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Unlocking Sustainability Transitions in Construction Materials in Europe: A Multi-Level Perspective on the Adoption of Rice Straw Ash

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Abstract

The construction industry is one of the largest consumers of resources and a significant contributor to environmental degradation in Europe, accounting for 50% of natural resource use, 34% of waste generation, and 5–12% of greenhouse gas emissions. In response to growing environmental pressures and regulatory demands, the sector needs to adopt sustainable material alternatives. This study examines the potential adoption of rice straw ash in the European construction sector. The research applies a PRISMA-based systematic literature review, integrated with the Multi-Level Perspective (MLP) framework, PESTLE, and SWOT analyses to provide a comprehensive assessment of the socio-technical dynamics influencing its adoption. The findings identify barriers including the absence of standards, fragmented supply chains, and inconsistent material quality. However, it highlights strategic opportunities such as the declining availability of conventional SCMs, alignment with the EU's regulations and circular economy principles, and growing public awareness of sustainable materials. The study concludes that advancing the transition to RSA will require regulatory support, the development of standards, and coordinated collaboration among stakeholders to achieve large-scale implementation. By integrating multi-dimensional transition factors, this research contributes actionable insights for advancing sustainable material adoption.

Keywords: sustainable; construction; rice straw ash; supplementary cementitious materials; circular economy

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1. Introduction

Circular economy (CE) aims at reducing the consumption of natural resources and minimizing waste generation by promoting the derivation of value from waste materials, thus closing the loop and fulfilling sustainability goals [1]. The increasing global emphasis on circular economy practices has spurred the construction industry to seek alternative materials to reduce environmental impact and support resource efficiency. The building and construction sector is one of the significant contributors to global environmental issues due to the substantial use of natural resources, waste generation, and high energy demand across different life cycle stages, such as extraction and manufacturing [2,3]. In the European Union (EU), buildings are responsible for approximately 50% of the use of natural resources, 34% of waste generation, and 5–12% of carbon emissions [4]. On the other hand,

more than five billion tons of agricultural residues are annually produced worldwide [5]. Globally, rice cultivation generates an estimated 800–1000 million tons of rice straw [6] and 104 million tons of rice husk every year [7]. Beyond rice residue, significant amounts of other agricultural waste are also produced every year, for example, over 500 million tons of wheat straw [8]. Most of these wastes are either burned or dumped in landfills, resulting in environmental, social, and economic issues [9].

The use of agricultural waste as a low-carbon Supplementary Cementitious Material (SCM) in cement and concrete production offers a promising solution to address these challenges. The shift from conventional materials to innovative alternatives is essential for achieving sustainability goals [10].

SCMs are powders made from siliceous, aluminosilicate, or calcium aluminosilicate compounds [11]. They are used to partially replace clinkers in Portland cement or concrete mixtures. Some SCMs, such as fly ash from coal-fired power plants, are by-products of other industries [11]; however, some of them are agricultural by-products, such as rice straw ash (RSA) and rice husk ash.

The utilization of low-carbon SCMs has gained attention for their ability to improve the durability and strength of construction products while reducing the environmental footprint of construction activities by reintroducing by-products, such as agricultural by-products, into industrial applications [12,13]. However, there is a lack of studies on the adoption and diffusion of them within the European construction sector, leaving a critical research gap. To address this gap, this study analyzes the factors influencing the adoption of low-carbon SCMs using RSA as an example in the European construction sector. RSA was selected for three main reasons: Firstly, rice cultivation generates huge amounts of straw globally [6], much of which is still burned or landfilled [14]. Secondly, it has a high silica content [14–17]. Finally, it has very limited adoption in Europe, making it a relevant case to investigate its transition.

RSA is derived from the combustion of rice straw and has emerged as a valuable by-product with potential applications in the construction sector [18,19]. Rice straw, which is an available agricultural residue in rice-producing regions (e.g., Southeast Asia), is typically disposed of through field burning. It leads to significant air pollution and environmental degradation [12,13]. However, the RSA contains high silica content and exhibits properties that can enhance the performance of cement and concrete [10]. Prior research has highlighted the pozzolanic properties of RSA, making it a valuable SCM. Therefore, RSA could be more widely utilized in concrete production [11,14–17]. Additionally, several studies have examined key factors influencing its effectiveness, such as chemical composition, combustion conditions, and the optimal RSA percentage in concrete [17–22]. Reported values of the optimum replacement percentage of cement with RSA in concrete can vary, depending on different factors like the cultivation practice for rice [20], combustion process, burning temperature, and time [21] as well as the addition of other materials. For instance, some studies reported an optimum of 10% [16,22–24]; however, some studies suggested a 20% replacement of cement with RSA [21]. Another study noted that a composite blend of 5% RSA and 7.5% microsilica achieved the highest compressive strength. Furthermore, a study demonstrated that combining 10% RSA with 10% microsilica significantly improved the strength properties [25] while other research mentions up to 20% RSA and 2.5% nano sesame stalk ash, showing the highest splitting tensile strength [26].

Some research has also assessed the environmental impacts of incorporating RSA into concrete production [13,27]. Additionally, several studies highlight that RSA contains a lower percentage of silica oxide and higher levels of alkaline oxides compared to rice husk ash. This higher alkali content can negatively affect how well cement and concrete hold

up [28]. Despite these compositional differences, RSA remains a promising SCM because it is widely available, has good pozzolanic activity, and supports the circular economy.

The Life Cycle Assessment results demonstrated that using rice straw as a biomass source for electricity generation, followed by using RSA as an SCM, can offset all significant environmental impacts, assuming substitution for conventional electricity sources [27]. As mentioned in the previous paragraph, there is a lack of studies on the adoption and diffusion of such materials within the European construction sector, highlighting the need for further exploration. To address this gap, the Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) factors influencing the adoption and diffusion of RSA are analyzed as Strengths, Weaknesses, Opportunities, and Threats (SWOT) under the multi-level socio-technical transition framework to comprehensively understand the dynamics at play.

This paper is structured as follows. Section 2 introduces the theoretical framework based on socio-technical transition theory and the multi-level socio-technical transition and system boundary of the study. Section 3 outlines the research methodology. Section 4 presents results and discusses the findings across the different levels influencing the adoption of RSA in the European construction sector. Finally, Section 5 concludes the paper.

2. Theoretical Framework

2.1. The Socio-Technical System

The adoption and diffusion of innovations (e.g., new products, processes, or practices) are associated with multiple challenges, as the transition process requires changes in existing socio-technical systems [29]. There are two main systems in transition: incumbent and niche socio-technical systems [30]. The key difference between these two systems lies in their level of organization and stability. In an incumbent system, the various components, such as rules, are mostly well-organized and work together smoothly. This makes the system stable [30]. On the other hand, niche systems provide space for innovation and experimentation [31]. These systems are still evolving, and their elements are not yet fully established. As a result, niche systems tend to be smaller in scale and less stable than incumbent systems, but they offer greater adaptability. Both socio-technical systems for implementing SCMs are shaped by a complex interplay of three interacting elements: infrastructures, actors, and institutions [31]. The actors in the incumbent system include construction companies, concrete producers, regulators and policymakers, environmental organizations, consumers, and governmental bodies.

The main actors emerging with the introduction of RSA are research organizations, public authorities, the supply chain, societal groups, production firms, users, and financial institutions (See Figure 1). The role of these actors is to exchange resources and build networks [31]. Each of these social groups has its own goal, and they operate within their own contextual environment. This means that they are somewhat independent but also rely on and interact with each other [32]. So, the coordination of their activities creates interdependence and connections between different parts of the system. For instance, the successful adoption of RSA requires researchers to validate its effectiveness, regulators to approve it, construction companies to accept and use the RSA, and consumers to demand it. Moreover, the interaction between different parts of the system can create synergies and friction, where the combined impacts of drivers increase or decrease the speed of adaptation to innovation [32].

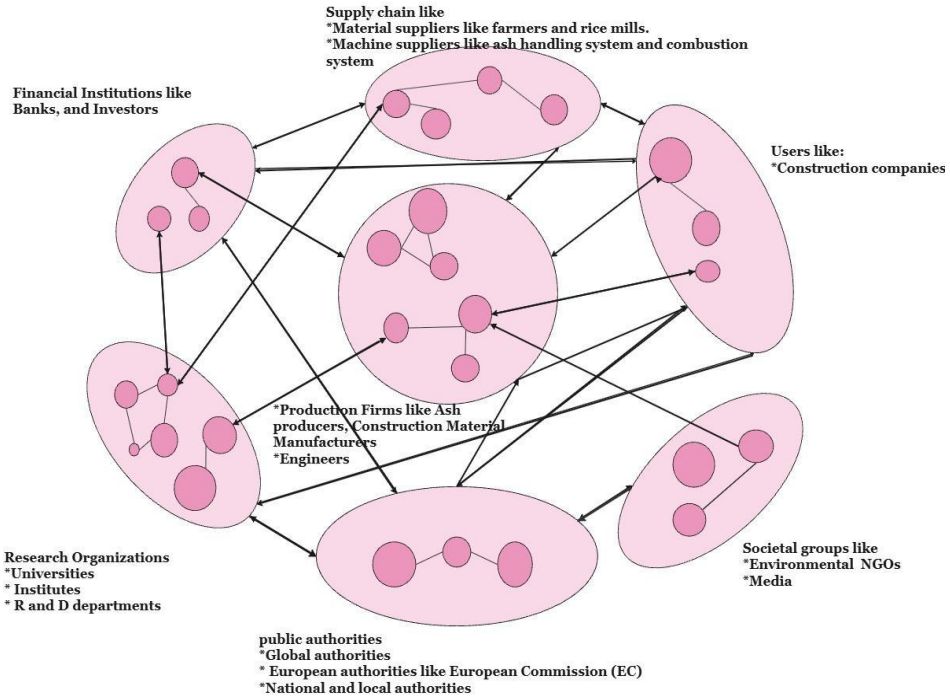


Figure 1. Social groups that produce socio-technical systems of diffusion of RSA in the construction sector in the EU. Adapted from [32]. Examples of actors within each group are marked with an asterisk (*).

These actors work within an institutional regime, which is the second element of the socio-technical system. An institutional regime is a flexible set of rules (such as standards and laws) and norms (such as values and personal beliefs) that shape how they act and interact [31]. In the case of the RSA system, the institutional elements of the incumbent system include existing standards and regulations (e.g., EN 206) and construction industry norms. However, new institutional elements, such as new standards and norms, can support the adoption of RSA as SCMs (e.g., new standards for pozzolanic materials of RSA).

The third element is infrastructure, which refers to all the physical and technical resources necessary for the socio-technical system to function properly [31]. Based on this, the elements in the incumbent system, consisting of infrastructure, include existing technologies and logistics used for concrete production and distribution. Combustion, treatment, and validation techniques are examples of the new technologies which aim to optimize the production and quality of RSA.

For a transition to occur, the incumbent system must become vulnerable to change, often due to pressures from the landscape or successful challenges from niche innovations. This destabilization creates opportunities for niches to scale up and potentially establish a new regime.

2.2. Multi-Level Socio-Technical Transition

Socio-technical transition is a comprehensive and broad process of change in market behavior, policy, and cultural meaning across the societal system [29], characterized by multi-actor and long-term processes [33]. The Multi-level Perspective (MLP) framework offers a comprehensive system-based approach to help analyze and understand the complex interactions among the dynamics of the transition occurring at different levels of analysis [31,34]. The core idea of MLP is that transitions are complex and nonlinear [35]. Additionally, it results from interactions across three levels of analysis: niches (the micro level), where innovations originate, regime (meso level), where practices and rules are established, and landscape (macro level), which includes external factors influencing the

system [31,32,34]. Regimes are nested within the landscape, and niches are embedded within regimes [31,36]. The central core of MLP is that the success of an innovation depends on the process in the niche, development in the regime, and the socio-technical landscape [36].

Niche provides a protected environment for testing and developing innovative ideas without pressure or barriers from the market [31,32]. Niches are significant for transitions as they serve as seeds for a systematic change process through experimentation, collaboration, networking, learning [35], visioning, and local projects [33]. A socio-technical regime is a semi-coherent network of interconnected rules and norms that guide the activities within social groups [29,35]. The socio-technical regime has different key dimensions, such as market, technology, policy, infrastructure, industry structure, and techno-scientific knowledge [35]. The regimes of the well-established, existing innovation systems create lock-in mechanisms which prevent transition to emerging innovation systems [29].

The socio-technical landscape refers to the broader external context and background that steers technological trajectories [31] and regime activities [37]. It consists of deep-seated structural factors, such as macroeconomic patterns, political systems, and culture, that are stable and slow to change [38]. The demands from the landscape, e.g., to mitigate climate change, put pressure on the existing regime to open up and facilitate innovations to be tested in niches. Figure 2 illustrates the dynamics of the RSA transition at different levels of analysis. This includes developments within niches (such as learning processes, local projects, and experimentation), the socio-technical regime (encompassing existing technologies, user preferences, infrastructure, and logistics), and landscape (including economic pressures, environmental concerns, and regulatory frameworks).

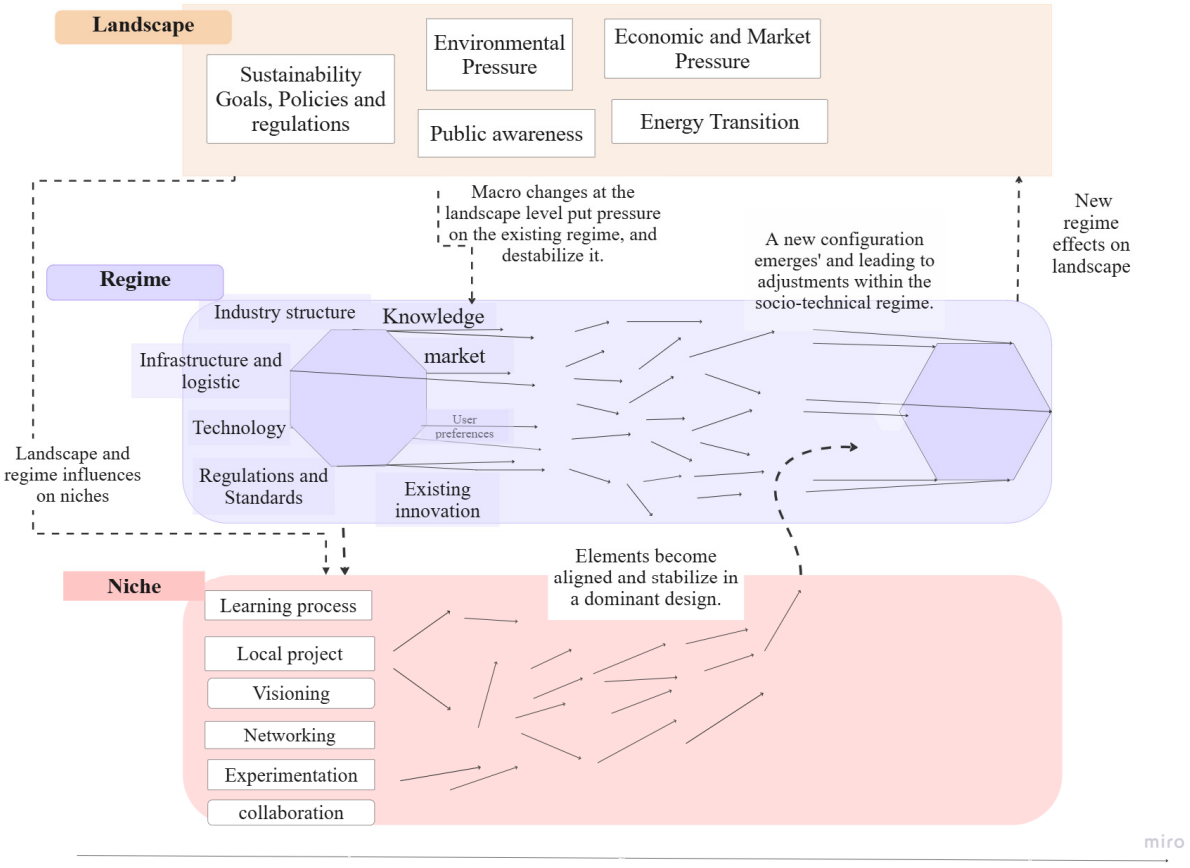


Figure 2. A visualization of the different levels of MLP and the dynamics of diffusion of RSA. Adapted from Ref. [35].

2.3. System Boundary

Defining the boundaries of an innovation system is a crucial step, as the way the system is delineated can significantly influence the research outcome [39]. In this study, the model of combination of sectoral, spatial, and technological systems is adapted [39]. As illustrated in Figure 3, this approach integrates sectoral dimensions (construction and agricultural sectors), spatial dimensions (the EU and major rice-producing regions, primarily South Asia), and technological dimensions. The implementation of RSA as an SCM in the EU is represented as TS2, while rice straw production is represented as TS3. The integration of these two technological systems is depicted as TS1.

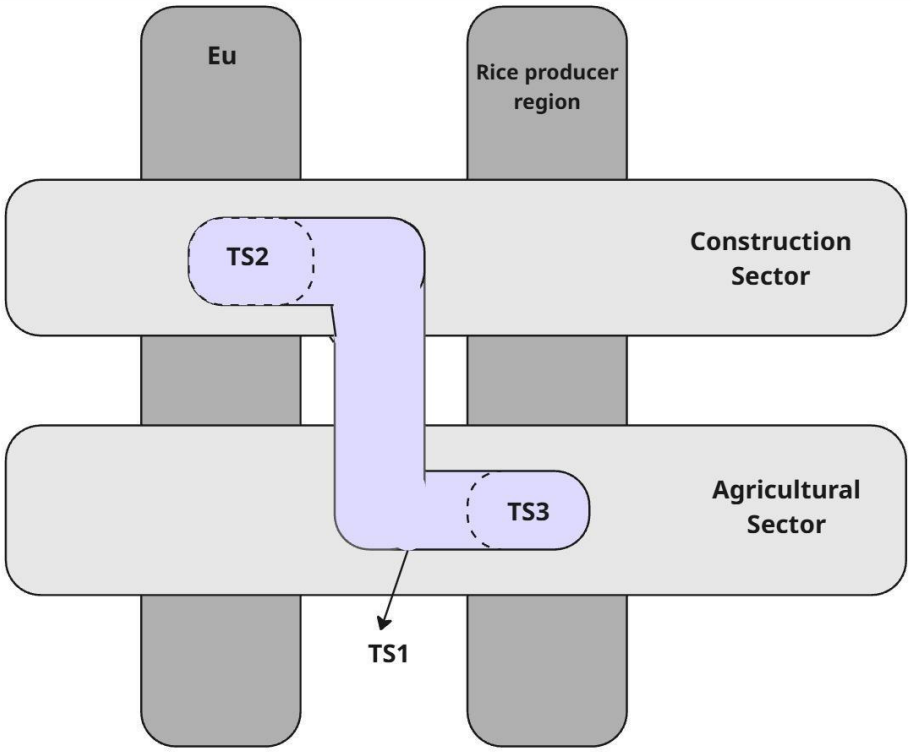


Figure 3. System boundary of the study. Adapted from Ref. [39].

3. Materials and Methods

In this study, the socio-technical transition process was analyzed by applying the Multi-Level Perspective (MLP), in which the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) factors influencing the adoption and diffusion of RSA were analyzed. A systematic literature review was conducted to better understand the state of the art and operationalize the methodological framework.

3.1. Systematic Literature Review

A systematic literature review was conducted, following the meta-analysis protocol PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [40], to understand the factors affecting the adoption of RSA in the construction sector or as an SCM. PRISMA establishes a framework to promote transparency and reproducibility [3]. Additionally, this enables readers to assess the reliability and credibility of the research findings [3].

A systematic literature review was conducted to extract data on SWOT and PESTLE analysis. The Scopus database was queried with the following terms:

TITLE-ABS-KEY ("Rice Straw Ash") AND TITLE-ABS-KEY (concrete) AND (TITLE-ABS-KEY (strength) OR TITLE-ABS-KEY (weakness) OR TITLE-ABS-KEY (opportunity) OR TITLE-ABS-KEY (threat) OR TITLE-ABS-KEY (barrier) OR TITLE-ABS-KEY (challenge) OR TITLE-ABS-KEY (driver) OR TITLE-ABS-KEY (limitation)) AND (LIMIT-TO (LANGUAGE, "English")) AND (EXCLUDE (SRCTYPE, "k")) AND (EXCLUDE (DOCTYPE, "tb")).

The initial search retrieved 41 records. After automated screening to exclude non-English articles, retracted papers, and book series entries, 37 studies remained for abstract evaluation. Of these, studies that did not focus on the research topic, specifically the implementation of RSA in concrete, were excluded, leaving 27 studies for full-text analysis. However, 2 of these were removed due to the unavailability of full-text access, resulting in 25 studies being included from the database. To ensure comprehensive coverage of the RSA implementation in concrete terms, an additional 25 relevant records were identified through alternative methods, such as citation tracking, and were included in the study. In total, 50 studies were included in the analysis (see Figure 4).

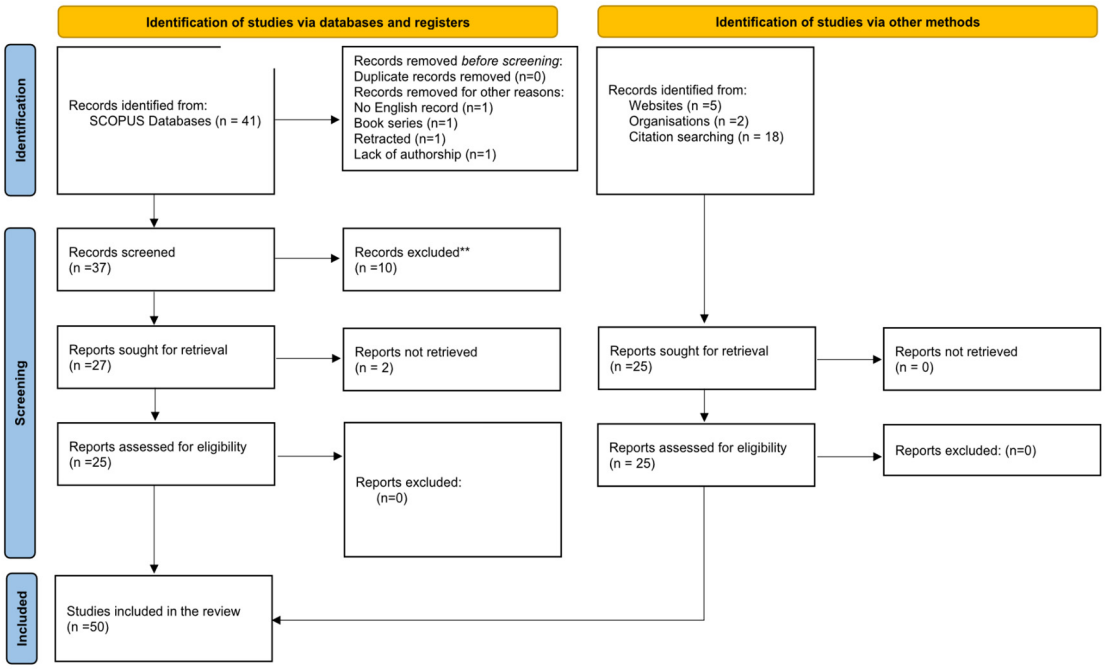


Figure 4. PRISMA Protocol for the Systematic Literature Review. The double asterisk (**) indicates the number of records excluded during the title and abstract screening stage. Adapted from [40].

The keyword "Europe" was added to the search query to ensure the inclusion of studies relevant to the European context. However, this refinement did not return any additional relevant records, highlighting a research gap in this area. To address this gap, supplementary studies and reports were manually identified and included through snowball sampling techniques. These sources specifically focused on the European Union's context, covering aspects such as regulatory frameworks, standards, and the use of other common SCMs.

3.2. SWOT, PESTLE, and Multi-Level Perspective Analysis

To address the objective, the present study employs a combination of SWOT, PESTLE analysis, and the MLP framework to explore the factors influencing the adoption of RSA in the European construction sector. The MLP framework, one of the most widely used frameworks for understanding transition [41], was selected to investigate the socio-technical transitions required for the adoption of RSA in the concrete industry in the EU. It examines the interaction between niche innovations, regimes, and the landscape. Ac-

cording to the Multi-Level Perspective, a regime shift occurs when a niche innovation is sufficiently developed, and the existing regime is disrupted by intense pressure from the landscape. This disruption allows innovations to emerge and eventually become part of the mainstream [37,38]. The MLP is relevant to the diffusion and adoption of RSA in the construction sector, since it proposes a framework for understanding the multi-level interactions that influence the adoption of RSA. Furthermore, this approach is aligned with prior studies [35,42,43] that used MLP to study the diffusion toward more sustainable materials and technology.

SWOT analysis is a valuable tool for analyzing the factors influencing socio-technical transition. Its main aim is to identify the internal (strengths and weaknesses) and external (opportunities and threats) characteristics of the system [37]. Strengths are internal positive attributes that boost performance, while weaknesses are internal limitations that hinder performance. Opportunities are external factors that can support the entity, while threats are external challenges that could delay the entity's goals [37]. The SWOT factors influencing the socio-technical transition processes can be categorized as Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) factors. Although PESTLE and SWOT analyses are traditionally used in management and business contexts, this study adapts them to systematically analyze the socio-technical factors influencing transitions. These methods have been previously applied in prior academic studies, such as examining the opportunities of digital tracking technologies in the precast concrete sector in Sweden [44], assessing sustainability in adaptive reuse projects [45], and analyzing strategies for the deep renovation market of detached houses [46].

4. Results and Discussion

This section examines interactions across three levels: niche innovations, socio-technical regimes, and the landscape of RSA.

4.1. Landscape Level

4.1.1. Opportunities

The cement industry faces significant environmental challenges due to its high greenhouse gas emissions (approximately 5–8% of global CO_2 emissions), energy consumption, and reliance on natural resources [47]. At the same time, the conventional disposal of rice straw often involves open-field burning, which releases harmful pollutants and greenhouse gases, contributing to air pollution and climate change [48]. A promising solution to address both issues is the incorporation of RSA as a partial cement replacement in concrete. By replacing a portion of cement with RSA, greenhouse gas emissions from cement production can be reduced, lowering the overall carbon footprint of the construction industry [23,27,28,49,50]. Studies show that incorporating RSA into concrete produces fewer emissions than traditional Portland cement while supporting circular economy policies and sustainable construction practices [13]. A cradle-to-gate analysis shows that producing 120 kg of RSA emits approximately 87 kg of CO_2 eq. In contrast, producing the same amount of Portland cement emits 846 kg of CO_2 eq. This shows a reduction of more than 89% in CO_2 emissions when substituting RSA for Portland cement as an SCM [27]. Additionally, repurposing rice straw waste into RSA prevents open burning, reduces air pollution, and promotes a circular economy and a more sustainable waste management approach. By addressing both the environmental issues of cement production and the impacts of rice straw burning, RSA offers a viable pathway toward greener construction and improved air quality.

The regulatory and policy frameworks play a critical role in driving the adoption of new materials. There are different global policies that promote the decreasing emission of

greenhouse gases and a circular economy, like the Paris Agreement [51] and the Sustainable Development Goals (SDGs), especially SDGs 9, 11, 12, and 13. In the EU, the Circular Economy Action Plan, the European Green Deal [52], and the Energy Performance of Buildings Directive [53] are some examples of regulations and initiatives for adopting sustainable materials, reducing energy consumption, and minimizing waste. Implementing RSA as an SCM in concrete aligns with these regulations and initiatives by repurposing agricultural waste into valuable construction materials (Figure 5).



Figure 5. Key Policy and Sustainability Agendas in the EU that support circular economy practices and their Relevance to RSA Adaptation (Source: Authors' own elaboration based on data from the literature [51–54]).

The EU Taxonomy Regulation sets CO_2 eq emission thresholds for sustainable cement production [54]. By replacing cement with RSA, producers can reduce their emissions. Additionally, RSA supports the Do No Significant Harm principle [54] by repurposing agricultural waste, reducing air pollution, and promoting circular economy practices. From 2026 onwards, the Carbon Border Adjustment Mechanism [55] will impose a carbon cost on imports of CO_2-intensive products, such as cement. Using RSA to replace part of the clinker can lower CO_2 emissions. In addition, it helps European producers reduce these

costs. Furthermore, under the Waste Framework Directive, RSA must meet end-of-waste status to be recognized as a secondary raw material [56].

Furthermore, rising construction costs are prompting the exploration of cheaper alternatives such as RSA, which can partially substitute cement. Cement production is a significant financial burden, accounting for 45% of the total cost of concrete. This high cost raises concerns about the economic feasibility of large-scale construction projects, highlighting the need to shift towards alternative materials. By partially substituting cement, RSA can contribute to potential cost savings [57,58]. In addition, it generates income for farmers and local industries [59], lowers waste management expenses, and decreases the environmental and health impacts [60] and costs associated with waste burning and cement production.

Additionally, the ongoing shift away from coal-fired power plants across Europe affects the availability of fly ash traditionally sourced from coal combustion [58]. This development encourages the exploration of alternative SCMs, like RSA, to ensure a consistent supply of sustainable materials for the construction industry [58]. Furthermore, existing sustainability and waste management policies in the EU prioritize the use of rice straw for energy production [61], which can support its diffusion in the EU.

Apart from regulatory pressures, increasing public awareness and changing consumer preferences are influencing the growing demand for sustainable materials in the EU [62,63], such as for straw-based products [64].

4.1.2. Threats

Despite these opportunities, several landscape-level threats pose a significant challenge to RSA's diffusion. Climate change may jeopardize the sustainability of future rice production and farming systems [65], which may affect the availability of RSA. Rice straw decomposition can release essential nutrients, such as potassium, nitrogen, and phosphorus, thereby improving soil fertility and reducing fertilizer dependency [48,66]. However, incorporating rice straw into the soil is labor-intensive, and its slow decomposition rate often prompts farmers to collect or burn it [48]. In response to these challenges, studies have proposed alternative uses for rice straw, such as composting to return nutrients into the soil [67] or utilizing it as a substrate for mushroom cultivation [68]. If rice straw is diverted from its natural decomposition process or alternative uses to concrete production, it may reduce the availability of nutrients for soil enrichment, potentially causing a decline in soil quality. This depletion of organic matter can lead to a greater dependence on chemical fertilizers [48], which increases energy use and greenhouse gas emissions [58,69] and may degrade soil health in the long term.

4.2. Regime

4.2.1. Opportunities

Although some SCMs are well-accepted and widely used, the availability of fly ash may decrease significantly in the EU over the coming decades due to the phasing out of coal power plants [58]. However, the EU does not rely solely on local fly ash; some countries also import it. For example, Germany, one of the biggest importers of fly ash in the EU, imported 36 shipments between November 2022 and October 2023 [70]. Still, the expected local scarcity of fly ash opens opportunities for RSA.

Additionally, the use of SCMs in concrete within the EU is governed by the EN 206 standard, which offers a general framework for concrete production. This standard allows for the partial replacement of cement with inert or pozzolanic materials [71]. This flexibility presents an opportunity for the introduction of innovative SCMs such as RSA.

Furthermore, continuous research and innovation in the different fields of implementing SCMs are being carried out in many parts of the world to develop a broader range of competencies in this field, particularly in areas such as organic and inorganic chemistry and treatment processes [72]. Moreover, European contractors have varied expectations regarding building materials, such as lower costs and higher productivity. These expectations, combined with growing environmental concerns, drive researchers to focus on developing building materials that feature low CO_2 emissions, long-term durability, cost-efficiency, and the use of recycled materials [72].

4.2.2. Threats

Traditional SCMs hold a significant market share in the EU. For example, fly ash has been used in concrete for more than five decades worldwide. In addition, more than nine million tons of fly ash are used in cement and concrete annually in Europe [73]. The market value of fly ash was about USD 3.36 billion in 2021 [11,74].

Fly ash is a mature and widely used SCM in the EU [11] due to its well-developed processing methods and the established standards that guide its use [75]. EN 450, first introduced in the 1990s, formally established its use in concrete and cement applications across the EU [75].

Blast furnace slag availability is tied to steel production, which is not expected to increase in the EU [76]. In 2016, approximately 19.5 million tons of blast furnace slag were utilized in the production of cement and concrete. Its use has been supported by EN 15167 since 2006. These materials benefit from well-developed supply chain systems, for instance, long-standing producers, processors, and distributors of fly ash in Europe [77]. Together with decades of technical validation and research, standards, infrastructures, and vested industry interests constitute powerful lock-in mechanisms that reinforce the dominance of incumbent SCMs. By contrast, RSA has not entered the European market or gained widespread use. This imbalance highlights the challenges of overcoming regime stability. The following paragraphs discuss these dynamics.

The EN206 standard permits the use of pozzolanic materials in concrete, as it does not specify detailed requirements for each SCM. However, the acceptance of SCMs often relies on additional European standards that provide detailed specifications for specific materials. For instance, fly ash must comply with EN 450 [78]. Silica fume is regulated under EN 13263, and ground granulated blast furnace slag under EN 15167-1. The RSA market faces competition from these well-established standard materials [64]. Introducing new SCMs, such as RSA, requires navigating these regulations, which can be challenging due to the need for new standards and quality assurance measures.

Despite the established framework for SCMs in the EU, some materials are used without specific standards. Limestone is one of the most widely used SCMs, simply ground without heating. While limestone's substitution potential is relatively low, its effectiveness increases significantly when combined with other aluminum-rich additions, such as fly ash [76]. Natural pozzolans, such as volcanic ashes, are considered in EN 197 (a European standard that specifies the requirements for cements used in construction) and are used in some areas of Europe, including Italy, Greece, and Slovenia. In 2003, approximately 150 million tons were used worldwide in the cement and concrete industries [76].

The lack of established standards for new materials may make it harder for construction companies to use such materials [79–81]. Some studies emphasized that product standards are a significant factor in the cement market [82]. Although the use of RSA in concrete is still under investigation and not yet widely adopted, initiating its development and establishing standards would enhance the consistency and effectiveness of this tech-

nology in the future. In particular, missing guidelines, standards, and assurances could be reduced by working towards new regulations.

The EU's existing technologies, logistics, and supply chains are optimized for traditional SCMs. The integration of RSA, primarily produced in Asia, introduces additional logistical challenges such as transportation, storage, variability in sourcing, processing, and quality assurance. Regions with limited infrastructure for collecting and transporting rice straw face challenges in promoting its widespread utilization [64].

The treatment process of RSA is crucial for its quality. Several factors, including temperature and combustion duration as well as the RSA quality, significantly influence its pozzolanic properties [28]. Therefore, a precise burning process and quality control are essential to ensure the effectiveness of RSA in the construction industry [83,84]. However, this process can be expensive, posing a challenge to the adoption of RSA in the construction industry.

Using RSA is a new and innovative approach that needs investment in infrastructure and processing facilities. The initial cost may be high due to limited production capacity and setup expenses. The overall cost is likely to decrease, with increased production (economies of scale), accumulated experience (learning-by-doing), and technological improvement (learning-by-searching) [85]. However, research on the specific production and processing costs of RSA and similar SCMs remains limited [86], highlighting the need for further economic assessment to fully understand its long-term potential.

While rice husk (not straw) ash has been widely used as a cementitious material, there is limited knowledge and information about new materials, such as RSA [80,81]. Although recent studies have investigated several new sustainable SCMs that could compete with RSA [87], the lack of case studies and large-scale projects hinders the adoption of sustainable new materials like RSA in the construction sector [80–82].

Different studies highlight significant variability in the quality and chemical properties of RSAs due to variation in raw materials, combustion conditions, and processing methods [21]. Such discrepancies affect RSA's performance in concrete applications and its broader adoption in the construction industry. Ensuring the consistency of RSA properties is crucial for its effective use in cementitious applications, underscoring the need for standardized testing and classification. Industry stakeholders may be reluctant to embrace RSA due to the uncertainties regarding its performance. Producers and consumers often hesitate to transition from conventional materials to new alternatives due to perceived risks and uncertainties [81]. To eliminate these uncertainties, more studies need to be performed on applying RSA.

4.3. Niche Innovation

4.3.1. Weaknesses

RSA increases the water demand of cement paste, since it contains considerable amounts of unburned carbon, which is highly porous and absorbs more water [14,21,83]. Moreover, it reduces workability [88] and increases the initial and final setting times of concrete [14,83,84,89].

Since RSA is a new SCM with no regulations or legislation governing its use in concrete, extensive research is needed to develop it into an European standard for the construction sector. Another challenge is the seasonal availability of rice straw, which affects industries relying on a consistent supply [64]. Moreover, some studies report that RSA contains relatively high alkaline levels [28], which can negatively affect how well cement and concrete hold up. Therefore, careful assessment and control of the alkali content are essential before its use in construction applications.

Additionally, the variability in reported chemical compositions and the inconsistent and incomplete data across studies highlight the need for standardized testing and classification of RSA. Implementing uniform guidelines will ensure reliable use of cement and concrete production, enhancing material performance and sustainability. Additionally, a standard specifically for using RSA in concrete is crucial for gaining acceptance in the EU construction sector.

4.3.2. Strengths

RSA possesses several strengths that make it a cost-effective [87], high-quality and environmentally friendly alternative in the construction industry. RSA has a low market price, which helps to reduce construction costs [28]. Its use decreases dependency on traditional cement, a major contributor to global greenhouse gas emissions. Additionally, concrete containing RSA has strong resistance to chemical attacks, reducing the occurrence of cracks in the concrete [21,26,88]. RSA can be combined with other SCMs, such as fly ash, to increase the quality of the concrete [90].

One of the significant factors related to the implementation of RSA in concrete is its pozzolanic properties. Several studies reported that RSA contains high silica content (often exceeding 70% by weight), which is essential for effective pozzolanic activity [14,17,25,87,91]. This supports RSA's potential to enhance concrete performance, as highlighted in several studies. Additionally, studies show that RSA contains four times more silica than cement [13]. Furthermore, studies have shown that RSA-blended concrete has higher long-term compressive strength [16,23,25,26] and better resistance to water [23] acid and sulfate attacks [16] compared to ordinary Portland cement.

Additionally, the availability of various public funding sources, such as Horizon Europe, supports research and innovation. Beyond laboratory optimization, scaling RSA into practical applications requires controlled environments for field testing. Regulatory sandboxes provide such a controlled and supervised framework [92]. They allow for innovations to be tested under real conditions [92].

Figure 6 presents the summarized results of a comprehensive analysis using the Multi-Level Perspective framework, combined with SWOT and PESTLE assessments, to evaluate the potential for adopting RSA as an SCM in the EU (See Appendix A).

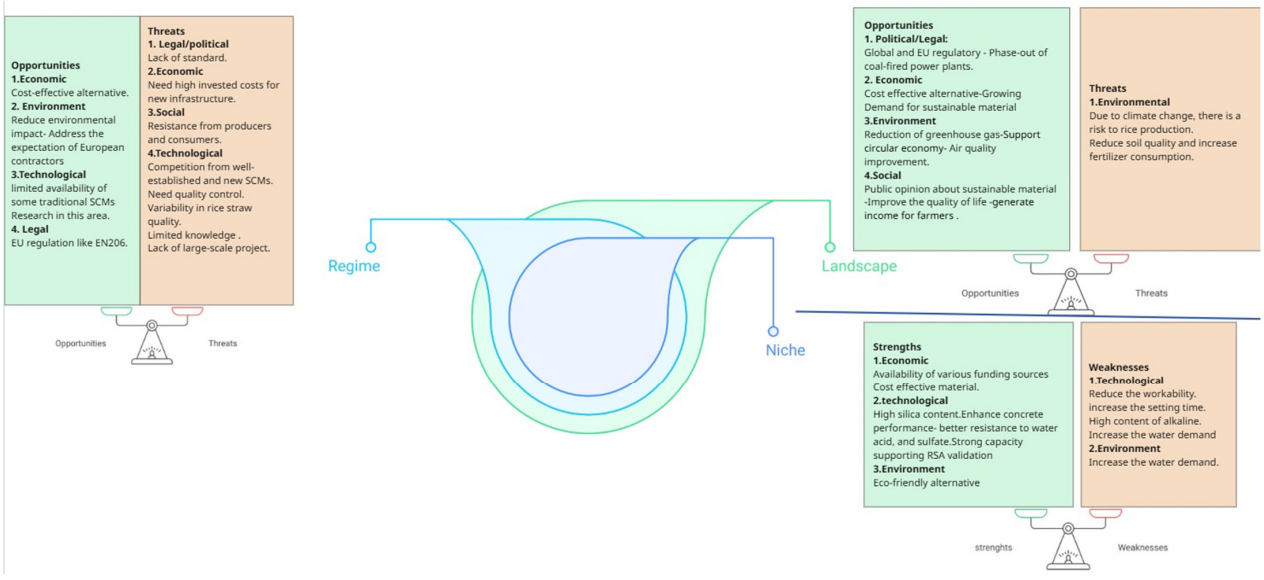


Figure 6. Results of MLP, SWOT, and PESTLE Analysis for the adoption of RSA (Source: Authors' own elaboration based on data compiled and adapted from the literature [14,21,23,28,48,58–60,62,63,65,71,72,83,84,88,89]).

5. Conclusions

This study investigates the potential adoption of low-carbon SCM, using RSA as an example, in the European construction sector. The research applies a PRISMA-based systematic literature review, integrated with the Multi-Level Perspective (MLP) framework, PESTLE, and SWOT analyses to provide a comprehensive assessment of the socio-technical dynamics influencing RSA adoption.

Adopting RSA as a low-carbon SCM in the European construction sector presents significant opportunities and notable challenges. At the landscape level, the urgent need for sustainable solutions in cement production and waste management, combined with pressure from regulatory frameworks, creates a favorable environment for RSA integration. However, climate change risks may affect rice production and consequently RSA production. At the socio-technical regime level, the scarcity of traditional SCMs, such as fly ash, opens opportunities for RSA; however, the lack of established standards and infrastructure for its supply chain presents significant barriers.

Addressing these regulatory and logistical challenges will be crucial for the successful implementation of large-scale projects. RSA demonstrates strong potential as a cost-effective, high-quality, and environmentally friendly SCM alternative at the niche innovation level due to its rich silica content and pozzolanic properties. RSA's properties, driven by high silica content, can improve concrete strength and durability. However, increased water demand, longer setting times, limited research, seasonal availability, and regulatory gaps can be considered as barriers.

To promote the use of RSA in Europe, the following adaptation strategies can be used:

(a) Developing European standards to ensure quality and market acceptance.
(b) Establishing supply chain infrastructure for processing, transport, and storage.
(c) Investing in research and technological innovation: research is needed to develop standards for the use of RSA in concrete. Investigating the long-term performance of RSA in concrete applications and exploring innovative processing techniques to enhance its properties will be vital.
(d) Collaboration among industry stakeholders, policymakers, and researchers is essential to create the infrastructure and market conditions that support the integration of RSA.

There are several mechanisms that can foster collaboration among stakeholders. One is the availability of the various public funding sources that support research. Additionally, regulatory sandboxes provide a controlled and supervised framework to test the innovation under real conditions. Another mechanism is industry consortia for pre-normative research, that is, a group of stakeholders, such as companies, that collaborate alongside formal standard-setting organizations to coordinate research and align on a shared technology roadmap [93]. Additionally, a "just transition framework" for coal-ash-dependent regions is crucial to manage social and economic impacts and support transitions [94].

This study is based on a literature review of existing studies, and therefore, its scope was limited by data availability. The SWOT analysis also has limitations, as it treats all factors equally and does not offer specific solutions or action plans. The SWOT analysis could be improved by incorporating quantitative or semi-quantitative methods to overcome these limitations.

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Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular economy
CO_2 eq	Carbon Dioxide Equivalent
EU	European Union
EN	European Norm
MLP	Multi-Level Perspective
PESTLE	Political, Economic, Social, Technology, Legal, and Environment
RSA	Rice straw ash
SCMs	Supplementary Cementitious Materials
SWOT	Strength-Weakness-Opportunity-Threat

Appendix A

Table A1. Results of MLP, SWOT, and PESTLE Analysis for the adoption of RSA in the EU.

Multi-Level Perspective	SWOT Analysis	PESTLE	Explanation
Landscape Level	Opportunities	Policy and Regulations	Increasing regulatory pressure to reduce greenhouse gas emissions and promote a circular economy on a global and EU scale. Energy transition from coal-fired power plants across Europe [58]. Existing sustainability and waste management policies [61].
		Economic	RSA is a cost-effective alternative to traditional cement, offering a more affordable option [57]. Growing demand for more sustainable materials in the EU.
		Social	Increasing environmental consciousness and public awareness about the environmental effects of products and changing their preferences [62,63]. Growing demand for more sustainable materials in the EU.
	Threats	Environmental	Due to climate change, there is a risk to rice production [65].
		Environmental	Diverting rice straw for ash production, instead of using it in an agricultural field, can reduce soil quality and increase fertilizer consumption [48].

Table A1. *Cont.*

Multi-Level Perspective	SWOT Analysis	PESTLE	Explanation
Regime Level	Opportunities	Technological and Legal	The limited availability of some traditional SCMs, such as fly ash, in the future opens opportunities for others, like RSA.
		Legal	Within the EU, there is a well-established standard (EN206) related to replacing cement with inert or pozzolanic materials [71]
		Economic and Environmental	The RSA can be considered a product that addresses the expectations of European contractors.
		Technological	Research and innovations are being carried out in this area.
	Threats	Economic and Technological	Competition from well-established SCMs RSA faces competition from new SCMs. RSA faces competition from traditional SCMs (without a standard).
		Legal	The lack of established standards for the implementation of RSA may make it harder for construction companies to use [79–81].
		Technological	The EU's existing logistics and supply chains are optimized for traditional SCMs, so integrating RSA into them will be challenging. The integration of RSA in the construction sector requires precise treatment and quality control, which can be costly and require new technologies. Rice straw variability and the treatment process have a significant impact on the quality of RSA and concrete performance [48,81]. Limited knowledge about RSA and a lack of large-scale projects can hinder the adoption of RSA in the construction sector.
		Economic	New infrastructure and technology will be costly.
		Social	Sometimes, producers and consumers resist switching from traditional materials to new alternatives due to perceived risks and uncertainty [81].

Table A1. *Cont.*

Multi-Level Perspective	SWOT Analysis	PESTLE	Explanation
Niche	Strength	Economic	RSA is a cost-effective option that decreases the amount of cement needed.
		Environmental	RSA reduces dependency on traditional cement, one of the significant contributors to greenhouse gas emissions.
		Technological	RSA has a proper amount of silica [26,87]. It increases the quality of the concrete. Concrete containing RSA has strong resistance to chemical attacks. RSA can be combined with other SCMs to improve the quality of the concrete.
	Weaknesses	Environmental and Technological	Increase the water demand for cement [14,21,83].
		Technological	Increase the setting time of concrete [14,83,84,89] Requires more research. The seasonal availability of rice straw affects industries that rely on a consistent supply. The alkaline content of RSA is high [28].

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