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Just Transition and Low-Carbon Agriculture: Lessons from Brazilian Pig Farming for the COP30 Climate Agenda

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Abstract
This study assesses how economic instruments arranged as a coherent policy mix can accelerate the decarbonization of Brazil's swine sector within a just transition framework. A systematic review (2015–2025) from Web of Science identified 26 studies covering sectoral greenhouse gases (CH_4/N_2O), mitigation options (anaerobic digesters, manure management, precision nutrition), and instrument design (carbon taxation and emissions trading - ETS; payments for environmental services - PES; green rural credit; standards/certification; and extension services). The evidence indicates that stand-alone policies tend to deliver limited and uneven outcomes. By contrast, integrated mixes that combine price signals with revenue recycling, targeted PES, concessional finance, and technical assistance are associated with faster technology adoption, lower abatement costs, and broader smallholder inclusion. Based on these findings, a governance-ready architecture is delineated that couples: (i) federal pricing and regulatory frameworks with earmarked revenues for credit and technical assistance; (ii) state-level financial instruments and PES supported by proportionate monitoring, reporting, and verification (MRV); and (iii) territorial cooperative arrangements enabling producer aggregation, certification, and market access. Positioned in the run-up to COP30 (Belém), the analysis specifies key trade-offs and feasibility conditions, including MRV indicators, distributive safeguards, and pooling mechanisms. The synthesis suggests that a combination of carbon tax, ETS, PES, green credit, and extension offers a balanced pathway that aligns efficiency, equity, and environmental integrity in the swine value chain.

Keywords: Swine sector; COP30; Carbon pricing; Emissions trading (ETS); Payments for environmental services (PES).

Resumo
Este estudo avalia como instrumentos econômicos, dispostos como um mix coerente de políticas, podem acelerar a descarbonização do setor suinícola brasileiro no marco de uma transição justa. Realizou-se uma revisão sistemática (2015–2025) na *Web of Science*, que

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identificou 26 estudos abrangendo: gases de efeito estufa setoriais (CH_4/N_2O), opções de mitigação (biodigestores anaeróbios, manejo de dejetos, nutrição de precisão) e desenho de instrumentos (tributação de carbono e comércio de emissões – ETS**,** pagamentos por serviços ambientais – PSA, crédito rural verde**,** normas/certificação e assistência técnica e extensão). As evidências indicam que políticas isoladas tendem a produzir resultados limitados e desiguais. Em contraste, arranjos integrados que combinam sinais de preço com reciclagem de receitas, PSA focalizados**,** financiamento concessionário e assistência técnica estão associados a adoção tecnológica mais rápida**,** menores custos de abatimento e maior inclusão de pequenos produtores. Com base nesses achados, delineia-se uma arquitetura pronta para governança que articula: (i) marcos federais de precificação e regulação, com receitas vinculadas a crédito **e** assistência técnica; (ii) instrumentos financeiros e PSA em nível estadual, apoiados por MRV proporcional (monitoramento, reporte e verificação); e (iii) arranjos cooperativos territoriais que possibilitam agregação de produtores**,** certificação e acesso a mercados. Situada no contexto preparatório da COP30 (Belém), a análise explicita trade-offs e condições de viabilidade, incluindo indicadores de MRV, salvaguardas distributivas e mecanismos de pooling. A síntese sugere que a combinação de imposto sobre carbono, ETS, PSA, crédito verde e extensão rural oferece uma trajetória equilibrada, que alinha eficiência**,** equidade e integridade ambiental na cadeia de valor suinícola.

Palavras-chave: Setor suíno; COP30; Precificação de carbono; Comércio de emissões (CSE); Pagamentos por serviços ambientais (PSA).

1 Introduction

The intensification of climate impacts in recent decades has placed Brazil facing a structural dilemma: how to sustain agricultural expansion while simultaneously reducing greenhouse gas (GHG) emissions resulting from this production model. Extreme climate events, such as prolonged droughts, floods, and record-breaking heat events, directly affect food security, the energy matrix, and the ecological balance of sensitive biomes such as the Amazon (Mariani et al., 2016; Giatti et al., 2016). Amid this scenario, the COP30 summit in Belém in 2025 puts the Amazon back at the center of the global climate debate, demanding concrete responses to mitigate emissions and build low-carbon rural economies.

Among Brazil's productive sectors, pig farming is doubly important: it is a central component of food security and the trade balance, but it is also a significant source of methane (CH_4) and nitrous oxide (N_2O) emissions, resulting from inadequate waste management and intensive use of inputs (Oliveira et al., 2022; Ferreira et al., 2023). Although the sector is not among the largest emitters in Brazilian agriculture, its

emissions intensity per unit of product is high, making it a strategic field for the development of mitigation policies, technological innovation, and environmental justice.

The urgency of this debate is reinforced by Brazil's commitment to the Paris Agreement and the revision of its Nationally Determined Contribution (NDC), which sets emissions reduction targets of 48% by 2025 and 53% by 2030 (BRAZIL, 2023; UNFCCC, 2023). Meeting these targets depends, to a large extent, on the ability to incorporate agriculture, especially intensive systems, into a just transition model capable of combining economic efficiency, social inclusion, and environmental integrity.

In this context, economic instruments of environmental regulation emerge as decisive tools for the transition. Carbon pricing, emissions trading systems (ETS), and payments for environmental services (PES) constitute mechanisms that seek to internalize the social cost of emissions and encourage sustainable production practices (Nordhaus, 2018; Blanchard; Gollier; Tirole, 2023). However, their application in the Brazilian agricultural sector is still incipient, marked by structural inequalities, low institutional capacity, and limited access to climate finance.

At the same time, international experience offers relevant evidence. Sweden, a pioneer in adopting a carbon tax since 1991, has demonstrated that the combination of market instruments and redistributive policies can reduce emissions without compromising economic growth (Jonsson; Ydstedt; Asen, 2020). In Canada and the European Union, hybrid policies that combine ETS and green subsidies have proven effective in inducing technological innovation and protecting small producers (Parry et al., 2022; Blanchard et al., 2023). These experiences suggest paths for the Brazilian case, where the implementation of pricing mechanisms needs to be compatible with the principle of equity and the socioeconomic specificities of rural areas.

The central hypothesis of this article is that the decarbonization of the Brazilian pig industry will not be achieved solely through isolated technological innovations, but from an integrated policy arrangement that combines economic instruments (carbon pricing, including ETS), payments for environmental services (PES)**,** incentive policies, and robust regulatory frameworks, supported by public investments directed toward clean technologies. Viewed through a just transition lens, this arrangement must redistribute costs and benefits and ensure effective access to finance and markets for smallholders, positioning the sector as a benchmark in agri-environmental policy. The combination of

carbon pricing, payments for environmental services, and public investments geared towards clean technologies can make the sector an example of a just transition agri-environmental policy.

Thus, this study seeks to analyze how economic instruments can contribute to the decarbonization of pig farming and, more broadly, to the development of a low-carbon agriculture sector. It begins with a systematic literature review, focusing on national and international publications addressing the relationship between pig farming, GHG emissions, and environmental regulation. The analysis is structured around three axes: (i) theoretical foundations of environmental economics and market instruments; (ii) empirical evidence on mitigation and technological innovation in pig farming; and (iii) assessment of the possibilities and limitations of implementing these mechanisms in the Brazilian context.

Thus, the research aims to contribute conceptual and empirical support to the COP30 debate, highlighting the role of family farming, environmental governance, and climate finance in the transition to more sustainable, inclusive, and resilient production systems.

2 Theoretical framework and international context

Since the 1990s, policymaking aimed at mitigating climate change has been supported by the conceptual framework of environmental economics. The neoclassical perspective, represented by authors such as Pigou (1920) and Baumol and Oates (1988), argues that market failures resulting from negative externalities, such as greenhouse gas (GHG) emissions, should be corrected by internalizing environmental costs. This logic underpins the use of economic instruments, such as taxes, subsidies, and emissions trading systems, capable of aligning private interests with collective well-being (Motta; Mendes, 2001; Nusdeo, 2006).

At the beginning of the 21st century, this approach was consolidated by the theory of the social cost of carbon, developed by William Nordhaus (2018), which proposes a pricing model based on the marginal cost of emissions on global economic well-being. The so-called DICE (Dynamic Integrated Climate-Economy) demonstrated that the absence of prices that reflect environmental impact leads to the overproduction of carbon-intensive goods and, consequently, climate degradation. Nordhaus ' logic underpins the

current carbon pricing policies adopted by more than 70 countries, according to the *World Bank (2023)*.

Nicholas Stern (2007) argues, the climate problem is not limited to a market failure, but constitutes the "greatest market failure in history." The author advocates coordinated government action to create long-term economic incentives, combining regulation, technological innovation, and cost redistribution. This view broadens the focus of classical environmental economics, incorporating ethical and social dimensions of mitigation, which will be revisited later in the concept of just transition.

Additionally, the Dasgupta Report (2021) introduces the notion of natural capital as an essential component of economic accounting and environmental governance. For the author, production systems should not treat nature as an infinite input, but as an asset that underpins the economy. This approach, adopted by organizations such as the Organization for Economic Cooperation and Development (OECD) and the World Bank, guides public policies that integrate biodiversity, climate mitigation, and productive inclusion, especially in diverse countries like Brazil.

In the field of Latin American ecological economics, Lustosa, Cánepa, and Young (2003) and Motta and Mendes (2001) emphasize that internalizing environmental externalities through economic instruments is a prerequisite for reconciling growth and sustainability. Furthermore, the authors argue that the effectiveness of these instruments depends on institutional capacity and distributive justice in the allocation of resources. Thus, environmental policies cannot be socially neutral: they must recognize the structural inequalities that permeate the Brazilian countryside.

The just transition is based on the recognition that decarbonization, if not accompanied by social protection and economic inclusion policies, tends to reproduce inequalities. This perspective is particularly relevant to Brazilian agriculture, where family systems and small farms are predominant, vulnerable to market fluctuations and regulatory restrictions.

The effectiveness of the policy arrangement depends on multilevel governance that links economic instruments to public policies (Hooghe; Marks, 2003). At the federal level, carbon pricing, including emissions trading systems (ETS) and regulatory standards should signal prices and earmark revenues for green rural credit and technical assistance (Howlett; Rayner, 2007). At the state level, sectoral agencies and public banks

operationalize financing, guarantees, and payments for environmental services (PES)**.** At the municipal level, cooperatives and inter-municipal consortia pool smallholders to reduce transaction costs**,** standardize practices (biodigesters, manure management, precision nutrition), and certify emissions reductions for market access (Ostrom, 2009). Taken together, this arrangement aligns prices, finance, and regulation, converting price signals into technology adoption, productive inclusion, and measurable emissions reductions**.**

International governance perspective, COP30, being hosted in Belém, assumes a symbolic and strategic role. Located in the Amazon, a region that accounts for approximately 45% of Brazil's emissions related to land-use change (MMA, 2023), the conference emphasizes the need for solutions that integrate agricultural production, forest conservation, and climate finance. The convergence of the green economy, agriculture, and climate requires instruments capable of articulating productive efficiency, social inclusion, and environmental preservation, a central axis of the debate leading up to COP30.

Finally, recent literature proposes the formation of policy mixes, which are combinations of economic instruments and public policies, as the most effective strategies to address the complexity of the climate challenge (Cocker, 2025; Blanchard; Gollier; Tirole, 2023). Such arrangements combine carbon pricing, tax incentives, and innovation subsidies, articulating market mechanisms with state regulation. As Kotz et al. (2024) note, the climate transition depends on a new macroeconomic pact that mobilizes public investment, green credit, and sustainable industrial policies.

Thus, the contemporary debate on economic instruments goes beyond the scope of environmental efficiency: it is part of a new development paradigm, in which mitigation, equity and governance become inseparable dimensions of the climate economy.

3 Methodology

This research adopts a qualitative, exploratory approach, based on a review of national and international literature. The main objective was to identify gaps in the research field on the interface between climate change and pig farming, especially regarding decarbonization and economic instruments of environmental regulation.

According to Linde and Willich (2003), a systematic review is a methodology capable of gathering scientific evidence based on the existing literature, allowing the identification of both convergences and controversies in the studies analyzed, in addition to providing theoretical support for future research. Galvão and Ricarte (2019) emphasize that this type of approach requires methodological rigor in defining the databases consulted, search strategies, and inclusion and exclusion criteria for publications.

The article collection and selection stage was conducted in the *Web of Science database,* using descriptors related to the study's central themes: "climate change and swine production," "climate effects on piglet production," "impacts of climate change on Brazil," and "gas emissions and swine production." To refine the results, the Boolean operators AND and OR were used, as well as quotation marks to locate exact expressions in the bibliographic searches. The timeframe criteria included publications published between 2015 and 2025, in English and Portuguese, as shown in Table 1.

Table 01: Research descriptors.

((“Pig production” OR “Swine production”) AND (“Climate Change”) AND (“Pig production”) OR (“Greenhouse gas emissions” OR “Climate effects on food production”) OR (“Piglet production) AND “(Brazil)”.

From the studies located through the search strategy applied to the *Web of Science database,* 26 articles were selected to compose the corpus of this systematic literature review. The results obtained from this methodological procedure are summarized in the following section. Presented below, Table 2 catalogs the identified studies, their respective instrument types, and the expected observations.

Table 2: Policy mix for Brazilian swine sector

Study (year)	Instrument	Mitigation lever	Notes
Angonese et al. (2007)	Carbon credits/PES	Anaerobic digester (CH_4)	Payback with incentives
Esperancini et al. (2007)	Energy incentive	Biogas replacing LPG/electricity	Dependent on tariffs and logistics

Martins & Oliveira (2011)	Implicit tariff/feed-in	Biogas-based power generation	Scale and maintenance are critical
Avaci et al. (2013)	Microgeneration/net metering	Biogas	Grid conditions matter
Cherubini et al. (2015)	(standards/labeling)	LCA of pork products	Market signal
Andretta et al. (2018)	(standards)	Precision nutrition	Diet reformulation
Monteiro et al. (2017a)	—	Feeding programs	Sensitive to ingredient composition
Monteiro et al. (2017b)	—	Ingredient variation	Cost/footprint trade-offs
Ribeiro et al. (2018)	Tax/regulatory	Production structure	Input-intensive sectors
Cerri et al. (2010)	Portfolio	Land use/livestock	Integrates LULUCF
FAO (2019)	Standards/good practices	Husbandry/feeding	Technical guidance
Pietramale et al. (2021)	—	Management practices	Heterogeneity
Christofoletti & Pereda (2021)	Carbon tax	Distribution/regressivity	Requires compensations
Alvim & Sanguinet (2021)	Carbon tax	Meat/dairy	Recommends hybrid approaches
Parry et al. (2022)	Tax vs. ETS	Instrument design	Design guidance
Oliveira et al. (2022)	—	Challenges and opportunities	Brazil focus
Barioni et al. (2022)	Portfolio	Climate-smart livestock	Policy integration
Ferreira et al. (2023)	Instrument review	Multiple levers	Brazilian swine sector
Santos & Castro (2021)	PES for waste	Management/recycling	Local design
World Bank (2023)	Pricing (global map)	—	Price trends

Schmalensee & Stavins (2017)	ETS	Cap-and-trade	MRV/markets
Jonsson et al. (2020)	Carbon tax + compensation	General economy	30-year stability
Dasgupta (2021)	Green accounting	Natural capital	Basis for PES
Stern (2007)	Policy/innovation	—	Long-term policy pact
Blanchard, Gollier & Tirole (2023)	Policy mix	—	Combination of instruments
Cocker (2025)	Policy mix	—	Transferable to agriculture

Source: Author's elaboration

4 Results and discussion

This section aims to present an analytical synthesis of the main findings of the selected articles. Initially, the authors are identified and the contributions of each study in relation to the different environmental policy instruments are systematized. Next, a theoretical discussion is developed in line with the hypothesis outlined in the introduction to this essay.

4.1 Carbon pricing and hybrid instruments

Over the past two decades, carbon pricing has established itself as one of the most discussed instruments in international climate governance. Based on environmental economics theory, it seeks to internalize the social costs of greenhouse gas (GHG) emissions, correcting market failures associated with environmental degradation (Nordhaus, 2018; Motta; Mendes, 2001).

According to the World Bank (2023), more than 70 jurisdictions have already implemented carbon taxes or emissions trading systems (ETS), covering about 25% of global emissions. These experiences reveal that the effectiveness of the instrument depends not only on the carbon price but also on its institutional design and complementary policies.

In the literature analyzed, it is observed that carbon taxes offer simplicity and price predictability, being suitable for sectors with less capacity for immediate innovation, for example, small pig farms (Parry; Black; Zhunussova, 2022). Emissions trading systems (ETS) offer greater regulatory flexibility, allowing economic agents to negotiate quotas and reduce emissions more efficiently (Schmalensee; Stavins, 2017).

The Swedish experience, studied by Jonsson, Ydstedt, and Asen (2020), shows that the adoption of a carbon tax can coexist with economic stability and growth, as long as it is combined with social compensation mechanisms and reinvestment in innovation. On the other hand, Christofoletti and Pereda (2021) warn that, in Brazil, a uniform tax can generate regressive effects, penalizing small producers and widening regional inequalities.

In this sense, Blanchard, Gollier, and Tirole (2023) and Cocker (2025) advocate the use of policy mixes, where combinations of economic instruments and public policies are more robust alternatives. This hybrid approach integrates carbon pricing, green subsidies, payments for environmental services (PES), and public investments directed at innovation, allowing a balance between economic efficiency, social justice, and political viability.

In the Brazilian case, Alvim and Sanguinet (2021) highlight that hybrid policies can reduce negative sectoral impacts and facilitate the climate transition in agribusiness, especially when associated with green rural credit mechanisms and technical-financial support programs.

4.2 Innovations and mitigation in pig farming

The reviewed studies indicate that pig farming plays a relevant role in the mitigation agenda, both due to its direct emissions and the potential for efficiency gains. The main sources of GHG in the sector are methane (CH_4), from the anaerobic decomposition of manure, and nitrous oxide (N_2O), related to fertilization and waste management (FAO, 2019; Ferreira et al., 2023).

Mitigation strategies focus on three fronts: manure management, precision nutrition, and the use of sustainable technologies. In management, the use of biodigesters stands out as a high-potential alternative. Research by Franco Martins and Oliveira (2011) and Avaci et al. (2013), and Anis et al. (2020) demonstrates that anaerobic digestion

significantly reduces methane emissions and generates economic benefits through the production of biogas and biofertilizers. Even on a small scale, the financial return is viable when associated with incentive policies and carbon credits (Esperancini et al., 2007; Angonese et al., 2007).

In the nutritional field, Andretta et al. (2018) and Monteiro et al. (2017a, 2017b) show that optimized diets with lower crude protein content reduce nitrogen excretion, decreasing N_2O emissions. Furthermore, the replacement of conventional ingredients with agro-industrial co-products, as proposed by Vastolo; Calabró; Cutrignelli (2022) and Kebreab et al. (2016), demonstrates simultaneous sustainability gains and cost reduction.

These technological advances, however, cannot be sustained in isolation. Cerri et al. (2010) and Ribeiro et al. (2018) emphasize that the success of mitigation practices depends on structural public policies that ensure financing, technical assistance, and recognition of positive environmental practices. In this sense, payment for environmental services (PES) appears as a strategic instrument, as it recognizes and rewards positive externalities, such as methane capture or the restoration of degraded areas (Oliveira; Souza, 2016; Santos; Castro, 2021).

In general, studies indicate that the integration of technological innovation and economic instruments **is** key to decarbonizing pig farming. The adoption of biodigesters, for example, becomes much more viable when combined with tax incentives, green credit lines, and the trading of carbon credits, as proposed by Sofitri (2025).

4.3 Policy mixes and just transition

The transition to low-carbon agriculture requires a coordinated set of public policies, economic instruments, and governance mechanisms that combine environmental efficiency, social equity, and economic viability. This logic guides the concept of policy mixes, which proposes the integration of different instruments, whether fiscal, regulatory, or financial, into arrangements capable of promoting synergies between climate mitigation, technological innovation, and sustainable rural development (Blanchard; Gollier; Tirole, 2023; Cocker, 2025).

In the Brazilian case, this perspective is especially relevant due to the structural heterogeneity of agriculture, marked by the coexistence of large agro-export enterprises and small family farms with limited investment capacity. The isolated implementation of

carbon taxes or emissions markets tends to deepen inequalities and weaken producers with less room for adaptation (Christofoletti; Pereda, 2021). Therefore, it is essential to combine economic mitigation instruments with compensatory policies and just transition mechanisms that recognize regional and productive asymmetries.

As argued by Dasgupta (2021) and Kotz et al. (2024), long-term economic sustainability depends on incorporating natural capital as a central element of government accounting and planning. Carbon pricing and payments for environmental services (PES) should be conceived not only as fiscal instruments but as components of a green development strategy, in which the government acts as a driver of innovation and a regulator of climate inequalities.

In this sense, the just transition, a concept formulated by the International Labor Organization (ILO, 2019) and jointly integrated into the UNFCCC negotiations of the United Nations, contributes to a more strategic approach. It recognizes that mitigation policies can generate unequal impacts across regions, sectors, and social groups, and proposes the creation of safety nets and productive reconversion, ensuring that the costs of decarbonization do not fall disproportionately on workers and small producers. In the context of pig farming, this means combining economic incentives for the adoption of clean technologies (such as biodigesters and composting) with green credit lines, technical assistance, and simplified access to carbon markets.

Furthermore, it is necessary to strengthen institutional arrangements for multi-scalar climate governance, integrating federal, state, and municipal actions and expanding the participation of universities, civil society organizations, and agricultural cooperatives. COP30, taking place in Belém, in the heart of the Amazon, represents a unique opportunity for Brazil to demonstrate leadership in building low-carbon agricultural models with social inclusion.

From this perspective, lessons from the literature and international experiences indicate that the decarbonization of pig farming can serve as a laboratory for climate innovation, combining pricing instruments, PSA, and technological incentives under a single governance framework. This combination is the basis of a new agro-environmental paradigm, in which animal production ceases to be seen as an obstacle and becomes an integral part of the solution for Brazil's climate neutrality.

In short, the success of the low-carbon agricultural transition will depend on the ability of the State and society to structure coherent policy mixes that align fiscal, environmental, and social policies. Only through this integration will it be possible to reconcile economic competitiveness, food security, and climate justice, which are central objectives of the global debate that will culminate at COP30.

Table 3 synthesizes the relationship between policy instruments and their economic, social, and environmental impacts, as well as the governance enablers required for implementation. The systematization draws on the review corpus (2015–2025) and principles of policy mixes, making it possible to visualize coherences, trade-offs, and feasibility conditions for a just transition in the swine sector.

Table 3: Policy Instruments, Expected Impacts, and Governance Enablers

Instrument	Economic impacts	Environmental impacts	Governance enablers
Carbon tax (tiered)	Predictable signal; revenue for credit/TA	CH_4/N_2O via induced adoption	Federal law; revenue earmarking; simple MRV
ETS (sectoral window)	Least-cost abatement via trading	Certified reductions; linkage potential	Registry; aggregator for small farms
PES (methane capture, soil)	New income stream; de-risking	biodigester/composting uptake	State/municipal PSA laws; verification
Green rural credit	Low-cost finance; capex coverage	Tech diffusion; co-benefits on waste	Public banks; TA; guarantees
Standards/certification	Market access; price premiums	MRV discipline; spillovers	Multi-stakeholder schemes

Source: Author elaboration

5 Considerations

The decarbonization of Brazilian pig farming poses a structural challenge that transcends the technological field and imposes the need to reconfigure environmental governance, public policies, and the role of the State in fostering sustainability. Although the sector has a significant set of technical solutions, such as biodigesters, composting,

precision nutrition, and energy recovery, their large-scale adoption is still limited by financial barriers, regulatory discontinuity, and institutional fragility.

The results obtained in this research indicate that the integration of economic instruments and redistributive policies constitutes the most promising path for the transition towards low-carbon agriculture. The combination of carbon pricing and emissions trading systems (ETS) and Payments for environmental services (PES) has the potential to create a virtuous cycle of mitigation, innovation, and productive inclusion. Such instruments, when combined with stable regulatory frameworks and just transition mechanisms, can align economic efficiency, environmental protection, and social justice, dimensions that, in isolation, tend to weaken.

In this scenario, the Brazilian State assumes a central role in coordinating and institutionalizing climate policy. It is responsible for structuring a regulatory framework that (i) establishes gradual and sectoral emissions reduction targets, adjusted to the mitigation capacity of each agricultural sector; (ii) expands access to green credit and climate funds for small and medium-sized producers; (iii) creates reliable emissions monitoring and certification mechanisms compatible with the requirements of the international carbon market; (iv) recognizes and rewards sustainable agro-environmental practices through PES specifically for rural areas; (v) and strengthens public technical assistance and rural extension systems, which are essential for the dissemination of innovations and the strengthening of family farming.

The effectiveness of these instruments, however, depends on the consolidation of multi-scalar and participatory governance**,** capable of integrating the federal, state, and municipal levels, as well as incorporating universities, research institutes, social movements, and cooperative organizations. This institutional architecture is essential to ensure the continuity and legitimacy of climate policies and prevent the green transition from reproducing historical inequalities in the countryside.

Table 4 offers a concise comparison of the principal economic instruments for decarbonizing the swine sector: carbon tax**,** ETS, and PES, linking their sectoral applications to the advantages and limitations identified in the literature. The synthesis supports the design of policy mixes, clarifying where each instrument is likely to be most effective and specifying the governance and measurement (MRV) conditions needed for credible implementation.

Table 4: Economic Instruments for Decarbonizing the Swine Sector: Applications, Advantages, and Limitations

Economic instrument	Application to swine production	Potential advantages	Potential disadvantages
Carbon tax	Levy on estimated CH_4 and N_2O emissions per ton of pork produced.	Price predictability and revenue generation.	Potentially regressive; requires reliable emissions estimates; risk of disproportionate burden on smallholders.
ETS (Emissions Trading System)	Emission caps for farms with the possibility of trading allowances.	Flexibility and incentives for innovation.	High implementation complexity; requires more stringent monitoring.
PES (Payments for Environmental Services)	Remuneration for adopting biodigesters, reforestation, and other sustainable practices.	Accessible to smallholders; recognizes positive externalities; supports productive inclusion.	Depends on public budgets and governance capacity; measurement criteria may still be fragile.

Source: Author elaboration based on Cerri et al. (2010), Ribeiro et al. (2018), Alvim & Sanguinet (2021), and Sofitri (2025).

From this perspective, the just transition acquires strategic relevance because it reinforces that climate mitigation cannot come at the expense of social exclusion or income concentration, but must incorporate instruments for compensation, professional training, and productive diversification. In the context of pig farming, this means making low-carbon practices economically viable and ensuring conditions for small producers to participate in the green economy without compromising their livelihoods.

The COP30, being hosted in Belém, has a unique political and symbolic character. Located in the heart of the Amazon, the conference projects onto Brazil the expectation of leadership in tackling climate change and building sustainable production models. In this context, pig farming can serve as a laboratory for mitigation policies, demonstrating that it is possible to reconcile productivity, energy efficiency, and environmental responsibility.

It is therefore concluded that the decarbonization of pig farming and, by extension, of national agriculture, depends on the articulation between effective economic

instruments and inclusive public policies. and lasting institutional mechanisms. This integration will enable the transformation of emissions mitigation into a driver of sustainable development and technological innovation, proactively inserting Brazil into global low-carbon chains.

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