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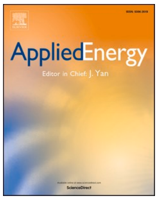

The economic feasibility and farmers’ adoption of battery electric tractors: a systematic literature review

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HIGHLIGHTS

- We selected 16 articles on BET economics and adoption using PRISMA methodology.
- BETs are economically competitive under specific conditions.
- High upfront costs remain the main barrier despite lower operating expenses.
- Farmers’ adoption is driven mainly by economic considerations; environmental and behavioral motives play a secondary role.
- Policy support, battery cost declines, and knowledge transfer are key to scaling up BETs.

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ABSTRACT

The transition to low-carbon technologies in agriculture has drawn increasing attention, with battery electric tractors (BETs) emerging as a promising alternative to conventional diesel-powered machinery. This study presents a systematic literature review following PRISMA guidelines to assess the economic feasibility of BETs and factors influencing farmers’ willingness to adopt them. We searched Scopus, Web of Science, and Google Scholar for studies published between 2018 and 2025. A total of 635 studies were retrieved, of which 16 studies were included, covering both techno-economic evaluation and farmer-focused adoption perspectives. Our findings indicate that BETs can be economically competitive under specific conditions, particularly in low-duty applications with high annual usage hours, and that their viability is further enhanced by financial incentives, declining battery costs, and integration into farm-level energy systems (e.g., photovoltaic generation), supportive electricity tariffs, and enabling policy frameworks, with additional potential in autonomous applications. The review shows that farmers’ adoption of BETs is primarily constrained by economic barriers, particularly high upfront investment costs and uncertainties related to battery performance, operational autonomy, and associated expenses. While non-economic factors such as environmental awareness, user comfort, and behavioral attitudes act as important motivators, the evidence indicates that financial viability constitutes a prerequisite for broader uptake across farm contexts. Widespread BET adoption will require both technological improvements and supportive policies, as well as knowledge dissemination to reduce uncertainty and build trust. These insights provide guidance for policymakers, technology developers, and researchers aiming to accelerate the adoption of low-carbon agricultural machinery.

1. Introduction

The increasing global population demands more food, which in turn requires greater energy inputs for agricultural production. To date, most modern farming systems have relied heavily on fossil fuels, particularly diesel, thereby intensifying greenhouse gas emissions (GHGs) and environmental degradation [1]. A substantial share of these emissions originates from diesel-powered internal combustion engines (ICEs), which remain the dominant energy source for agricultural machinery [2–5]. Among agricultural machines, tractors are both the most common type of farm equipment and one of the most prolific consumers of fuel

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Abbreviations

BET	Battery Electric Tractor
BEV	Battery Electric Vehicle
ICE	Internal Combustion Engine
TCO	Total Cost of Ownership
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
GHGs	Greenhouse Gas Emissions
PV	Photovoltaics
EV	Electric vehicle

[6,7]. As the global population continues to grow, the number of agricultural machines, particularly tractors, has steadily increased over the years to support the rising demand for food production [8,9]. Meanwhile, diesel engines exhaust emissions such as carbon oxides (CO, CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) are carcinogenic to humans [10] and can also damage soil and crops [11].

The depletion of oil resources and its high prices, increasing environmental pollution, and intensifying climate change have driven governments worldwide to design and implement decarbonization policies for a gradual transition to low-carbon economies, as highlighted by the Paris Agreement on Climate Change [12–19]. As of September 18, 2023, 124 countries have committed to achieving carbon neutrality by 2050 or 2060 [20]. Electrification is emerging as a potential solution for this politically enforced demand, offering benefits such as reduced reliance on fossil fuels, eliminated emissions, improved energy efficiency, and increased productivity in off-road equipment [21,22]. The introduction of stricter environmental and emissions regulations (Supplementary Table S1), including for ICEs, is among the primary factors that have prompted off-road equipment manufacturers to explore electrification [23]. As a result, they are investing in battery-powered machinery systems for alternative powertrains to comply with evolving standards while enhancing energy efficiency and sustainability. Electrification of agricultural tractors is becoming increasingly viable due to advances in electric powertrain technologies.

One of the most promising technological innovations in agricultural machinery is the battery electric tractor (BET) – powered exclusively by an electric motor and utilizing rechargeable batteries that can be charged via an electrical socket, charging station, or alternative renewable energy sources. Among electrified powertrain alternatives (battery electric, hybrid, and fuel cell electric), the battery electric configuration represents the most straightforward approach to tractor electrification due to its architectural simplicity, which also allows for an easier transition from conventional tractors [9,24,25]. The development of fully electric tractors has a long history, evolving through several distinct stages, from early 20th-century cable-powered prototypes to modern lithium-ion-based designs, with current prospects pointing toward integration with renewable energy and autonomous farming systems (see Supplementary Table S2 for a detailed overview).

Electric tractors provide numerous benefits for sustainable agriculture, including reduced fossil fuel consumption, zero local emissions, and cleaner agricultural operations than traditional diesel-powered models [26,27]. The role of electric tractors in promoting environmentally friendly farming practices, in alignment with the principles of sustainable development, positions this technology as a form of disruptive eco-innovation [28,29]. Undoubtedly, this is a technologically complex innovation requiring intensive research and development (R&D) and significant knowledge flows, which can guide decisions on further transformation towards more sustainable designs, particularly during the early stages of technology development [30]. The introduction of electric tractors has progressed more slowly than anticipated and remains in its early phase, particularly when compared to the electrification of road vehicle and construction machinery [31,32]. Research at this stage is especially valuable as it provides opportunities to refine or redesign the technology, ensuring that it achieves the desired economic, environmental, and social outcomes [33,34].

The body of literature on the electrification of agricultural tractors is growing rapidly. Previous studies, including reviews, have explored the current state of emerging electric technologies in agriculture, highlighting their advantages and limitations (Supplementary Tables S3 and S4). However, among the various dimensions of innovation, actual total costs and the role of farmers' perceptions are poorly represented. Economic considerations are either briefly mentioned in passing or reduced to a general reference to the high initial costs of electric tractors, with an urgent need highlighted for further investigation into ownership, operating, and maintenance costs [e.g., [35,24,25,21,5,36,37]]. This may be attributed to the fact that, in the last few decades, sustainability has risen to the center of economic discourse and gained more substantial significance, shifting the focus away from traditional economic development strategies [38]. At the same time, achieving sustainable change in agriculture requires not only technological and environmental advancements but also economic adjustments. Historical examples underscore the importance of demonstrating clear economic benefits to drive the adoption of technological innovation. For instance, while conventional tractors had a profound impact on agricultural productivity during the twentieth century, the technology was introduced as early as the 1890s, yet its widespread adoption and diffusion took more than 50 years [39,40]. The studies suggest that the slow diffusion of tractors until the 1930s was driven by various factors such as financial barriers in terms of cash costs and debt obligations [41], uncertainty in agricultural market prices [42], institutional constraints [43], small farm size [44,45], and the prolonged coexistence of the animal and mechanical modes of production [46]. Nevertheless, regardless of the reasons for the delayed adoption, once tractor technology evolved to become sufficiently general in purpose and advanced to a level where farmers recognized its technological and economic superiority and accepted it, widespread tractorization occurred [47,48]. A positive feedback mechanism, often referred to as a network effect, emerged: as more farmers adopted the same technology, the benefits associated with compatibility, shared knowledge, maintenance services, and supplier availability grew, further incentivizing adoption across the sector. Once a particular technological standard achieved dominance, it paved the way for economies of scale in production and distribution [49]. This historical experience offers valuable insights into the potential trajectory of agricultural electrification, highlighting the factors that may influence its adoption and eventual transformation of the sector.

The study employs a systematic literature review to examine existing evidence on the economic feasibility of BETs and the factors influencing farmers' willingness to adopt this emerging technology. The review addresses the following research questions (RQs):

- **RQ1:** Under what conditions are BETs economically competitive with conventional tractors?
- **RQ2:** What economic and non-economic factors influence farmers' willingness to adopt BETs?

These questions guide the synthesis of findings from both economic assessments and farmer-focused adoption studies. While technical and environmental aspects of BETs have been widely studied, less is known about their economic viability and the factors shaping farmers' adoption decisions. Meanwhile, shifting farmers' choices from diesel-powered tractors to electric tractors requires strong supporting evidence, particularly financial aspects [e.g., [50]]. By integrating economic performance indicators with evidence on farmers' attitudes and behaviors, this review identifies how economic considerations act as key drivers or barriers to BET adoption. This combined approach provides a holistic understanding of both the current status and future potential of BETs in agriculture, while identifying key economic incentives, institutional mechanisms, and barriers that shape the transition toward more sustainable farming systems. To the best of our knowledge, this is among the first attempts to systematically synthesize evidence specifically on the economic feasibility and farmers' adoption of BETs. While previous reviews have primarily focused on technical architectures, environmental performance, or life-cycle impacts of electrified agricultural machinery, the present review places economic feasibility and farmer adoption at the center of analysis and explicitly links cost structures with behavioral drivers.

The findings will be beneficial not only to researchers but also to policymakers, technology developers, and agricultural stakeholders aiming to promote low-carbon agricultural mechanization. Specifically, this review can support the development of targeted policies, financial instruments, and awareness strategies to facilitate the successful integration of BETs into diverse farming systems. Moreover, fellow researchers may draw on these insights to formulate hypotheses for replication and confirmatory studies.

The paper is divided into six sections. Section 1 is the introduction; Section 2 describes the method; Section 3 elucidates the research findings; Section 4 highlights the discussion; Section 5 offers conclusions of the study; Section 6 presents limitations and future research.

2. Methods

2.1. Systematic literature review

We conducted this systematic literature review to synthesize and evaluate existing knowledge related to our defined research questions. Reporting followed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines [51], which provide a 27-item checklist to support transparent and consistent reporting. The process involved four steps: (1) identifying relevant studies based on predefined inclusion and exclusion criteria, (2) screening and selecting eligible studies, (3) organizing and summarizing the included literature, and (4) reporting the study selection process and results using a PRISMA flow diagram. In addition, we conducted a quality appraisal of the included studies and assessed the risk of bias. The PRISMA 2020 Checklist and the PRISMA 2020 for Abstract Checklist are provided in Supplementary Tables S5 and S6. The review protocol was not registered in PROSPERO, OSF, or another public registry; however, the eligibility criteria, search strategy, and screening procedure were predefined prior to study selection and applied consistently.

2.2. Search strategy and eligibility criteria

The literature search was conducted using three databases: Scopus, Web of Science and Google Scholar. These sources were selected to ensure broad coverage of peer-reviewed literature relevant to the research questions, while Google Scholar additionally supports identification of grey literature. Given the early stage of research on BETs and the limited number of peer-reviewed studies, we expanded eligibility to include (i) conference papers indexed in Scopus and (ii) grey literature (e.g., working papers and reports) retrieved via Google Scholar. Grey-literature records were assessed using the same predefined eligibility criteria as journal articles and were additionally appraised for methodological quality and source credibility using a structured quality appraisal framework (Section 2.5). The search strategy was implemented using database-specific queries applied to the title, abstract, and keyword fields (where available). Search terms were developed around three core concepts: (i) the target tractor configuration (electric tractor), (ii) the sector (agriculture), and (iii) the main analytical focus (economic assessment and adoption). These concepts were combined using Boolean operators (AND/OR) to create a balanced search strategy, and synonyms were included to maximize sensitivity and reduce the risk of missing relevant studies. The full database-specific Boolean search strings are provided in Supplementary Table S7. The search period was set from 2018 to 2025, reflecting the sharp increase in BET-related publications after 2018. Scopus results show that more than 73% of BET studies were published after 2018, while in Web of Science the share exceeds 79%. The final search was conducted on 29 July 2025.

In addition to Scopus and Web of Science, Google Scholar was screened using the same publication years and a simplified search string to identify additional grey literature. This step did not yield additional peer-reviewed studies but identified grey literature sources that were assessed for eligibility and quality and were subsequently included when relevant.

Eligibility criteria were predefined to ensure transparent and reproducible study selection. Studies were included if they met at least one of the following criteria: (i) provided an empirical economic assessment of BETs in an agricultural context using a clearly documented methodology (e.g., cost analysis or total cost of ownership components), or (ii) examined farmers' attitudes, perceptions, or willingness to adopt BETs in agricultural settings. Only English-language publications published between 2018 and 2025 were considered. Studies were excluded if they (i) focused on hybrid tractors, fuel-cell tractors, or other alternative powertrain systems rather than BETs, (ii) investigated electric tractors outside agriculture (e.g., industrial, construction, or forestry applications), (iii) did not report sufficient methodological information to support interpretation of results, or (iv) did not address economic feasibility outcomes or adoption-related perceptions relevant to the research questions.

2.3. Study selection

All records retrieved from the database searches were exported and screened in two stages. First, titles and abstracts were screened against the predefined eligibility criteria to remove clearly irrelevant records. Second, the full texts of potentially eligible studies were assessed for inclusion. Screening was performed independently by the two authors, and disagreements were resolved through discussion until consensus was reached.

Some studies initially appeared to meet the inclusion criteria based on title and abstract but were excluded following full text assessment. These studies focused on electric tractors other than BETs, addressed non-agricultural applications, did not include an economic feasibility analysis and instead emphasized technical or engineering aspects, or lacked a sufficiently described empirical methodology.

The screening process resulted in the final set of studies included in our review. A summary of the selection procedure is presented in Fig. 1.

The search strategy retrieved 635 records. After removing duplicates, 574 records remained for title and abstract screening, and 530 records were excluded based on the exclusion criteria. The full texts of 44 reports were assessed for eligibility. Finally, 16 studies were included, of which 9 provided an economic assessment and 7 reported farmer survey evidence related to the adoption of electric tractors. Among the included studies, three were grey literature sources presenting economic analyses of BETs, and one was a peer-reviewed conference paper reporting farmer survey results.

2.4. Data extraction and synthesis

Data were extracted from all included studies using a predefined extraction template to ensure consistency and comparability. Extracted information included study characteristics, analytical approach, tractor type and power class, key economic indicators (cost components and/or TCO outcomes), adoption-related variables, and main findings relevant to the research questions. Data extraction was performed independently by two reviewers. Any discrepancies were resolved through discussion until consensus was reached.

No statistical imputation or transformation of outcome data was performed; quantitative values were extracted as reported. To enhance

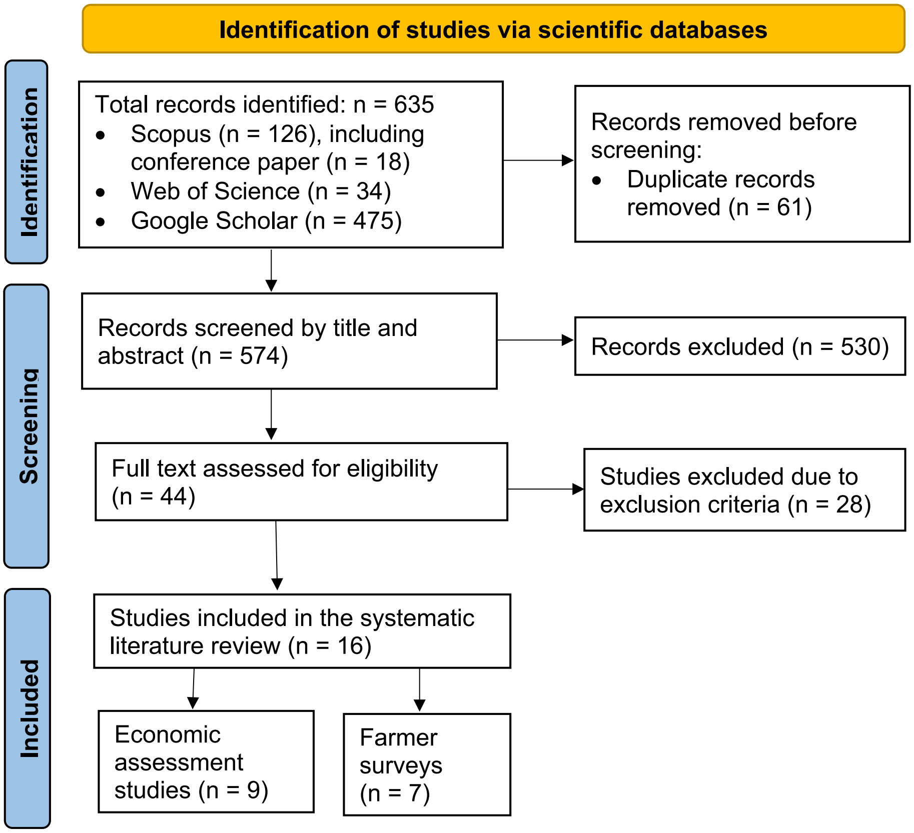

Fig. 1. PRISMA flowchart diagram of study selection.

comparability, monetary values were converted to U.S. dollars and inflation-adjusted to constant 2022 USD, and tractor power ratings reported in horsepower were converted to kilowatts using standard conversion factors. When multiple scenarios were reported, results were extracted at the scenario level and synthesized narratively. Missing or unclear information was not inferred and was addressed through qualitative comparison and cautious interpretation.

Given the substantial heterogeneity in study designs, data sources, analytical methods, and reported outcome measures, a quantitative meta-analysis was not appropriate. Instead, a descriptive narrative synthesis was conducted. Studies were grouped by primary focus into economic assessment studies and farmer survey studies, with each study contributing only to the synthesis aligned with its design and objectives, and findings were compared across countries, farm contexts, and analytical assumptions.

For economic assessment studies, results were synthesized by comparing cost structures, TCO outcomes, and sensitivity analyses across scenarios, as presented in Sections 3.1.1. and 3.1.2. For farmer survey studies, adoption barriers, drivers, and contextual factors were systematically compared across studies. To enhance transparency and analytical rigor, adoption-related factors were categorized thematically and subsequently aggregated using a qualitative weighted-sum approach, as described in Section 3.1.3 and Supplementary Table S16.

Results of individual studies were presented using structured summary tables, while synthesized findings were displayed using comparative figures and schematic diagrams to facilitate cross-study comparison. Additional methodological details and extended results were provided in Supplementary Tables.

2.5. Quality appraisal and risk-of-bias assessment

To ensure transparency and reproducibility, all included studies were subjected to a structured quality appraisal and risk-of-bias assessment prior to synthesis. Given the methodological heterogeneity of the included studies, including techno-economic analyses and survey-based research, a custom quality appraisal rubric was developed, drawing on established principles from CASP and JBI checklists and adapted to the specific characteristics of economic feasibility and adoption research. Study quality appraisal was used as a pragmatic proxy for assessing risk of bias, consistent with PRISMA 2020 guidance.

The quality appraisal framework consisted of predefined criteria covering: (i) clarity of research objectives, (ii) transparency and reproducibility of methods, (iii) appropriateness of economic assumptions or survey design, (iv) data quality and sources, (v) robustness of analysis and treatment of uncertainty (e.g., sensitivity analysis, subgroup analysis, sampling limitations), and (vi) discussion of limitations and potential sources of bias. Each criterion was scored on a three-level scale (1 = criterion fully met; 0.5 = partially met; 0 = not met). The full rubric and scoring rules are reported in Supplementary Table S8.

All included studies were independently appraised by two reviewers. Discrepancies in scoring were resolved through discussion until consensus was reached. Study type (economic assessment or farmer survey) and publication type (peer-reviewed journal, conference proceeding, or grey literature) were recorded for each included study and reported alongside quality scores. Per-study quality scores and justifications are reported in Supplementary Table S9. No study was excluded solely on the basis of quality score; however, studies assessed as lower quality, particularly grey literature and conference sources, were interpreted with caution and were not used as sole evidence for key conclusions.

Risk of bias was assessed qualitatively as part of the appraisal process, with particular attention to potential sources of bias relevant to economic and adoption studies, including assumption-driven modelling choices, limited empirical validation, small or non-representative survey samples, and selective reporting of outcomes. Grey literature sources were additionally screened for source credibility, transparency of methods, and consistency with peer-reviewed evidence.

Quality appraisal results informed the synthesis by guiding the weighting of evidence across studies and by supporting robustness checks in the interpretation of results. Key findings were cross-validated against higher-quality and peer-reviewed studies, and conclusions were framed to reflect the overall strength and limitations of the available evidence base. A sensitivity analysis excluding grey literature sources was conducted to assess robustness, and the main conclusions remained unchanged.

3. Results

We present our results in two sections, structured according to the research questions. First, we overview the economic competitiveness of BETs relative to conventional diesel tractors. We complement this subsection by providing a comparison of the cost of battery electric and diesel tractors. Second, we examine factors influencing farmers' acceptance of BET technology.

3.1. *Economic assessments of battery electric tractors feasibility in agriculture*

3.1.1. *Overview of economic competitiveness of BETs*

Based on the nine selected studies included in the systematic literature review, BETs are found to be economically competitive or nearing cost competitiveness with conventional diesel-powered tractors under specific conditions. The integration and interpretation of findings across these studies were informed by the quality appraisal described in Section 2.5, with greater interpretative weight given to higher-quality and peer-reviewed studies. For this purpose, Table 1 summarizes the main findings on the economic viability of BETs in different countries sorted by publication date.

In general, the reviewed studies demonstrate that the economic feasibility of BETs is highly context-specific. Key influencing factors include tractor size (particularly power rating), task intensity (light-, medium-, or heavy-duty), the level of autonomy, the integration of renewable energy systems, and the availability of policy incentives such as subsidies, tax relief, and discounted electricity rates. BETs tend to achieve cost competitiveness most consistently in low-duty applications (e.g., short-duration, low-power tasks such as mowing, spraying, and light transport) and on small to medium-sized farms, especially when tractor power remains below or around 50 kW. In contrast, electrification of high-power or heavy-duty tractors (above 100 kW) remains economically challenging due to current battery limitations and higher initial costs and operational burdens. Furthermore, autonomous electric tractors around 50 kW show additional cost-saving potential by reducing labor demands and extending daily operation hours, although supervision intensity remains a cost-sensitive factor.

3.1.2. *Total costs comparison of BETs and ICE tractors*

There is a broad consensus among the scholars, farmers and the public that BETs are significantly more expensive than ICE tractors, which negatively affect their diffusion. Therefore, this subsection investigates this claim. To evaluate the economic feasibility of BETs, all reviewed studies conducted total cost comparisons with conventional diesel tractors (and, in the case of [8], also with a hybrid tractor). These analyses employed the total cost of ownership (TCO) approach[1], which accounts for all current and future costs associated with a new technology under defined assumptions [60,61]. The TCO method is widely applied in comparisons between electric and conventional on-road

Table 1
Summary of economic competitiveness of battery electric tractors in the reviewed studies.

Study	Country	Method	Tractor type, power (kW)	Main findings
Götz et al., 2025 [52]	Germany, Ethiopia, Rwanda	Total costs of ownership (TCO) for a 12-year period and sensitivity analysis	Electric tractor (60 kW) and diesel tractors: Massey Ferguson MF 5710 M Dyna 4 (71 kW) for Germany and SAME explorer 90 MD (62 kW) for Rwanda and Ethiopia	Electric tractor demonstrated lower TCO than diesel in Germany and Rwanda in selected scenarios due to fuel and maintenance cost savings. In Ethiopia, results were more ambiguous, with the diesel tractor outperformed the BET, primarily due to limited annual operating hours in wheat production and higher relative electricity costs. Sensitivity analysis confirmed that cost competitiveness of BETs is highly dependent on electricity price, battery lifespan, and tractor utilization. Autonomy and renewable energy integration can improve economic performance under the right conditions.
Ali et al., 2025 [8]	USA	Total costs of ownership (TCO) for a 15-year period and sensitivity analysis	Electric, hybrid, and diesel tractors with nominal power 70 hp (~51.5 kW) based on a reference tractor	Electric tractors are cost-effective for light-duty tasks (engine loads inferior to 20%) with sufficient annual utilization, offering up to 19% lower TCO compared to diesel powertrains and producing zero local emissions. For medium-duty tasks (30%-60% load), hybrid tractors perform similarly to diesel, but with up to 30% lower NOx emissions. Heavy-duty tasks (loads above 60%) remain challenging for electrification due to unaffordable costs.

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[1] Although only five of the reviewed studies explicitly applied the TCO method (Table 1), the remaining four used cost models that closely align with the TCO framework, incorporating key cost elements such as capital and operating expenses under defined assumptions.

Table 1 (*continued*)

Study	Country	Method	Tractor type, power (kW)	Main findings
Imam et al., 2025 [53]	India	Total costs of ownership (TCO) for a 10-year period	Electric tractor 30 kW and 29.4 kW diesel tractor	A comparative analysis of the 10-year TCO between diesel and electric tractor reveals that, despite higher upfront costs, BETs can offer cost savings over time due to lower fuel and maintenance expenses. These long-term savings make BETs a financially attractive option for smallholder farmers, especially when supported by targeted incentives or innovative financing models.
Proctor, 2022 [54]	USA	Total costs of ownership (TCO) for a 7-year period and sensitivity analysis	Electric tractor Solectrac CET 30 hp (∼ 22.3 kW) and diesel tractor John Deere 2032R 32 hp (∼23.9 kW)	While the electric tractor has a higher upfront cost, the TCO over its lifespan is comparable to that of the diesel tractor primarily due to lower operating costs for the electric tractor, including cheaper fuel (electricity) and reduced maintenance expenses.
Shao & Anup, 2022 [55]	India	Total costs of ownership (TCO) for a 10-year period and uncertainty	Tiger Electric tractor 15 KW released by Sonalika and diesel tractor 15 kW Sonalika GT 20	The TCO of a compact electric tractor in India is only 3% higher than that of a diesel tractor. Electric tractors could be very cost-competitive if some incentives can be provided such as government subsidies, discounting of Goodsand Services Tax and insurance rates, reducing electricity tariffs in the agricultural sector, supporting charging system infrastructure, reducing interest rates for agricultural loans. The cost gap between electric and diesel tractors can be bridged by one or more incentives.
Vogt et al., 2021 [56]	Brazil	Cost calculation method (Vogt, 2018) is based upon the conversion of investment costs and direct operating costs into total hourly operating costs of diesel and electric tractors	Prototype electric tractor 9 kW and Agritech TC14S 10.3 kW diesel tractor	Within four alternative configurations, the electric tractor system is competitive with a diesel tractor, when tractor has 500 yearly working hours and 6 h maximum per day, and with 1000 annual tractor working hours and 15 h per day. The performance of the electric tractor is superior to diesel. The hourly cost of the electric tractor is 2 to 3 times lower than the traditional tractor.
Lagnelöv et al., 2021 [57]	Sweden	Overall costs calculation as a combination of annual ownership and operating costs, including battery and timeliness costs complemented by sensitivity analysis	Autonomous electric tractor 50 kW (2 units) and diesel tractor 250 kW	In a simulated scenario, autonomous battery electric drive systems can achieve comparable or lower annual costs than traditional manned diesel systems, mainly through reduced operating costs that outweigh higher investment and timeliness costs. Autonomy is essential for maintaining work efficiency and ensuring cost competitiveness; however, the analysis revealed a high sensitivity to the degree of autonomy, with fully monitored BED systems showing higher costs than diesel systems. While battery size and lifespan significantly influenced the total costs, operating costs proved to be more decisive than investment costs overall.
Gao & Xue, 2020 [58]	China	Cost model of electric transformation of diesel tractor,	Electric and diesel tractors with power range from	Full electric transformation of diesel tractors in China is

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Table 1 (*continued*)

Study	Country	Method	Tractor type, power (kW)	Main findings
		carried out by evaluation of the life cycle cost, the sensitivity coefficient and the payback period of incremental investment (IPBP)	7.35 kW to 73 kW	economically viable for smaller tractors (≤36.8 kW) depending on battery type. Although upfront cost is 2-5 times higher, the life cycle cost of electric tractors is about 60% of diesel tractors. Maximum payback period for electric tractors with lithium battery is 2.05 years. The electric transformation of tractors that require high power output is unsuitable, either economically or given the limitations of current battery technology
Melo et al., 2019 [59]	Brazil	Cost calculation method (Vogt, 2018) is based upon the conversion of investment costs and direct operating costs into total hourly operating costs of diesel and electric tractors when using renewable energy source (photovoltaic modules)	Prototype electric tractor 9 kW and diesel tractor Yanmar Agritech 10.3 kW	The electric tractor application is economically viable when involving renewable energy sources, even for small scale family farming. Despite the higher investment costs compared to diesel tractor, integration of renewable energy systems offset these initial expenses over time.

Note: *Where power was reported in horsepower (hp), values were converted to kilowatts using the standard conversion factor (1 hp = 0.7457 kW).*

vehicles [e.g., [62–65,50,66–69]], as it effectively captures long-term cost savings and trade-offs that extend beyond the initial purchase price. When purchasing new vehicle technology such as a BET, this analysis is crucial for farmers' decision-making, as it helps them understand the true cost of owning an electric vehicle over its entire lifetime. In parallel, manufacturers and governments can use TCO-based evaluations to design more targeted strategies and supporting policies for promoting electric vehicles adoption.

The total cost assessment in the reviewed papers included both capital expenditures (CAPEX) and operating expenditures (OPEX) of alternative technologies against ICE to identify the most economical choice of vehicle. CAPEX typically represents the fixed capital costs that are paid at the time of acquisition for the vehicle and infrastructure. Some studies included financial costs to one-time costs. These cover interest and other charges resulting from borrowing money to purchase the tractor. OPEX refers to operating costs such as maintenance and repairs, fuel, electricity, insurance premiums, battery replacement and others that occur during the lifetime of technology [63]. However, there is no single TCO model. Each model may incorporate its own set of cost drivers specific to the product being evaluated [e.g., [70]] and categorizing can vary depending on the modeling approach. Debate in the literature about the costs to include when calculating the total cost of new technologies is ongoing [67]. The prevalence of abstract theoretical models and simulations in several reviewed studies instead of using TCO methods attribute to data limitations, given the relatively recent emergence of BETs on the market. Consequently, the scope and specificity of cost components varied across studies depending on their objectives and assumptions (Table 2). For instance, two reviewed studies incorporated opportunity costs into OPEX: Shao and Anup [55] accounted for them as the waiting time associated with fueling or recharging, while Lagnelöv et al. [57] considered them as timeliness costs resulting from delays in performing critical field operations, primarily due to equipment limitations. Götz et al. [52] included external battery packs and battery replacement costs in CAPEX. Some authors also included taxes, financing and insurance in cost estimations, although not all accounted for additional costs related to battery replacement, depreciation or residual value. It can be assumed that the authors of the reviewed studies considered the specific characteristics of the tractor market and country-level economic conditions in their analyses.

Next, we illustrate the cost comparison to the extent possible, given the different analytical approaches used in the reviewed studies. Although BETs may already be cost-efficient compared to ICE tractors, cost-benefits often remain non-transparent to farmers. One of the main reasons is the relatively high total cost of acquiring BETs compared to conventional tractors. The cost literature stream outlines two methods for considering the purchase price of vehicle [63]. The first of these reflects the bottom-up approach, where the purchase price is estimated based on the individual vehicle components. Six of the reviewed studies applied this method, including Götz et al. [52], Ali et al. [8], Gao & Xue [58], Vogt et al. [56], Lagnelöv et al. [57], and Melo et al. [59]. These studies model hypothetical electric tractor systems using simulations or component-based cost estimations. The second method is based on representative reference vehicles, where the purchase price is derived from actual commercial models available on the market. Three of the reviewed studies employed this approach to analyze the cost performance of existing electric tractors (Proctor [54], Shao & Anup, [55], and Imam et al. [53]).

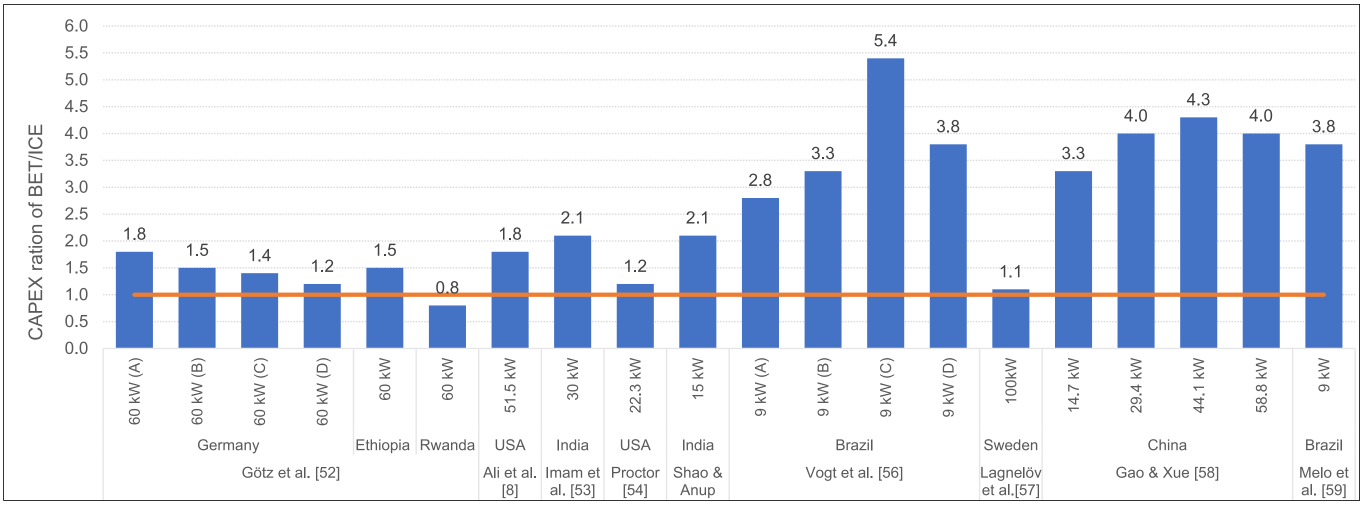
Fig. 2 illustrates the CAPEX ratio between BETs and ICE tractors across various countries and power classes, as reported in the reviewed studies. A ratio above 1.0 indicates that BETs have a higher initial investment cost than their ICE counterparts. Different studies analyzed multiple BET configurations, which contribute to variability in CAPEX ratios shown in Fig. 2. For example, Vogt et al. [56] evaluated four configurations for family farming in Brazil, while Gao & Xue [58] assessed conversion costs across multiple power classes. Götz et al. [52] applied a bottom-up cost model with country- and farm-specific scenarios (Germany, Ethiopia, Rwanda), and Lagnelöv et al. [57] reported CAPEX for two autonomous electric-drive tractors. Key techno-economic assumptions and scenario definitions across all reviewed studies are summarized in Supplementary Table S10. To enhance the comparability of initial cost estimates, we provide a table below Fig. 2 showing the CAPEX values for both BETs and ICE tractors.

While most reviewed studies confirm that BETs tend to involve higher CAPEX than ICE tractors, this is not universally the case. For instance, Götz et al. [52] found that in Rwanda, the CAPEX for a BET was lower than for the comparable diesel model. This unexpected outcome was due to two key factors: (1) a high total tax burden (45%) on diesel-powered vehicles in Rwanda, and (2) a cost-optimized design of the BET tailored specifically for grassland farming, which was further supported by favorable policy measures promoting its adoption. These findings challenge the commonly held perception that BETs are always more expensive to acquire. Nevertheless, most studies reported higher initial investment costs for BETs. The highest CAPEX ratio (5.4) was observed in the 9 kW configuration (C) in Brazil (Vogt et al. [56]), where

Table 2
Main cost components in the reviewed studies.

Cost elements	Götz et al. [52]	Ali et al. [8]	Imam et al. [53]	Proctor [54]	Shao & Anup [55]	Vogt et al. [56]	Lagnelöv et al. [57]	Gao & Xue [58]	Melo et al. [59]
Capital expenditures (CAPEX):	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tractor purchase price	✓	✓	✓	✓	✓	✓	✓	✓	✓
Additional battery pack	✓					✓			
Infrastructure:		✓				✓	✓		✓
- Battery changing system							✓		
– Charger station		✓					✓		
– Pivot						✓			
– Trailer						✓			
– Diesel storage tank						✓			✓
– Photovoltaic system									✓
– Autonomy system							✓		
Taxes	✓	✓			✓				
Financing	✓	✓	✓	✓	✓		✓		
Subsidy	✓								
Operating expenditures (OPEX):	✓	✓	✓	✓	✓	✓	✓	✓	✓
Maintenance and repairs	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy costs (fuel, electricity)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Insurance	✓	✓			✓	✓		✓	✓
Opportunity costs					✓		✓		
Battery replacement	✓	✓	✓				✓	✓	
Depreciation	✓					✓			✓
Residual value	✓	✓					✓	✓	
Operator cost							✓		

✓ **Inclusion of cost elements in the study:** When a study presented multiple scenarios, all cost elements included across those scenarios are marked.
Note: *The tractor purchase price includes the battery pack for commercial models. For prototype or conceptual models, it represents the combined cost of all components necessary to build a functional tractor, including battery pack.*



CAPEX BET, k$	159.6	132.3	122.9	101.9	146.0	92.4	90.8	20.1	39.5	12.2	24.0	29.1	47.2	33.4	282.0	15.7	28.7	41.7	56.1	33.4
CAPEX ICE, k$	88.2	88.2	88.2	88.2	95.6	112.4	50.2	9.7	33.5	5.8	8.7	8.7	8.7	8.7	253.3	4.7	7.2	9.8	14.0	8.7

Fig. 2. Capital expenditures (CAPEX) comparison between battery electric tractors and diesel tractors in the reviewed studies. **Source:** Authors' synthesis and calculations based on data reported in the reviewed studies. ***Note:*** *All CAPEX values were first converted from the original study currency to U.S. dollars and then inflation-adjusted to constant 2022 USD (see Supplementary Table S11). The four configurations labeled 60 kW (A-D) are based on scenarios modeled by Götz et al. [52] for Germany. They reflect variations in farm type and policy support: 60 kW (A) – wheat farm without subsidies, 60 kW (B) – wheat farm with subsidies, 60 kW (C) – grassland farm without subsidies, 60 kW (D) – grassland farm with subsidies. The four 9 kW configurations (A-D) are drawn by Vogt et al. [56] for family farming in Brazil. Each configuration reflects different component setups: 9 kW (A) - Basic configuration, including tractor and onboard battery; 9 kW (B) – Basic configuration (tractor and onboard battery) plus trailer carrying interchangeable packs; 9 kW (C) – Incorporates a cable-fed power system from a stationary source (home base), including the basic configuration and pivot; 9 kW (D)– A configuration combining features from B and C. The tractor tows a trailer with battery packs, which are connected to a mobile cable feed system in the field. The configuration includes tractor and onboard battery, pivot and trailer.*

extensive infrastructure such as a stationary cable feed system and pivot contributed significantly to the overall cost. Other configurations in the same study also showed elevated CAPEX due to added trailers and interchangeable battery packs. High CAPEX ratios (3.3–4.3) were also reported by Gao & Xue [58] in China, though this was largely due to the low cost of local diesel tractors (e.g., Huanghai JinMa series), not unusually high BET costs. In contrast, studies from developed countries (USA, Sweden) showed lower CAPEX ratios, though the absolute BET costs were higher due to more advanced technology and larger tractor classes. Götz et al. [52] also presented multiple configurations for Germany, varying by crop type (wheat vs. grassland) and subsidy availability. These scenarios highlight the potential of policy support to significantly reduce upfront costs and improve the competitiveness of BETs. In summary, although high CAPEX remains a key barrier to BET adoption, especially for smallholders and in developing countries, it is not an inherent feature of technology. Design optimization, local economic and tax conditions, and targeted subsidies can lead to competitive or even lower capital costs for BETs compared to diesel tractors.

In Fig. 3, we illustrate the purchase price comparison between BETs and their ICE counterparts. The figure is based on data from the reviewed studies where such information was available. The analysis reveals a clear trend: while BETs consistently command higher upfront purchase prices, the extent of this price difference varies significantly depending on the country and tractor configuration. Detailed monetary context (original currency, price year, data sources) as well as the purchase price modelling approach and included components are provided in Supplementary Table S12.

BETs consistently exhibit higher purchase prices compared to their ICE counterparts, though the magnitude of the price gap varies considerably by country and tractor configuration. These figures highlight the substantial upfront cost barrier to BET adoption, especially in contexts dominated by cost-sensitive smallholders.

It is widely acknowledged that the high purchase price of battery electric vehicles (BEVs), including BETs, is primarily driven by the cost of the battery pack [71]. Some reviewed studies reported the battery cost as a separate component. This allowed us to estimate its contribution to the tractor purchase price. The battery typically accounts for 30% to 35% of the total cost [53,54,56,57,59]. If a farmer opts to purchase an auxiliary or spare battery, the initial investment cost increases significantly. For example, in the study by Götz et al. [52], the addition of an external battery pack increased the CAPEX by: 15% for the wheat farm in Germany, 8% for the grassland farm in Germany, 16% for the wheat farm in Ethiopia, and 10% for the grassland farm in Rwanda. Similarly, in Vogt et al. [56], the external battery in configuration B increased CAPEX on 40.3%, in configuration D – by 35.5%.

Furthermore, the lifespan of lithium-ion batteries is limited, often requiring replacement after 8 to 10 years of use [72]. This limited lifespan and the high cost of battery replacement negatively impact the long-term cost competitiveness of BETs compared to diesel-powered alternatives. However, ongoing improvements in battery technology have enhanced battery performance, including higher energy density, faster charging times, better thermal management, and longer operational life [73]. These advancements have contributed to a significant decline in battery prices, falling from $780/kWh in 2013 to $139/kWh in 2023 [74]. This downward trend in battery costs is expected to continue in the coming years (to $80/kWh in 2030), driven by technology innovation and manufacturing improvement, further strengthening the economic case for electrified agricultural machinery [74,75].

Despite the high initial capital costs, all reviewed studies proposed various mechanisms to mitigate the economic burden of adopting BETs. A key area of potential savings lies in OPEX, particularly energy and maintenance costs. They are generally lower for BETs than for their diesel counterparts, although the extent of savings varies by study. For instance, Imam et al. [53] report that energy expenses for BETs are approximately 7.6 times lower, and maintenance costs 2.7 times lower than those for internal ICE tractors. Proctor [54] estimates that BETs reduce energy costs by 6.7–7.6 times depending on the scenario and maintenance costs by 1.2 times compared with ICE tractors. According to Götz et al. [52], in Germany, energy expenses for BETs were lower by 25% (subsidized PV wheat farm) or by 7% (grid grassland farm), while maintenance costs were reduced by 1–2%. However, lower energy and maintenance costs do not always translate into overall economic benefits. High upfront capital investments and additional operating costs, including battery replacement, can offset these savings and present significant barriers to adoption.

To assess the overall economic viability of BETs, TCO is considered

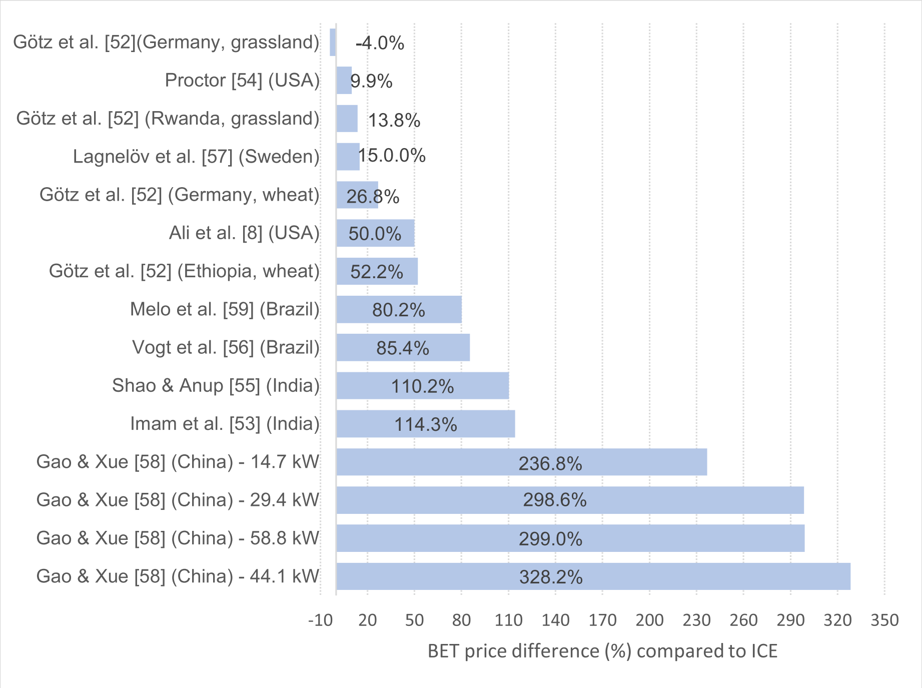


Fig. 3. Purchase price difference between BET and ICE tractor in the reviewed studies. **Source**: Authors' synthesis and calculations based on data reported in the reviewed studies. ***Note:*** *For each study, the purchase price difference between BET and ICE tractors is calculated within the same study context. As Fig. 3 reports relative price differences (%) rather than absolute monetary values, cross-country currency conversion and inflation adjustment are not required. For studies reporting multiple scenarios, separate entries are shown where purchase prices vary by country, farm type, or tractor power class (e.g., Götz et al. [52]; Gao and Xue [58]). Purchase prices do not include taxes or financing costs. Key scenario and modelling assumptions are summarized in Supplementary Table S10.*

the most comprehensive approach. Although only five of the studies reviewed include a full TCO assessment, they collectively provide valuable information on 20 different scenarios (Fig. 4). The scenarios vary by region, farm type, tractor configuration, and usage intensity and offer a broad view of the economic feasibility of BETs under different operating conditions.

Analysis of Fig.4 reveals substantial variation in the TCO ratio (BET/ICE) across scenarios, underscoring the context-specific nature of BET cost competitiveness. In half of the scenarios, BETs exhibit a TCO premium, primarily due to high initial capital costs that are not offset by lower OPEX of BETs. However, in the other 10 scenarios, particularly those with high annual operating hours, self-produced PV electricity, or favorable policy support, BETs reach near parity or even cost advantages over ICE tractors. As annual usage hours have a major impact on total energy consumption, several reviewed studies modeled usage intensity to better assess cost-efficiency. Ali et al. [8] enhanced this analysis by integrating average motor load with annual operating hours, offering a more differentiated view of BET utilization intensity. This approach enabled the modeling of light-, medium-, and high-duty scenarios, linking energy consumption directly to operational demand. The study shows that light-duty tasks, characterized by low motor loads (up to 20%) and high operating hours (>800 h/year), can make BETs economically viable. Götz et al. [52] similarly confirmed the competitiveness of BETs under conditions of high utilization (833 h/year in all cases) and low-intensity tasks, such as those on grassland farms. The economic performance of BETs was further enhanced in scenarios involving photovoltaic electricity production and investment subsidies. Proctor [54] also examined the influence of annual operating hours in three farm-type scenarios. Although exact motor load data were not provided, the study demonstrated that TCO improves under higher energy use. This effect is evident in the "Workhorse" scenario, where the tractor is used for energy-intensive tasks like tilling on small farms or vineyards. Even reviewed studies that did not conduct full TCO modeling acknowledged the importance of BET usage hours. For example, Vogt et al. [56] estimated that under high-utilization conditions (750-1000 hours per year), BETs could reduce hourly operating costs by 30-50% compared to ICE tractors. Melo et al. [59], Gao & Xue [58] and Lagnelöv et al. [57] also considered increased annual operating hours in their analyses. Across these studies, variations in tractor utilization intensity clearly demonstrate that high operational workloads significantly reduce OPEX, thereby enhancing the cost-effectiveness of BETs and improving their TCO performance.

Together with scenario-based strategies, a variety of cost-reduction mechanisms have been identified that can make BET economically attractive (Supplementary Table S13).

Sensitivity analysis conducted in the reviewed studies revealed that the economic viability of BETs is highly dependent on several key parameters. Proctor [54] demonstrated that BETs cost competitiveness is most sensitive to their initial purchase price, annual operating hours, and equipment lifespan, whereas ICE tractors are notably sensitive to rising diesel prices. Ali et al. [8] analyzed scenarios with and without government subsidies, under varying diesel prices and battery lifespans, and found that public support and battery cost declines substantially improve economic feasibility. Imam et al. [53] applied Monte Carlo

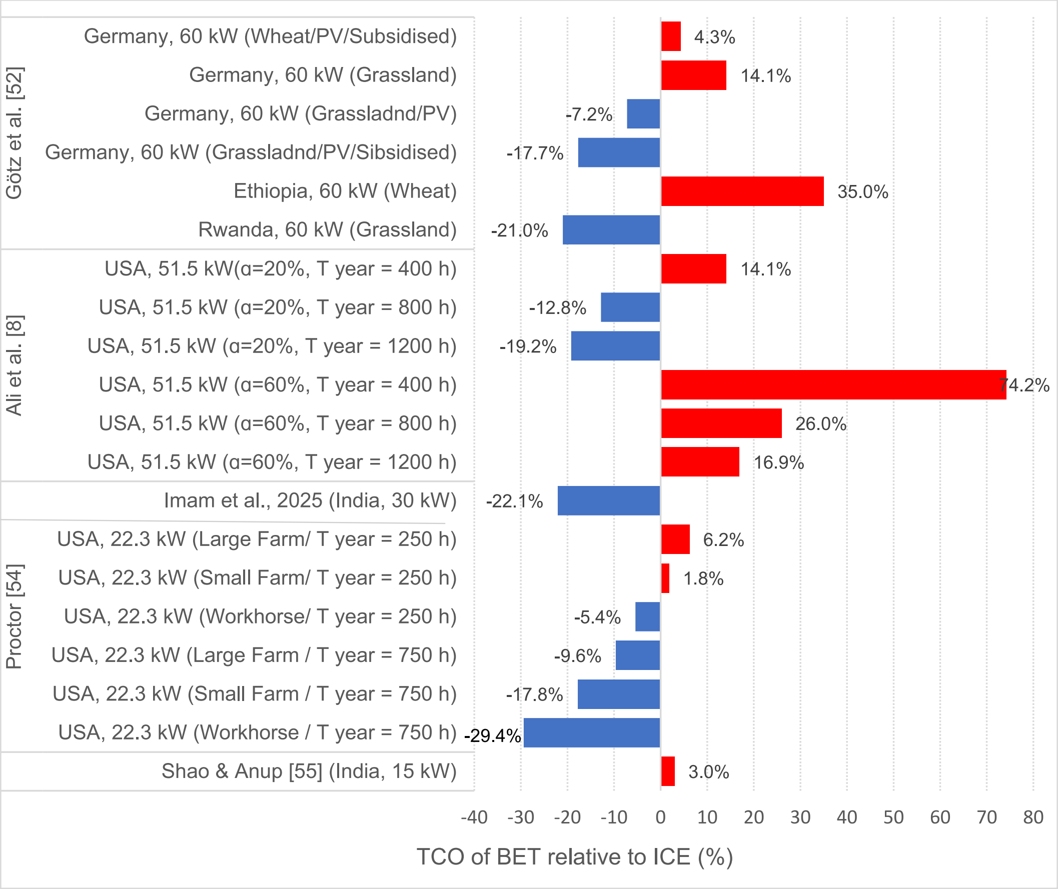


Fig. 4. TCO of BETs relative to ICE tractors across 20 farm scenarios in the reviewed studies. **Abbreviations**: PV = Photovoltaic, α = average motor load, T year = yearly working time of tractor in hours, kW refers to the motor power of BET used in the scenario. ***Note:*** *Values above 0% indicate higher TCO for BETs compared to ICE tractors (red bars), while values below 0% indicate a lower TCO for BETs (blue bars). According to Proctor [54], a "Large Farm" scenario – the BET is mainly used for transport and moving, a "Small Farm scenario" – the BET does a large portion of the work including tilling, moving, and general utility use, and a "Workhorse scenario" – the BET is only used for energy intensive tasks like tilling. Key techno-economic assumptions and scenario definitions are summarized in Supplementary Table S10.*

simulations to examine uncertainty in factors such as energy costs, interest rates, and battery replacement timing, highlighting the importance of stable input conditions. Lagnelöv et al. [57] examined how labor costs influence the economic outcome of autonomous BETs, showing that savings in operator wages significantly affect the cost balance. Shao and Anup [55] evaluated different electricity tariffs, charging patterns, and opportunity costs, demonstrating that reduced power prices and broader access to fast-charging infrastructure could eliminate the total cost gap between electric and diesel tractors. Götz et al. [52] conducted a sensitivity analysis for the Rwanda grassland scenario, where the BETs had the lowest TCO. They found that annual usage hours had the greatest impact on total cost. Additional influential parameters included battery price, component costs and energy prices. These sensitivity analyses consistently identified purchase price, electricity/fuel prices, utilization rates, battery replacement costs, and policy incentives as the most influential variables.

The findings of this section emphasize that BET adoption depends on favorable economic and policy conditions. While BETs currently face higher capital costs than ICE tractors, the reviewed studies show that with supportive policies, efficient usage scenarios, and continued declines in battery and energy costs, BETs can achieve cost competitiveness over their lifetime. These findings underscore the importance of a holistic cost evaluation and contextual adaptation when assessing the economic feasibility of BET adoption.

3.1.3. *Farmers' adoption of battery electric tractors*

This section analyzes empirical data from seven studies conducted across North America, Europe, and Asia, focusing on farmers' willingness to adopt BETs.

Although many policymakers have established targets to reduce fossil fuel use in agriculture, and technology suppliers have introduced promising electrification solutions (Supplementary Table S14), the actual transition to electric tractors remains slow [5,76]. The transformation from niche innovation to widespread adoption depends heavily on farmers' willingness to adopt new technologies. Numerous studies have emphasized that a substantial time lag often exists between the development of agricultural innovations and their broad uptake by producers [77,78], a delay that must not be overlooked when projecting the impact of emerging technologies [79].

In recent years, growing attention has been devoted to understanding farmers' perceptions of new agricultural technologies, with valuable insights generated for policymakers, practitioners, and researchers alike [80–88]. While there is a robust body of research on EV adoption in the private and transport sectors [e.g., [89–91]], the agricultural context poses unique challenges. In particular, electrifying farm vehicles involves significantly higher energy demands during short, intensive operational periods – making the transition more complex than that of passenger EVs [5,9,21,92].

Considering that electric tractors are still under development and testing, farmers' initial perceptions, attitudes and cost considerations are critical to their further successful adoption. Since tractors are central to mechanized farming, their electrification represents a pivotal step in achieving climate-smart agriculture and energy transitions at the farm level. Table 3 presents a comparative summary of seven empirical surveys examining these factors. Understanding the perceived barriers and motivating incentives reported across diverse farming contexts is essential for designing effective support mechanisms and technology strategies tailored to the agricultural sector's unique demands.

The reviewed farmer surveys exhibit considerable variation in sample size (n = 14, 40, 141, 156, 281, 334, 411; see Table 3 for details). This heterogeneity is characteristic of research on BET adoption – an emerging field with limited commercial availability, varying awareness levels, and practical challenges in accessing diverse farmer populations. Sample sizes were chosen (or accepted) based on study objectives,

Table 3
Adoption of battery electric tractors: Insights from farmers' surveys.

Reference	Country	Survey specific	Adoption attitudes	Barriers	Incentives
Michels et al., 2024 [93]	Germany	Online questionnaire with 141 full-time livestock farmers from various regions of Germany in 2022	Farmers' intention to adopt increases with improved performance, especially when alternative tractors are shown to match diesel models in capabilities	Low range, high investment costs, poor infrastructure	Environmental awareness, alignment with future regulations, appeal to younger/educated farmers
Wu et al., 2024 [94]	China	Online survey of 281 full-time agricultural producers in three provinces across China (Jiangsu, Sichuan and Hebei)	Farmers who hold positive attitudes and perceive substantial benefits toward alternative fuel machinery such as BETs have a considerably higher probability of adopting these technologies	High capital costs, lack of knowledge about technology, complexity of machinery	Environmental advantages, cost savings, increased efficiency, social influence
Sok & Hoestra, 2023 [95]	The Netherlands	Online survey of 156 farmers (76 dairy farmers and 81 arable farmers) in 2020	Over 50% of dairy and more than 60% arable farmers are unlikely to buy an electric tractor within the coming 10 years	Working time in hours, range, purchase price	Lower operation costs (maintenance and higher lifetime of the components), maximum torque at the standstill condition, independent wheel drive
Bessette et al., 2022 [96]	USA	Interviews with 14 small-scale organic vegetable, fruit, and cut-flower farmers in the US Midwest and Mid-Atlantic during 2021-2022	29% are not willing to buy a BET	Long-term performance, safety (farmers' concerns about physical and operational risks associated with BET systems), battery weight, high and unpredictable battery costs	Reduced noise, exhaust fumes, GHGs, and fuel costs
Lombardi & Berni, 2021 [97]	Italy	Face-to-face interviews with 411 nursery farmers in the province of Pistoia	Small farms and younger farmers more willing; under 40 more environmentally motivated	High price, low engine power, battery cost/lifespan	Environmental benefits; suited for small farm
Riedner et al., 2019 [98]	Austria	Online survey of 334 farmers in Styria; 30% with EV experience, 70% without	Farmers with EV experience are more positive; those without emphasize battery recharge time more	Range, transportation capability of goods, battery recharge time	Importance of environmental friendliness, driving performance
Caban et al., 2018 [99]	Poland	Questionnaire of 40 farm owners (field/horticultural crops, fruits, animal husbandry) in the Lubelskie and Swietokrzyskie voivodship	75% not planning to buy; prefer traditional drive	Poor battery range, high price, lack of knowledge about electric tractors	Positive view of electromobility in agriculture

methodological approaches, and practical feasibility. For instance, Michels et al. [93] employed confidence-interval-based calculations; Riedner et al. [98] applied descriptive checks for regional typicality on key demographic (age, gender) and farm characteristics (business type) despite explicitly acknowledged non-representativeness and a bias toward EV-experienced respondents; Wu et al. [94] adopted stratified random sampling with eligibility-based targeting of full-time farmers; Lombardi et al. [97] relied on random sampling justified by sector suitability in a specialized intensive nursery area; Sok and Hoestra [95] provided detailed descriptions of sampling frames and recruitment strategies supporting exploratory or analytical objectives. Bessette et al. [96] and Caban [99] adopted smaller or feasibility-based samples appropriate for early-stage or niche investigations. Although none of the studies aim for strict statistical representativeness of the global or national farmer population, several employed targeted or stratified approaches to enhance relevance within specific high-potential contexts. Survey findings are therefore synthesized as valuable context-specific insights from early-aware, specialized, or high-potential farmer groups.

Survey findings indicate that interest in BETs varies significantly across countries and farm types, shaped by structural conditions, policy context, and farmer profiles. Small-scale, organic, and environmentally conscious farmers show comparatively higher willingness to adopt, driven by pro-environmental values, health concerns, and alignment with sustainable practices [96,97]. However, this interest is often tempered by concerns about high upfront costs and limited technical maturity, particularly regarding battery performance and lifespan. In contrast, in countries like China [94] and the Netherlands [95], where farming is more commercialized and large-scale, adoption is more conditional on economic feasibility and infrastructure readiness. Here, barriers such as limited charging infrastructure, battery range, and price-performance uncertainty weigh heavily. Nevertheless, in China, younger, more educated farmers on larger farms demonstrate stronger adoption potential, suggesting that modernization and generational transition may gradually enhance BET uptake. In Germany [93] and Austria [98], adoption intent is strongly linked to performance parity with diesel tractors, policy expectations, and environmental consciousness, particularly among farmers with prior EV experience. Interestingly, even technologically open farmers remain cautious unless BETs prove reliable and cost-effective under real field conditions. Overall, the surveys reveal a nuanced picture: environmental motivation and openness to innovation foster adoption among smaller and organic farms, while economic rationality, infrastructure, and proven performance dominate decision-making in more conventional and large-scale systems.

Technology acceptance in agriculture is a complex phenomenon influenced by a wide range of factors, including economic, financial, technological, socio-demographic, and institutional dimensions [85,86]. We identified 43 distinct adoption factors that influence farmers' uptake of BETs, as reported across seven reviewed articles. To facilitate analysis and interpretation, we categorized these factors into six overarching groups based on thematic similarity and underlying mechanisms: (1) technical, (2) economic, (3) environmental and sustainability-related, (4) institutional and market, (5) farmer socio-demographic, and (6) behavioral factors. The diversity of these factors highlights the multidimensional nature of BET adoption and reinforces the understanding that technological diffusion in agriculture is highly context-specific.

To better reflect the varied influence of adoption determinants, we categorized the identified factors into three groups: (i) motivators, (ii) barriers, and (iii) context-dependent factors whose impact varies depending on farm structure, economic and technological conditions, or policy environments. For instance, farm size may facilitate adoption in smallholder settings where lower-powered BETs are sufficient, but act as a constraint for large-scale operations requiring higher power and autonomy (Supplementary Table S15).

The largest group of adoption factors mentioned by farmers in the reviewed surveys consists of economic and technical variables, which are closely interlinked. Notably, many of the most frequently mentioned technical barriers (e.g., limited battery range, long charging time, insufficient charging infrastructure, and battery lifespan) translate directly into economic consequences for farmers. For instance, concerns about long charging time [98,99] and lack of fast-charging options [94] are not only operational issues but also result in downtime and lost productivity, thereby increasing opportunity costs. Similarly, limited engine power or short battery life may necessitate the use of additional tractors, battery replacements, or changes in field logistics, all of which entail added expenses [93,95]. The influence of each factor may vary depending on farm characteristics, local infrastructure, regional policy environments, and the stage of technological development. This variability makes it difficult for policymakers and practitioners to address all potential barriers and drivers simultaneously.

In addition to economic and technical factors, several environmental and sustainability-related motivators emerged strongly in the reviewed surveys. Farmers who identified as environmentally conscious or aligned with sustainable farming practices were more likely to express interest in BETs [96,97]. Perceived contributions to GHG reduction, cleaner air, and alignment with environmental regulations played a key role in fostering positive attitudes. While these factors rarely acted as standalone drivers of adoption, they reinforced the attractiveness of BETs, especially when paired with financial or policy incentives. However, their effectiveness often depended on farmers' values, peer influence, or market signals, highlighting their context-dependent nature.

Institutional and market factors primarily appeared as barriers in the form of insufficient knowledge dissemination, lack of training opportunities, and limited demonstration projects [94,98]. Several studies emphasized that without trusted information sources or peer engagement, uncertainty and skepticism surrounding BETs increase. Conversely, access to reliable information, media exposure, and stakeholder engagement (e.g., from suppliers or advisors) acted as motivators, especially among younger or more innovative farmers. These findings underscore the importance of building institutional capacity and fostering knowledge-sharing ecosystems to support adoption.

Regarding farmer socio-demographic variables, evidence pointed toward their context-dependent role. For example, smaller farms and younger, more educated farmers often showed greater openness to BET adoption, particularly when environmental values or previous experience with electric vehicles were present [94,97]. However, in some contexts, larger operations were more financially equipped to absorb the high capital costs. This indicates that factors like age, farm size, and production type can either facilitate or hinder adoption, depending on broader structural and economic conditions.

Finally, behavioral factors played a nuanced role in shaping farmer attitudes. Trust in new technologies, perceived usefulness, and openness to innovation were considered positive perceptions. These factors acted as strong motivators, especially when reinforced by prior exposure to EVs or successful pilot experiences [93,94]. In contrast, emotional attachment to diesel tractors, satisfaction with current systems, and inertia contributed to resistance and skepticism. These barriers are often subtle but deeply rooted, suggesting that behavioral and psychological dimensions should not be underestimated when designing adoption strategies.

To provide more actionable insights, we therefore created a master list of 16 factors that were most consistently and strongly emphasized across the reviewed surveys. We did not include all 43 factors for two main reasons: (i) several factors were mentioned only once and lacked further discussion in most articles; (ii) including a larger number of factors would dilute key insights and reduce analytical clarity. The selected 16 factors were classified into barriers and drivers, providing an actionable overview of which factors hinder adoption and which can accelerate it. We assessed each factor's level of importance using a weighted sum model approach [100] and ranked both the most influential barriers and drivers' factors reported in the literature (Fig. 5). The resulting scores reflect the consistency and emphasis with which

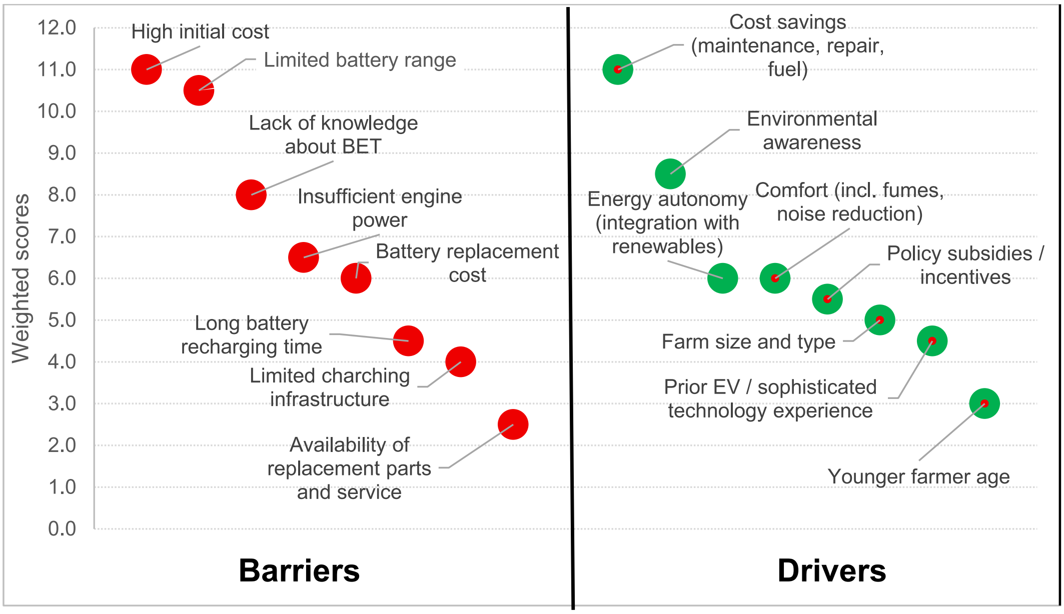


Fig. 5. Barriers and drivers for battery electric tractors adoption across farmers' surveys. ***Note:*** *The ranking method involved four steps:* ***Step 1****: For each survey, we identified whether a factor was mentioned as a key barrier or driver, emphasized with priority (e.g., highlighted in conclusions, results, ranked lists, summary tables, or discussed as a dominant factor), or explicitly ranked in surveys (if available).* ***Step 2****: We scored each factor's importance per study using the following scale: 2 = strong impact (ranked among the top 3 in the study), 1 = moderate impact (impacted factors but not the top 3), 0.5 = weak impact (mentioned or discussed, but not emphasized), 0 = not mentioned.* ***Step 3****: Scores were summed across all studies to obtain a composite importance score for each factor.* ***Step 4****: Factors were ranked from highest to lowest based on their total scores. All studies were weighted equally in the aggregation; survey sample size was not used as a weighting factor due to heterogeneity in study design and objectives.*

adoption factors are reported in the literature, rather than their statistical prevalence in the farming population. Fig. 5 is based on a qualitative weighted-sum synthesis of adoption factors across studies; detailed per-study scoring is provided in Supplementary Table S16.

Fig. 5 illustrates the relative influence of the 16 most critical factors on the adoption of BETs as identified across the reviewed literature. Notably, economic factors dominate both categories, indicating that cost-related considerations are central to farmers' decision-making processes. On the barriers side, high initial investment and battery replacement cost scored the highest, reflecting widespread financial concerns. Conversely, the most influential drivers include cost savings on maintenance, repair and fuel, policy subsidies, and potential savings from on-farm renewable energy use, underscoring how financial incentives and operational efficiency can positively shift adoption behavior. This emphasis on economic conditions suggests that addressing cost-related barriers while enhancing financial incentives could yield the most immediate policy impact. Technical, behavioral, environmental, and institutional factors also play important roles but with generally lower aggregate scores, highlighting the need for a multifaceted but economically grounded approach to policy and intervention design.

4. Discussion

This review set out to answer two core research questions: (i) under what conditions are BETs economically competitive with diesel tractors, and (ii) what economic and non-economic factors influence farmers' willingness to adopt them. By synthesizing findings from both cost-based economic assessments and adoption studies, we provide an integrated perspective on the dual challenge of making BETs financially viable while ensuring they are accepted by end users.

Our findings confirm that BETs remain in the early stages of development. They are currently feasible only in specific farming contexts. Most economic assessments and surveys focus on small-scale farms, horticulture, vineyards, organic farming, and greenhouse production. In these settings, lower power needs and shorter working hours align with BETs' technical limitations. This pattern reflects broader research showing that early BET deployment is concentrated in low-duty applications where constraints on range, charging, and battery capacity are less restrictive [7,9,32,101–104]. Because of the insufficient energy and power density of state-of-the-art lithium-based batteries, full electrification of tractors above 120 kW remains unfeasible [105].

Our research also indicates that farmers' environmental awareness is growing. However, this rarely translates into willingness to pay the price premium for BETs. If battery technology achieves cost parity with diesel while meeting fieldwork requirements, BETs could become a transformative solution [106]. In short, farmers are likely to transition to electric tractors once they provide equivalent power, performance, and reliability to diesel models at price parity. Until then, high investment costs remain the main barrier.

Economic assessments from our reviewed articles and broader research [e.g., [107–109]] show that energy and maintenance costs are significantly lower for electric vehicles. This makes them an attractive long-term prospect. However, these savings do not always offset high CAPEX or additional operational costs. As a result, BETs (Fig. 4) or other EV [60,110,111] may have a less favorable TCO compared to ICE tractors. Farmers recognize these benefits and cite them as a key driver for BET adoption (Fig. 5). Yet awareness alone has not translated into widespread uptake. A lack of knowledge about BET technology creates misconceptions and fears that slow diffusion. Riedner et al. [98] showed that farmers without EV experience overrated charging times, while Bessette et al. [96] found concerns about unpredictable battery maintenance and weather-related performance. Farmers typically expect BETs to operate for a full working day without charging interruptions [93,99]. As one farmer in Bessette et al. [96] put it: *"Why replace a diesel tractor that can work all day without any problems with a tractor that costs more and takes six hours to charge after only 4–6 hours of use?"* Addressing such concerns requires proactive dissemination of reliable information by educational institutions, consultative authorities, and agricultural advisory groups [112].

Beyond purely economic considerations, other motivations also shape farmers' decision-making. These include social, psychological, and status-related factors. Evidence from Nepal and Turkey shows that small-scale farmers often prefer high-powered tractors, even when lower horsepower options would suffice [113,114]. Similar trends have been observed in Switzerland, where many farmers purchase high-powered tractors but operate them far below capacity. This results in excess investment and higher life cycle costs without proportional efficiency gains [115]. Such tendencies toward over-capacity purchasing may further slow BET adoption. This is likely unless counterbalanced by incentives, awareness campaigns, and demonstrations highlighting the cost-effectiveness of lower-powered electric models.

Agriculture is moving towards the concept of Agriculture 5.0 [92], where precision farming, automation, and decision-support systems become standard. In this context, electrification of tractors and integration with robotic systems highlight on-site renewable energy as a key strategy for improving efficiency, energy independence, and supply security. Both our review of economic studies and surveyed farmers emphasized the importance of on-farm renewable energy sources for BET adoption. Electric tractors are well positioned for integration with autonomous and precision technologies [116,117], supporting the shift toward intelligent and automated farming [118].

While current deployment remains concentrated in small-scale operations, the long-term trajectory points toward an integrated electrified farm system. Following dominant design theory, BETs may evolve incrementally until a breakthrough enables wider adoption [50]. Advances in battery technology, such as ultra-fast charging, battery swapping, improved durability, and cost reduction, are expected to make higher-powered tractors (≥100 kW) commercially viable by 2030 [119,120]. This development would allow their use to expand beyond light tasks to energy-intensive field operations.

The global market outlook is also positive. For example, BIS Research [121] projects the electric tractor market to grow from \$98.7 million in 2022 to \$234 million by 2028 (CAGR 14.1%), reflecting broader demand for digitalization and low-emission farming [122]. Taken together, these trends indicate that BETs will become part of a broader ecosystem of electrified, renewable-powered, and intelligent farm machinery, paving the way for a fully sustainable agricultural landscape. A conceptual synthesis of the farm-level conditions under which battery electric tractors are more likely to achieve economic competitiveness is provided in Supplementary Figure S1.

Parallels can be drawn with the slow diffusion of diesel tractors, which initially spread only in niche contexts before scaling up [44,45]. Farmers coexisted with horses for a prolonged period, reflecting the inertia of established practices and the gradual process of recognizing the practical advantages of mechanization [46]. During the early stages of mass tractorization, diesel tractors and horses coexisted on farms until the eventual displacement of animal traction. BET adoption is likely to follow a similar trajectory: technological improvement and cost reduction are necessary, but adoption will remain gradual until farmers are convinced of operational reliability and clear relative advantages. Policy support will therefore be essential to close the cost gap and address behavioral barriers, helping farmers reorient their priorities toward the long-term benefits of electrification. Building on the identified cost drivers, adoption barriers, and enabling conditions discussed above, targeted policy instruments can play a critical role in accelerating the diffusion of BETs. Rather than addressing a single constraint, effective policy mixes must simultaneously reduce upfront investment costs, lower operational expenditures, and mitigate perceived risks related to reliability and usability. Table 4 maps key policy levers to their primary mechanisms and their expected effects on TCO and farmer adoption. These policy levers reflect mechanisms discussed in the reviewed studies (see Supplementary Table S13) as well as policy instruments commonly highlighted in the broader literature on technology diffusion and agricultural innovation.

Table 4

Policy levers influencing battery electric tractor economic feasibility and adoption.

Policy lever	Mechanism	Expected effect TCO	Expected effect on adoption
Purchase subsidies/ investment grant	Reduce upfront cost	↓ CAPEX → ↓ TCO	↑ adoption (especially early adopters)
Low-interest loans/ leasing support	Reduce financing burden	↓ annualized CAPEX	↑ adoption in capital-constrained farms
Electricity price incentives (agricultural electricity tariffs)	Lower charging cost	↓ OPEX	↑ adoption where utilization is high
Tax exemptions/tax relief	Reduce purchase-related taxes	↓ CAPEX → ↓ TCO	↑ adoption via improved affordability
Research & Development support	Improve performance & reliability	No short-term effect; future ↓ CAPEX/OPEX	↑ adoption via improved reliability and reduced uncertainty
PV incentives/on-farm renewables	Self-generation	↓ OPEX and volatility	↑ adoption (energy autonomy valued)
Carbon tax/fuel tax	Raise diesel operating cost	↑ diesel OPEX (relative BET advantage)	↑ adoption via stronger economic case
Charging infrastructure programs	Improve access & reliability	indirect (↓ downtime costs)	↑ adoption via feasibility
Demonstration & extension programs	Knowledge & trust building	No direct effect	↑ adoption via risk reduction

The future of BET adoption will depend not only on technological progress and economic viability but also on embedding principles of responsible research and innovation (RRI) and comprehensive sustainability assessment (SA) into their development and deployment [123]. This means that BET innovation, especially at the early stages of technology development, should be co-developed with farmers, policymakers, manufacturers, and society at large. Doing so ensures that technological solutions address real-world needs, minimize unintended consequences, and remain adaptable to diverse farming contexts. At the same time, sustainability assessment offers a holistic framework to evaluate BETs beyond cost competitiveness. It encompasses environmental benefits, such as emissions reduction; social aspects, such as farmer well-being and rural equity, and institutional dimensions, such as supportive policies and advisory systems. Together, RRI and SA provide a forward-looking approach that situates BET adoption within broader agricultural transitions. This helps to ensure that electrification contributes not only to efficiency and competitiveness but also to long-term sustainability and societal acceptance.

5. Conclusions

This systematic literature review synthesizes findings from both cost-based economic assessments and farmer-level adoption studies to provide an integrated perspective on the dual challenge of making BETs economically competitive while ensuring they are accepted by end users. These conclusions should be interpreted in light of the substantial heterogeneity in study designs, tractor configurations, farming systems, and policy contexts across the reviewed literature. Rather than yielding universally applicable prescriptions, the review identifies consistent patterns across studies that clarify the conditions under which BETs are most likely to be economically viable and adopted. The following conclusions can be drawn:

- BETs are currently economically viable under context-specific sets of conditions, predominantly characterized by high annual utilization (over 800 h/year) in low-duty applications. Crucially, cost competitiveness can be achieved when coupled with on-farm renewable energy generation (e.g., PV), autonomous technologies, and supportive financial mechanisms. Economic considerations emerge as the dominant determinant of farmers' adoption of BETs. High upfront investment costs are consistently identified as the primary adoption barrier, particularly for smallholders and in emerging economies, while uncertainty related to battery costs further reduces attractiveness despite potential long-term savings in fuel and maintenance expenses. Sensitivity analyses confirm that purchase price, annual utilization rates, and battery cost assumptions are among the most decisive parameters influencing cost-effectiveness. Overall, these findings indicate that farmers primarily evaluate BETs through an economic lens, making financial viability a prerequisite for broader adoption. Accordingly, these findings do not imply that BETs are currently competitive across all farming systems or tractor power classes, but rather that economic feasibility emerges under clearly defined and often restrictive conditions.

- Adoption incentives differ across farmer profiles. Environmentally conscious, experienced in using EV, or younger farmers tend to be more open to innovation and may be motivated by sustainability goals. However, for the broader farming population, economic viability remains the decisive factor. While many farmers express openness to BETs, actual uptake is often constrained by financial uncertainties, lack of practical experience, and concerns about performance reliability, especially in the absence of strong economic incentives or demonstration projects.
- Contextual factors play a critical role in shaping both economic outcomes and adoption likelihood. Farm size, production type, local infrastructure, prior experience with EVs, and national policy frameworks all influence whether BETs are perceived as feasible and attractive investments. Policy instruments aligned with carbon-neutrality objectives, including financial incentives, electricity tariffs, and renewable energy support, as well as differences in assumed energy costs, particularly diesel versus electricity price fluctuations, directly shape economic assessments and adoption considerations in the reviewed studies, and are therefore expected to influence the future promotion of BETs.
- Behavioral and institutional factors should not be underestimated. Lack of awareness, trust, training opportunities, and exposure to peer experiences can significantly slow adoption, even where economic conditions are favorable. Well-designed knowledge dissemination and demonstration efforts are essential to accelerate uptake.
- Policymakers and technology developers must take a dual approach: simultaneously lowering financial and technical barriers (e.g., through cost-reduction mechanisms, infrastructure investment, and R&D in battery technologies) while strengthening enabling environments through education, training, and incentive programs.

This review highlights the need for integrated, evidence-based strategies that align technological innovations with the lived realities and economic constraints of farmers. Future research should expand on real-world performance data, farmer co-design initiatives, and long-term impact assessments across diverse farming systems. Only through such interdisciplinary and context-sensitive approaches can the promise of BETs be fully realized in global agriculture. However, given the early stage of commercial deployment and the predominance of modelling-based and small-sample evidence, the conclusions of this review should be viewed as indicative rather than definitive, highlighting plausible pathways for BET adoption rather than forecasting near-term diffusion at scale.

6. Limitations and future research

This review has several limitations that should be acknowledged. First, the number of reviewed studies specifically addressing the economic feasibility and adoption of BETs remains limited, with only 16 articles meeting the inclusion criteria. This scarcity of research largely reflects the emergence of technology, where empirical evidence is still evolving. Consequently, the findings should be interpreted with caution, as the current evidence base provides an initial understanding rather than broadly generalizable conclusions. Second, existing economic assessment studies exhibit considerable heterogeneity in cost methods, assumptions, tractor configurations, and policy contexts, which limits comparability and hampers consistent conclusions regarding BET cost competitiveness. Third, given the early stage of BET development, most available evidence relies on simulations, prototypes, or small-scale pilot projects rather than widespread commercial deployment. As a result, extrapolating cost or adoption outcomes to broader farming contexts remains challenging. Fourth, the reviewed farmer surveys vary substantially in sample size, sampling strategies, and degrees of representativeness, reflecting differences in research objectives and the early stage of BET diffusion. While several studies justified their designs based on specific objectives and contexts appropriate for their analytical aims, most surveys do not claim full statistical representativeness of national farming populations. Adoption-related findings should therefore be interpreted as context-specific insights from early-aware, specialized, or high-potential farmer groups rather as population-wide estimates.

This review has several limitations related to the review process. First, the search was restricted to English-language publications and a defined set of databases, which may have resulted in the omission of relevant studies. Second, quality appraisal involved interpretative judgments, particularly when applying common criteria across different study designs. Finally, due to heterogeneity in study designs, outcome measures, and analytical assumptions, a formal statistical meta-analysis was not appropriate. Instead, findings were synthesized using structured comparative and semi-quantitative approaches, including harmonized CAPEX comparisons, TCO analysis, and a qualitative weighted-sum aggregation of adoption factors.

Building on the identified limitations, several avenues for future research emerge. First, there is a clear need for more empirical studies examining the economic feasibility and adoption of BETs across diverse farming systems and regions. As technology matures, longitudinal studies capturing real-world operational data from commercially deployed BETs will provide more robust and generalizable insights into cost structures, performance, and adoption patterns. Second, advances in battery technology merit closer examination regarding their potential to alleviate key technical constraints affecting BET feasibility, notably limitations in energy density and charging duration. Emerging solutions, including higher-energy-density batteries, fast-charging systems, and battery swapping concepts, may influence future cost structures and operational suitability and therefore warrant dedicated technical investigation. Third, future economic assessments should prioritize comprehensive TCO analyses across different countries, tractor power classes, farm structures, and operational contexts. Developing standardized TCO reporting metrics specifically tailored to agricultural machinery and extending beyond generic EV TCO models would substantially improve the comparability of empirical and modelling studies and yield stronger evidence on BET cost competitiveness relative to conventional tractors. Harmonized assumptions regarding key techno-economic and operational parameters are particularly important to address the heterogeneity identified in existing literature. Fourth, future research would benefit from larger, probability-based farmer surveys and harmonized sampling approaches as BET commercialization progresses. Finally, integrating economic, behavioral, and sustainability perspectives will be essential to capture context-dependent adoption drivers and better understand the conditions under which BETs can become both economically viable and widely adopted.

CRediT authorship contribution statement

Olga Kozak: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Petyo Bonev:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 4.0 in order to improve the readability of the text. After using ChatGPT 4.0, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2026.127913.

Data availability

No data was used for the research described in the article.

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