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RESEARCH ARTICLE

The French plastics industry's path-dependent transition towards the circular economy

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ABSTRACT
This article investigates adoption by French plastics industry companies of circular eco-innovation strategies, such as recycling of fossil-based plastics, production of bio-based copies of fossil polymers, and development of new bio-based plastics. Primary data were collected via interviews with various plastics value-chain stakeholders and were supplemented by a substantial amount of secondary data. Analysing these data through an evolutionary theoretical framework lens that combines the multi-level perspective on sociotechnical transitions with organisational path dependence theory addresses two limitations in the existing literature: the fragmented analyses of the determinants of circular eco-innovations and contradictory interpretations of the potential of new bio-based plastics to disrupt prevailing industrial structures in favour of the circular economy. Our results demonstrate the relevance of path dependence theory at the value chain level and highlight the importance of (inter-)organisational mechanisms in the industry circular transition.

KEYWORDS
Plastics; path dependence; lock-in; eco-innovation; circular economy

JEL CLASSIFICATION
L65; O33; O38; Q55

1. Introduction

Concern over the negative environmental effects of the plastics value chain has accelerated.[1] The OECD (2022) estimates that the volume of plastic waste generated worldwide each year more than doubled between 2000 and 2019 to reach 353 million tons. In 2019, only 9% of plastic waste was recycled, 50% went to landfill, 19% was incinerated and 22% leaked from controlled waste management systems thereby increasing land and water pollution. Over 90% of the world's plastics production relies on primary ('virgin') feedstocks, which are predominantly fossil-based. Moreover, the increased production of plastics by fossil-based (notably coal-based) economies has further increased the global plastics chain carbon footprint (Cabernard et al. 2022). In 2021, packaging was the largest end-use market for plastics, accounting for 44% of plastics consumption worldwide and 39% of consumption in Europe (excluding textile applications) (Plastics Europe 2022). In 2020, in the 27 EU Member States, plastic packaging waste was estimated to be around 35 kg per inhabitant on average, 13 kg of which was recycled (Eurostat 2023). However, recycling rates for plastic packaging vary widely across countries, with France having a particularly low rate of 21%.

This has prompted more and more public authorities in Europe to introduce regulations aimed at making the plastics value chain more circular (Bening, Pruess, and Blum 2021). The concept of circular economy (CE) has been debated widely among practitioners and academics alike (Blomsma and Brennan 2017; Korhonen, Honkasalo, and Seppälä 2018; Merli, Preziosi, and Acampora 2018). Essentially, it can be viewed as a means of achieving sustainable development through a system of reducing or, alternatively, reusing, recycling, and recovering materials (Geissdoerfer et al. 2017; Kirchherr et al. 2023; Kirchherr, Reike, and Hekkert 2017). Regulations on the management of household plastic waste, adopted in Europe and France from the early 1990s, were aimed primarily at increasing recycling rates, reducing the amount of waste produced and strengthening extended producer responsibility (EPR). Table 1 presents a chronology of the main European and French regulatory milestones.

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[1]The plastics value chain includes all activities related to the design, production, use, and end-of-life of plastics (Johansen et al. 2022).

Table 1. Chronological overview of key regulatory developments on household plastic waste management in Europe and France.

Year	Policy objective	Level	Regulation / legal instrument	Scope and relevance for household plastic waste
1992	Extended Producer Responsibility (EPR)	France	Decree n° 92–377 of 1 April 1992 on packaging waste	Established the foundations of the household packaging EPR scheme, making companies that sell packaged products financially responsible for collection and sorting of plastic waste.
1994	Recycling mandates	EU	Packaging and Packaging Waste Directive (PPWD) 94/62/EC	Established the EU framework for management of packaging waste. Introduced recycling and recovery targets for packaging waste.
2008	EPR	EU	Waste Framework Directive 2008/98/EC	Provided the overarching EU waste policy framework. Formalized EPR for packaging and plastic waste streams.
2018	EPR	EU	Directive (EU) 2018/851 amending the Waste Framework Directive	Strengthened EPR schemes.
2019	Waste reduction/ recycling mandates	EU	Single-Use Plastics (SUP) Directive (EU) 2019/904	Introduced targeted measures for single-use plastics. Required polyethylene terephthalate (PET) beverage bottles to contain at least 25% recycled plastic by 2025 and 30% by 2030.
2020	Waste reduction/ recycling mandates	France	Law n° 2020–105 of 10 February 2020 (AGEC law – Anti-Waste for a Circular Economy law)	Transposed into French law several measures from the Single-Use Plastic Directive. Strengthened national objectives for plastic packaging: 20% reduction and 100% recyclability of single-use plastic packaging by 2025, and reinforced EPR.
2024	Recycling mandates/ waste reduction/EPR	EU	Packaging and Packaging Waste Regulation (PPWR)	Replaced Directive 94/62/EC with a single regulation directly applicable in all Member States. Strengthened the EU regulatory framework for packaging in several areas.

These regulations have led to an increased use of recycled plastic among both upstream and downstream actors in the European and French plastics value chains. Some suppliers of plastic raw materials and compounds, as well as manufacturers and plastics-consuming companies, have also explored alternative approaches to achieving a CE, such as the development and use of bio-based plastics (Barbaut et al. 2023; Befort 2021; Chadha 2011; Iles and Martin 2013, Liliani, Tjahjono, and Cao 2020; Pyka et al. 2022). Bio-based plastics are polymers derived in part or entirely from biomass rather than fossil-based feedstocks (Massardier, Belhaneche-Bensemra, and Lazaric 2023). Bio-based plastics include so-called 'drop-in bio-plastics' such as bio-PET (bio-based Polyethylene terephthalate plastic) with the same chemical structure as fossil-based plastics, and 'new bio-based plastics' such as Polylactic acid (PLA) or Polyhydroxyalkanoate (PHA) plastics, which have distinctive chemical structures and potentially interesting functionalities such as biodegradation (Befort 2020; Loubet et al. 2022; Pyka et al. 2022). In 2021, bio-based plastics (i.e. drop-in and new) accounted for just 1.5% of world plastics production and only 2.3% of European plastics production (Plastics Europe 2022). These bio-based plastics are used mainly by the packaging sector (European Bioplastics 2022). Recycled plastics, drop-in bioplastics, and new bio-based plastics are the three main types of circular eco-innovations developed in the plastics industry. Compared to conventional alternatives, i.e. virgin fossil-based plastics, these three types of plastics have a lower environmental impact throughout their life cycle (Cecere et al. 2014; Kemp and Oltra 2011; Rennings, Markewitz, and Vögele 2013).

The aim of the present article is to improve our understanding of the CE-focused eco-innovation strategies adopted recently by French plastics companies and their potential impacts on the plastics industry's circular transition. Our study relies on primary data obtained from semi-structured interviews with various players in different positions along the plastics value chain and masses of secondary data gathered from reports and the authors' participation in professional and academic events. While the plastics value chain is global, a country-specific approach (i.e. France) is justified by the fact that, to an extent, the industry organisation and players' strategies are adapted to the individual country's specific characteristics and regulations.

The literature identifies various drivers of and barriers to the development and diffusion of circular eco-innovations (de Jesus and Mendonça 2018; de Jesus et al. 2018; Suchek et al. 2021). However, the relationships among these different factors and their overall effects are often overlooked. Furthermore, characterisations of the circular eco-innovations (especially bioplastics) produced in the plastics industry and their potential to disrupt current industrial structures are highly contradictory. While some studies frame new bio-based plastics as radical and systemic eco-innovations (Chadha 2011; Pyka et al. 2022), others consider them incremental innovations that perpetuate the essential characteristics of the prevailing system (Befort 2021; Bening, Pruess, and Blum 2021).

To address this dual issue of fragmented approaches and contradictory interpretations, we are proposing an evolutionary analytical framework that combines the multi-level perspective (MLP) on sociotechnical transitions (Geels 2019; Geels and Schot 2007) with (inter-)organisational path dependence theory (Sydow, Schreyögg, and Koch 2009, 2020). When interpreted using this theoretical framework, our data show how the characteristics inherited from past organisation and industry trajectories, institutional (particularly regulatory) changes, and the eco-innovation strategies of the various value-chain actors interact to shape the direction and pace of the circular transition in the French plastics industry.

Our approach makes three main contributions. First, we provide a detailed characterisation of the lock-in by the plastics industry to virgin fossil-based polymers, which constrains and shapes all eco-innovation strategies. Second, we offer an in-depth examination of the most prevalent circular eco-innovation strategies, i.e. the recycling of fossil-based plastics and the introduction of drop-in bioplastics, as well as their impacts on the trajectory of the industry. Third, our original analysis of circular eco-innovation strategies based on new bio-based polymers highlights the limitations of the opposition between 'incremental eco-innovations' and 'radical eco-innovations'. We demonstrate that, without breaking with the disposable economy, new bioplastics possess a disruptive potential for the plastics value chain that distinguishes them from other eco-innovations. More broadly, our study contributes to empirical applications of sociotechnical transition and path dependence theories and concepts, by demonstrating their combined operational value for framing the inter-organisational level, and their heuristic value.

The rest of the paper is structured as follows. Section 2 describes the theoretical framework that informs our empirical findings. Section 3 presents our qualitative research methodology and describes the data. Sections 4 and 5 respectively present and discuss our findings, and Section 6 concludes the article.

2. Theoretical framework

This section develops the theoretical and conceptual foundations for our analysis of the circular transition in the French plastics industry. We begin by reviewing the circular eco-innovations literature and highlighting the fragmented and sometimes contradictory interpretations of the dynamics of plastics industry eco-innovations (2.1). We argue for an evolutionary approach that integrates the multi-level perspective (MLP) on sociotechnical transitions with (inter-)organisational path dependence theory (2.2). This framework offers a systemic, multi-layered, and dynamic lens for analysing the circular strategies of plastics firms and their effects on the evolution of the French plastics industry.

2.1. Circular eco-innovations in the plastics industry

The idea of a CE has become central to the process of adapting the plastics industry to reduce environmental problems. The CE features prominently in corporate strategies, industry roadmaps, and regulatory frameworks and is the subject of a burgeoning academic literature and debate on the topic (Blomsma and Brennan 2017; Korhonen, Honkasalo, and Seppälä 2018; Merli, Preziosi, and Acampora 2018). However, the analysis of recently published (2017–2021) academic research shows a certain conceptual 'consolidation' in how CE is understood (Kirchherr et al. 2023). There appears to be a convergence around the idea that the CE refers to a set of '*core principles*', namely 'reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain', to achieve 'sustainable development' ('*aims*'), whose implementation requires 'a broad alliance of stakeholders' ('*enablers*'). This emerging consensus has not prevented 'differentiation' in approaches. In particular, Kirchherr et al. (2023, 9) identified technology and innovation as emerging themes in analyses of enablers for the CE transition. Recent work at the nexus of the CE and eco-innovation literatures attests to this trend (Cainelli, D'Amato, and Mazzanti 2020; de Jesus and Mendonça 2018; de Jesus et al. 2018; Gonçalves, Galliano, and Triboulet 2021; Kiefer, González, and Carrillo-Hermosilla 2019; Suchek et al. 2021).

In this literature strand 'eco-innovations' are defined as 'new or modified processes, techniques, practices, systems and products to avoid or to reduce environmental harms' (Rennings, Markewitz, and

Vögele 2013, 333). They may be technological or non-technological and may relate to goods, services, processes, marketing methods, organisational forms or business models (de Jesus et al. 2018). They differ from other innovations by the fact that their 'environmental impact on a life cycle basis is lower than those of relevant alternatives' (Cecere et al. 2014; Kemp and Oltra 2011, 249). According to this definition, bio-based plastics, biodegradable plastics and recycled plastics are generally considered to be eco-innovations or 'sustainable plastics', compared to virgin fossil-based plastics (Siltaloppi and Jähi 2021).

Research starting in the mid-2000s has identified various drivers of and barriers to the generation and diffusion of CE-related eco-innovations (de Jesus and Mendonça 2018). The main drivers include environmental regulation, demand for sustainable products and inter-organisational collaboration (Cainelli, D'Amato, and Mazzanti 2020; de Jesus and Mendonça 2018; de Jesus et al. 2018; Gonçalves, Galliano, and Triboulet 2021), factors that are highlighted in studies focusing specifically on plastics eco-innovations (Bening, Pruess, and Blum 2021; Siltaloppi and Jähi 2021; Stumpf, Schöggl, and Baumgartner 2023) and, particularly, bio-based plastics (Pyka et al. 2022). In the case of development of bio-based plastics, the ability to collaborate with various actors along the value chain is especially emphasised (Chadha 2011; Iles and Martin 2013; Liliani, Tjahjono, and Cao 2020).

While the literature identifies a set of factors that contribute to the success (or failure) of plastics sector circular eco-innovations, it rarely examines the relationships among these factors and their overall effects. Another shortcoming of the existing literature is the contradictory conclusions regarding the degree of novelty of plastics sector eco-innovations and their potential to disrupt industry structures. Most studies distinguish between 'incremental' and 'radical' eco-innovations (Rennings, Markewitz, and Vögele 2013). The former 'entail small improvements with respect to existing solutions', while the latter 'are characterized by high degrees of technological novelty [in the case of technological eco-innovations], a rupture with existing solutions and considerable environmental benefits' (Kiefer, González, and Carrillo-Hermosilla 2019, 157). Systemic radical eco-innovations are the most disruptive, as they involve system level, technical, organisational or other changes rather than micro-level changes to components, for example (Kiefer, González, and Carrillo-Hermosilla 2019; Rennings, Markewitz, and Vögele 2013).

The way in which bio-based plastics and especially PLA plastics are understood varies considerably. Some authors consider them to be radical and systemic eco-innovations capable of bringing about a paradigm shift in the plastics industry (Chadha 2011; Pyka et al. 2022) or leading, at least, to significant technical, business, and organisational changes throughout the plastics value chain (Iles and Martin 2013; Liliani, Tjahjono, and Cao 2020). In complete contrast, Bening, Pruess, and Blum (2021, 9) argue that 'the development of bioplastics [i.e. "biobased and biodegradable" plastics] [. . .] keeps the overall setup and functioning of the value chain and its major infrastructure intact'. Befort (2021, 2, 7) is even more explicit and refers to PLA as a 'drop-in innovation' or 'an innovation presented as sustainable and whose objective is the reproduction of the dominant paradigm', namely 'the economy of waste'.

This fragmented and contradictory stream of work on circular eco-innovations in the plastics industry has led to the significant theoretical challenge of how these various contributions can be integrated into a coherent theoretical framework. To fill this gap, we adopt an evolutionary perspective aimed at addressing the systemic, multi-layered, and path-dependent interactions among the technological, organisational, strategic, industrial, and institutional factors involved in the CE transition. To achieve this, we combine two complementary approaches: the MLP on sociotechnical transitions and (inter-)organisational path dependence theory.

2.2. An evolutionary perspective on the path-dependent CE transition

The transition from a linear to a circular economy is a path-dependent process (Korhonen, Honkasalo, and Seppälä 2018) which, according to path dependence theory, involves 'dynamical systems that are neither completely deterministic nor purely random in their workings, and in which the specific details of history govern the unfolding course of development' (David 2007, 92). This process is characterised by interactions among several technological, economic, regulatory, cultural, etc. factors (de Jesus and Mendonça 2018). These interactions occur at different levels, such as the individual, (inter-)organisational, industrial, and institutional levels (de Jesus et al. 2018; Kirchherr, Reike, and Hekkert 2017; Merli, Preziosi, and Acampora 2018). As argued elsewhere, evolutionary economics is particularly well suited to addressing the path-dependent, systemic, and multi-layered processes of circular transitioning based on eco-innovations (Brette and Lazaric 2025; Cecere et al. 2014; Chizaryfard, Trucco, and Nuur 2021).

In the vast body of evolutionary literature, the MLP on 'sociotechnical transitions to sustainability' was developed to analyse the eco-innovation strategies implemented by the different types of firms within an industry, the determinants of these strategies and their impacts on the particular industry's transition trajectory (Geels 2019; Geels and Ayoub 2023; Smith, Voß, and Grin 2010). In general, the MLP is employed to analyse technological changes and their effects through the interactions among three levels, that is, micro-level niches, meso-level sociotechnical regimes, and macro-level landscapes (Geels 2002, 2019). Sociotechnical regime is the set of rules that govern the relationships among the industry incumbents and between these firms and various stakeholders. The system rests on settled bases, such as specific technologies, infrastructures, or user patterns. It is characterised by dynamic stability, 'meaning that innovation still occurs but is of an incremental nature' (Geels 2002, 1260). The MLP literature argues that radical technological innovations are often developed in spaces that are relatively protected from market selection forces. Within these niches, innovations are improved and made viable through a learning process (Smith, Voß, and Grin 2010). The diffusion of a radical innovation from niche to regime level can benefit from the stress a changing landscape imposes on the sociotechnical regime. A period of turbulence in the sociotechnical regime can create 'windows of opportunity' for niche innovations, which, in turn, can lead to changes to the existing sociotechnical rules and the opening up of a transition pathway (Geels and Schot 2007). While some radical innovations succeed in moving beyond niche level, without pressure from the external landscape, attempts to extend the innovation to regime level are thwarted by the regime's reproduction mechanisms, which ensure its dynamic stability.

The MLP provides a relevant framework to analyse the transition of an industry from a linear to a circular sociotechnical regime, such as a shift from fossil-based plastics production to sustainable bioplastics production (Pyka et al. 2022). The MLP allows us to examine both the influence of systemic and multi-layered interactions among a range of factors in the circular transition and the impacts of firms' path dependence on their individual circular eco-innovation strategies. Also, since MLP is a middle-range theory, it allows the integration of results from complementary works (Geels 2019). Given the importance of inter-organisational relations along the plastics value chain in the success (or failure) of circular eco-innovations (especially bioplastics) in the plastics sector (see Section 2.1), it would seem appropriate to add to the MLP framework contributions related to (inter-)organisational path dependence theory.

The path dependence literature highlights the self-reinforcing mechanisms that can cause technological, market, organisational, industrial, and/or institutional systems to become locked-in and difficult to escape from (Arthur 1989; Brenner and Zu Jeddeloh 2024; David 1985). Lock-in is a source of inefficiency if it prevents the system affected from evolving towards a better alternative. 'Carbon lock-in' or persistence of an unsustainable economic system based mainly on high-carbon technologies is a typical example of a system being captured in a Pareto-dominated state, caused by a path-dependent process (Foxon 2011, 2013; Korhonen, Honkasalo, and Seppälä 2018; Seto et al. 2016).

The self-reinforcing processes at work in path dependence dynamics are diverse and depend on the nature of the systems involved. Increasing returns, sunk costs, economies of scale, and network externalities can lead to the types of lock-in referred to above. At the same time, several self-reinforcing social mechanisms have been identified as crucial in the context of 'organizational path dependence'; they include 'complementarity effects', 'coordination effects', 'learning effects', and 'adaptive expectation effects' (Sydow, Schreyögg, and Koch 2009). Complementarity and coordination effects are rooted in 'the relationality of routines', that is, in 'interdependent networks of routines' (Feldman et al. 2016, 2021; Lazaric 2024). Kremser and Schreyögg's (2016, 703) seminal study shows that the development of organisations gives rise to the formation of 'clusters of routines' or 'system[s] of complementary routines, each contributing a partial result to the accomplishment of a common task'. In the organisation, these routines clusters act as a '*selection* mechanism' that 'affect[s] the adoption and implementation of new routines' (Kremser and Schreyögg 2016, 702). Therefore, the dynamics of routines clusters is likely to result in organisational path dependence (Sydow 2021).

While the organisational path dependence and relationality of routines literatures focus primarily on processes within a single organisation, the self-reinforcing mechanisms they identify are at work, also, at the inter-organisational level (Burger and Sydow 2014). Broadening the scope to this level allows the business model to be conceptualised as a system of organisational routines, adopted by the firm, that govern the interactions between the firm's members and the various actors (i.e. consumers, competitors, suppliers, public authorities, and other stakeholders) in its industrial environment (Brette and Chassagnon 2021). This understanding highlights the routines underpinning the sociotechnical regime (in the MLP context) and the essential role of the interdependencies among the organisational routines of the various actors in the regime for ensuring regime stability. This can be seen clearly in the case of lock-in in such sectors as the plastics industry, which involve a diversity of complementary actors (Brette and Lazaric 2025).

Lock-in that derives from (inter-)organisational path dependence 'does not mean standstill but rather a process of continuous reproduction' (Sydow, Schreyögg, and Koch 2020, 730). It is a process that may be subject to 'path extension', that is, 'an effortful and creative form of maintaining and further exploiting an established path', which can be seen as an organisational manifestation of the dynamic stability of the sociotechnical regime as described in the MLP. In contrast to this process of incremental evolution, which does not question the dominant action pattern, 'path breaking' is unlikely to emerge from within the organisation. The opportunity to break from the organisation path can derive from a change to the institutional (especially the regulatory) context which may become less conducive than before (Foxon 2011, 2013; Seto et al. 2016; Sydow, Schreyögg, and Koch 2009).

3. Research methodology

We employ an exploratory qualitative research approach (Yin 2017) to provide a holistic and in-depth understanding of the circular transition process in the plastics value chain. This approach allows us to capture the actions, representations, and motivations of various actors based on their specific characteristics, past trajectories, and value-chain positions. It should be noted that this research was conducted by an interdisciplinary team that included two economists (first two authors), a management PhD student (third author), and a polymer chemistry and materials engineering researcher (fourth author). In recognition of its interdisciplinary relevance, the research was supported by the French National Centre for Scientific Research (CNRS) Mission for Transversal and Interdisciplinary Initiatives (MITI).

3.1. Sample selection and case selection

To obtain comprehensive information on the plastics value chain, we conducted interviews with a sample of actors in different parts of the upstream and downstream value chain (see Figure 1). They included plastics resin producers, plastics-consuming companies, recyclers, and some institutional actors. The aim was to gain insights and gather opinions from a range of actors representing a diversity of activities, firm sizes, and interests, to understand how these organisations contribute to and are impacted by the plastics industry transition. We were particularly interested in their approach to circular eco-innovations – especially bio-based plastics – which present a range of characteristics that are more or less disruptive to the existing plastics value chain. Finally, we wanted to provide a realistic picture of the institutional and regulatory contexts in which eco-innovation strategies are defined and implemented.

To collect information on the upstream value chain, we interviewed two French plastics producers: P1 and P2. These companies were selected based on their innovative approaches to the production of plastics and their extensive partnerships with both public and private organisations which are indicative of the

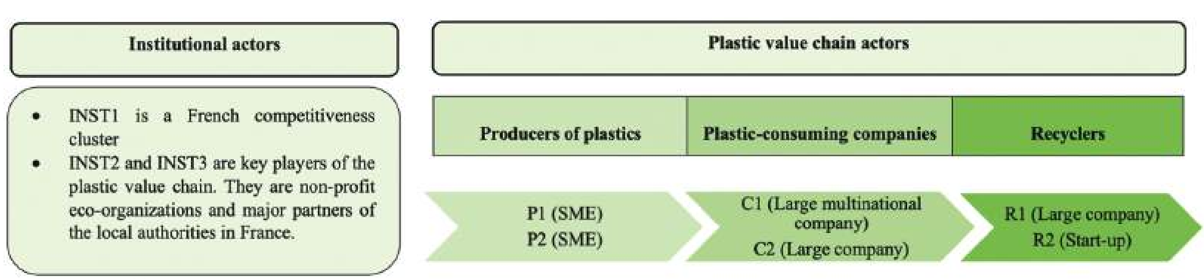

Figure 1. Primary data: actors interviewed.

potential success of their projects. P1 is a French firm, classified as a Small/Medium-sized Enterprise (SME), that originated from university research. It specialises in developing and producing a 100% bio-based plastic compound derived from animal proteins. This polymer is distinguished by its water solubility and biodegradability under natural conditions, which significantly increase its end-of-life benefits. However, these features reduce its application since such a polymer cannot be used to contain moist elements. P2 produces compounds from by-products sourced mainly in France. It specialises in the distribution of bio-based compounds, such as PLA and PHA, in any quantity including small batches that other firms consider unprofitable.

Industry demand for plastic compounds comes from companies that use these materials in their own products. We interviewed two such companies involved in different sectors. C1 is a multinational agri-food company; C2 is a technology company that designs and produces plastic automotive equipment. Both companies' strategies prioritise sustainable development, but they do not collaborate with P1 or P2. C1's circular packaging department is part of the Ellen MacArthur Foundation and The New Plastics Economy group. As a company that relies heavily on plastic packaging for its food products, C1 has been affected by recent regulations, such as the EU Single-Use Plastics Directive and the French AGEC (Anti-Waste for a Circular Economy) Law (see Table 1). We interviewed the Director of the Global Circular Packaging Department to discover how the market players are adapting to these regulations and whether they are considering potential replacement of conventional plastics with innovative (especially bio-based) plastics. In C2, we interviewed a former eco-design and recycling manager to obtain information on C2's interest in innovative plastics as part of its efforts to reduce its environmental footprint. The company has strategic partnerships aimed at incorporating recycled plastic materials into car parts. The information provided by this interviewee allowed us to identify potential barriers to and incentives for use of bio-based plastics in the automotive sector.

In the downstream plastics value chain, recyclers are crucial for reducing the environmental impact of plastics waste. Our information on this important stage in the value chain came from interviews with employees from two recycling companies that adopted distinct approaches. R1 is a large, well-established company that supports public local authority collection, sorting, and recovery of plastic waste. R2 is a start-up that has developed an innovative recycling process. Its original offering relies on decentralised and easy-to-use equipment, allowing direct recycling by firms with recyclable waste. The information derived from these interviews provided an understanding of the specific conditions required to adapt recycling infrastructures to the recycling of bio-based plastics and to compare the responses from a small innovative company using cutting-edge technology to those of a large company with many years of experience in the sector.

At the institutional level, regulation plays a major role in the transition to CE. We interviewed stakeholders with close links to the French State, including the project coordinator of INST1, a plastics sector 'competitiveness cluster', that includes 'a combination of companies, higher education hubs, and public or private research units, engaged in a partnership to create synergies in the frame of innovative projects, on a regional (sometimes interregional) scale' (Brette and Chappoz 2007, 393). This cluster supports innovations in bio-based products. We also interviewed the manager for R&D in eco-design at INST2, a private not-for-profit eco-organisation which promotes recycling of household packaging and graphic papers. INST2 is significant in terms of its contribution to coordinating the collection and sorting of plastics and its close collaborations with plastics-consuming companies to ensure compliance with the regulation. INST2 is also responsible for communicating with households to raise awareness of recycling issues and provides services designed to increase and improve recycling. Finally, we conducted an interview with a member of INST3, a company committed to sustainable development and transition to a CE. INST3 provides plastics recovery solutions to businesses and municipalities. These qualitative data gave us a better understanding of the priorities of public authorities in relation to the circular transition of the plastics value chain.

Table 2 summarises our reasons for selecting the actors interviewed. Although there were other actors (particularly compound producers and plastics-using companies) with similar characteristics, our eventual choice of firms was motivated by relationships established during cooperative research projects between these firms and the fourth author's laboratory, which is one of the main academic research centres on

Table 2. Primary data: main objectives of the interviews carried out.

Types of actors	Actors	Justifications of the choice	Objectives of the interviews	Date of the interviews	Duration of the interviews	Transcribed pages
French producers of compounds	P1 (SME) P2 (SME)	Innovative actors Numerous partnerships with public and private organisations	Identifying the barriers faced by producers of innovative plastics, notably bio-based, to diffuse their innovations	14 April 2022 14 April 2022	65 min 60 min	20 16
Plastic-using companies	C1 (Large company) C2 (Large company)	Present sustainable development as central to their strategies Allow to observe the potential demand for plastic compounds in the sector	Understanding the strategies of plastic-consuming companies in the face of new regulations Characterising the interest for innovative plastics of key players in the middle of the value chain Identifying potential barriers and incentives regarding the use of bio-based plastics	1 March 2022 3 March 2022	71 min 82 min	15 20
Recyclers	R1 (Large company) R2 (Start-up)	Allow to compare the views on innovative plastics of a large company and a start-up downstream in the value chain	Determining the required conditions for adapting recycling infrastructure to innovative, especially bio-based, plastics	7 April 2022 25 March 2022	57 min 83 min	16 19
Institutional actors	INST1 INST2 INST3	Regulations play a crucial role in the diffusion of innovation, and these players have a close link with the State	Gaining a better understanding of the current regulatory context concerning plastic issues Understanding the priorities of public authorities regarding the diffusion of conventional and innovative (bio-based in particular) plastics Outlining future regulations	11 April 2022 12 April 2022 13 July 2022	51 min 52 min 50 min	14 15 21

polymers in France. The trust relationships established during these earlier research projects allowed access to the most appropriate individuals in the selected companies and enabled in-depth and frank discussions.

3.2. Data collection

Primary and secondary data were collected between February 2022 and March 2023. The primary data come from 9 semi-structured interviews (60–90 min each), which, since this was during the COVID-19 pandemic, were conducted online. All four authors were involved in the development of the interview guide and the interviews, with each author asking questions related to their specific area of expertise. The semi-structured interview guide explored five key themes, with the theme sub-questions adapted to the organisation being interviewed (see Annex 1). The authors were free to ask questions that went beyond the interview guide. Interviews were recorded with the interviewees' consent. This semi-structured interview method allowed us to gather in-depth and wide-ranging primary data on the various CE-related eco-innovations strategies implemented in the French plastics value chain and their impacts.

Each of the interviewees represented a stakeholder type identified as important by the MLP framework on sociotechnical transitions. The plastics compound producers, P1 and P2, are both SMEs that have developed niche innovations in bio-based plastics on the fringes of the sociotechnical regime. R2 is representative of a highly innovative small business, in the recycling field. C1 and C2 are typical of large plastics-using companies in two major sectors – agri-food and automotive – which, due to the volumes of plastics they absorb, play a structuring role in the sociotechnical regime. R1 is a large plastics recycling company that exemplifies another type of sociotechnical regime structuring actor. Finally, INST1, INST2, and INST3 are representative of 'institutional intermediaries' that play a critical role in establishing and enforcing the regulatory principles intended to promote the circular transition of a sociotechnical regime (Fischer, Pascucci, and Dolfsma 2021).

However, we acknowledge that our sample size is small and has some limitations. First, we cannot accurately assess the representativeness of our interviewees. Second, our sample does not include representatives of the most upstream links in the value chain, such as large plastics raw materials suppliers like TotalEnergies. We also did not interview any converters involved between compound producers and plastics-using companies. These limitations are partially offset by the collection of a large amount of secondary data from reports issued by private, semi-public, and public organisations, and participation in relevant events (see Annex 2). Our involvement in various technical and scientific communities allowed access to a large body of additional information on the technical, economic, and organisational dimensions of the plastics value chain. This very diverse information ranges from formal public data to more informal data, shared orally, whose validity was confirmed by their recurrence.

3.3. Data analysis

The interviews were transcribed by the third author who also conducted the initial coding of the data. This initial coding was refined by the four authors working jointly, in an iterative process. All four authors contributed to the data analysis and discussion.

The data analysis was inspired by our theoretical framework, which we adapted to the empirical context of the plastics industry. Our reflective approach was based on a back-and-forth method, between the data collected and the literature. We began by open coding the data (Yin 2017) to identify key concepts, which we compared continuously to the literature. We repeated the iteration until saturation (Ravenswood 2011). The coding was conducted collaboratively and interactively and included additional themes that emerged from our discussions.

To increase the validity of the results and take advantage of the authors' multidisciplinary backgrounds, we ran a cross-analysis based on our complementary scientific skills and diverse perspectives. Finally, we triangulated the primary data by combining it with secondary data derived from reports, events, and company websites.

3.4. Technological context of the case study

Our research required close observation of the chemical trajectories related to the plastics industry. These dynamics were shaped by the production of a range of polymers that have given rise to different types of plastics. Polymer production is usually based on monomer reactions. Polymeric materials, either bio-based or fossil-based, are often formulated with stabilisers, fillers, plasticisers (Aouachria et al. 2019) and flame retardants (Delamarche et al. 2020, 2022). The relative ease of production of most polymers explains their ubiquity and the fact that the accumulated plastic waste has reached the stage where the plastics environmental footprint can no longer be ignored (Liu et al. 2023). In this context, bio-based plastics, particularly emerging biodegradable bioplastics, can be considered a more sustainable alternative to fossil-based plastics.

Bio-based polymers, such as starch, are either extracted from biomass or polymerised from bio-sourced building blocks (Sandei, Massardier, and Brunel 2022). So far, their production is based mostly on petrochemical additives (e.g. thermal or ultraviolet stabilisers). From a technological perspective, the properties of new bio-based polymers, such as PLA, are different from those displayed by conventional plastics such as fossil-based PET, or drop-in bio-based plastics such as bio-based PET. These different properties can create significant constraints for product designers and converters (Iles and Martin 2013; Johansen et al. 2022; Shamsuyeva and Endres 2021). The development of new bio-based plastics recycling chains, which currently do not exist, would require close cooperation among scientists, standards committees, and industry actors (Olatayo, Mativenga, and Marnewick 2023). Thus, Johansen et al. (2022) underline the need for a holistic approach to identify the challenges and solutions related to the various stages of the plastics value chain.

Although some studies consider that we still lack tools to measure the benefits of bio-based plastics (Bishop, Styles, and Lens 2021; L. Chen, Pelton, and Smith 2016; Ita-Nagy et al. 2020; Jeswani et al. 2021; Molina-Besch 2022; Rybaczewska-Blazejowska and Mena-Nieto 2020; Shen, Worrell, and Patel 2010; Tamburini et al. 2021), Madival et al. (2009, 1183) argue that '[l]ife cycle assessments of bio-based polymer resin and products historically have shown favourable results in terms of environmental impacts and energy use compared to petroleum-based products'. In a recent study, G. Chen et al. (2025) assess the economic, health, and environmental impacts of the large-scale diffusion of emerging biodegradable bioplastics in China, from a systemic perspective. They conclude that 'bioplastics improve all life cycle indicators, including a 7.71% reduction in global warming potential and a 9.74% decrease in terrestrial ecological toxicity, eutrophication, and human toxicity, all exceeding 8%'. This is associated with an 8.68% reduction in health costs over 30 years.

4. Empirical findings

The data collected show that, to varying degrees, French plastics companies have developed three main categories of circular eco-innovations as substitutes for virgin fossil-based plastics: recycled fossil-based plastics, drop-in bioplastics, and new bio-based plastics. Our findings highlight the role of four main (positive or negative) influences on the development and diffusion of these eco-innovations in the French plastics industry: the relative costs of using different kinds of plastics (4.1); regulations and consumer demand (4.2); and a set of (inter-)organisational factors (4.3). This section examines these factors in turn. Section 4.4 summarises the main manifestations of each type of factor and their effects on the different eco-innovation categories. Section 5 develops and discusses the path-dependence analysis of these interacting factors that is essential to understand the evolution of the French plastics industry.

4.1. Costs-related factors

Virgin fossil-based plastics have long been the manufacturers' preferred choice. Their mass production and efficient development process based on accumulated expertise have led to economies of scale and learning effects that have significantly reduced average production costs. Adoption of this approach by more and more companies has resulted in positive feedback loops that have further reinforced the use of virgin fossil-based plastics. This has led to a situation of lock-in, in which the requirements associated with fossil-based plastics are influencing the decisions of the actors along the value chain and limiting their ability to consider alternatives. Compared to the dominant model of virgin petrochemical plastics, recycled and bio-based plastics are perceived generally as exploratory and costly:

> Fossil-based PET is the most affordable option, recycled PET costs almost twice as much as virgin PET, the bio-sourced PET is approximately at the same price of the recycled PET. (INST2)

The low profitability of plastics recycling is due, mainly, to the high costs of collection and sorting, which generally cannot compete with the low costs involved in producing virgin plastics: 'Plastic recycling is a non-profitable business, notably due to the price of virgin plastic' (C1). Historically, the price of recycled material was determined based on the price of virgin fossil-based materials and application of a discount, which, when the price of oil dropped, made the economic activity of recyclers unprofitable. As R1 pointed out: 'Before regulatory obligations [. . .], the market was also not ready to pay the price, so a discount was applied', reducing the incentives to invest.

In addition, a lack of economies of scale, due, in part, to low production capacity, makes adoption of bio-based plastics the exception rather than the norm: 'It is simply the global production capacity that is not there, that is not keeping up for now' (INST2). P1 is an example of a producer of innovative bio-based plastic compounds that is struggling to achieve scale economies and compete with conventional plastics: 'For now, we don't have this dynamic of economies of scale, so process and costs are difficult to forecast'. As a result, the price of bio-based plastics is unattractive compared to fossil-based plastics. This price difference varies depending on the type of plastic and its origin:

> The costs [of bio-based plastics] are higher than those of petro-based plastics. They can cost between 2.5 and 8 times more per kilogram. We have PLA which is just over 3 times the purchase price [of the polymers it can substitute]. Then there are bio-PP, bio-PET which are 2.5 to 8 times more expensive. (P2)

4.2. Regulation and consumer demand

The 2019 European Single-Use Plastics (SUP) Directive and the 2020 French AGEC law prompted changes to the recycled plastics market. By increasing demand for recycled plastic and stimulating investment aimed at increasing the quantity and quality of recycling, these new regulations gave a boost to the recycling sector:

> When we were too expensive, our customers went back to virgin plastic. Now, with regulatory obligations, the demand for recycled plastics exceeds supply and the price of recycled plastic is no longer determined by the price of oil but by our process costs. (R1)

Regulatory developments often work in synergy with existing organisational know-how, which can amplify learning effects. For example, since the necessary technology has been adopted by recyclers, the EU SUP Directive requires integration of a certain quantity of recycled PET in plastic bottles. R1 told us that: 'Across Europe, there are many factories that are capable of producing clear PET for food-grade applications, and that's why the directive started with that – it was easier'. In addition, consumer preferences influence industry priorities regarding recycling of fossil-based plastics.

> There is a preference for recycled material over bio-sourced material because using recycled material helps reduce dependence on oil and waste generation by transforming waste into recycled materials. Today, what is criticized is waste, that is what consumers see in the streets, in the sea, or in the forests. (C1)

In the German context, consumers have been shown to prefer eco-innovations based on recycled plastics over bioplastics for food packaging, as they are more uncertain about the sustainability of bioplastics (Herrmann, Rhein, and Sträter 2022).

Nevertheless, several plastics-consuming companies have expressed interest in adopting bio-based materials in the short to medium term:

> My big clients, my major accounts [plastics-using companies], all have in mind to switch to bio-based and recycled materials. (INST2)

> Will we invest in bio-sourced materials? Probably in the future, but for now, our commitment is to use 30% recycled materials by 2025. (C1)

While regulation has encouraged the use of recycled materials, it has not led to a significant increase in the spread of new bio-based plastics: 'If there is no regulation that imposes something, there is little chance of things evolving. We live in an economy-driven world, and as long as it's more expensive . . .' (C2). In fact, current regulation that makes recycling mandatory is tending to discourage rather than promote more widespread use of new polymers. As C2 explained, 'the emergence of new bio-based plastics will only be possible if they can be easily recycled'. In theory, a number of these new plastics, such as PLA, are recyclable. However, introducing new bio-based plastics into existing recycling streams can disrupt efficient recycling of other plastics; improper sorting of plastic waste can cause operational problems with recycling machinery and lead to contamination of recycling streams (Ansink, Wijk, and Zuidmeer 2022). As R1 explained, 'we advocate that these products should not enter the packaging industry because their degradation temperature will be lower than our working temperature, and therefore as soon as we work with PLA, it will degrade'. This issue was referred to repeatedly by our interviewees at all levels along the value chain:

> All recyclers are requesting that bio-based plastics be discontinued [with the exception of drop-ins], as they pollute the recycling streams. [. . .] So it can be a problem not to consider the end of life of bio-based materials from the outset. (C2)

> What more and more people who work on the development of new polymers are saying is: be careful, they must fit into existing recycling systems. We will not create new systems, or at least not right away, so they must be able to integrate into these systems. (INST1)

In contrast to the new bio-based plastics, drop-in bioplastics can be integrated into existing materials production and recycling processes without the need for significant investment in new equipment. Drop-in bioplastics are designed to mimic the structure of fossil-based plastics and only require changes upstream in the value chain.

4.3. (Inter-)organisational factors

Any disruptions to the plastics value chain can give rise to tensions reflecting potential misalignments among the industry players' interests, particularly given the chain's complexity:

> These are value chains that are extremely long, there are a huge number of actors, a huge number of steps, and these are very capital-intensive markets. (P1)

> Everyone sees their own economic interest. That's why working as a sector is really difficult. Recyclers focus on their side, as do manufacturers and suppliers, and there is little transfer of knowledge between them. (C2)

The multiplicity of the actors in the value chain complicates the adoption of innovations, such as new bio-based plastics, as these can disrupt established processes and expertise and require implementation of new practices, thereby increasing the need for coordination among stakeholders.

P1, a producer of a biodegradable bio-based plastic, highlighted the challenges faced by suppliers of innovative plastic materials:

> We need to make sure that our material has the right properties, the right fluidity, to keep up with the company's production rates, otherwise people will not want to work with our material … The validation of a new material by the entire chain of converters is already extremely resource and time-consuming. (P1)

For its product to be adopted, P1 must ensure that its innovative resin is compatible with its customers' processes: 'It took us two years of process work and material formulation … for the product to be economically viable for all intermediaries in the industry'. P1 highlighted the difficulties involved in identifying suitable partners: 'It is necessary to find the right actors in the value chain who are willing to dedicate time and therefore money to conduct experiments, which is not always easy'. Plastic converters, that is, firms that transform compounds into plastics products, are known for their reluctance to engage in innovation activities that require adaptations to their technologies, machinery, and skills. To address this problem, P1 has forged direct contacts with plastics consuming companies in various sectors: 'We will work with "market players" [i.e. plastics consuming companies] because we know that they can convince plastic processing companies' (P1).[2] The skills accumulated by converters in the production of fossil-based plastics may become obsolete if their customers (the market players) adopt new bio-based plastics.

The obstacles to opening new sorting and recycling channels for innovative bio-based plastics are both economic and (inter-)organisational. Developing a dedicated recycling infrastructure requires significant investment, whose profitability would depend on the amount of plastic available for recycling and demand for this recycled plastic. The decision to build an infrastructure requires it to be profitable for all parties involved and, especially, for sorting centres and recyclers: 'In France, there are more than 150 sorting centres. We need to simplify; we need to create volume because it costs money' (C1).

The greater the number of sorting centres, the larger the volume of plastic waste required for recycling technology adaptations to be economically viable.

Currently, production of new bio-based plastics in France is insufficient to justify the multi-million-euro investments required for their recycling. This problem is exacerbated by the diversity of bio-based plastics, each with specific properties: 'There is no solution that ticks all the boxes today, anywhere in the world' (INST2). Lack of standards for bio-based plastics results in low production volumes for several niche innovations. Even PLA, currently the most widely used type of innovative bio-based plastic, has not reached the scale required to justify investment in dedicated recycling channels: 'Today, the quantities of PLA on the market are not sufficient to be valorised after sorting' (R1).

Moreover, given the complexity of the value chain and uncertainties about its future development, network externalities have a detrimental impact on the spread of innovative bio-based plastics. As R1 explained:

> We should not add complexity to what already exists. It [the plastics value chain] is already fragile, so we do not see it [referring to new bio-based plastics] as a miraculous solution to the problem of plastics in the world.

Companies' choices are influenced by their expectations regarding future regulation, technological advances, and others' strategic decisions. Each firm seems to be waiting for some other firm to make the first move, that is, make a risky investment, which has the effect of reinforcing 'expectations of expectations': 'For now, PLA is not taking off because there is no recycling supply chain and everyone is waiting for someone else to create it, no one really wants to put in 30 million euros' (INST2). The absence of a dedicated recycling infrastructure for new bio-based plastics significantly reduces their environmental appeal and prevents their benefits from being fully exploited.

This reluctance to invest in new bio-based plastics is evident, also, in research policies, such as the COTREP (Technical Committee for the Recycling of Plastic Packaging) guidelines. COTREP was created in

[2]DuPont has implemented a similar strategy to support the market for its 'renewably-sourced' Polytrimethylene terephthalate or PTT (Iles and Martin 2013, 45).

2001, in France, to develop recyclable plastic packaging and has since become a major advocate of eco-design principles for plastic packaging:

> The philosophy of COTREP is to work on what is put on the market and what has a dedicated recycling stream. So, it's true that there are new polymers coming into the market that don't necessarily have a dedicated recycling stream, but we are not going to work on them. (INST3 and COTREP member)

Large-scale development of innovative bio-based plastics would require joint efforts and close coordination among the various players in the value chain, i.e. plastics producers, converters, users, and recyclers.

4.4. Synthesis of empirical findings

Table 3 summarizes our main empirical findings. The recycling of fossil-based plastics is the dominant circular eco-innovation strategy in the French plastics industry. It has benefitted from significant support in the form of European and French regulations on plastic waste management adopted since the 1990s. These regulations have helped ensure the long-term viability of certain applications of recycled plastics by partially decoupling them from fluctuations in the relative prices of virgin fossil-based plastics and, consequently, from oil price volatility. The development of recycled fossil-based plastics has also benefitted from other favourable factors downstream in the value chain. These materials meet consumers' environmental expectations without introducing systemic disruptions to the organisation of the long and complex plastics value chain.

While European and French CE regulations do not actively support drop-in bioplastics, they do not impede their diffusion either. Because they can be easily processed within existing sorting and recycling infrastructures, they comply with regulatory recyclability requirements. Their main obstacle to wider adoption remains their

Table 3. Key factors in the circular transition of the French plastics industry and their effects on the development of CE-related eco-innovations.

Key factors (drivers or barriers)	Main manifestations	Effects on circular eco-innovations
Costs-related factors	– Virgin fossil-based plastics benefit from low production costs. – Recycling has historically been unprofitable. – Bio-based plastics suffer from a lack of investment in R&D, production capacity, and recycling infrastructure.	Effects of relative costs of virgin fossil-based plastics on – recycled fossil-based plastics: *negative* – drop-in bioplastics: *negative* – new bio-based plastics: *very negative*
Regulation	– European and French regulations have improved the profitability of recycling. – Regulations promoting recycling hinder the development of bio-based plastics, with the exception of drop-in bioplastics.	Effects of current regulations on – recycled fossil-based plastics: *positive* – drop-in bioplastics: *neutral* – new bio-based plastics: *negative*
Consumer Demand (This factor is addressed indirectly, through the perspectives of industrial and institutional actors and relevant literature)	– Consumers are showing interest in bio-based plastics. – But they prefer eco-innovations based on recycling.	Effects of consumer demand on – recycled fossil-based plastics: *very positive* – drop-in bioplastics: *positive* – new bio-based plastics: *positive*
(Inter-) Organisational Factors	– The plastics value chain is long and complex. – Eco-innovation pathways that rely on well-established organisational systems are favoured. – The large-scale development of new bio-based plastics is hampered by the lack of standards and the uncertainty surrounding their future development (wait-and-see approach). – Significant and coordinated organisational changes are needed to move new bioplastics out of their niche markets.	Effects of (inter) organisational factors on – recycled fossil-based plastics: *positive* – drop-in bioplastics: *neutral* – new bio-based plastics: *very negative*

production costs relative to fossil-based plastics. Despite the distinctive environmental benefits they may offer, such as biodegradability, new bio-based plastics receive no regulatory support and are even penalised by recyclability requirements. Overall, these materials face significant barriers to diffusion resulting from a combination of mutually reinforcing economic (i.e. cost-related), marketing, and (inter)organisational factors across the value chain. The diversity of these bio-based plastics negatively affects their unit costs of production, use, and recycling, while also complicating consumers' understanding of their respective environmental benefits. Furthermore, their potential to disrupt the organisation of the existing plastics value chain contributes to the reluctance of many actors to adopt them.

5. Discussion

Interpreting the data we collected through the theoretical lens presented in Section 2 sheds new light on three major issues related to the evolution of the plastics value chain in France: unsustainable lock-in of the chain (5.1); the path extension of the plastics sociotechnical regime through the integration of certain circular eco-innovations (5.2); and the disruptive potential of new bio-based plastics in the plastics industry circular transition (5.3). We conclude this section by summarising the main contributions of our study (5.4).

5.1. Unsustainable lock-in of the plastics value chain

Our data confirm the existence of a lock-in in the plastics value chain in France towards virgin fossil-based feedstocks, in line with previous findings (Bening, Pruess, and Blum 2021; Chadha 2011). As Pyka et al. (2022, 46) argue, '[a]ll networks and actors along the supply chains, from extraction to use and disposal are established and have been more or less uncontested for the past sixty years'. Our empirical findings highlight the economic advantages of adhering to the standard for virgin fossil-based plastics and the potential costs for most industry players of not doing so. Economies of scale reduce unit production costs. Incumbent players benefit from the productivity of existing infrastructure and accumulated knowledge. Network effects encourage new entrants to comply with the current standard, offering them the opportunity to benefit from the installed base and the advantages associated with the depth of the market.

In addition to the abovementioned factors, which have been highlighted in the technological and industrial path dependence literatures (Arthur 1989; Brenner and Zu Jeddeloh 2024; Cecere et al. 2014; David 1985, 2007), our data demonstrate the significance of mechanisms associated to organisational path dependence in the plastics industry lock-in. The organisational level self-reinforcing social mechanisms described by Sydow, Schreyögg, and Koch (2009, 2020) are evident but are even more pronounced at the inter-organisational level. The two related mechanisms of coordination and complementarity effects, in particular, contribute to the plastics value-chain inertia. Coordination effects refer to the idea that the greater the number of actors adhering to a rule, the more efficiently they interact and the stronger the incentives for new actors to adopt the rule (or conversely, the higher the costs of non-compliance), and the more likely the rule will become established over time. An example of a long-standing rule in the plastics industry is the use of fossil-based PET to produce disposable bottles. This rule encompasses a variety of organisational routines related to different actors in the value chain, including suppliers of plastics raw materials, compounders, converters and bottling companies. In addition, these different organisational routines are often interdependent, with each governing a specific activity whose efficiency depends on the fulfilment of other related routines. For instance, the routines governing mechanical production of bottles depend on the routines governing the formulation of compounds (e.g. which additives to include in PET), routines governing the use of bottles, routines governing the use of bottling machines (e.g. which settings to apply), etc. The stronger these complementarities, the more potentially costly it can be to change a routine, since any change risks disrupting the efficiency of some related routines or even the entire system of routines.

Coordination and complementarity effects have significant implications for the market selection and replication processes throughout the plastics value chain. Organisational routines have long been identified as a source of firm distinctiveness, determining its economic performance and constituting a unit for selection in business competition (Nelson and Winter 1982). Coordination and complementarity effects give rise to a higher-level unit for selection in business competition: routine clusters. Furthermore, in industries characterised by complex value chains involving closely intertwined actors, such as the plastics industry, market processes lead to the selection of groups of firms with highly complementary business models (Brette and Chassagnon 2021; Brette and Lazaric

2025). Once selected, these business models tend to self-perpetuate through the replication of the underlying clusters of organisational routines. Thus, the plastics value-chain lock-in can be analysed as a systemic emergent effect resulting from multi-layered and path-dependent interactions within the plastics sociotechnical regime. This inter-organisational lock-in does not prevent firms operating in the current sociotechnical regime from introducing innovations, as long as they do not disrupt the primary routines networks governing their interactions. Examples of such non-disruptive innovations include changes in the colour or shape of PET bottles.

5.2. The path extension of the plastics sociotechnical regime

Our empirical findings are consistent with the view, in the MLP literature and organisational path dependence theory, that lock-in of a sociotechnical regime is characterised by dynamic stability or 'path extension' (Geels 2002; Sydow, Schreyögg, and Koch 2020). This means that the sociotechnical regime exhibits a degree of malleability, allowing the incorporation of certain changes without an effect on its fundamental structures. The sources of novelty in the plastics value chain occur at the three levels identified in the MLP framework (Geels 2002, 2019). The most significant changes to the macro landscape in recent years include the evolution of citizens' social demands and the integration of these aspirations into environmental policy guidelines. These shifts have led to changes in European and French plastic waste management regulations and, particularly, the rules related to packaging waste, at the meso level of the sociotechnical regime. Firms' responses to these changes in the market and regulatory environments include the development of two main types of innovation.

The first model includes micro-level niche innovations that present a high degree of novelty and can be profitable in narrow speciality markets (Gao, Song, and Guo 2020). Typical examples are biodegradable bio-based plastics for specific, small-volume applications. The distinct properties of the new bio-based plastics stem from their chemical structures, which differ from those of fossil-based plastics. To exploit these properties requires changes to multiple organisational routines throughout the value chain, from raw materials suppliers to plastics recyclers. For instance, using new bio-based plastics to replace PET for the production of disposable bottles requires changes in raw material sourcing, compound formulation, bottle manufacturing, recycling processes, and so on. These changes also have a systemic dimension, since they affect complementary routines involving multiple actors. In line with MLP theory, this type of eco-innovation is produced mainly by new entrants that do not have complex networks of established routines requiring adaptation and that can serve a market of atypical consumers willing to pay a higher price for the environmental benefits these innovations provide.

The second model includes innovations, developed at the meso level, by incumbent firms that can integrate them into their existing mass production systems at limited additional cost. Examples include recycled plastics and drop-in bioplastics. Coordination and complementarity effects, combined with the high learning costs that would be required to introduce more disruptive innovations, favour these 'path extension' dynamics that do not require systemic adjustments to the dominant patterns of action along the value chain (Sydow, Schreyögg, and Koch 2009, 2020). In other words, the core firms in the sociotechnical regime have responded to changes in their selection environment by adopting new organisational routines that do not involve systemic changes to their main routine networks. This highlights the empirical interplay between external selection processes acting on organisations (in particular, regulatory and market processes) and selection processes operating within organisations or at the interface between organisations (i.e. path-dependent selection processes for new (inter-)organisational routines).

It can be observed that neither of these two main types of eco-innovation substantially challenges the existing sociotechnical regime, either because they affect only the fringes of the regime or because their characteristics allow them to fit within the dominant system. However, this does not detract from their environmental value. The first model generates substantial environmental benefits in certain specialised markets, while also fulfiling the dual function of exploring new R&D directions and serving as an inspiration for other industry players, including incumbents. The second type of innovation can lead to significant environmental benefits within the prevailing system (Pyka et al. 2022; Rennings, Markewitz, and Vögele 2013). For example, legislation requiring a minimum proportion of recycled materials to be incorporated in the manufacture of plastic bottles has made the recycled PET market viable, transforming it into a complementary good rather than a substitute for virgin fossil-based PET.

5.3. The disruptive potential of new bio-based plastics

Our data challenge interpretations of new bio-based plastics based on the opposition between 'incremental eco-innovation' and 'radical eco-innovation'. Considering bio-based plastics, such as PLA, as radical eco-innovations (Chadha 2011; Liliani, Tjahjono, and Cao 2020; Pyka et al. 2022) is problematic because this ignores the fact that these plastics perpetuate the disposable economy paradigm. Conversely, considering PLA as an incremental (Bening, Pruess, and Blum 2021) or 'drop-in innovation' (Befort 2021) overlooks the fact that the conditions for the spread of this polymer in the plastics value chain differ substantially from those related to recycled plastics and bio-based copies of fossil polymers, that is, polymers that the value-chain actors refer to as drop-ins. Our empirical findings demonstrate that the new bio-based plastics generate significant and specific 'structural tensions' or 'circular tensions' (Chizaryfard, Trucco, and Nuur 2021) throughout the value chain. So far, these tensions have hindered the diffusion of this kind of circular eco-innovation. However, in the future, certain factors could mitigate some of these barriers and allow room for positive feedback effects. The consequences of such a disruption, if it occurs, remain uncertain, but are likely to affect the trajectory of the sociotechnical regime to a greater or lesser extent.

Our empirical findings suggest that a combination of factors could potentially open new pathways towards a circular transition of the plastics value chain. To date, the lack of regulatory support for new bio-based plastics in European and French policies is one of the main reasons why firms remain reluctant to invest in large-scale development of these products. However, regulation and the influence of key plastics industry actors may evolve. Should the regulatory environment become more predictable and supportive, some major industry players would likely accelerate the development of new bio-based plastics. These actors have the economic power to invest in the development of infrastructures for these materials and to drive a reorganisation of the value chain around them (Brette and Chassagnon 2021).[3]

TotalEnergies, the leading French oil company, invested in PLA production capacity in partnership with Futerro, a Belgian biotechnology and chemical company, and later with Corbion, a Dutch group and world leader in lactic acid production. The Total Corbion joint venture established a PLA plant in Thailand with a capacity of 75,000 tons per year. However, the original plan to develop an industrial site in France with a capacity of 100,000 tons per year was abandoned. Futerro, which already operates a large PLA production facility in China, has since embarked on an independent project to build a PLA production plant in France with a capacity of 75,000 tons per year. In April 2024, Futerro and the Tereos group, a global leader in sugar and cereal production and processing, announced a partnership. The agreement provides for the annual supply of 150,000 tons of dextrose to Futerro's biorefinery, derived from locally produced wheat starch.

These various actions show that the development of new bio-based plastics is an option being considered by some major industry players as part of their eco-innovation strategies. However, it remains difficult to predict the overall impact of these initiatives on the trajectory of the value chain since the decisions of the industry incumbents are not independent. Our data show that the strategic decisions of actors along the value chain are based on 'adaptive expectations effects'. These effects refer to the propensity of organisation members to adopt what they perceive as 'best practices', based on the assumption that others are doing the same and a desire to be on the 'winning side' (Sydow, Schreyögg, and Koch 2009, 700). These strategic interdependencies can result in nonlinearities in the evolution of the value chain, potentially leading to 'tipping points' (Geels and Ayoub 2023; Zeppini and Frenken 2018). In this regard, we agree with Pyka et al. (2022, 45, original emphasis) that '[i]n a complex transition process already modest progress towards a higher share of bio-based products might have the potential to radically transform production and consumption once it reaches a *tipping point*'. Characterisation of such a tipping point in the plastics value chain is beyond the scope of this article and will be the subject of further research.

5.4. Contributions to the literature

Table 4 presents the main contributions of our study

[3]Iles and Martin (2013, 46) analysed DuPont's strategy 'to develop a range of bioplastic markets rather than restricting itself to a niche market, and to take reasonable risks in developing biopolymers with novel properties to create new markets altogether'.

Table 4. Contributions of the study to the analysis of circular eco-innovation strategies and of their effects on the transition of the plastics industry.

Theme	Existing Literature	Our study
The unsustainable lock-in of the plastics value chain around virgin fossil-based polymers	– Highlights the significance of costs in the unsustainable lock-in (e.g. economies of scale, network effects). – Identifies self-reinforcing social mechanisms underlying organisational path dependence.	– Applies organisational path dependence theory at the value chain level. – Highlights the role of (inter-)organisational mechanisms in the plastics unsustainable lock-in. – Frames lock-in as a systemic emergent effect resulting from multi-layered and path-dependent interactions within the plastics sociotechnical regime.
The path extension of the plastics sociotechnical regime	– Highlights the dynamic stability of sociotechnical regimes. – Characterises the innovations that can be introduced in industries, without disturbing the fundamental structures of sociotechnical regimes.	– Identifies the recycling of fossil-based plastics and the development of drop-in bioplastics as manifestations of the path extension of the plastics sociotechnical regime. – Highlights the joint effects of multiple drivers in the development and integration of these eco-innovations into the plastics sociotechnical regime. – Emphasises the environmental value of these eco-innovations.
The disruptive potential of new bio-based plastics	– Analyses new bio-based plastics through the lens of the opposition 'incremental' vs 'radical eco-innovations'. – Develops conflicting characterisations of these eco-innovations and of their disrupting potential.	– Highlights the limitations of the opposition 'incremental' vs 'radical eco-innovations' to capture the complexity of eco-innovations dynamics in the plastics industry. – Discusses the possibility that the development of new bio-based plastics could initiate an evolutionary dynamic of cumulative change that could disrupt the current plastics sociotechnical regime.

6. Conclusion

This research aimed to contribute to the analysis of circular eco-innovation strategies, their determinants, and their effects by examining the case of the French plastics value chain. We collected extensive and in-depth qualitative data and analysed them through an evolutionary – that is, systemic, multi-layered, and path-dependent – theoretical lens. This lens was applied within a framework that integrated the multi-level perspective (MLP) on sociotechnical transitions and organisational path dependence theory. This approach enabled us to address two of the shortcomings in existing literature: namely, the fragmented analyses of the determinants of circular eco-innovations and the contradictory interpretations of new bio-based plastics. Our study demonstrates the importance of the interactions between the various determinants of circular eco-innovations in shaping firms' strategic choices and the trajectory of the plastics industry. In particular, our work highlights the self-reinforcing organisational path dependence mechanisms, both within and across organisations, and their impacts on the circular transition process of the plastics value chain. Taking these evolutionary mechanisms into account led us to qualify the sharp distinction between incremental and radical eco-innovations, which often structures and polarises debates on new bio-based plastics. Our research shows that the disruptive potential of various circular eco-innovations lies on a continuum rather than in a binary opposition. Furthermore, assessing the potential effects of different forms of circular eco-innovations on industry trajectories requires analysing how they affect the various actors along the value chain, and do so cumulatively. Taking these systemic effects into account leads to more nuanced and less definitive conclusions regarding the prospects for the spread of circular eco-innovations and their capacity to steer the industry's circular transition.

Our conclusions are idiosyncratic because they are based on context-specific French data. Although the European Union has tried to establish a common regulatory framework for managing plastic waste in recent decades, there continue to be significant differences in the implementation of CE practices among European countries. These differences result in significant disparities in recycling rates, which can be explained by the historical trajectories and variations in the transposition of European directives into national laws of different European countries.[4] Path dependence theory teaches us that these specificities matter. However, these idiosyncrasies do not prevent us from drawing some general conclusions regarding the

[4]The recent replacement of the PPWD by the PPWR (see Table 1) was aimed at increasing the harmonisation of plastic waste management regulation across the EU.

circular transition of the plastics industry. First, certain characteristics of the plastics value chain derive from technological and material factors that are not specific to individual countries. Second, some of the key players in the value chain operate in several countries, under a global strategy.

We hope that similar research will be carried out in other countries to highlight commonalities and differences in the circular transition of the plastics industry across countries and to inform a transnational analysis of these dynamics. The complicated and, so far, unsuccessful discussions aimed at concluding an international treaty to substantially limit plastic pollution demonstrate the importance of such work.

From a policy perspective, our findings suggest that certain regulatory adjustments could encourage the wider adoption of new bio-based plastics. The first priority should be to improve the production and dissemination of relevant information on the various environmental impacts of different fossil-based and bio-based plastics throughout the plastics value chain, such as greenhouse gas emissions, soil and water pollution, and threats to biodiversity. The terms 'bioplastics' and 'bio-based plastics' are too broad and too vague to describe materials' diversity. Further, upstream in the value chain, the production of biomass for bio-based plastics has varying environmental impacts, depending on the origin of the feedstock, the production location and the inputs required for their production. Downstream, the environmental impacts of plastic waste leakages also vary significantly, depending on the type of plastic. While some innovative bio-based plastics are highly biodegradable, even under natural conditions, drop-in bioplastics have the same harmful impacts on living ecosystems as do fossil-based plastics when discarded in the environment. The lack of information on the environmental impacts of different bio-based plastics can lead consumers to misjudge their respective benefits. Therefore, producers should be required to provide much greater transparency regarding the characteristics and impacts of the products they place on the market. For example, they should be required to use clear, accurate, and standardised labelling describing these impacts. Better information could also serve as the basis for regulatory changes aimed at promoting the widespread use of biodegradable bio-based plastics with limited impact on ecosystems for certain applications. For instance, use of these plastics could be authorised for single-use products as part of an amendment to the SUP Directive (see Table 1), which currently bans them in the same way as conventional plastics. Finally, the current high level of regulatory uncertainty surrounding future rules for bio-based plastics is discouraging long-term investment and coordination within the value chain. More predictable and stable regulatory signals would be crucial to enable bio-based plastics to transition from niche markets to widespread adoption.

Future research should further analyse the non-linear dynamics of circular eco-innovations developed in the plastics industry, using a broader range of methods. From this perspective, we are currently pursuing two complementary lines of research. The first involves tracing the trajectories of various circular eco-innovations in the plastics industry, using patent data to identify their determinants and analyse their interrelationships. The second requires the use of qualitative as well as quantitative methods and focuses on the structuring role played by the business models of certain companies in the plastics value chain, as both a source of inertia and a potential lever for change.

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Annexes

Annex1. Interview guide

Theme 1: Presentation of the organisation and business model
For ex. Could you introduce your organisation by outlining its core activities, key value propositions, and market positioning? *How does your organisation support firms across the value chain in driving innovation and adapting to industrial and environmental transitions?*
Theme 2: R&D strategy and innovation
For ex. What is your company's R&D strategy? *Who are your main R&D partners, and how do they contribute to fostering innovation?* *What are the key criteria that guide your company in adopting environmental innovations?* *Have you recently implemented any such innovations? If so, what were the main challenges faced, and what motivated their adoption?*
Theme 3: Integration of circular economy in the business model of the organisation
For ex. Have you integrated the principles of the circular economy into your business model? *What were the key drivers of this transition (e.g. regulatory requirements, business strategy, market demand, . . .)?*
Theme 4: Use and development of bio-based plastics
For ex. Does your organisation currently use or promote bio-based plastics or develop related technologies? What types of bio-based plastics do you use, and for which applications? *What impact have they had on your activities in terms of costs, processes, recycling, etc.?* *How do regulations influence the adoption of bio-based plastics, and do you anticipate any future regulatory changes?* *What other factors influence your choices regarding the use and development of bio-based plastics?*
Theme 5: Perspectives regarding bio-based plastics
For ex. Are you considering adopting bio-based plastics in the future? *What impact would their introduction have on your activities in terms of costs, processes, recycling, etc.?* *In your opinion, what are the main areas for improvement in the development of bio-based plastics (e.g. technological innovations, end-of-life management, stakeholder coordination)?* *How do you see this market evolving in the medium and long term?*

Annex 2. Secondary data sources used

Secondary data	
Events	**Organisation responsible for the event planning**
Technical Day: Eco-design driven by end-of-life strategy	Axelera – Competitiveness cluster
4th European Congress on Eco-Plastic S3	Polymeris – Competitiveness cluster
GDRPO2022: Third meeting of the Polymers and Oceans research group 2022	5 institutes of the CNRS: INP, INC, INEE, INSU and INSIS
Webinar on public procurement strategy for recycled plastics	Region of Auvergne-Rhône-Alpes (France)
Spring of innovation 2022	RRI (Research Network on Innovation)
Webinar 'My laboratory as an actor of sustainability and social responsibility'	Quares
BIOLOOP inauguration conference BIOLOOP: Laboratory for New BIOsourced Polymers for a Circular Economy	BIOLOOP PRIME team
Reports	**Author(s)**
Patents for tomorrow's plastics Global innovation trends in recycling, circular design and alternative sources (1–57 pages) October 2021	European Patent Office
RECORD Report (https://record-net.org/): Biosourced and/or Biodegradable Plastics at End of Life (1–282 pages) July 2020	Rémy Bayard, Adélie Breuil, Agathe Jullien, Valérie Massardier, Mickael Mireux, Gabriel Vinault
Plastic Recycling Watch Bulletin (1–22 pages) December 2021	Axelera and Polymeris
Extra-financial reporting and accounting: what maturity of methods for what possible uses? (1–146 pages) January 2022 https://record-net.org	L. Dupuy, M. Horiot (APESA)
Biosourced materials: maturity of different sectors and sources, state of knowledge and expert opinions (1–12 pages) 2021 https://record-net.org	P. Poignant (Evea), P. Bono (FRD) and L. Tiers (IAR)
El dorado of Chemical Recycling, State of play and policy challenges (1–27 pages) August 2019 https://zerowasteeurope.eu/library/el-dorado-of-chemical-recycling-state-of-play-and-policy-challenges/	Zero Waste Europe
Chemical recycling: where do we stand? (1–36 pages) January 2021 https://www.polyvia.fr/sites/default/files/2021-01/Dossier%20recyclage%20chimique%202020.pdf	Polyvia
A circular economy for plastics (1–239 pages) 2019 https://op.europa.eu/en/publication-detail/-/publication/33251cf9-3b0b-11e9-8d04-01aa75ed71a1/language-en/format-PDF/source-87705298	European Commission Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M.
Analysis of the plastic recycling value chain in France. (1–37 pages) February 2013 https://www.entreprises.gouv.fr/fr/etudes-et-statistiques/dossiers-de-la-dge/analyse-de-la-chaine-de-valeur-du-recyclage-des-plastiques-france	Deloitte
AMI's Plastics Recycling World magazine (1–78 pages) January/February 2022 https://content.yudu.com/web/1rl19/0A42x3p/PRWJanFeb22/index.html	AMI
Synthons alternatifs pour la production de PET, PS, PP et PE (Alternative building blocks routes for the production of PET, PS, PP and PE) report for CITEO https://www.citeo.com/	Raphael Brunel, Valérie Massardier, Mael Guenegan, Benjamin Sandei and Yann-Ulrich Feuzing Tango