sustainability-related topics (e.g., fuel efficiency, life cycle assessment, emissions), whereas articles in *Nongye Gongcheng Xuebao* (CSAE) and *Nongye Jixie Xuebao* (CSAM) focus more on control devices, optimization techniques, experimental results, and electric tractor components.

Two additional points can be drawn from Table 1. First, the PY\_start parameter (the year of the earliest publication in this field for each journal) shows that the oldest relevant publication among these top journals was in 2015 for *Nongye Gongcheng Xuebao* (CSAE). This relatively recent start date underscores the novelty of research on electric tractors. Second, the journals *Journal of Cleaner Production* and *IEEE Access* exhibit high total citation counts for their articles on this topic (130 and 106 citations, respectively), suggesting that publications in these venues have achieved notable visibility and impact.

Table 1 – Main journals by published articles

| Journal                                  | H_index | G_index | TC  | NP | PY_start |
|------------------------------------------|---------|---------|-----|----|----------|
| Energies                                 | 4       | 7       | 87  | 7  | 2022     |
| Biosystems Engineering                   | 3       | 4       | 19  | 4  | 2022     |
| Nongye Gongcheng Xuebao - CSAE           | 3       | 3       | 22  | 3  | 2015     |
| Nongye Jixie Xuebao - CSAM               | 3       | 4       | 18  | 4  | 2023     |
| Computers and Electronics in Agriculture | 2       | 2       | 25  | 2  | 2022     |
| IEEE Access                              | 2       | 2       | 106 | 2  | 2021     |
| Journal of Cleaner Production            | 2       | 3       | 130 | 3  | 2021     |
| Agricultural Engineering.eu              | 1       | 1       | 1   | 1  | 2024     |
| AgriEngineering                          | 1       | 1       | 2   | 1  | 2024     |
| Applied Energy                           | 1       | 2       | 5   | 2  | 2024     |

Source: Author's elaboration

H\_index and G\_index: research citation impact; TC: total citations; NP: number of publications; PY\_start: publication year

A keyword analysis was conducted and presented in a thematic evolution map (Figure 2). This map is divided into four quadrants that classify research themes into: motor themes (well-developed and currently important topics), emerging or declining themes (topics either on the rise or waning in relevance), basic themes (foundational topics with lower development), and niche themes (highly specialized topics).

Figure 2 shows clusters of keywords, where the size of each block reflects the frequency of occurrence. Several topics stand out as motor themes – highly relevant and well-developed in current research – such as “electric tractor(s)” and “design”; “fuel cell”, “agricultural tractors”, and “hybrid electric tractors”; as well as “energy management”, “consumption”, and “control strategy.”



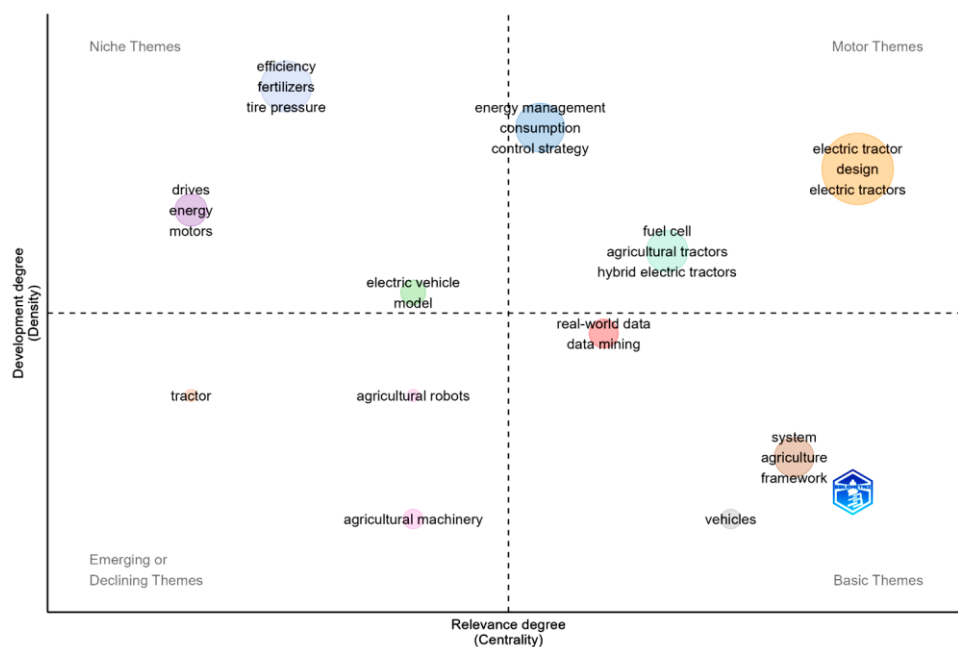
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These dominant topics still contain research gaps, indicating opportunities for further investigation. Meanwhile, themes like “agricultural robots,” “real-world data,” and “data mining” are classified as emerging themes. These subjects are growing in relevance but remain relatively underdeveloped, suggesting an increasing concentration of research interest and outstanding questions in these areas. Notably, many emerging themes are directly linked to computing, artificial intelligence (AI), and telemetry (Lanças *et al.*, 2024; Marques *et al.*, 2022).

In contrast, other topics – such as “efficiency,” “fertilizers,” “tire pressure,” “drive,” “energy,” and “motors” – appear as niche themes. These are well-developed but highly specialized topics with relatively lower overall relevance in the context of this bibliometric analysis. It is important to note that being categorized as a niche theme does not imply a lack of importance. Rather, given the specific scope of our search strings and the time frame analyzed, these keywords fall into a niche category within the electric tractor research landscape.

Figure 2 – Thematic evolution map on tractor electrification and sustainability



Source: Author's elaboration

Figure 3 presents a three-field plot connecting the leading countries, top authors (by corresponding author), and most frequent keywords in the dataset. In terms of publication output, China (55 publications), Italy (45), Germany (18), and Iran (18) rank as the most prolific countries, followed by Austria (12), Romania (8), the United States (8), and Brazil (7). (Note that Figure 3 lists only each article's corresponding author, so not all co-authors are displayed.) A full-text analysis of the articles confirms substantial international collaboration, with many studies involving authors from multiple countries.

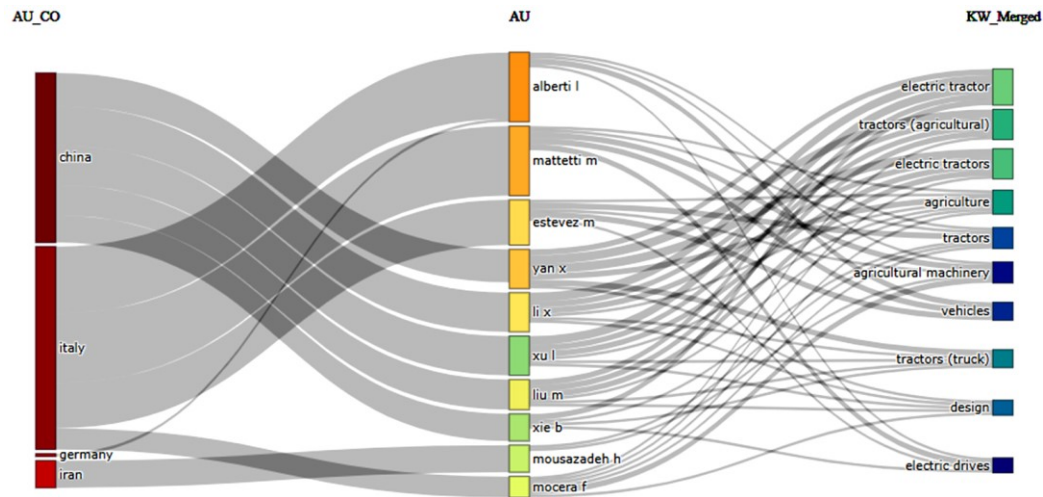
Italy stands out in particular, nearly matching China in the volume of research output on ETs. In addition to its strong industrial base and long tradition in agricultural machinery, Italy has several universities and research centers with expertise in agricultural

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electrification. One notable initiative is the national “Green SEED” project (funded under the PRIN 2017 program), which aims to develop more electric and sustainable agricultural tractors. This project – led by Luigi Alberti at the University of Padova with a budget of €514,146 – illustrates Italy’s commitment to advancing agricultural electromobility.

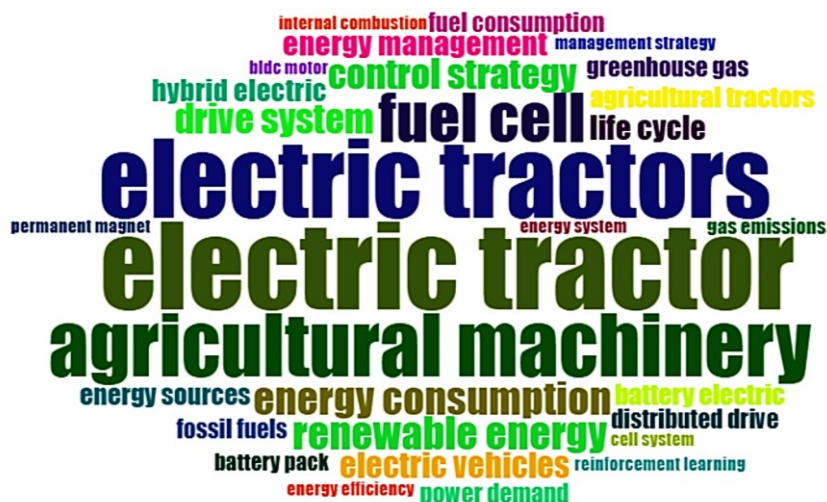
Figure 3 – Three field plot about countries, authors and keywords



*Source: Author's elaboration*

Finally, a word frequency and co-occurrence analysis was conducted on the abstracts of all 71 documents using a bigram word cloud (a visualization of two-word combinations). Figure 4 illustrates this analysis, highlighting the 30 most frequent two-word phrases in the dataset.

Figure 4 – Bigram word cloud of terms from the document abstracts, relating to electric tractors and sustainability



*Source: Authors' elaboration*



Figure 4 reveals a strong association between electric tractor terminology (e.g., “electric tractor(s),” “battery electric,” “hybrid electric,” “fuel cell,” “battery pack”) and sustainability-related terms (e.g., “renewable energy,” “greenhouse gas,” “fuel consumption,” “emissions,” “fossil fuels”). This pattern reflects a consistent effort in the literature to portray ETs as a viable solution to the negative externalities of conventional farming, particularly through the reduction or elimination of fossil fuel use.

#### 4 CONCLUSIONS

This study mapped the scientific literature on electric tractors (ETs) with an emphasis on sustainability using bibliometric analysis. It identified overall research trends, highlighted both emerging and declining themes, and pinpointed the main contributing authors, journals, and countries in this field.

The results indicate that ETs and sustainability have attracted increasing academic interest. ETs are closely linked to advances in battery technology, computing, robotics, and artificial intelligence. Consequently, the growth of research on ETs will inevitably intersect with these domains, highlighting the inherently interdisciplinary nature of this field.

ETs offer a viable alternative to enhance agricultural sustainability. While this new technology faces challenges, as is typical for any innovation, these are likely offset by its cost-benefit advantages for farmers. As renewable energy becomes increasingly prevalent in agriculture, ETs can be recharged at minimal cost to producers, which may substantially accelerate their adoption. Another key observation is the integration of the Internet of Things (IoT) in agriculture, which facilitates production quality control. ETs can also be integrated into these systems due to their onboard digital technologies. This integration enables farmers to focus on tasks that require closer attention.

This study provides an overview of the research landscape on ETs and sustainability. Future research should further explore the intersections of ETs with artificial intelligence, robotics, and computing, and examine the challenges these technologies may face across diverse terrains, climates, and crop types.

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