

Review

Policy Instruments for Bioenergy Development: Review, Classification, and Systematic Analysis

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Abstract

Bioenergy is a cornerstone of the global energy transition and is vital to achieving ambitious climate goals such as the IEA's Net Zero Emissions by 2050 Roadmap and the Paris Agreement. However, its deployment is still limited by high capital costs and low cost-competitiveness. Numerous studies have examined policy measures to support bioenergy development, but a comprehensive review of these policies is needed to identify effective strategies. This study presents a systematic literature review that classifies and analyzes supportive policy instruments for bioenergy promotion, filling a key gap in earlier reviews. In doing so, we present a classification framework of the supporting policies and investigate their co-occurrence, modeling methodologies, and supply chain impacts across 156 peer-reviewed articles (2015–2025). The analysis reveals that price-based instruments are the most prevalent policy mechanisms, often combined with market-based approaches creating integrated support schemes. The review and its findings could provide a benchmark for policymakers and researchers seeking to design targeted, fiscally sustainable, and effective interventions to accelerate bioenergy transition.

Keywords: energy transition; bioenergy; biomass; supportive policies; policy instruments; policy modeling; literature review

1. Introduction

A growing global energy demand has accelerated the exhaustion of fossil fuel reserves, triggering serious concerns not only for the long-term impacts on the environment but also for the sustainable energy provision of the future [1,2]. The adoption of renewable energy sources is widely regarded as an effective strategy for addressing environmental concerns and securing a sustainable energy supply for the future [3], a trend that is reflected in the steady increase in the global share of renewable energy in primary energy consumption over the past decade (Figure 1) [4]. This upward trajectory is expected to continue, with renewable energy consumption in the power, heat, and transport sectors projected to increase by nearly 60% between 2024 and 2030 under the main-case forecast [5].

Biomass, a prevalent form of renewable energy, is defined as organic material derived from living organisms. Its diverse sources include plant and animal matter, forest wood, agricultural residues, seaweed, by-products from farming and forestry, and organic waste from industrial, human, and animal activities [6]. The main biochemical constituents of biomass (cellulose, hemicellulose, and lignin) determine its energy potential and suitability



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for thermochemical and biochemical conversion processes [7]. Biomass exhibits several characteristics that enhance its utility as a renewable energy source. Notably, it functions as a reliable energy reservoir due to its capacity for long-term storage with minimal degradation. For example, wood pellets can be stored for up to six months when maintained in environments with humidity below 10% [8]. Biomass is also capable of supporting a base load energy supply, similar to fossil fuels, which makes it suitable for meeting continuous electricity demand [9]. The energy obtained from biomass is termed bioenergy, and it currently represents the largest global source of renewable energy, accounting for approximately 12% of global final energy consumption [10]. Modern bioenergy, meaning the conversion of biomass into heat, electricity, or fuels using advanced technologies [11] (hereafter ‘bioenergy’), alone accounts for nearly 55% of total renewable energy consumption, playing a critical role in global energy transition strategies [12]. Within the International Energy Agency’s (IEA) Net Zero Emissions by 2050 roadmap, bioenergy is projected to contribute between 15% and 20% of the total energy supply by 2050. Achieving this would necessitate a threefold increase in the implementation of bioenergy technologies compared to current levels [13]. Given the advantageous characteristics of biomass and its central role in the IEA’s Net Zero Emissions by 2050 roadmap, bioenergy is anticipated to play a pivotal role in the global renewable energy transition toward more sustainable energy systems.

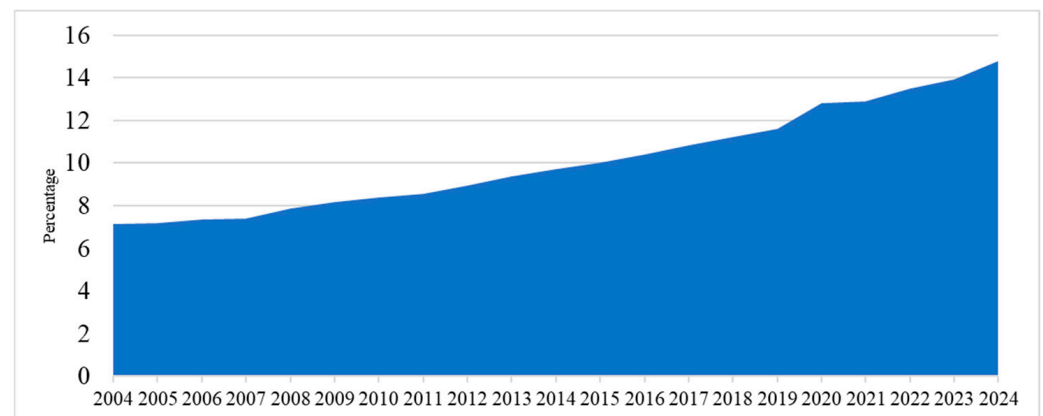


Figure 1. Global share of renewable energy in primary energy consumption (2014–2024).

In addition to the factors previously outlined, the global technological push for a renewable energy transition is reinforcing bioenergy’s growth. The Paris Agreement, established during the 21st Conference of the Parties (COP21) in 2015, is a pivotal global accord aimed at tackling climate change. Its core objective is to limit the rise in global average temperature by significantly reducing greenhouse gas (GHG) emissions [14]. A key component of this agreement requires signatory nations to submit Nationally Determined Contributions (NDCs), outlining their specific climate goals and policy measures [15]. Crucially, this global push has significantly accelerated the renewable energy transition. A generalized method of moments (GMM) estimation using panel data from 2000–2022 provides empirical evidence of the Paris Agreement’s positive influence on renewable energy deployment in both developed and developing countries [16]. This suggests that countries are increasingly promoting renewable energy sources to align with institutional expectations and uphold their international reputations [16].

Despite robust policy commitments, such as the IEA’s Net Zero by 2050 roadmap and the Paris Agreement, bioenergy deployment continues to face substantial challenges. Key challenges include high upfront capital requirements and limited cost competitiveness, which hinder its broader adoption in national and international energy strategies [17]. Developing essential infrastructure, like processing facilities and distribution networks,

requires significant investment. This is often unfeasible without strong public funding or appealing financial incentives [18]. Also, the emerging state of the bioenergy markets in many regions poses a significant challenge, characterized by uncertain demand and a lack of long-term price stability. The entrenched economic advantage of fossil fuel infrastructure presents a substantial barrier to implementing policy measures aimed at creating a more equitable competitive environment for renewable energy sources [19]. Consequently, although bioenergy holds significant potential, its large-scale adoption remains hindered by persistent challenges.

It is worth mentioning that, on one hand, ambitious global commitments to the renewable energy transition are calling for strong policy support, while, on the other hand, challenges in bioenergy adoption underscore the need for targeted and effective interventions. Indeed, the development and ongoing expansion of any renewable energy sector heavily rely on the support mechanisms established within the framework of its energy policies [20]. To address the challenges in bioenergy adoption and accelerate its integration, governments at national, state, and local levels have introduced supportive policies. These initiatives primarily aim to improve the economic attractiveness of bioenergy [21]. The Renewable Energy Directive (RED-I) defines supportive policies as any instrument or mechanism employed by Member States to encourage renewable energy use. This promotion occurs by either decreasing energy costs, raising its selling price, or increasing the volume purchased, potentially through renewable energy obligations [22].

Given the critical role of the supportive policies, it is essential to understand their functioning, implementation, and overall effectiveness. Numerous studies have analyzed various support mechanisms for bioenergy. Therefore, a comprehensive review of this body of literature is vital. Analyzing and categorizing the existing papers is crucial to synthesize current knowledge and the concentrated policy–research focus within the sector and pinpoint gaps in research. Such an analysis provides a foundational understanding of what has worked, thereby informing future policy recommendations and guiding more effective bioenergy development.

Reviewing the literature reveals that a large number of review papers have investigated and reviewed bioenergy policies and frameworks. However, many of the existing studies have primarily focused on the policies or frameworks of a specific country or a group of countries, rather than systematically analyzing scientific papers that explicitly treat supportive policies as a research subject. For example, ref. [23] investigated India's National Biofuel Policy, focusing on its role in regulating biofuel production and marketing. The study examined key policy instruments, such as the government's mandates for blending ethanol with gasoline and providing incentives for bio-based fuels. In a cross-country review, ref. [24] reviewed bioenergy policies in the EU, US, Japan, and China, focusing on China's waste biomass strategies. The study identified challenges in feedstock use, governance, and technology, proposing solutions like demo zones and carbon market integration. It concluded that effective policies, innovation, and institutional support are vital for sustainable biomass energy. Another cross-country review [25] examined biomethane policies in nine major markets, three in Europe (Germany, the United Kingdom, and Sweden) and six outside Europe (Brazil, Canada, China, Japan, South Korea, and the USA), to identify key regulatory instruments, policy gaps, and best practices for deployment. However, only a limited number of reviews have investigated papers that consider these supportive policies as their primary focus. For instance, ref. [26] provided a thorough analysis of bioenergy policies and regulations, primarily using the European Union as a benchmark, to examine their incorporation into bioenergy supply chain optimization models. In terms of policy analysis, the authors first categorize bioenergy support frameworks into four groups: direct incentives, fiscal measures, market-based, and indirect programs.

The study then investigates how these policy categories are represented in optimization literature, focusing exclusively on papers that employ optimization methodologies. In another review study [27], the authors examined research published over the last decade, focusing on the mapping of bioenergy sustainability and policies exclusively within Indonesia and Malaysia. A section of this study focused specifically on bioenergy policy, revealing that most policy-related papers concentrated on two key areas: sustainability and energy security. The former primarily addressed the environmental impacts of bioenergy development, while the latter highlighted bioenergy's role as a reliable and sustainable energy source for national development and economic well-being. It is worth noting that general environmental policy instruments primarily address the environmental impacts associated with bioenergy development such as land-use change, biodiversity protection, and carbon stock conservation.

A key acknowledged gap in the above-mentioned body of literature is a lack of focus on understanding the interplay among these diverse policies, particularly identifying the policies that are most frequently implemented in combination. More importantly, none have systematically classified and analyzed the existing body of literature that has employed these policies with a comparative analysis of their outcomes. The majority of existing reviews, such as the global bioenergy synthesis study [28] and the study on Ethiopia's bioenergy sector [29], often emphasize legislative and regulatory frameworks without systematically classifying broader policy instruments, applying modeling methods, or mapping policies across supply chain stages. Only a limited number of studies have examined broader supportive policies, and these investigations remain scarce and are often restricted by a narrow focus. For instance, they focus exclusively on a single bioenergy type [30], biomass type [31], research methodology investigation [26], or a particular country or group of countries [32]. Therefore, one objective of this study is to provide a systematic review of research that focuses on supportive measures, policies, and instruments designed to promote bioenergy.

This creates a critical gap in understanding how supportive policy instruments are operationalized across various modeling approaches, biomass types, and supply chain stages. The novelty of this research lies in its systematic review and categorization of the academic literature based on the specific economic and regulatory instruments used, the modeling techniques applied, the position within the supply chain targeted and the bioenergy type targeted for investigation. In doing so, this study not only consolidates scattered insights across disciplines but also creates an integrated framework for evaluating the methodological treatment of policy support in bioenergy development. As such, it addresses a foundational gap and provides a strategic resource for researchers, policymakers, and practitioners seeking to design more targeted and effective policy interventions. The paper is organized as follows. Section 2 outlines the research framework, including the literature review design, search strategy, and identification process. Section 3 presents the screening and selection of relevant studies, while Section 4 structures and interprets the findings through thematic analysis. Section 5 introduces the policy classification, followed by Section 6, which focuses on policy modeling. Section 7 examines supply chain perspectives, and finally, Section 8 concludes with key insights and policy implications.

2. Methodology

We adopt a Systematic Literature Review (SLR) approach to provide a transparent and unbiased synthesis of existing research [33]. The review follows four main steps: defining the research framework, systematically searching literature across databases, screening papers using predefined criteria, and extracting and synthesizing key insights. This process

allows identification of patterns, classification of policy instruments, and detection of research gaps in the bioenergy policy field.

2.1. Literature Review Framework

The first essential step in conducting a systematic literature review (Figure 2) is to clearly and meticulously define the scope and boundaries of the study. Accordingly, the study is guided by the following research questions:

1. Which policy instruments have been applied in bioenergy studies, which are most frequently used, and which combinations of policies are studied most often?
2. Which supply chain stages are targeted by these policies?
3. Which biomass and bioenergy types are most commonly addressed?
4. What gaps exist in the literature on policy impacts across supply chain stages and biomass types, and how can this guide better bioenergy policy design?

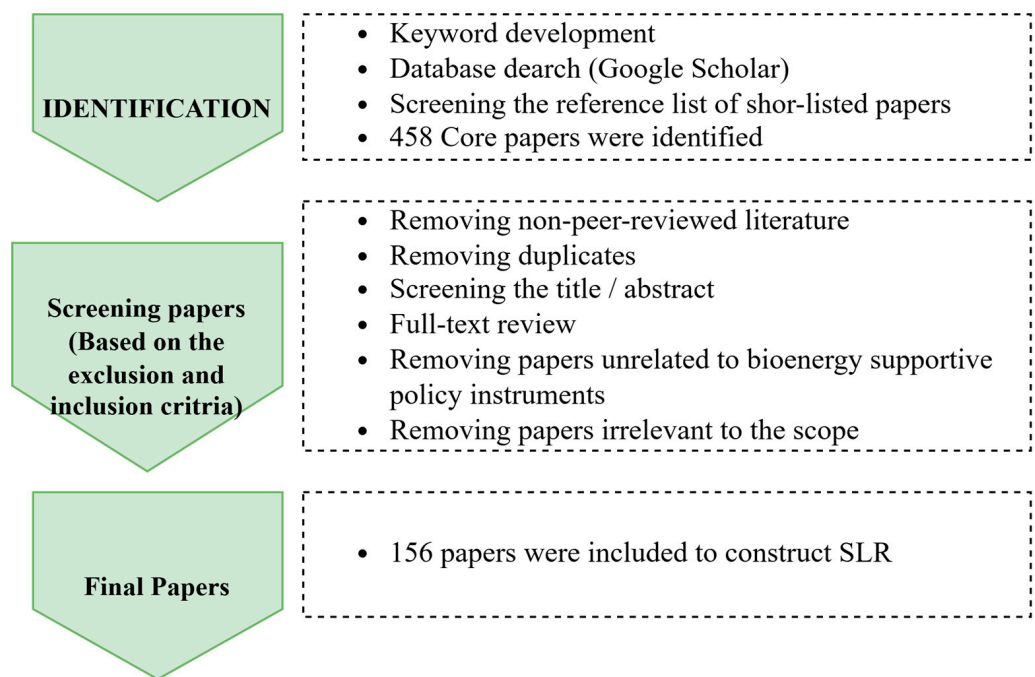


Figure 2. Review process of finding related papers (2014–2024).

2.2. Literature Search & Identification

To ensure high scholarly standards, only peer-reviewed journal articles published up to August 2025 were included. The peer-review process involves critical evaluation by independent experts, which strengthens the reliability and validity of findings and minimizes the risk of bias [34]. In line with the second step of the review process, an initial set of keywords was developed to guide a comprehensive and focused literature search. To ensure a comprehensive and systematic keyword selection process for the literature review, a multi-step approach was adopted. Initially, a set of highly cited and influential papers in the field was selected based on relevance to the research topic. These foundational studies were analyzed to extract recurring terms, themes, and terminologies commonly used in titles, abstracts, and keyword sections. The identified keywords and their derivatives were added to an evolving keyword list. This iterative process was repeated, refining and expanding the keyword set until thematic saturation was achieved. To structure the final search query, keywords were grouped into thematic categories using the Boolean operator “OR” within categories and “AND” across categories. The finalized keyword sets shown in Table 1 (grouped by similar policy functions and mechanisms to facilitate clear analysis

and comparison of policy instruments in bioenergy) were employed as a structured search query across academic databases. The search targeted titles, abstracts, and keyword fields to ensure both precision and comprehensive coverage of relevant literature. This approach aligns with established practices in systematic literature reviews [35], ensuring the retrieval of a well-rounded body of work for analysis.

Table 1. Keyword Sets by Bioenergy Policy Category.

Sets	Keywords
Set 1	"bioenergy" OR "biomass" OR "biofuel" OR "bioethanol" OR "biodiesel" OR "biogas" OR "bio-based energy" OR "wood pellet"
	AND
Set 2	"FiTs" OR "Tendered FiTs" OR "FiTs Auction" OR "Auction-Based Pricing" OR "Competitive Bidding" OR "Renewable Energy Auction" OR "Contract For Difference" OR "CfD" OR "Carbon Tax" OR "Carbon Pricing" OR "Environmental Taxes" OR "Tariff Policy" OR "Anti-Dumping Measures" OR "Production Subsidy" OR "Consumption Subsidy" OR "Fuel Subsidies" OR "Energy Consumption Subsidy" OR "Fuel Consumption Subsidy" OR "Subsidy For Energy Use" OR "Subsidy" OR "Energy Subsidy" OR "Bioenergy Subsidy" OR "Biomass Subsidy" OR "Biofuel Subsidy" OR "Bioethanol Subsidy" OR "Biodiesel Subsidy" OR "Biogas Subsidy" OR "Bio-Based Energy Subsidy" OR "Wood Pellet Subsidy" OR "PTC" OR "Price-Based Instruments" OR "Price Support Mechanism" OR "Import Tariff" OR "Tariff Barriers" OR "Trade Tariffs" OR "Bioenergy Trade" OR "Biofuel Import"
Set 3	"Feed-In Premium" OR "FiP" OR "Emissions Trading System" OR "ETS" OR "Cap-And-Trade" OR "Carbon Offsets" OR "Baseline-And-Credit Systems" OR "Green Certificate Trading" OR "Green Certificate" OR "Renewable Energy Certificate" OR "Tradable Green Certificate"
Set 4	"Quota system" OR "Renewable Portfolio Standard" OR "Renewable Obligation" OR "Blending Mandates" OR "Mandate"
Set 5	"Investment Tax Credit" OR "ITC" OR "Grants" OR "Public Funding" OR "Government Loan" OR "Subsidized Loans" OR "Dedicated Public Funds" OR "Investment Support" OR "Research And Development Support" OR "Tax Relief" OR "Tax Exemption" OR "Indirect Tax Incentive" OR "Tax Credit" OR "Rebate Policy" OR "Economic Incentive" OR "Support Scheme" OR "Incentive" OR "Value-Added Tax Exemption" OR "VAT Exemption"
Set 6	"Green Public Procurement" OR "Sustainable Procurement" OR "Government Procurement Policy" OR "Information & Education Campaigns"
Set 7	"Policy" OR "Regulatory Framework"

3. Literature Screening & Selection

After applying our defined search query for peer-reviewed journal articles published in English between 2015 and 2025, a total of 458 records were retrieved from Google Scholar. These articles then underwent a rigorous two-step screening process. First, their titles and abstracts were evaluated against our inclusion and exclusion criteria to ensure relevance. Subsequently, the remaining articles were subjected to full-text screening and reference list reviews to finalize the set of papers for in-depth analysis. This systematic approach ensured that the selected studies were of high academic quality and directly relevant to bioenergy policy instruments. To maintain the rigor and relevance of our review, studies were excluded based on several criteria. We filtered out all non-English papers, as well as any that were unrelated to bioenergy or policy instruments. Additionally, we omitted studies for which full texts were not accessible and excluded all non-peer-reviewed literature, such as conference proceedings, editorials, book chapters, and grey literature.

This review exclusively considers studies that directly address bioenergy policy assessment. We included papers only if their primary focus was on policy mechanisms designed to promote or develop bioenergy. Conversely, studies that focused solely on environmental

considerations were excluded. For instance, papers assessing the environmental impacts of bioenergy, such as land use change, biodiversity loss or carbon stock changes [36], were not included unless they directly linked these findings to specific policy instruments used for bioenergy production promotion. This boundary also led to the exclusion of studies primarily concerned with broader environmental enhancement through policy; for example, a paper by [37] was excluded because its objective was to review policies for enhancing ecosystem services like habitat provision and soil improvement, which falls outside the scope of this review. Moreover, the reference lists of the initially identified papers were carefully reviewed, and additional studies were excluded due to duplication, limited relevance, or insufficient conceptual clarity. As a result of this rigorous screening process, a total of 156 papers were selected for further in-depth analysis, forming the empirical foundation of this systematic review.

4. Analysis

The literature was systematically structured and interpreted through a methodological approach that categorized studies by policy instrument type, modeling approach, supply chain segment, biomass and bioenergy type, and geographic region. This section first presents a bibliometric analysis of the literature, followed by an in-depth examination of the selected studies.

4.1. Bibliometric Analysis

The distribution of papers analyzing supportive policies for bioenergy development across journals is presented in Table 2, while a visual summary of the leading publication outlets is illustrated in Figure 2. Overall, the reviewed studies were published across a diverse set of 78 journals, indicating broad interdisciplinary engagement with supportive bioenergy policy research. Among these outlets, Energy Policy, Energy, Applied Energy, Journal of Cleaner Production, Renewable and Sustainable Energy Reviews, Renewable Energy, Sustainability, Biomass and Bioenergy, Biofuels, Science of the Total Environment, IIE Transactions, Biofuels, Bioproducts and Biorefining, and GCB Bioenergy represent the most prominent contributors, collectively accounting for nearly one-third of all publications. The bar chart in Figure 3 highlights the relative dominance of these leading journals, thereby complementing the comprehensive tabular information provided in Table 2 and improving the clarity of cross-journal comparison.

Table 2. Distribution of journals and published papers (2015–August 2025).

Journal	No. of Papers	Journal	No. of Papers
Energy Policy	16	Sustainability	5
Energy	7	Biomass and Bioenergy	4
Applied Energy	7	Biofuels	4
Energies	6	Science of The Total Environment	4
Journal of Cleaner Production	6	IIE Transactions	3
Renewable and Sustainable Energy Reviews	6	Biofuels, Bioproducts and Biorefining	3
Renewable Energy	5	GCB Bioenergy	3
Energy Reports	3	Forest Policy and Economics	2
Energy Economics	3	American Journal of Agricultural Economics	2
Forests	3	PLOS Climate	2
World Trade Review	2	European Journal of Operational Research	2

Table 2. *Cont.*

Journal	No. of Papers	Journal	No. of Papers
Journal of Air Transport Management	2	Energy, Sustainability and Society	1
International Journal of Production Research	2	Agricultural and Resource Economics Review	1
Annual Review of Resource Economics	1	Energy & Environment	1
Mitigation and Adaptation Strategies for Global Change	1	Processes	1
Journal of Forestry Research	1	Environment, Development and Sustainability	1
Journal of Sustainable Forestry	1	Clean Technologies and Environmental Policy	1
Sustainable Energy Technologies and Assessments	1	Biomass Conversion and Biorefinery	1
Climatic Change	1	Geoforum	1
Journal of Forest Business Research	1	Climate Change Economics	1
International Forestry Review	1	Renewable Energy Focus	1
Gases	1	Sustainable Production and Consumption	1
The Innovation Energy	1	Process Safety and Environmental Protection	1
Carbon Management	1	PLOS One	1
Energy Research & Social Science	1	Systems	1
International Journal of Environmental & Science Education	1	Waste and Biomass Valorization	1
Education Sciences	1	Technological Forecasting and Social Change	1
Waste Management & Research	1	Enterprise Information Systems	1
International Journal of Hydrogen Energy	1	Resources, Conservation and Recycling	1
Heliyon	1	Natural Resources Forum	1
Environmental Economics and Policy Studies	1	European Review of Agricultural Economics	1
Environmental Science & Technology	1	Journal of Environmental Management	1
Journal of Agricultural Economics	1	Environmental Research Communications	1
Chemical Engineering Research and Design	1	Asia-Pacific Journal of Chemical Engineering	1
BioEnergy Research	1	The Energy Journal	1
The Journal of World Energy Law & Business	1	Economic Systems Research	1
Resources	1	Asian Social Science	1
Energy Conversion and Management	1	Fuel	1
Journal of the Agricultural and Applied Economics Association	1	The Journal of Agrobiotechnology Management & Economics	1

A total of 34 countries have contributed publications, as shown in Figure 4. The world-wide geographical distribution of papers was extracted based on the authors' affiliations, with the United States of America (USA), China, and Canada emerging as the leading contributors. The number of case studies analyzed in the literature exceeds the number of contributing jurisdictions, totaling 43, as also presented in Figure 4. This figure further illustrates the geographic distribution of case studies that were actually conducted or reported in the reviewed literature. However, 12 papers did not include any case studies, while the USA, China, the European Union, Germany, and the United Kingdom (UK) account for the largest share of reported case studies.

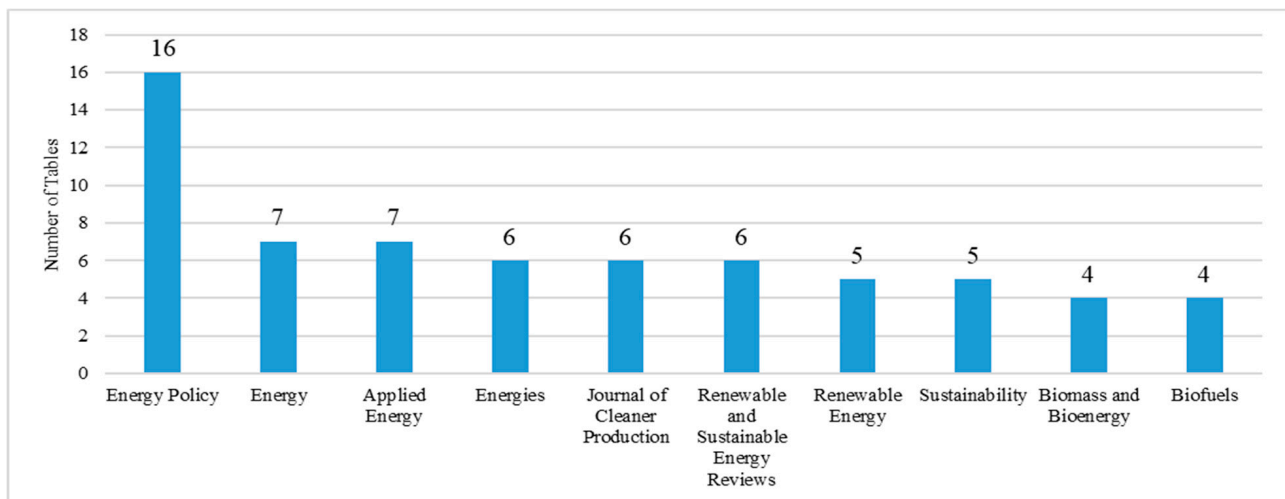


Figure 3. Top Contributing Journals in Supportive Bioenergy Policy Research (2015–August 2025).

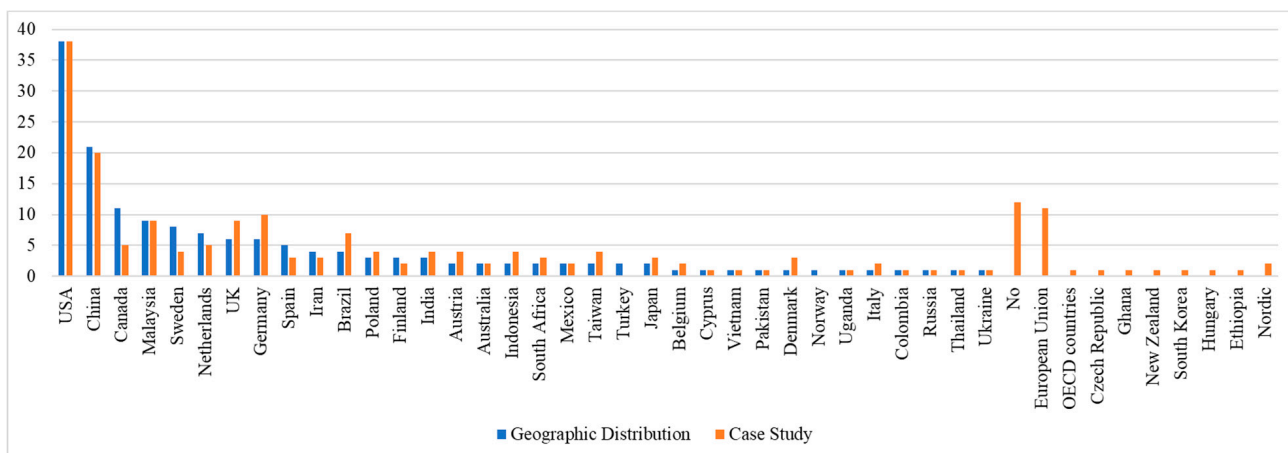


Figure 4. Global Distribution of Supportive Bioenergy Policy Case Studies and Publications (2015–August 2025).

4.2. In-Depth Analysis

Bioenergy is produced from a wide range of raw materials. The reviewed studies employed a variety of feedstocks, which can be grouped into well-established categories. These include agricultural residues (e.g., straw, corn stover, bagasse, husks, shells), energy crops (e.g., switchgrass, miscanthus, jatropha, sugar beet), forest-based biomass (e.g., logging residues, wood chips, sawdust, bark), livestock waste (e.g., manure and slaughterhouse residues), algae (microalgae and macroalgae), and municipal and industrial organic waste (e.g., food waste, yard waste, sewage sludge). In some studies, the raw material was not specified, or a general term such as ‘biomass’ was used without indicating a specific type. This categorization offers a consistent framework for comparing studies and emphasizes the diverse resource base that underpins bioenergy systems.

In the analysis of supportive policies for bioenergy development, energy crops are the most frequently studied biomass feedstock, featured in 45 of 156 publications (29%). Close behind are forest-based biomass and agricultural residues, each discussed in 40 of 156 studies (26%) (Figure 5). Together, these three categories dominate the policy analysis landscape for bioenergy. In addition, general biomass was examined in 35 of the 156 studies, highlighting its continued relevance in the field.

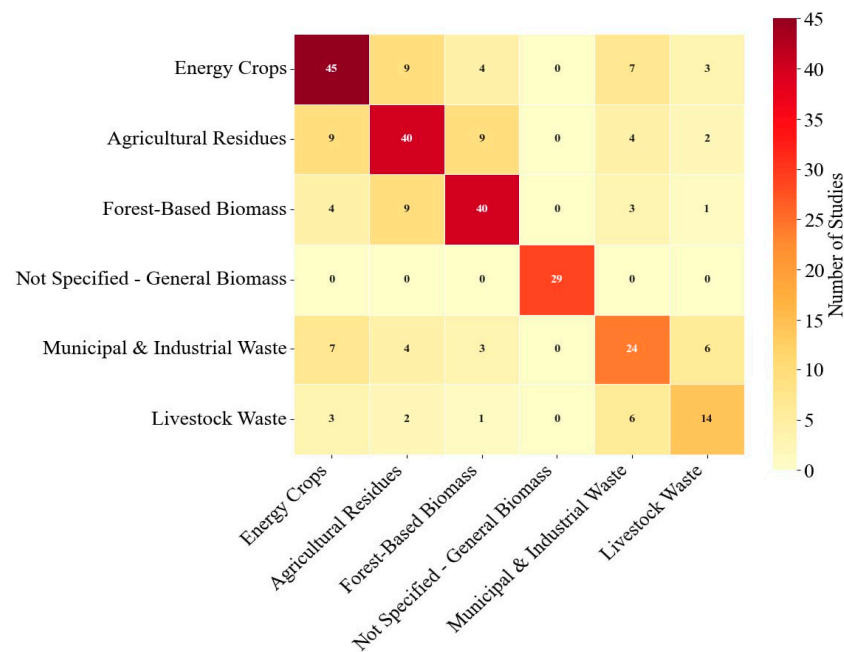


Figure 5. Distribution of Biomass Types in Supportive Bioenergy Policy Publications.

In contrast, algae-based biomass has received significantly less attention, representing only 2% (3 out of 156) of the total publications, indicating it is a less-studied area for policy development. The literature shows that there are a number of studies considering multiple feedstocks. The co-occurrence of Energy Crops & Agricultural Residues and Agricultural Residues & Forest-Based Biomass (each considered in 15 studies) signifies a mature research emphasis on feedstocks fueling liquid biofuels and bioelectricity generation. Conversely, the other most common combined raw materials, Energy Crops & Municipal & Industrial Waste (7 studies) and Municipal & Industrial Waste & Livestock Waste (6 studies), indicate a burgeoning policy interest in biogas, representing a key area for policy diversification toward circular economy objectives. Figure 6 shows the percentage of bioenergy types studied in analyses of policies for bioenergy development. The quantitative distribution of research attention highlights a clear hierarchy in policy analysis for bioenergy development. Liquid biofuels received the most substantial focus, accounting for approximately 41% (64 out 156 papers) of the research, directly reflecting the market dominance of transport-sector mandates. Following this, bioelectricity and biogas received significant, yet lesser, attention at 21% and 18%, respectively. Critically, bioheat and solid bioenergy products are severely marginalized, with each representing about 8% of the studies. This distinct pattern demonstrates a pronounced policy–research deficit in the thermal and solid biomass sectors, indicating that the prevailing academic discourse is disproportionately driven by policy instruments targeting the mature liquid fuel market.

A systematic classification of bioenergy policies is essential for evaluating the effectiveness of policy instruments and identifying strategic gaps. Beyond this, a deeper analysis is required to understand policy functions and interactions. Such an analysis is crucial for discerning the ideal combination of policies that will achieve desired outcomes, while also revealing the collaborative benefits created by these policies or, conversely, any adverse side effects that may arise [38]. Therefore, given the importance of bioenergy policy classification, this section investigates and analyzes the different categories of policies.

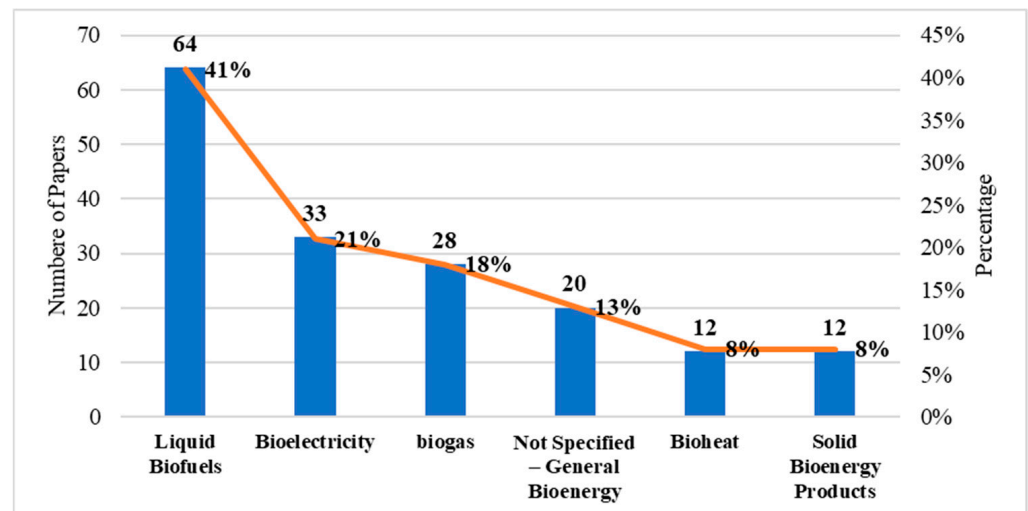


Figure 6. Distribution of Bioenergy Types in Supportive Bioenergy Policy Publications.

5. Policy Classification

A number of studies have proposed different categorizations. For instance [39] developed a framework that classified governmental policies for bioenergy development into two categories: economic and regulatory. The economic category was further divided into direct and indirect incentives. The paper specifically analyzes the impact of direct support, using subsidies as an example, and indirect incentives, exemplified by technology development funds, on bioenergy development and the coordination and profitability of biomass supply chain stakeholders in Canada. In another study [40], the major U.S. biodiesel-supporting policy mechanisms were categorized into five groups: biodiesel fuel use mandates, biodiesel fuel use incentives, biodiesel production incentives, biodiesel fueling infrastructure incentives, and biodiesel fleet development incentives. The efficacy of these policy approaches was subsequently determined through statistical modeling. It's worth noting that certain price-based instruments, such as FiTs, were not included in this classification, indicating a narrower focus on specific policy types. Ref. [41] proposed a policy classification framework that groups all biomass subsidies into four distinct categories based on the specific costs they seek to mitigate: production, transport, product, and operating subsidies. Crucially, this framework focused exclusively on subsidies and therefore did not account for broader carbon policies, such as cap-and-trade programs. The authors then used a game-theoretic model to assess the effectiveness of these different subsidies in the United States and China. In a different classification approach, ref. [42] developed a four-tier classification structure to categorize nearly 500 federal and state policies supporting electricity and heat production from forest biomass in the United States. The classification was based on the policy's approach (incentive, regulation, information), type (e.g., tax incentive), subcategory (e.g., tax exemption), and specification (e.g., sales tax exemption). However, the study did not investigate broader market-based policies such as Emissions Trading Systems (ETS). In a broader classification, ref. [43] introduced a framework with seven policy categories for the U.S. wood energy sector including those aimed at lowering project capital costs, government mandates, and rural energy grants. The paper reviewed historic trends to explore the impact of these policies and energy prices on wood energy consumption. It is important to note that this framework focused on these specific policy types and therefore did not account for broader price-based policies, such as FiTs. Ref. [26] proposed a different and broader classification framework compared to the past studies that categorized policies into four groups: direct incentive payments (financing), fiscal measures, market-based incentives and indirect supportive programs. A key limitation

of this classification is that it did not consider carbon credits, such as the Investment Tax Credit or Production Tax Credit.

While the aforementioned studies have provided valuable, albeit limited, frameworks for policy classification, there remains a need for a more integrated approach. Existing classifications often focus on specific regions, bioenergy types, or narrow policy sets, and frequently omit key instruments such as price-based or carbon-related measures. These limitations restrict cross-study and cross-region comparison, motivating the comprehensive five-category framework proposed in this study. In this study, we introduce a comprehensive classification system. These policy categories were derived by grouping instruments according to their core function and mechanism of intervention. Categorizing policies based on their core function and intervention mechanism enhances analytical clarity and comparability. This approach reveals how specific policy instruments influence behavior and are instrumental in identifying gaps, overlaps, and complementarities within the broader policy landscape. Therefore, to the best of our knowledge, bioenergy support policies can be divided into 5 main categories and a total of 21 distinct subcategories. The five main categories are: A. Price-Based Instruments, B. Market-Based Instruments, C. Quantity-Based Instruments, D. Investment and Capital Support, and E. Behavioral and Sustainability Measures.

Figure 7 illustrates the policies investigated to promote bioenergy production, with several papers analyzing multiple policies. Price-Based Instruments are the most commonly used to support bioenergy, emerging in 77 of 156 papers, representing 49% of the studies. This means they are used in almost half of the research to promote bioenergy production. Market-Based Instruments are the second most frequently considered policy, appearing in 46 of 156 studies, or 29%, which highlights their significant role in bioenergy development.

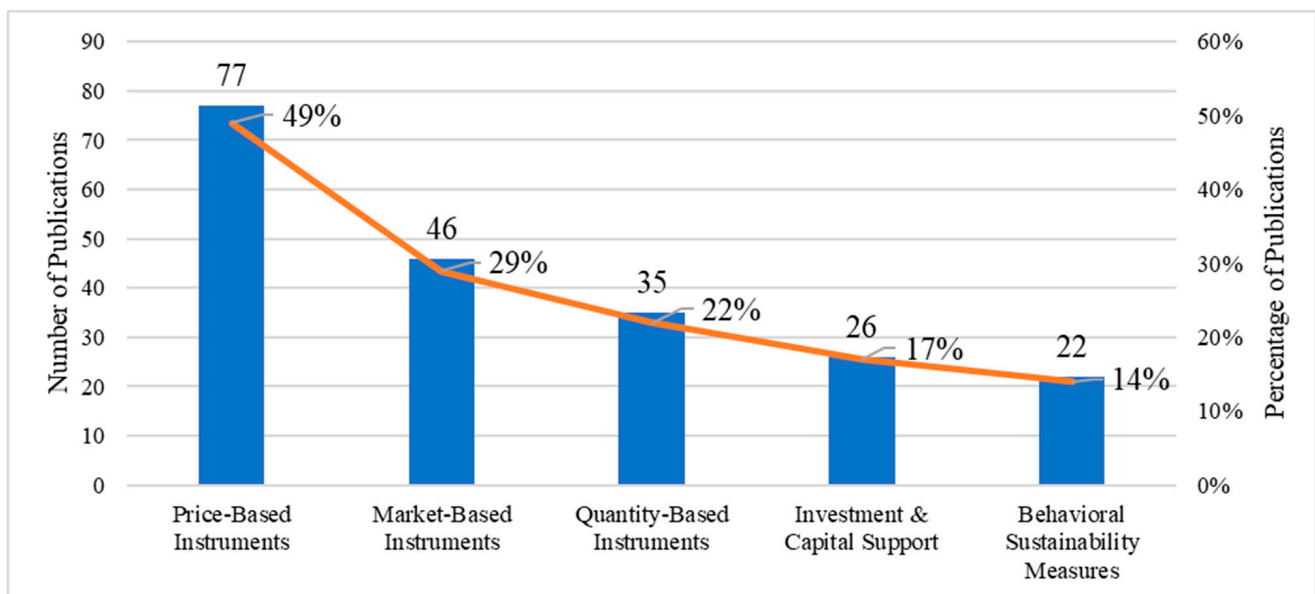


Figure 7. Number and Percentage of Publications by Policy Category.

The third most used policy is Quantity-Based, considered in 35 papers, accounting for 22% of the total. Given that bioenergy development requires substantial investment, Investment & Capital Support policies are also a prominent focus, appearing in 26 of 156 papers, which is 17% of the literature. Finally, Behavioral Sustainability Measures are discussed in 22 papers, representing 14% of the studies. In the following sections, each of these policy types will be investigated in detail.

A. Price-Based Instruments

The principle that demand decreases as price increases is a fundamental concept leveraged by price-based policy instruments [44]. These policies, such as taxes or surcharges, operate by directly adjusting the price of a good or service to the consumer. By increasing the price of a less-desired product (e.g., fossil fuels), a policy effectively disincentivizes its use. Conversely, subsidies can lower the price of a preferred alternative (e.g., bioenergy), thereby stimulating demand and influencing market behavior to align with sustainability goals. This direct link between price and consumption is what makes price-based policies a powerful tool for achieving specific outcomes. In fact, 77 out of 156 papers in the review investigated price-based instruments, underscoring their central role in shaping bioenergy development. Price-based policies function by directly influencing the economic decisions of producers and consumers to promote the development and use of bioenergy. These instruments are specifically designed to influence consumer and producer behavior by adjusting prices within established markets. By doing so, they create a more favorable financial landscape for bioenergy to compete with conventional fossil fuels. This is achieved by either increasing the cost of conventional, carbon-intensive energy or by decreasing the cost of bioenergy. Price-based policies can be implemented through a number of different instruments, including: 1. Feed-in Tariffs (FiTs), 2. Contract for Difference (CfD), 3. Auction-Based Pricing/Tendered FiTs, 4. Carbon Tax, 5. Production & Consumption Subsidy, 6. Production Tax Credit (PTC), 7. Environmental Taxes, 8. Anti-Dumping Measures. The review of the literature reveals that researchers have focused on a select number of price-based policy instruments, with a significant concentration on those that provide long-term revenue stability for producers. FiTs, in particular, are the most frequently investigated policies, underscoring their prominence as a mechanism for mitigating investor risk in bioenergy projects, accounting for 31% (24 out of 77) of all studies that examined price-based instruments as shown in Figure 8. Studies on FiTs show their application in various sectors, from bioelectricity generation to biomethane production, consistently highlighting their ability to ensure financial stability and enhance economic viability. For example, research on palm biomass residues in Malaysia and waste-to-energy facilities demonstrates that FiTs not only secure revenue but also provide a flexible framework for optimizing feedstock selection, improving efficiency, and encouraging the adoption of advanced technologies like anaerobic digestion [45,46]. However, some studies also indicate that FiTs effectiveness is conditional on factors such as feedstock competitiveness [47] and sufficient government funding [48].

In alignment with price-based policy strategies, a distinct body of research examines the role of carbon taxes (29%) and broader environmental taxes (9%) as tools for correcting market failures. This focus on internalizing the environmental costs of emissions is a key characteristic of these price-based instruments, with 38% of the studies in this category concentrating on this objective. These policies are designed to incentivize a transition to cleaner fuels like bioenergy. The effectiveness of these taxes has been demonstrated in various contexts. For example, a study on the application of a carbon tax on air travel in China confirmed its ability to reduce emissions and increase the blending ratio of biofuels [49]. Similarly, research into a specialized Carbon Exergy Tax (CET) in Brazil found that it not only incentivized carbon reduction but also promoted higher thermodynamic efficiency in biomass systems by rewarding more efficient energy conversion processes [50]. Furthermore, the concept of carbon tax revenue recycling has been investigated as a powerful mechanism to promote cleaner energy, by using the revenue generated from the tax to subsidize biomass and coal co-firing practices [51]. These findings collectively highlight the potential of carbon and environmental taxes to drive sustainable change by creating direct economic incentives for reducing emissions.

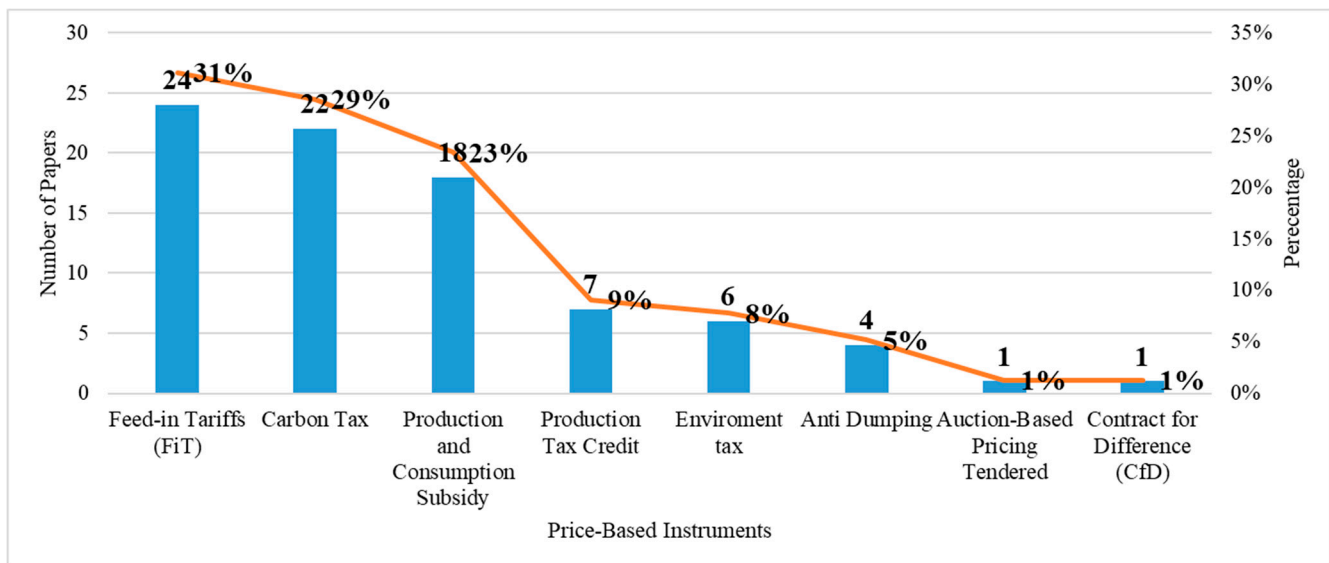


Figure 8. Frequency of Price-Based Policy Instruments (Number and Percentage).

Within the body of literature on price-based policies, a significant portion focuses on Production and Consumption Subsidies (23%), which represent the third most common policy instrument. These policies are distinct because they place the fiscal responsibility on the government to directly lower the cost of bioenergy, thus de-risking investment and making cleaner fuels cost-competitive with conventional alternatives. For example, research on subsidies for rural household biogas digesters in China demonstrates their necessity for overcoming high upfront costs and ensuring the long-term operational viability of small-scale projects [52]. Similarly, studies on crop straw and tiered electricity subsidies highlight their pivotal role in stimulating the supply of raw materials and enhancing overall bioenergy output [53,54]. However, this research also underscores the critical need for optimal fund allocation to maximize social welfare and avoid supply chain inefficiencies. A key form of production subsidy, Production Tax Credits (PTCs), accounts for a notable 8% of studies. These are explored for their ability to promote specific technologies like biomass co-firing by helping producers absorb additional operational costs and optimize resource utilization [55].

In addition to the policies mentioned above, other instruments have been investigated, though with less frequency. Research on Anti-Dumping Measures (5%) and Auction-Based Pricing (1%) and CfDs (1%) reveals a critical area of focus for future research. While Auction-Based Pricing is less commonly studied, it has a substantial influence on the international bioenergy market. For example, the imposition of anti-dumping duties by countries like the USA is a direct tool to protect domestic industries from foreign competition deemed unfair [56]. Such measures are particularly relevant for internationally tradable products like biodiesel or wood pellets, highlighting a significant need for more research to understand how these policies shape global supply chains and affect the development of the bioenergy sector.

The research on price-based policies is notably concentrated on the two largest energy sectors: Liquid Biofuels (36%) and Bioelectricity (30%) as shown in Figure 9. This focus reflects a strategic policy interest in areas where price signals can most effectively displace fossil fuels. The prominence of liquid biofuel studies is reinforced by a strong linkage to associated raw materials, primarily Agricultural Residues (29%) and Energy Crops (20%), while Biogas (17%) research is most connected to Municipal & Industrial Waste (14%) and Agricultural Residues (29%) as shown in Figure 10. Conversely, the policy literature

shows a significant deficit in support for the thermal sector, with Bioheat (10%) and Solid Bioenergy Products (4%) being significantly under-researched.

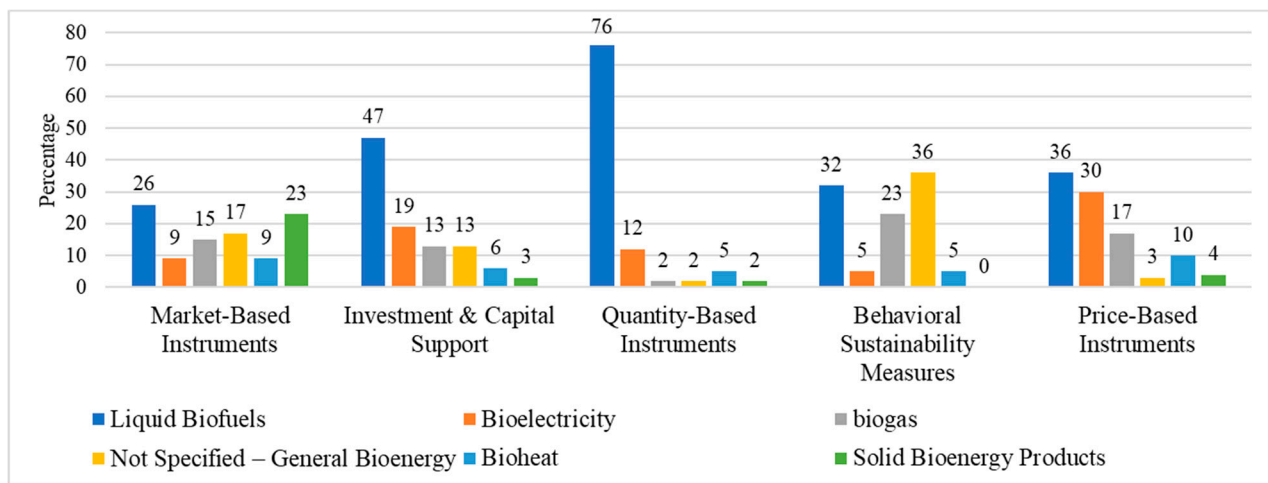


Figure 9. Percentage of Bioenergy Types Examined in Price-Based Policy Studies.

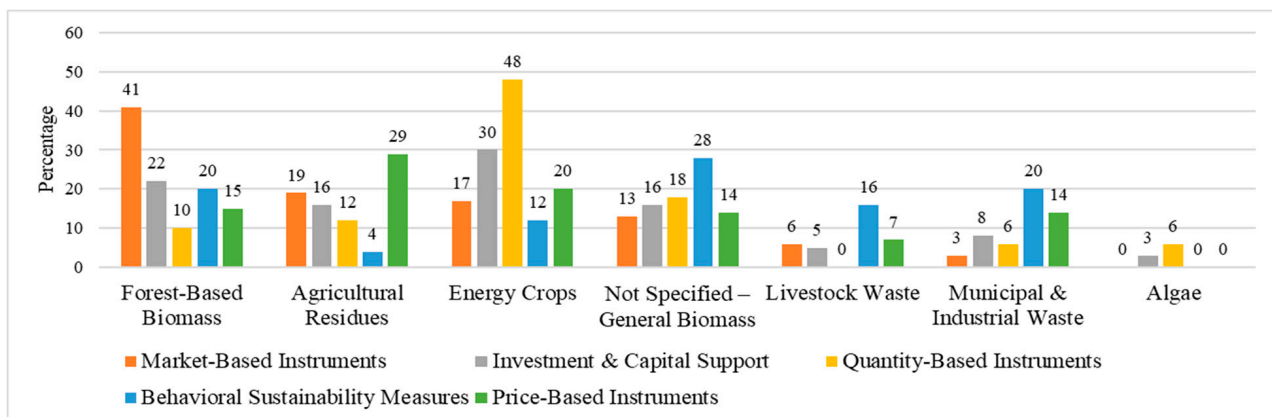


Figure 10. Percentage of Biomass Types Examined in Price-Based Policy Studies.

A deeper analysis of the specific instruments reveals targeted policy application. FiTs, the most studied price instrument, are overwhelmingly used to promote grid-connected energy, concentrating on Bioelectricity (35%) and Biogas (32%). In contrast, the Carbon Tax is predominantly investigated for Liquid Biofuels (41%), highlighting its function as a key policy tool for transport sector decarbonization. Production and Consumption Subsidies offer broader support, being studied almost equally for Liquid Biofuels (45%) and Bioelectricity (40%). Finally, the narrow focus of Anti-dumping measures almost exclusively on Liquid Biofuels underscores the use of trade-related instruments to address specific international market stability issues for transport fuels.

The policy literature reveals a key distinction among price-based instruments based on their fiscal impact. Tools like carbon taxes, anti-dumping duties, and auction-based pricing mechanisms are revenue-generating, broadening government finances through levies or competitive bidding. Conversely, measures such as FiTs, subsidies, tax credits, and CfDs impose a fiscal burden, requiring direct government expenditure or foregone revenue to incentivize deployment.

This fiscally burdensome category is primarily researched for Bioelectricity (36%) and Liquid Biofuels (27%), indicating these capital-intensive sectors require the most direct financial support to achieve price-competitiveness and market scale (Figure 11). Geographically, research on these instruments is heavily concentrated in major economies

with significant government capacity: China (17%), the USA (16%), and Malaysia (12%). This pattern confirms that large nations frequently employ direct fiscal support as a core strategy to drive large-scale bioenergy transition and secure national energy goals.

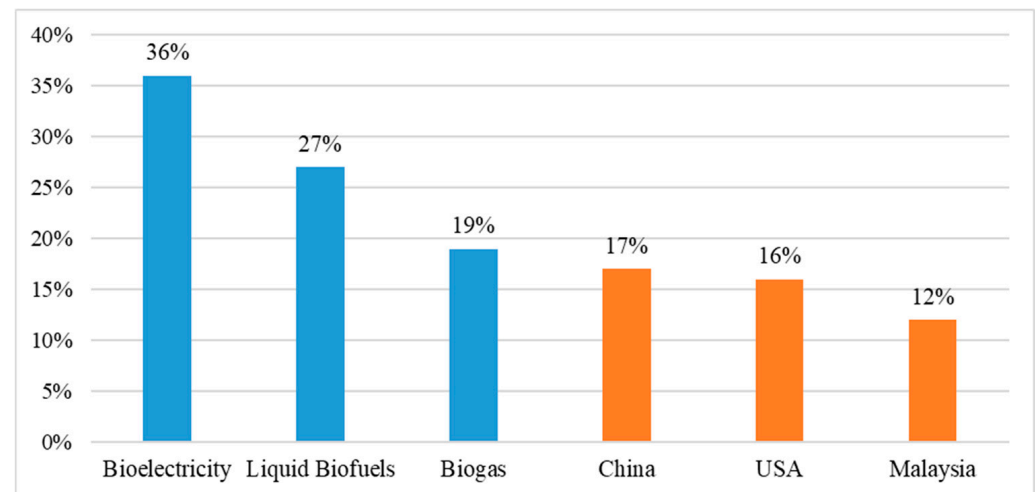


Figure 11. Adoption of Fiscal-Burden Price-Based Policies by Country and Bioenergy Type.

B. Market-Based Instruments

Market-based policies constitute the second most analyzed policy instrument in the literature, with 29% (46 out of 156 papers) of studies focusing on their application. Market-based policies use economic incentives and tradable mechanisms, such as taxes, or carbon trading schemes, to allow the market to determine the most cost-effective way to achieve policy goals. These policies can be implemented through a number of different instruments, including: Emissions Trading Systems (ETS) or Cap-and-Trade, Carbon Offsets, Baseline-and-Credit Systems, Green Certificate Trading, and Feed-in Premiums (FiPs).

ETS, commonly referred to as cap-and-trade schemes, represent a foundational market-based policy instrument designed to manage and reduce greenhouse gas emissions. The mechanism sets an overall emissions cap for a given sector and allows regulated entities to receive or buy a limited number of emission allowances within that cap [57]. The literature highlights the versatility and application of ETS in the bioenergy sector, with a substantial portion of the reviewed papers focusing on its implementation, representing 57% (26 out of 46 studies) as shown in Figure 12, focused on this instrument. For instance, studies on the biofuel supply chain have demonstrated how an ETS provides economic incentives to reduce emissions in biofuel production through tradable carbon allowances, enabling firms to balance compliance costs with operational flexibility [58]. A particularly prominent example is the European Union Emission Trading Scheme (EU ETS), which has been modeled to assess the economic viability of co-firing biomass with coal in key European economies. The findings reveal that co-firing offers significant potential for emissions reduction and is economically competitive under specific carbon price levels, provided biomass prices remain low [59]. Furthermore, ETS is recognized as a powerful tool for integrating carbon pricing into corporate decision-making. A study on Finland's energy and materials industry, for example, demonstrated how a data-driven internal carbon pricing mechanism, linked to EU ETS allowance prices, can enhance profitability and optimize wood procurement while ensuring carbon neutrality [60]. While promising, research on bioenergy with carbon capture and storage (BECCS) within the EU ETS framework indicates that without specific incentives for negative emissions, BECCS remains an additional cost under the current structure [61]. Beyond the energy sector, cap-and-trade systems have also been shown to be effective in managing land-use conflicts, with one study demonstrating their ability to

limit farmland allocation for energy crops, thereby safeguarding food production while still supporting the biofuel industry [62]. The practicality of this instrument in motivating coal-fired power plants to transition to lower-carbon generation has also been evidenced in studies from China [63]. Nevertheless, the effectiveness of ETS is highly sensitive to the chosen cap level and carbon price, necessitating careful and dynamic policy design to reconcile environmental objectives with economic stability [64,65].

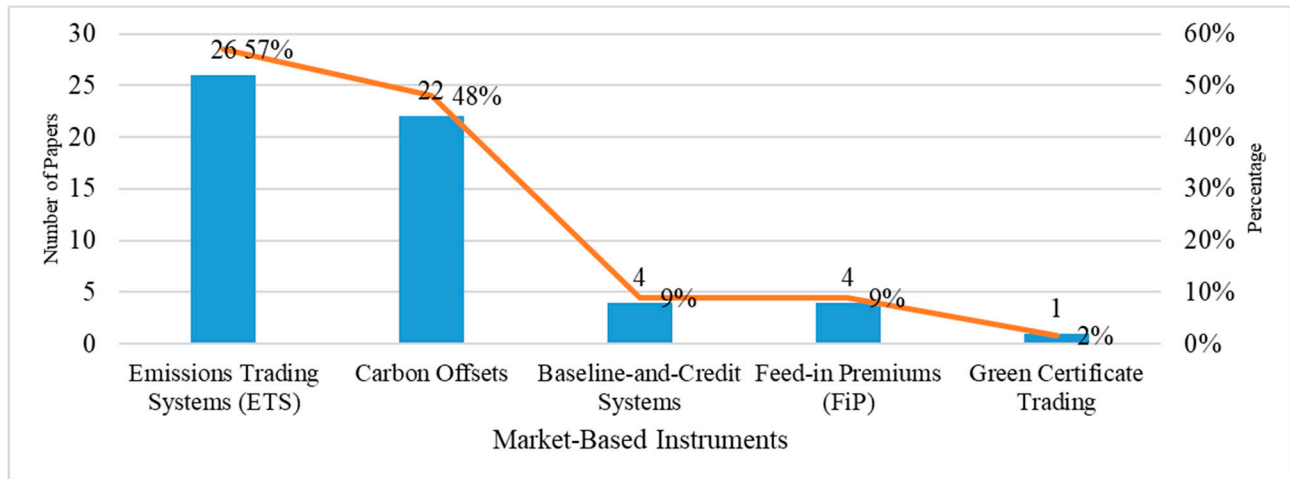


Figure 12. Frequency of Market-Based Policy Instruments (Number and Percentage).

Following ETS, carbon offsets emerge as another important market-based mechanism, encouraging both emission reductions and carbon sequestration. This instrument operates by creating a tradable credit for each unit of CO₂ avoided or removed from the atmosphere, providing a crucial tool for monetizing the environmental benefits of forestry and bioenergy projects [66–68]. A substantial portion of the academic discourse, with 48% (22 out of 46) of the reviewed papers on market-based policies focusing on this topic, underscores its relevance. Research has extensively investigated the use of carbon offsets to support national climate and decarbonization goals. Studies from Russia and China, for instance, have examined how this instrument can leverage vast forest resources to generate tradable credits, providing financial incentives for sustainable forestry and bioenergy projects [66,68]. In the United States, carbon offsets are being explored to enhance returns on timberland investments and encourage landowners to manage forests for both carbon sequestration and woody biomass production. However, the long-term viability of this instrument is contingent upon robust methodologies and accounting frameworks that can ensure the permanence and verifiability of the offsets, particularly in the face of risks like wildfires [69]. While carbon offsets are frequently employed to validate the carbon neutrality of biofuel combustion, their effectiveness can be constrained by the inherent complexities of carbon accounting and stringent additionality criteria [70]. Ultimately, carbon offsets provide a flexible and market-driven pathway to align economic and environmental objectives. However, their long-term impact is highly sensitive to evolving carbon prices and the integrity of the carbon accounting framework [71].

Moving beyond these widely studied mechanisms, less extensively investigated are Baseline-and-Credit Systems, Green Certificate Trading (GCT), and Feed-in Premiums (FiPs), which collectively account for 20% (9 out of 46) of the reviewed literature. Baseline-and-credit systems and FiPs each account for 9% (4 out of 46) of the papers, while GCT accounts for 2% (1 out of 46). Baseline-and-credit systems, such as Carbon Intensity (CI) crediting protocols, reward producers for reducing emissions below a predetermined baseline. This mechanism provides a flexible economic incentive for producers to adopt

low-carbon practices without dictating specific methods [72]. Research on CI crediting in the U.S. has demonstrated its cost-effectiveness in promoting the production of low-carbon feedstocks, and by financially incentivizing practices like no-till farming. These policies can increase the supply of low-carbon feedstocks and provide economic benefits to rural communities [72]. Similarly, GCT has been implemented to provide market-driven incentives for renewable energy production, as exemplified in Flanders, Belgium. This system sets mandatory quotas for electricity suppliers, allowing renewable energy producers to trade certificates for each megawatt-hour generated [73]. While designed for cost-efficiency and technological neutrality, GCT research indicates that it can lead to unintended outcomes, such as a preference for short-term, low-cost solutions like biomass co-firing over other long-term renewable sources. This highlights that even well-designed market-based systems require careful regulatory oversight to prevent biases and ensure desired long-term outcomes [73]. FiPs represent a more market-driven form of intervention compared to traditional FiTs [74], allowing renewable energy producers to sell electricity at wholesale market prices while receiving an additional premium. This mechanism mitigates market price risk, providing a predictable revenue stream and thereby encouraging investment in new bioenergy projects.

A detailed analysis of market-based instruments reveals a nuanced application of these policies across different bioenergy sectors. Studies on solid bioenergy (23%) and forest-based biomass (41%) are primarily associated with carbon offset mechanisms, as illustrated in Figures 8 and 9. This is because these instruments are uniquely well suited for monetizing the dual benefits of forestry, carbon sequestration and biomass production. Offsets directly incentivize improved forest management for carbon sequestration, with the resulting woody biomass often converted into solid bioenergy products. In contrast, ETS are primarily used to promote Liquid Biofuels (26%), with a focus on feedstocks like Agricultural Residues (19%) and Energy Crops (17%). ETS, by setting an overarching cap on emissions, is a powerful regulatory tool for large-scale, industrial-level processes, such as those involved in liquid biofuel production. This mechanism creates a financial incentive for these industries to reduce their carbon footprint by sourcing cleaner feedstocks. Figure 9 further suggests that market-based policies are less applicable for managing the conversion of Livestock Waste (6%) and Municipal Waste (3%) into bioenergy. These policies, which rely on verifiable carbon credits and tradable allowances, are not well-suited to the dispersed and complex nature of waste management, which often requires different policy approaches.

The analysis of market-based instruments highlights a crucial distinction based on fiscal risk. Instruments like FiPs and GCT are associated with high fiscal risk because they necessitate direct government payments or financial interventions to stabilize markets or support renewable producers, potentially straining public budgets. Conversely, mechanisms such as ETS, especially when allowances are auctioned, present a low fiscal risk, as they generate public revenue while shifting the cost of compliance to regulated firms. Similarly, Carbon Offsets and Baseline-and-Credit systems impose minimal fiscal burden, with most transactions occurring between private parties.

Research overwhelmingly concentrates on these lower-risk mechanisms, with approximately 89% (41 out of 46) of the reviewed studies focusing on just three instruments: ETS, Carbon Offsets, and Baseline-and-Credit systems as shown in Figure 13. This significant focus suggests a clear governmental preference for policy tools that balance environmental goals with risk mitigation for the public purse. Specifically, the popularity of ETS is attributed to its ability to generate revenue while imposing costs on firms, Carbon Offsets transfer investment responsibility to private actors, and Baseline-and-Credit systems incen-

tivize low-carbon practices without requiring substantial public expenditure, thus ensuring greater political feasibility and long-term sustainability.

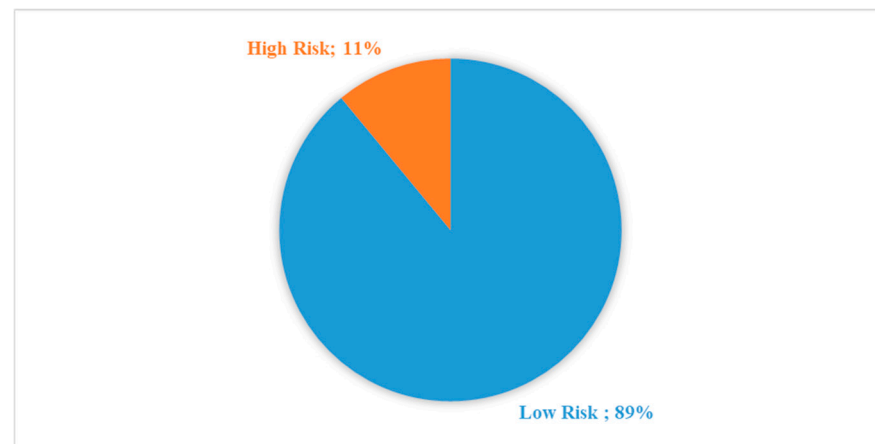


Figure 13. Fiscal Risk of Market-Based Policy Instruments in Bioenergy.

C. Quantity-Based Instruments

Quantity-based instruments are the third most used policy, appearing in 22% (35 out of 156 papers). These policies promote bioenergy by setting a specific target for its use, rather than influencing its price. This approach creates a guaranteed market and directly drives demand by mandating a minimum volume or percentage of biofuels in the energy supply. This approach shifts the focus from cost competitiveness to compliance, forcing industries to incorporate a certain amount of bioenergy regardless of price fluctuations. Unlike market-based or investment-based policies, their primary mechanism is a direct regulatory requirement.

Blending mandates, which require a minimum percentage of biofuels to be mixed with conventional fuels, are the most prevalent quantity-based policy, representing 86% (30 out of 35) of the literature as shown in Figure 14. They are considered the core tool for stimulating market demand because they create a clear, enforceable obligation for fuel producers and distributors [75]. This ensures consistent demand, drives industry growth, and directly impacts fossil fuel displacement and greenhouse gas reduction [76]. For instance, a study conducted in Germany demonstrated that biomethane mandates for heating in buildings effectively stimulated product offerings, even in the absence of substantial subsidies, by capitalizing on existing regulatory frameworks [77]. However, while blending mandates can be effective in stimulating market demand, their success is not absolute and often hinges on the presence of complementary policies, without such support, these mandates may generate market distortions or impose additional compliance burdens. For example, in the European Union, a biofuel mandate was deemed necessary to achieve ambitious emission reduction targets, yet it was also shown to increase overall energy system costs [78]. Similarly, in the U.S., the Renewable Fuel Standard (RFS) blending mandate directly influences market dynamics. When the mandate is binding, biofuel prices become more dependent on feedstock costs rather than fossil fuel prices, making risk management strategies crucial [79]. A study in Malaysia found that mandates successfully reduced crude palm oil stocks and increased its price; however, they failed to significantly boost biodiesel production due to low profitability, suggesting that mandates alone are insufficient without additional incentive [80]. A study in the EU also showed that, while mandates can influence biomass use, technological improvements and market forces are generally more effective in enhancing efficiency and reducing reliance on such mandates [81]. Despite their effectiveness in stimulating demand, highly progressive blending mandates in countries

such as Indonesia have been associated with significant economic risks, including larger trade deficits and increased government subsidy requirements [82,83].

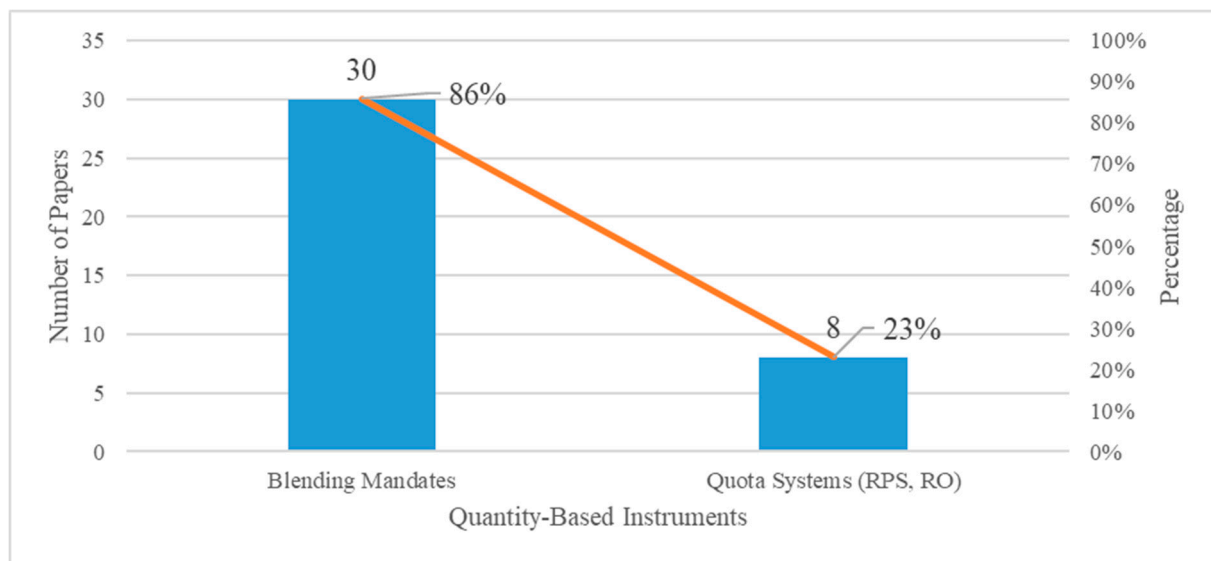


Figure 14. Frequency of Quantity-Based Policy Instruments (Number and Percentage).

Beyond blending mandates, Quota Systems, such as Renewable Portfolio Standards (RPS) and Renewable Obligations (RO), account for 23% (8 out of 35) of the literature. These policies work by mandating that a specific percentage of energy must be sourced from renewables. While blending mandates are a type of quota system focused on liquid fuels, this broader category applies to electricity and other sectors. These instruments are effective because they set enforceable targets that drive long-term renewable deployment [84]. A key difference is that quota systems often target the overall renewable share, giving companies flexibility in how they meet the target, which can be more cost-effective. For example, in China, a mandatory total target for densified biomass fuel was set to transition from fossil fuels, but the study concluded that setting mandatory targets alone was not enough and needed to be balanced with a focus on production quality and market development [85]. This shows that while quotas can create a framework for growth, they must be part of a broader policy mix to ensure sustainable industry development. The Renewable Fuel Standard in the U.S. also functions as a quota system, using tradable compliance certificates (RINs) to achieve its mandated volume targets for various biofuel types [84].

The literature shows a strong focus on a single fuel type. Nearly three-quarters (76%) of papers on quantity mandates examine liquid biofuels, such as ethanol and biodiesel, with energy crops serving as the primary feedstock in 48% of these studies (as shown in Figure 10). This focus has created a path-dependent system in which both industry and research predominantly prioritize conventional liquid fuels; notably, 29 of the 30 papers examining blending mandates consider only liquid biofuels. Only the less commonly used quota systems show any engagement with bioelectricity (4 out of 8 papers), often derived from forest residues, highlighting that important alternatives for decarbonizing heat and power are largely overlooked in favor of the established, but resource-constrained, transport fuel sector.

D. Investment and Capital Support

Investment and Capital Support policies are a crucial category of instruments designed to mitigate the financial risks associated with bioenergy projects. They work by directly reducing the high upfront capital costs or long-term financial uncertainty for investors and producers. This technology-push approach aims to bridge the gap between research

and commercial-scale deployment, making bioenergy projects more economically viable and competitive with conventional energy sources. Unlike market-based instruments that create price signals through a market, these policies provide direct injections of capital or tax relief. Investment and capital support is the fourth most used policy, accounting for 17% (26 out of 156 papers) as shown in Figure 15, and its key instruments include Grants, Loans, and Dedicated Public Funds, Tax Exemptions or Reductions, VAT exemption (value added tax exemption), and Investment Tax Credits (ITCs). By far the most studied investment support mechanism, a significant portion of the literature, accounting for 77% (20 out of 26), focuses on grants, loans, and dedicated public funds. Studies consistently highlight their direct impact on project feasibility by targeting high initial investments. For example, public subsidies covering 40–60% of the cost of agricultural biogas plants in Poland were essential to ensure economic viability and attract private investment [86]. Such support demonstrates how government intervention can help overcome the financial barriers that often limit farmer participation in the biogas sector [86,87]. Similarly, in the UK, investment support for bioethanol production from wheat straw is considered a key factor in attracting funding and encouraging the use of agricultural residues that would otherwise go unused [88]. Besides supporting individual projects, these policies also foster technological innovation and infrastructure development. For example, government grants and R&D funding accelerate the commercialization of advanced biofuels and help reduce the financial risks associated with early-stage technologies [89,90]. Additionally, incentives for fuel distribution infrastructure have been shown to correlate significantly with increased biodiesel consumption at the state level in the U.S. [40]. Following this, tax exemptions and reductions represent the second most studied instrument, with 35% (9 out of 26) of the research. These policies work by lowering the cost of bioenergy production or consumption through fiscal relief, rather than directly influencing energy prices. One study on Brazil's ethanol market, for example, shows that tax exemption policies can make ethanol more price-competitive with gasoline, thereby promoting its adoption [91]. However, the effectiveness of these policies is not always straightforward. Research on Brazil's ethanol market suggests that tax exemptions can have complex and even ambiguous impacts on ethanol and sugar prices due to flexible production and competing market demands [91]. Furthermore, VAT Exemption, a specific form of tax exemption, accounts for 8% (2 out of 26) of the literature. Studies show that this incentive can significantly improve the economic viability of bioenergy projects by reducing both capital and operational costs [92]. In Colombia, for example, a VAT exemption on machinery and equipment was found to make waste-to-energy projects more attractive for investment, especially in larger urban centers [92]. Similarly, a proposed VAT exemption in Indonesia is intended to reduce the gap between biomass production costs and regulated prices, making projects more financially viable, though legal reform would be required [93]. Finally, Investment Tax Credits (ITCs) represent another form of capital support, but no studies in the reviewed literature have examined their application in the bioenergy sector.

The policy research on Investment and Capital Support instruments reflects a clear pattern of targeting sectors that require maximum financial de-risking by the state. Liquid Biofuels (47%) and Energy Crops (30%) are the most frequently studied recipients of these policies, particularly grants, loans, and dedicated public funds. This dominance is consistent with their highly capital-intensive nature and reliance on direct government expenditure to achieve competitiveness, as these instruments impose a high fiscal cost and place most project risk on the state. Conversely, instruments that incur an indirect fiscal cost (foregone revenue), such as VAT exemptions, appear more frequently in studies of Forest-Based Biomass (22%) and Biogas (13%), where established markets allow for greater risk transfer to private actors. Research attention remains minimal for waste-to-energy

solutions (Municipal/Industrial Waste: 8%; Livestock Waste: 5%) and novel feedstocks like algae (3%), indicating a lack of significant, risk-absorbing public capital support and a corresponding policy–research deficit in these nascent sectors (Figure 10).

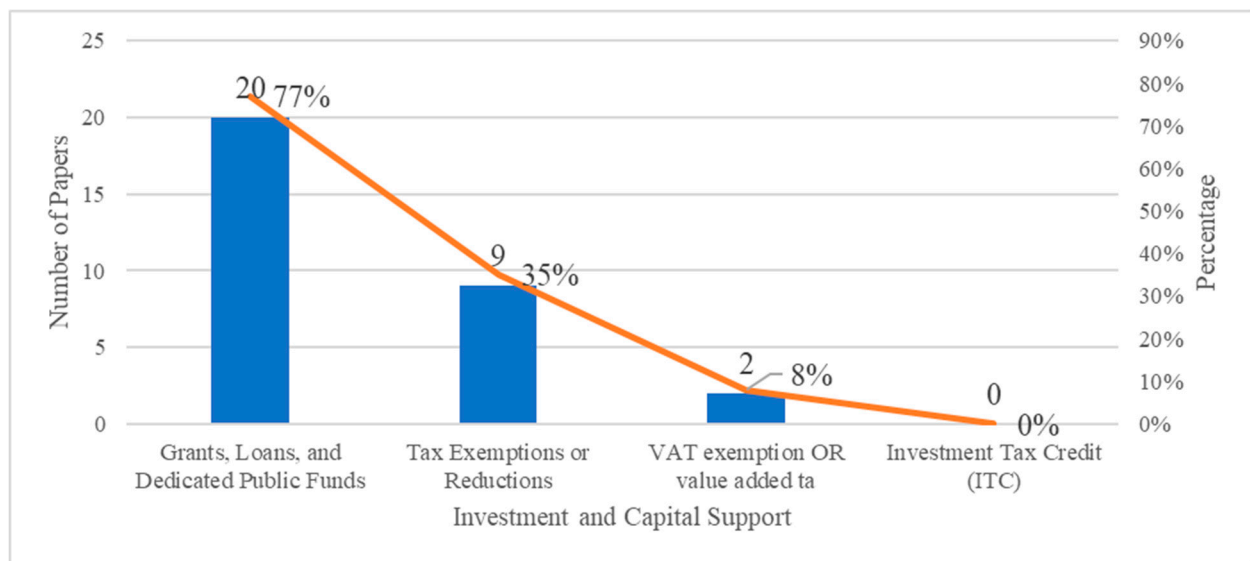


Figure 15. Frequency of Investment and Capital Support Policy Instruments (Number and Percentage).

E. Behavioral Sustainability Measures

Behavioral Sustainability Measures are the lowest used policy, accounting for 14% (22 out of 156) of the literature. These policies do not rely on direct financial incentives or regulatory mandates; instead they focus on influencing attitudes, knowledge, and social norms to encourage voluntary, sustainable behaviors. This approach enables individuals and organizations to make informed, environmentally conscious choices, thereby supporting the adoption of bioenergy.

Information and Education Campaigns are the most studied behavioral instrument, accounting for a significant 86% (19 out of 22) of the literature. These campaigns are crucial for fostering public acceptance and awareness, which are often major barriers to bioenergy deployment [94,95]. For instance, studies in Australia found that providing clear, simple information increased public support for biogas by 5–10% [96], and in Poland, awareness was a more significant factor than socioeconomic conditions in a household's willingness to adopt biogas technology [97]. These campaigns are not limited to the general public, as research also highlights their role in targeted education for students and professionals to increase interest in sustainable practices [98]. The effectiveness of these campaigns often depends on how information is framed; for example, portraying bioenergy as a method of waste utilization can significantly boost public acceptance [99]. In the aviation sector, focused campaigns led by credible organizations are essential to improve public understanding of biofuel benefits and to accelerate their market adoption [100,101].

Green Public Procurement (GPP), which accounts for 14% (3 out of 22) of the research, is a complementary behavioral measure that leverages the purchasing power of public entities to create local demand for renewable energy, such as biogas [102]. GPP can involve municipalities purchasing biogas vehicles or public institutions procuring electricity from renewable sources, often relying on a voluntary consumer element. Studies on Green Pricing Programs in the U.S. found that while enrollment is currently low, consumers value flexibility, local energy generation, and carbon emission reductions, all of which can be leveraged through better public education and outreach [103]. The success of GPP,

however, requires a clear political vision, active participation from local authorities, and stable investment support to build the necessary infrastructure and actor networks [102].

As shown in Figure 9, much of the research and policy attention is directed toward general bioenergy (36%) and general biomass feedstocks (28%), reflecting an emphasis on understanding overall public attitudes rather than focusing on specific technologies or raw materials. Among specific feedstocks, Municipal & Industrial Waste and Forest-Based Biomass each account for 20% of studies, highlighting the social challenges associated with these resources. Waste-to-energy projects often encounter local opposition due to concerns about odor and aesthetics, while forestry biomass can raise land use and environmental issues, underscoring the need for behavioral policies to overcome social barriers. Similarly, Biogas (23%) benefits from such campaigns, suggesting a focus on building public acceptance for waste-to-energy conversion. In contrast, Energy Crops (12%) and Agricultural Residues (4%), which are primarily supported through economic and regulatory measures, receive less attention in this policy category, as do Bioelectricity (5%) and Bioheat (5%). These lower percentages imply that these sectors are either less reliant on behavioral interventions or have already addressed social acceptance challenges effectively.

6. The Co-Occurrence of Policy Instruments in Bioenergy Research

A critical advancement in policy research is the move from studying instruments in isolation to analyzing their combinations. This review distinguishes between simple co-mention and deeper integrated analysis. Integrated analysis is defined here as studies that model, simulate, or quantitatively assess the interactions between two or more policy instruments within a unified methodological framework. This approach is essential for understanding synergies, trade-offs, and the real-world performance of policy mixes.

The analysis reveals that certain policy categories are far more likely to be analyzed in combination, pointing to established strategic priorities. The frequency of these integrated analyses underscores the strategic centrality of Price-Based Policies, which are combined with other categories more often than any alternative, as shown in Figure 16. The most prevalent analytical pairing is Market-Based and Price-Based Policies (17 out of 156 studies). This reflects a research priority on frameworks that use market signals (e.g., carbon prices) alongside direct financial incentives (e.g., subsidies) to correct market failures and de-risk investments simultaneously. The next most common combination involves Price-Based Policies and Investment and Capital Support (12 studies), demonstrating a focused strategy on mitigating high upfront capital costs with grants or loans while ensuring long-term revenue stability through price guarantees. This is followed by integrated studies of Price-Based and Quantity-Based Policies (9 studies), a crucial mix for ensuring that volume mandates (e.g., blending targets) are economically feasible. Furthermore, the combination of Investment and Capital Support with Quantity-Based Policies (11 studies) represents a secondary but vital research theme aimed at reducing the capital intensity of new bioenergy infrastructure needed to meet mandated demand.

At the instrument level (Figure 17), the most frequently co-modeled pair is Emissions Trading Systems (ETS) and Carbon Offsets (10 studies). This indicates a significant research effort dedicated to understanding flexible compliance mechanisms where regulated entities can use offsets to meet cap-and-trade obligations. The close pairing of ETS and Carbon Tax (9 studies) highlights academic interest in comparing and contrasting these two primary carbon-pricing mechanisms to avoid double regulation or design hybrid systems. Other notable co-modeled pairs, such as FiTs and Grants & Loans (6 studies) and Blending Mandates and Grants & Loans (5 studies), underscore the recognized necessity of coupling demand-pull or price-stability instruments with direct capital support to make bioenergy projects bankable. In summary, while many studies mention multiple poli-

cies, the integrated analysis of specific combinations—particularly those linking financial de-risking with market creation—defines the current frontier of sophisticated bioenergy policy research. This trend confirms that the field prioritizes complex policy designs aimed at establishing financial viability and market certainty as the foundational drivers for sector growth.

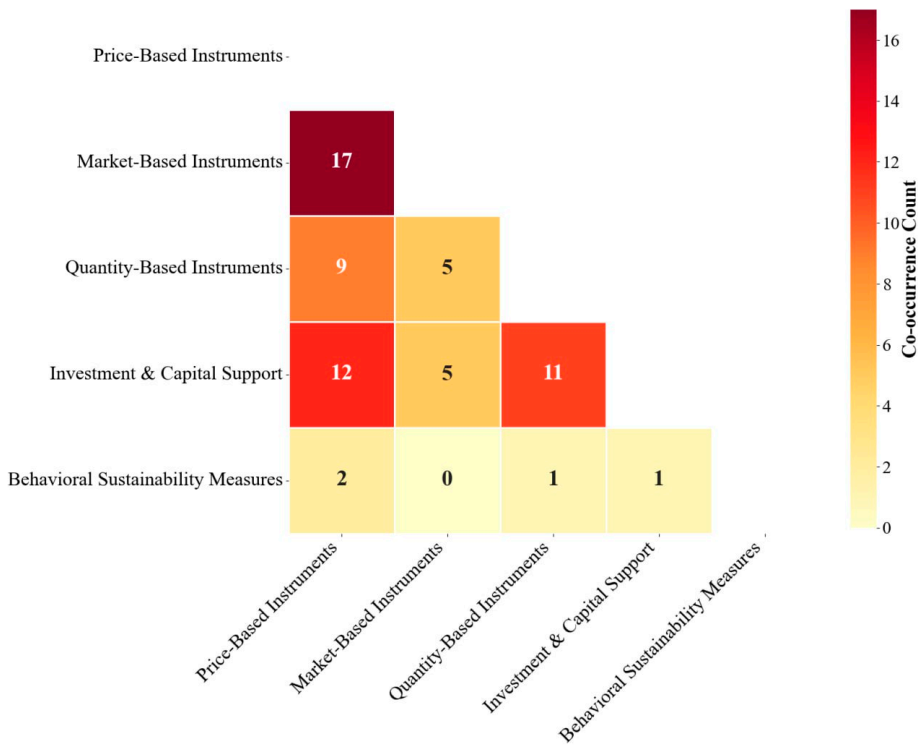


Figure 16. Co-Occurrence of Bioenergy Policy Categories Across Reviewed Studies.

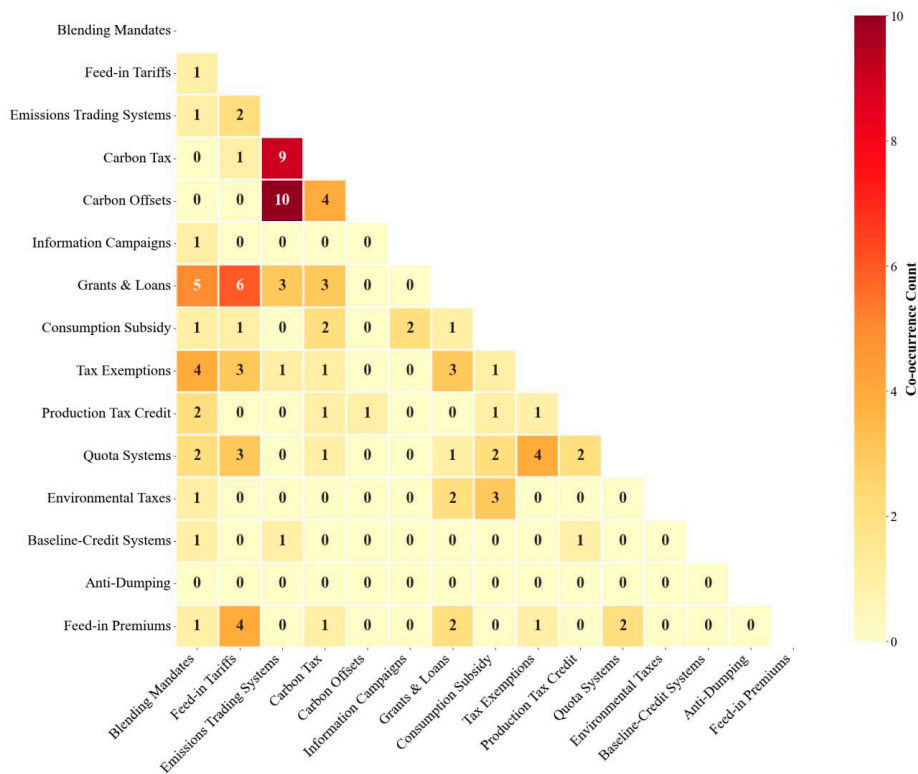


Figure 17. Most Frequent Co-Occurrences of Policy Instruments in Bioenergy Studies.

7. Supply Chain Perspectives

While previous sections focused on classifying policy instruments and examining their co-occurrence patterns, Section 7 extends this analysis by considering the bioenergy supply chain perspective. This approach contextualizes the policy instruments within different stages of bioenergy development, from feedstock production and logistics to processing, conversion, and end-use. By mapping policies to supply chain stages, we can identify which instruments are predominantly targeted at specific points in the value chain and where gaps exist. This connection provides a logical progression from understanding what policies exist and how they are combined to how they are applied across the bioenergy system, offering a more comprehensive view of policy impact and strategic priorities.

To visualize this mapping, Figure 18 illustrates how policy instruments concentrate across the supply chain. Key patterns include the following: (1) Price-Based (77 studies, 49%) and Investment Support (26, 17%) strongly target Processing & Conversion (83 studies, 53%); (2) Quantity-Based (35, 22%) and Behavioral (22, 14%) focus exclusively on Demand (68, 44%); (3) Logistics represents a critical gap (9 studies, 6%); (4) instrument specialization varies across the chain.

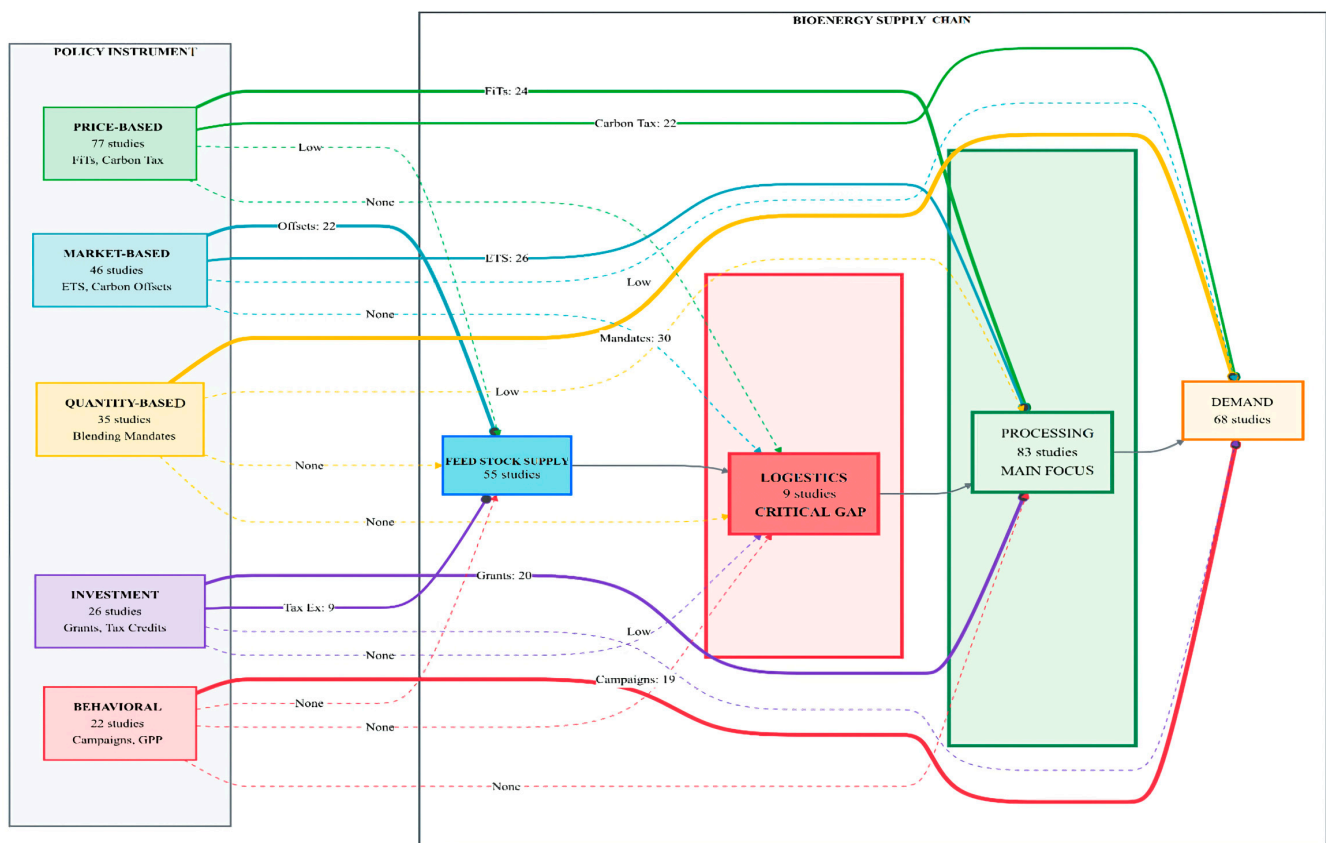


Figure 18. Distribution of Policy Focus on Supply Chain Stages in Bioenergy.

Given that some studies consider a range of policy instruments, they simultaneously investigate at various stages of the supply chain. Therefore, in this part we decouple the policy effects to determine their relative efficacy across various stages of the supply chain. The biomass-to-bioenergy supply chain begins with feedstock supply, which includes the production, harvesting, and gathering of raw biomass from its origins. This is followed by logistics (transportation), focused on moving feedstock to processing plants or distribution hubs. Next, processing & conversion transforms the biomass into usable bioenergy products, encompassing both pretreatment steps (e.g., drying, pelletizing) and main conversion

processes such as biopower, biofuels, or biochemicals. Finally, the end-use/demand stage delivers the finished products to consumers, including households, industries, and the transportation sector. By mapping policy support across these segments, feedstock supply, logistics, processing & conversion, and end-use, this section highlights where policy concentration is strongest and where potential gaps or bottlenecks exist along the entire bioenergy pathway.

Policy support for the bioenergy sector is primarily concentrated on the Processing & Conversion and Demand Side stages. A detailed review of the literature reveals that 53% (83 out of 156) of policies are designed to address production challenges and facilitate the conversion of raw materials into bioenergy (Figure 17). Concurrently, a significant portion, 44% (68 out of 156), directly targets the demand side to incentivize consumption. This dual focus underscores a strategic emphasis on strengthening both the production and market sides of the bioenergy industry. A meaningful share of policy attention is also directed at the Supply Side, accounting for 35% (55 out of 156) of policies, which indicates efforts to promote sustainable feedstock sourcing. The most notable finding, however, is the minimal policy attention paid to Logistics (transportation), which represents only 6% (9 out of 128) of the reviewed policies. This points to a critical area for future policy development, as efficient transportation serves as the essential link connecting all other stages of the bioenergy supply chain, from feedstock supply to processing and final delivery to the end-user. To better understand how specific policy instruments influence these different stages of the bioenergy supply chain, a deeper analysis is provided subsequently.

Price-based policies are primarily used to promote bioenergy with a specific focus on the Processing & Conversion stage of the biomass-to-bioenergy supply chain. This is evident in the literature, where 21 out of 26 papers on FiTs specifically target this stage. To address cost-competitiveness, studies often employ sophisticated models that ascertain the ideal level of financial backing for bioenergy production [104]. For instance, a notable investigation optimized China's biomass power generation subsidy, concluding that a strategically designed FiTs is critical. Such a policy design achieves a "win-win situation" by successfully maximizing company profitability and environmental outcomes while minimizing the government's financial outlay [104].

Beyond direct subsidies, other price-based and investment policies also focus on production. Carbon taxes, for example, are a prevalent instrument, with 19 out of 23 reviewed studies mentioning their use to regulate production facilities. These taxes incentivize the use of lower-emission fuels like biomass, making them a direct regulatory influence on the conversion process. A study on biomass co-firing with coal used a bi-level multi-objective optimization model to find the best strategies for managing a hybrid carbon tax and ETS, confirming that a carbon tax can effectively promote cleaner energy generation at the plant level [105]. Similarly, trade instruments like anti-dumping duties are designed to protect domestic bioenergy producers from foreign competition, thereby preserving market opportunities and ensuring the viability of local production facilities [56].

Furthermore, Investment & Capital Support policies are heavily concentrated on the Processing & Conversion stage to address the high upfront costs of building new facilities. Instruments like VAT exemptions and grants or loans are crucial for improving the economic feasibility of bioenergy projects. For example, a study in Colombia found that VAT exemptions and other tax incentives were essential for making waste-to-energy projects economically viable, particularly in larger urban centers [92]. Another techno-economic analysis used discounted cash flow to appraise the investment in a cellulosic bioethanol plant, highlighting how such support can make a biorefinery a viable investment within a low-carbon future [88]. This strategic focus underscores a collective understanding

that the most significant financial and technical barriers to bioenergy lie in its production and processing.

The second most targeted area by policies is the demand side. This is primarily driven by two key policy categories, Behavioral Sustainability Measures and Quantity-Based Instruments, which create a pull for bioenergy products from end-users.

Behavioral Sustainability Measures are exclusively focused on influencing the demand side. The entire body of literature reviewed on this topic (22 out of 22 papers) targets consumer perception and behavior. Studies on Information & Education Campaigns, for example, use surveys and models to analyze how providing nuanced information about bioenergy affects public perception, attitudes, and the intention to use bioenergy [106]. In another study, which investigated biodiesel supply chains, advertising expenditures were explicitly incorporated as a determinant of demand, thereby treating consumer awareness as a strategic decision variable within the system [107].

Similarly, Quantity-Based policies are overwhelmingly aimed at the demand side, with 37 out of 38 papers in this category investigating this stage. These policies promote bioenergy by creating a guaranteed, or “virtual,” demand through instruments like blending mandates. A study on OECD countries found a direct positive relationship between blending mandates and an increase in domestic biofuel production, confirming that these policies effectively stimulate demand which, in turn, incentivizes supply [90]. While blending mandates are a common tool to promote biofuel consumption in countries like India [108], the literature notes that these policies are not always effective in achieving broader environmental or social goals [109].

While most studies focus on demand, a notable exception is the Quota System, a quantity-based instrument where supply-side analysis is more prevalent. This policy directly addresses the supply side of the chain. It provides financial subsidies linked to the quantity of production, specifically designed to incentivize farmers to cultivate bioenergy crops by mitigating financial risk and covering high establishment costs. The research demonstrated that the Quota System can significantly reduce the total cost of fulfilling a biofuel mandate, thereby showcasing a distinctive case of a quantity-based policy promoting feedstock supply rather than targeting final consumption [110].

In contrast to the demand-side focus, the supply side of the bioenergy supply chain is primarily targeted by Market-Based policies. Within this category, Carbon Offset instruments are the most prominent, used in 16 out of 22 papers to influence feedstock sourcing. These policies provide financial incentives to feedstock suppliers, such as farmers or forest managers, to implement practices that reduce greenhouse gas emissions. For instance, studies on the California compliance offset program show how it incentivizes dairy farmers to install methane digesters, thereby generating carbon credits and a new revenue stream [111]. Other research explores how carbon offsets can be used to promote sustainable forestry and land-use practices by assigning a monetary value to the carbon sequestered by these activities [112]. These studies underscore how market-based mechanisms can drive bioenergy feedstock supply by turning environmental benefits into a tradable commodity.

It is important to note that very few studies have investigated the logistics (transportation) stage of the supply chain, with this critical link appearing in only 6% (9 out of 156) of the literature. One example is an optimization model that examines the trade-off between carbon credit costs and the transportation of biomass, revealing how a cap-and-trade system can influence decisions about shipping biofuels and the overall costs and emissions of the supply chain [58]. The minimal attention to this stage represents a significant research gap, as logistics is the essential connector between feedstock supply, processing, and final delivery.

8. Conclusions

This systematic review provides a comprehensive analysis of supportive policy instruments for bioenergy development, drawing on 156 peer-reviewed studies published between 2015 and August 2025. By consolidating fragmented evidence across disciplines, the review identifies key patterns in research focus and strategic policy design, while also revealing critical gaps that continue to constrain the sector's advancement.

Overall, the synthesis highlights a policy landscape characterized by increasingly sophisticated yet highly concentrated interventions. It delineates the dominant strategic paradigms shaping contemporary bioenergy policy research, examines their structural limitations, and outlines forward-looking directions for policy evolution to more fully realize the contribution of bioenergy within the renewable energy transition.

The findings of this review provide clear and systematic answers to the four research questions (RQs) that guided the study. RQ1 is answered by the clear dominance of price-based, market-based, and investment-support instruments, revealing financial de-risking as the paramount policy objective. RQ2 finds that policy support is strategically concentrated on the processing/conversion and demand-side stages, while the logistics and transportation segment remains critically underexplored. RQ3 identifies a strong research concentration on liquid biofuels from established feedstock pathways (energy crops, agricultural residues), indicating a technological path dependency that sidelines waste-to-energy and bioheat applications. Finally, RQ4 is addressed by translating these structural gaps into a forward-looking agenda: the identified deficits directly guide the need for integrated policy mixes, targeted diversification toward neglected sectors, and more adaptive, data-driven governance frameworks to unlock bioenergy's full sustainable potential.

8.1. Dominant Paradigms and Strategic Focus

The analysis highlights three principal and interconnected strategic paradigms that currently shape the policy–research landscape:

1. Primacy of financial de-risking

The policy instrument portfolio is strongly dominated by mechanisms—particularly Price-Based (e.g., Feed-in Tariffs) and Market-Based instruments—aimed at ensuring economic viability and reducing high upfront capital risks [104,113]. Their frequent co-occurrence with Investment and Capital Support instruments confirms that improving cost-competitiveness remains the central driving objective in both policy design and academic research. The instruments vary significantly in terms of the level of certainty they provide to investors: Feed-in Tariffs offer high price certainty over the long term, while Market-Based tools such as Emissions Trading Systems introduce more variable and market-dependent risk-return profiles.

2. Consolidation of technological path dependency

Research and policy attention remain highly concentrated on liquid biofuels and their established feedstock pathways, especially energy crops and agricultural residues [27,89]. While this focus has supported the scaling of mature technologies, it also reinforces a capital-intensive deployment model and limits diversification toward waste-to-energy pathways and the bioheat sector.

3. Dual supply-chain focus with a critical omission

Policy support is primarily directed toward the Processing and Conversion stage and the Demand Side in order to address production constraints while simultaneously stimulating market uptake. However, the intermediary Logistics and Transportation stage

receives minimal attention (approximately 6% of studies), creating a structural gap that may generate bottlenecks and increase system-level costs [113].

8.2. Critical Challenges and Limitations of Current Policy Instruments

These dominant strategic approaches are associated with several interconnected challenges that may reduce policy effectiveness and weaken sustainability outcomes:

- Fiscal burden and design sensitivity

Price-based instruments, particularly Feed-in Tariffs and direct subsidies, can impose long-term public expenditure commitments. Their effectiveness depends strongly on accurate calibration (e.g., tariff levels and degression rates), requiring continuous adjustment to prevent inefficiencies or market distortions [104,113].

- Market distortions and unintended consequences

Quantity-based mandates, such as fuel-blending targets, can successfully create demand but may also increase overall system costs, contribute to trade imbalances, and intensify land-use pressures when implemented without complementary safeguards [78,82,109].

- Implementation complexity and integrity risks

The credibility of Market-Based instruments, including emissions trading systems and carbon offset mechanisms, relies on robust monitoring, reporting, and verification frameworks [57,70]. Challenges related to carbon accounting, additionality, and price volatility may undermine environmental integrity and investor confidence [71]. Furthermore, while these instruments offer high flexibility in compliance pathways, they also require sophisticated market infrastructure and regulatory oversight to function effectively.

- Reinforced technological lock-in and fragmented development
- Continued concentration on liquid biofuels and conventional feedstocks creates a self-reinforcing cycle of research attention and investment [27,89], limiting the development of circular-economy feedstocks such as municipal solid waste and constraining expansion of the bioheat sector.

8.3. Future Policy Trajectories and Desired Instrument Evolution

Addressing these limitations and aligning bioenergy with circular-economy and net-zero objectives requires a transition toward more integrated, adaptive, and inclusive policy frameworks. Key future directions include:

1. Integrated hybrid policy portfolios

Future policy design should move beyond single-instrument approaches and combine complementary mechanisms—for example, linking carbon pricing with targeted production support or integrating sustainability quotas with certification schemes and Green Public Procurement. Further research is needed to model the dynamic interactions and system-wide impacts of such policy mixes across the full supply chain. Designing such portfolios requires balancing instruments that provide high certainty for investors with those that offer flexibility and market responsiveness.

2. Targeted instruments for strategic diversification

Breaking existing path dependency requires policies that specifically support underdeveloped segments:

- Logistics and infrastructure: grants, tax incentives, and public–private partnerships for biomass aggregation, storage, and transportation systems.

- Bioheat and waste valorization: differentiated incentives such as heat premiums, district-heating investment credits, and market commitments for waste-derived bioenergy [102].
- Next-generation innovation: expanded R&D funding and pilot-scale support for emerging technologies, including algal biofuels and BECCS [89].
- Adaptive and data-driven governance

Future policy frameworks should incorporate review mechanisms and digital monitoring tools to enable performance-based adjustment over time, supporting more responsive and evidence-based governance [60].

3. Stronger behavioral and social-institutional integration

Economic instruments should be complemented by behavioral and institutional measures, including public communication strategies, Green Public Procurement, and community benefit-sharing mechanisms, to enhance social acceptance and support a just transition [99,100].

8.4. Concluding Synthesis

As the global energy transition accelerates, effective bioenergy policy remains essential for achieving climate mitigation targets. Although current research demonstrates increasing sophistication in optimizing established sectors, it also risks reinforcing a narrow and path-dependent deployment model. The comparative summary of policy instruments presented in this review (Table 3) illustrates the distinct yet complementary roles of price-based, market-based, quantity-based, investment, and behavioral measures, particularly in terms of the trade-offs between flexibility and certainty they offer to stakeholders. Addressing the identified gaps—through integrated policy design, targeted diversification, adaptive governance, and socially inclusive frameworks—is therefore critical for guiding the sector toward a more resilient and sustainable future.

Table 3. Comparative summary of policy instruments.

Dimension	Price-Based	Market-Based	Quantity-Based	Investment Support	Behavioral Measures
Primary Mechanism	Adjust prices (taxes/subsidies)	Tradable permits or certificates	Mandatory volume targets	Capital grants or tax relief	Information and education
Fiscal Impact	High burden or revenue	Low burden or revenue	Low direct cost	High burden	Minimal cost
Key Sector Focus	Liquid biofuels, electricity	Liquid biofuels, solid biomass	Liquid biofuels	Liquid biofuels, energy crops	General bioenergy, biogas
Supply Chain Focus	Processing and conversion	Feedstock supply and conversion	Demand side	Processing and conversion	Demand side
Risk Allocation	Government and industry	Market and private actors	Industry	Government	Low or none
Certainty Level	High (e.g., feed-in tariffs)	Variable (market-driven)	High (mandates)	Project-specific	Variable
Flexibility	Moderate	High	Low	Low	High
Common Pairings	Market-Based, Investment	Price-Based, Carbon offsets	Price-Based, Investment	Price-Based, Quantity-Based	Often standalone

This review provides a structured foundation for the development of more comprehensive and effective bioenergy policy strategies capable of supporting the broader renewable energy transition.

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