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Towards the development of source separation and valorization of human excreta? Emerging dynamics and prospects in France

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The source separation of human excreta (urine and/or feces) offers an alternative to conventional sanitation systems (flush toilets/public sewers) that is appealing in several respects, especially in environmental terms and for agricultural purposes, as a source of natural fertilizer from local and renewable resources. In France, systems for the separate collection of human excreta have previously been confined to the rural sphere and mainly implemented at the individual scale. However, since the 2010s, experimental projects in excreta source separation have been observed in urban areas, at the scale of individual houses and collective buildings, or even neighborhoods. This article, drawing on interdisciplinary social science research conducted within the French research program OCAPI (on ecological transition in nutrition/excretion systems), investigates these innovative projects for the source separation of human excreta in urban areas. Our work lies on a territorial approach, based on a cross-sectional analysis of experimental projects in three cities (Paris, Bordeaux and Grenoble), complemented by the mobilization of the "multi-level perspective" and the "technological innovation systems" frameworks. We study the trajectory and factors of development of source separation in France, its implementation dynamics and territorialisation pathways. Our analysis shows that source separation is still in an emerging phase in France. It is currently experimented in cities through diversified projects and approaches. This diversity applies both to socio-technical choices and territorial embeddedness' forms. Adopting a prospective point of view, we then point out main obstacles and drivers to the scaling-up of this innovative practice: beyond technical issues, shared social values, stakeholder alignment issues and organizational challenges are essential. Finally, we consider possible directions for its development, ranging from the spread of a homogeneous solution to the continuation of a diversity of approaches on different territories.

KEYWORDS

source separation, excreta, nutrition/excretion system, sustainability transition, sanitation, urine-based fertilizer, innovation, circular economy

1 Introduction

The conventional food system on one hand, and on the other the sanitation system, face a series of challenges for which the need to find solutions is increasingly pressing: greenhouse gas emissions, environmental degradation, fresh water shortage, pressures on food supplies, etc. (Billen et al., 2012; Bodirsky et al., 2012; Larsen et al., 2016). Source separation, which represents an alternative sanitation approach in which different effluents are collected separately (urine, feces, and/or greywater), offers several benefits compared to conventional sanitation technologies, based on public sewers and treatment plants: it can generate savings in water, energy and reagents, and help to protect aquatic environments and water resources (Larsen et al., 2013). For agriculture, excreta—and particularly urine, which contains most of the nutrients (nitrogen, phosphorus and potassium) in wastewater—can be valorized as natural fertilizers which, in contrast with mineral and synthetic fertilizers, come from renewable resources (Martin et al., 2020). Moreover, the agricultural valorization of excreta can help to restore a mutualistic relationship between city and countryside, based in the circular economy, while at the same time contributing to local food resilience.

In France, since the mid-2010s, experiments have been taking place with urban excreta source separation projects, at the scale of individual houses and collective buildings, or even neighborhoods. This article, based on research conducted within the OCAPI research program (École des Ponts ParisTech),[1] investigates the emergence in France in the last 15 years of experimental urban excreta source separation projects in cities, and hence the arrival of an alternative to the existing conventional sanitation system.

Since the 2010s, a series of works has been carried out to study the dynamics of implementation of pilot projects and the obstacles and drivers for the development of excreta source separation in Europe. Some studies develop a global analysis (Larsen et al., 2021), others are centered on the dynamics observable in specific areas, in particular in northern Europe and countries such as Sweden, Denmark and Germany, which are precursors in this field (Skambraks et al., 2016; McConville et al., 2017). The situation in France has not been the subject of a specific study so far. This article aims at enriching this series of works, by analyzing the development trajectory of source separation on the French territory.

The works conducted on source separation of human excreta in Europe, or in other industrialized countries such as the United States and Australia, have revealed a series of drivers and obstacles to the development of the practice. The different technical aspects of the question seem relatively mature, with various possibilities existing both for urine diversion toilets and for the treatment and agricultural recovery of materials (Martin et al., 2020; Larsen et al., 2021). With regard to willingness among consumers to recycle urine as crop fertilizer, studies conducted at the international level show a rather favorable situation provided that the issues are well explained, with nevertheless contrasts depending on countries (Segre Cohen et al., 2020; Simha et al., 2021). However, the rise of source separation still seems limited by a series of factors, such as: the absence of an obvious economic model for the deployment of the practice, the lack of a clear regulatory framework, or institutional support that is still insufficient at international, national and local levels (Skambraks et al., 2016; McConville et al., 2017; Larsen et al., 2021). Some studies highlight the fact that the implementation of such innovative projects implies organizational challenges, as the creation of new forms of collaboration between actors from various sectors (urban planning, water, sanitation, agriculture), the capacity to share roles, responsibilities and risks between stakeholders and the need of coordinator and leader actors (Kerber et al., 2015). Other works underline the necessary support and involvement of the concerned communities for a correct functioning of the systems, notably of toilets (Beal et al., 2020; Schreiber et al., 2020).

In this paper, we focus on source separation projects that have emerged these last years in France in urban areas. We analyze their forms, dynamics and possibilities of development in the French context. With a background in social geography, our work lies on a territorial approach to sustainability transition studies, complemented by the mobilization of the multi-level perspective (MLP) and the technological innovation systems (TIS) frameworks (presented in part 2). First, we develop a multi-level analysis of factors leading to the development of source separation in France, and its recent emergence in cities (part 3). Then, we study the implementation dynamics and the territorialisation pathways of this innovative practice, through a cross-sectional analysis of experimental projects in three cities, Paris, Bordeaux and Grenoble (part 4). In the last part of the article, we adopt a prospective point of view. Based on the TIS framework, we study the obstacles and drivers to the scaling-up of source separation, and bring out the main challenges of legitimation for a transition from "niche" experiments to wider implementation (Geels, 2002). We finally consider possible directions for the development of the practice on different territories, ranging from the spread of a

1 « Organisation des cycles Carbone, Azote, Phosphore dans les territoires » (OCAPI), cf. www.leesu.fr/ocapi

homogeneous solution to the continuation of a diversity of approaches (part 5).

2 Research position and methodological approach

Our analysis is grounded at the interface of three conceptual frameworks. The first and main one is a territorial approach of sustainability transition studies, with three case studies in different French cities. In addition, we use the "multi-level perspective" (MLP) framework in order to encompass the interaction between factors situated at different analytical levels (niches, regimes and landscape). We also mobilize the functional approach developed by the "technological innovation system" (TIS) community to analyze the dynamics, and inducement and blocking mechanisms for the diffusion of source separation in France.

2.1 A territorial approach to sustainability transition studies. . .

Our work falls within the field of "geography of transitions," that adds a territorial dimension to sustainability transition studies (Hansen and Coenen, 2015; Huguenin, 2017; Kohler et al., 2019).

"Sustainability transition studies" emerged in the 1990s in response to growing awareness of the unsustainability of the development models of the richest industrialized countries. It is centered around the conviction that "environmental problems (. . .) require radical shifts to new kinds of socio-technical systems (. . .). Therefore, a central aim of transitions research is to conceptualize and explain how radical changes can occur in the way societal functions are fulfilled" (Kolher et al., 2019, p.2).

The "geography of transition" approach addresses more specifically urban experiments and transitions (Castan Broto and Bulkeley, 2013; Evans et al., 2016; Marvin et al., 2018; Raven et al., 2019), analyzing "the conditions, processes and pathways through which urban living labs and experiments emerge, (...) [and] how experiments 'scale up' and shape wider institutional change beyond their initial geographies" (Kolher et al., 2019, p.15).

Our work seeks to examine "territorial trajectories of transition" (Lapostolle, 2021). As Lapostolle, we consider that transitions are embodied in different ways in different territories and that it is necessary to analyze the logics and forms of this territorial embeddedness, i.e., the way in which projects fit into territories from a spatial point of view, but also in terms of actors' interplay. So far, this approach has mainly been used to study transitions of energy and agri-food systems (Lamine, 2012; Lapostolle, 2021). We consider it relevant to mobilize this approach for sanitation systems because of the irreducibility of its territorial dimension.

Our analysis is based on detailed case studies of source separation projects conducted in three French cities: Paris, Bordeaux, and Grenoble. This multi-site approach is essential in order to understand why transitions happen and how they are embodied in particular territories. It enables to study "the way the socio-technical, political, and spatial context creates or prevents opportunities for collective action, for demand, and for implementation of alternative transition trajectories (Rosenbloom, 2017)". It also helps to develop close-grained analysis of the interplay of actors connecting the spatial and institutional scales (Lapostolle, 2021). This approach allows us to highlight a diversity of dynamics of actors and forms of projects depending on territorial configurations.

2.2 . . .In combination with the "multi-level perspective" and "technological innovation system" frameworks

The analytical framework developed by the "multi-level perspective" (MLP) approach (Geels, 2002; Geels, 2007; Geels, 2018; Geels and Schot, 2007) provides a useful additional tool through which to describe and analyze the multiscale factors that may explain the current emergence of source separation in urban contexts, as well as to highlight the obstacles and drivers that hinder and promote the spread of this practice.

The MLP approach identifies three levels in the analysis of socio-technical systems and their transitions. The meso-level regime constitutes the socio-technical system's organizational level. Encompassing all the technologies, processes, rules, and practices associated with all the actors in a given sector, it is associated with relatively stable institutions and infrastructures. The macro-level landscape is the backdrop that sustains the operation of society and the biosphere. This broader level includes the social and cultural norms that underpin the existing socio-technical system, as well as macro-orientations of a political, economic, or environmental nature. Landscape level changes can disrupt the existing regime. Micro-level niches are spaces where alternatives to the dominant operation of the regime can be explored, and which form incubators for innovations that may eventually diffuse beyond niches. The MLP approach will be used here to analyze the development trajectory of excreta source separation in France till today.

Recently, Rosenbloom (2020, p.339) has emphasized the need to widen the MLP approach in order to consider multisystem interactions, arguing that "socio-technical transitions are not isolated to single systems but may involve quite fundamental changes that span multiple systems". This observation is particularly applicable to our object of study. In this article, we have chosen to use the concept of "nutrition/excretion system" (Esculier, 2018, p.89-90), coming from a territorial ecology approach, which entails the study of the flows of energy and materials that support human

INSET 1 Presentation of the three cases studied

Au Clair du Quartier (Grenoble): A participatory apartment block with feces collection

Au Clair du Quartier (ACQ) is a four-story participatory housing block containing five apartments, together with shared areas. Located on a plot that belongs to the City of Grenoble and that was transferred under the "Innovative Habitat" call for projects issued in 2011, the building was constructed by its residents. The construction work took place in 2016 and the residents moved in 2017. The dry toilets project is part of a global ecological approach to housing, reflecting the residents' desire to contribute to the sustainable management of the flows they produce (water, energy, biowaste, etc.). The apartments are fitted with urine diversion dry toilets (UDDT). Feces is collected by bucket and composted in the shared garden, while urine goes into the public sewer. Since 2021, the residents have begun using the compost produced from feces on fruit trees in the garden.

La Fumainerie (Bordeaux): An experimental urban network for the collection of excreta from dry toilets

The non-profit La Fumainerie (LAFUM) association was set up in 2019 in Bordeaux, with the aim of supporting city residents who would like dry toilets in their homes, but might not have gardens or space to store and use excreta at home. A two-year experiment, from July 2020 to July 2022, was launched with local authority subsidies. LAFUM association installs UDDT in the homes of individuals and in other structures wishing to participate, then collects the materials by delivery tricycle for valorization by partner companies. At the beginning of 2022, there were 34 volunteer households and 4 other structures participating in the experiment. Feces are composted. Initially, the urine was supposed to be recovered to produce agricultural biostimulants, but this option has been dropped, and other valorization solutions are now being explored. LAFUM association would like to maintain the network after the experiment, which raises the question of the socio-economic model to adopt in order to make it viable.

Saint-Vincent-de-Paul (Paris): A project for urine separation across a future eco-neighborhood

In 2016, an urban development zone was created on the site of the former Saint-Vincent-de-Paul (SVP) hospital in the 14th arrondissement in Paris. This 3.4 ha (8.4 acre) site is the target of a conversion project to develop an eco-neighborhood with 600 homes, stores, and various amenities. Construction began in 2018, and should be completed in 2024. The City of Paris wants to make SVP a pilot site for its ecological transition policies. The urine separation project in SVP was driven by elected municipal officials, who asked in 2018 to study the possibility of trialing this innovative approach in the future eco-neighborhood. The outlines of the project were established at the end of 2020. The system consists of urine diversion low-flush toilets and dry urinals in the buildings, a separate urine collection network, and a local treatment plant. Both are public infrastructures. The urine will be treated by nitrification-distillation to produce a concentrated fertilizer, which will be used initially on the City's green areas. SVP is the first source separation project in France to be implemented at the scale of a whole neighborhood.

metabolism. Indeed, this concept combines within a broader but coherent system two systems that are closely linked in socio-ecological terms, nutrition and excreta management. The development of source separation requires a concomitant change in the systems concerned, in order to reconnect excreta management with agricultural production, whose links were broken in Europe in the 20th century (Barles, 2011). A multi-systems approach is therefore necessary to analyze the obstacles and drivers affecting its development. Nevertheless, our study focuses on issues related to the introduction of source separation devices in cities, rather than those related to the agricultural use of excreta. These aspects, which are only marginally discussed in this paper, would benefit from further research.

In addition, we mobilize the Technological Innovation Systems (TIS) approach (Bergek et al., 2008a; 2008b; Markard et al., 2016). The TIS approach develops an understanding of the dynamics of TIS, both in terms of structural growth and key innovation-related processes. According to this approach, the structural components of a TIS include, besides the technology, the actors, networks and institutions contributing to its development, diffusion and application. The development of a TIS is also linked to key processes, called "functions." Their state and strength affect how innovations develop. Bergek et al. (2008a) distinguish 7 critical functions: knowledge development, resource mobilization, influence on the direction of research, entrepreneurial experimentation, market formation, legitimation, and development of positive externalities. As the authors point out, structural and functional development of a TIS are coupled, and also depend on external factors at different levels, e.g., regime/landscape (*Ibid.*). Considering that source separation is emerging as a new TIS in France we will analyze its structural and functional dynamics, and examine the existing obstacles and the levers to be put in place for a wider dissemination of the practice.

2.3 Study fields and methods of investigation

The study presented in this article is mainly based on a cross-analysis of emerging separative human excreta management projects in three French cities: Au Clair du Quartier in Grenoble, La Fumainerie in Bordeaux and Saint-Vincent-de-Paul in Paris (see Inset 1 and Figure 1).

These projects were studied over the period 2019–2021 as part of the DESIGN research project funded by France's national research agency (ANR)[2]. These cases were selected from 17 collective urban source separation projects identified in France (see Figure 2; Table 2 in Section 3.2), the aim being to include a variety of situations in terms of: territorial configurations (urban configuration and project scale); project types (matter valorized and methods chosen); and actors involved (project initiators, inter-actor dynamics); and different phases of implementation (conception, preparation, operation) during the period of study. The purpose in studying experimental projects at different phases was to

2 https://anr.fr/Projet-ANR-17-CE22-0017

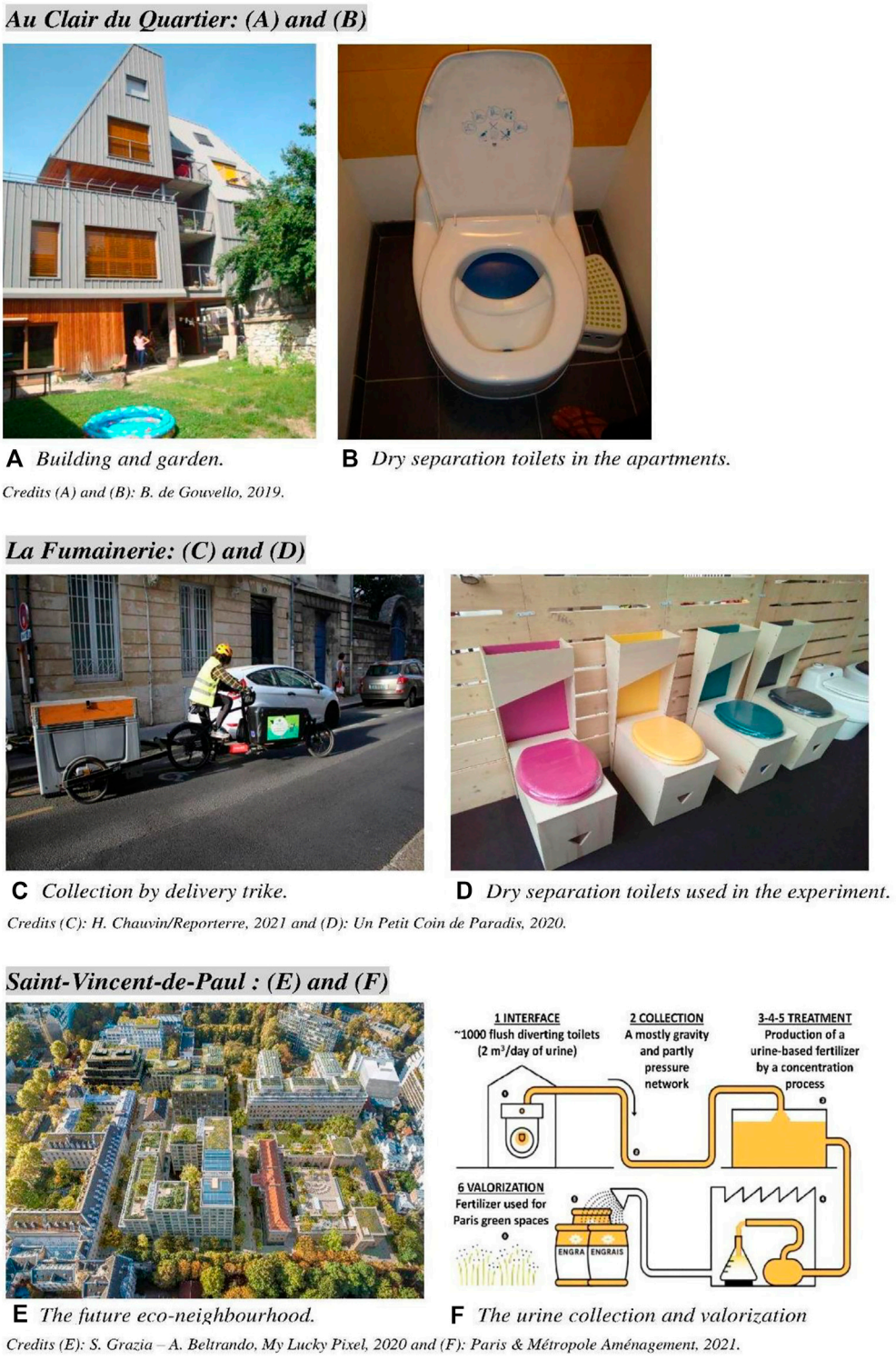

FIGURE 1
Case illustration. **(A)** Building and garden. **(B)** Dry separation toilets in the apartments. **(C)** Collection by delivery trike. **(D)** Dry separation toilets used in the experiment. **(E)** The future eco-neighbourhood. **(F)** The urine collection and valorization system.

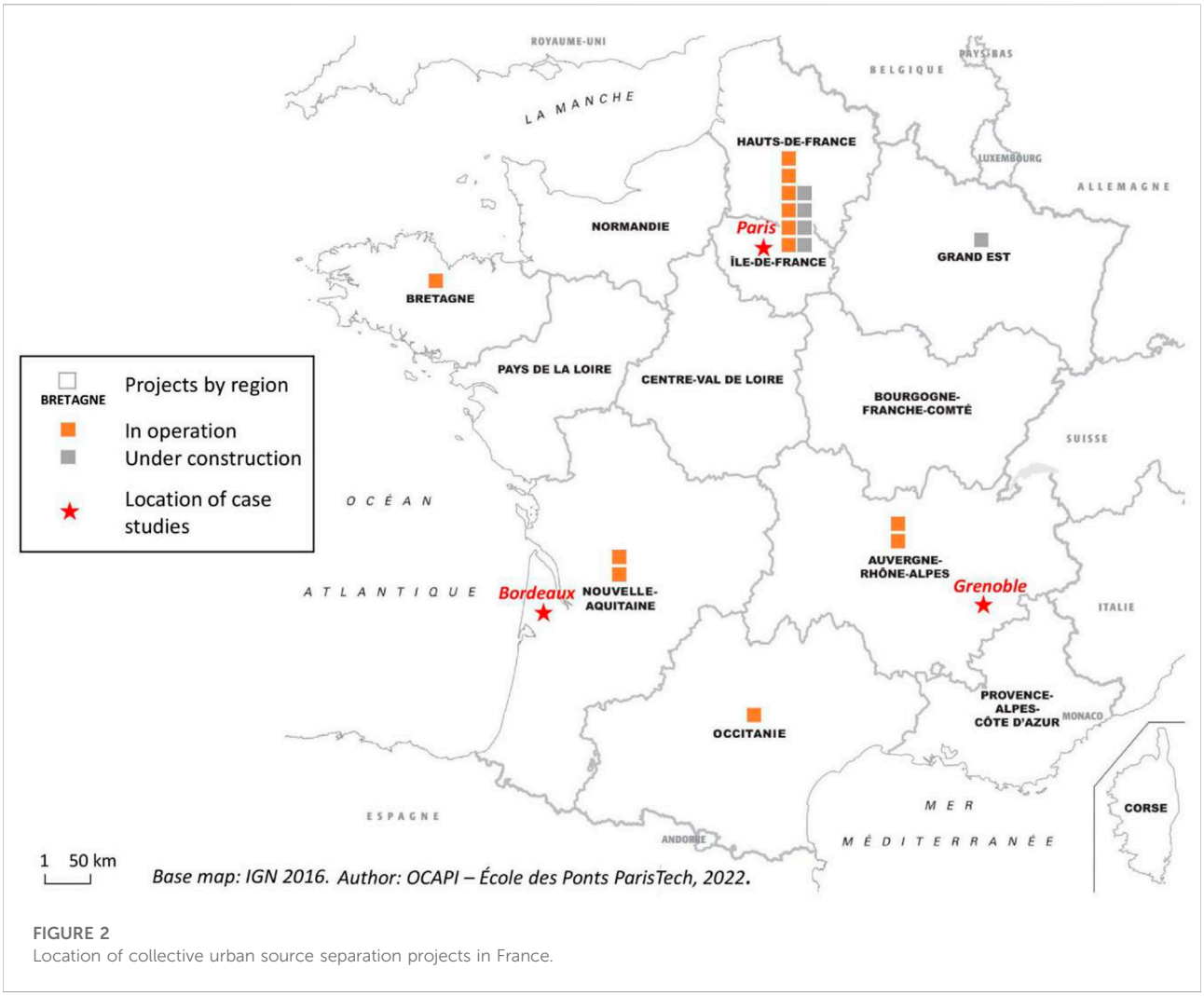

FIGURE 2
Location of collective urban source separation projects in France.

explore the conditions of emergence, operation, and sustainability of these projects.

The studies were undertaken through semi-structured qualitative interviews. From 7 to 25 interviews were conducted, depending on the case. Each time, we interviewed the project initiators, actors taking part in the definition and implementation of the projects, actors responsible for the collection, treatment and valorization of excreta, as well as the users of toilets. In addition, we consulted and analyzed documents, both official and occasionally unofficial, associated with the projects studied (see Table 1). The themes addressed in the interviews were: stakeholders' motivations and dynamics, problems encountered and ways of solving them, decision-making methods, possible pathways for a larger scale deployment of source separation. When the projects were already implemented, the excreta management practices and their evolution were also discussed.

The three case studies resulted in research reports (Joveniaux and de Gouvello, 2021a, 2021b; Audureau, 2021). This article is based on a cross-analysis of the results of these three cases, put into dialogue with other works.

Our work also draws on range of research undertaken within the OCAPI team since 2014 and in particular, the identification and tracking of emerging source separation projects in France, regularly updated; a working group run in collaboration with SIAAP[3] on the topic of the "source separation of domestic wastewater" within Arceau Île-de-France.[4] These works are used in this article to situate the three case studies within a national context and within broader dynamics observed across France and deepen the diversity of situations partly analyzed through these three case studies.

3 Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne.

4 https://arceau-idf.fr/groupe-de-travail/gtt-separation-la-source

TABLE 1 Type of actors interviewed and documents studied for each case.

	Au Clair du Quartier	La Fumainerie	Saint-Vincent-de-Paul
Type of actors (number of interviews) (7; 25; 11)			
Project initiators	Residents (6*)	Non-profit association made up of citizens (9)	Paris municipality (1)
Other actors taking part in the definition and implementation of the projects	Architect (1)	Local authorities (4)	Public development company (2), project management support (4), local water agency (1), researcher (1)
Actors responsible for the collection, treatment and valorization of excreta	Residents (6*)	Private companies (2), associations of collection and valorization of biowaste (2)	Municipal technical department (2)
Users of toilets	Residents (6*)	Members of the experimentation (8)	n/a
Documents			
	Minutes of meetings, Websites and Presentation documents	Minutes of meetings, Websites	Feasibility study on urine separation and documents destined to the steering committee
		Presentation documents	

*The interviewed residents are the same.

3 The recent emergence of urban source separation projects in France: Factors and trajectory

In their comprehensive book on source separation written in 2013, Larsen et al. devote chapters to various European countries that are pioneers in the sector, emphasizing that, beyond common issues, the trajectories are singular each time. In this section, we describe the more recent emergence of source separation in France, highlighting its specificities using the MLP approach.

3.1 Factors favorable to the development of source separation in France: At the crossroads of environmental and food security issues

Transitions in socio-technical systems can be driven in particular by changes in the "landscape," which disrupt the dominant regimes (Geels, 2002 and, Geels, 2007).

In terms of the "landscape" associated with the practice of source separation, we can observe interlocking pressures on food supplies and sanitation. As regards food supplies, conventional food production employs synthetic and mineral fertilizers which leave a deep ecological footprint. Producing synthetic nitrogen fertilizers by the Haber-Bosch process demands large amounts of energy, which is produced using increasingly scarce and greenhouse gas emitting fossil fuels (Smil, 2004). Phosphorus-based fertilizers use mining resources that are unevenly distributed around the world (Cordell, 2010). This situation creates growing tensions on the international fertilizer market (rising prices, shortages). Moreover, the food production and distribution chain discharges large quantities of nitrogen and phosphorus, which contributes to the eutrophication of aquatic environments and to atmospheric pollution. Urban sanitation systems in industrial countries are likewise showing their limitations, notably in France (Esculier, 2018; Esculier et al., 2018). Flush toilets are highly water intensive, at a time of growing water shortages. Processes used in water treatment plants are costly in equipment, chemical reagents, and energy, and are only partially effective. The discharge of nutrients into rivers and streams contributes to eutrophication. Moreover, under the impact of climate change, minimum flow rates in waterways are falling, which diminishes their capacity to dilute effluents and increases the risk of ecological degradation.

In France, the case of the Seine river in the Île-de-France region is emblematic: wastewater management in Greater Paris has many limitations, exacerbated by the fact that the Seine has a relatively low flow rate in relation to the still growing agglomeration's population (Legrand et al., 2021). Maintaining the quality of water resources is a key issue in this region. Despite the treatments introduced, a third of the nitrogen that enters the sanitation system continues to be discharged into the Seine, and water quality thresholds in the downstream area of Paris have been breached. The conventional urban sanitation system has another limitation: it has very limited potential for resource recovery. Mixing the different flows (urine, feces and domestic wastewater), and collecting and transporting them together to treatment plants, makes it difficult to recover and valorize their components (nutrients, organic matter, water…). In Île-de-France, only 4% of the nitrogen and 41% of the phosphorus from human excreta are exploited in agriculture through the spreading or composting of sewage sludge (Esculier et al., 2018).

Faced with these challenges, several studies have shown the potential of decentralized excreta source separation systems in

TABLE 2 Characteristics of 17 collective urban source separation projects identified in France.

Name of the project	Location	Region	Project initiator	Type of excreta separation	Type of toilets	Type of buildings	Number of toilets	Date of delivery > ending
Fondation pour le Progrès de l'Homme	Paris	Île-de-France	Private sector	Urine (U) + Feces (F)	Dry toilets (DT)	Office building	<10	2015
Ecole des Ponts/ OCAPI	Champ -sur-Marne	Île-de-France	Public sector	U/F	Urine diversion dry toilets (UDDT) + Dry urinals (DU)	Public access building	<10	2016
La Cité fertile	Pantin	Île-de-France	Private sector	F	UDDT	Public access building	10 to 100	2017>2022
Jacques Chirac leisure center	Rosny-sous-Bois	Île-de-France	Public sector	U + F	DT	Public access building	10 to 100	2020
Restaurant Le 211	Paris	Île-de-France	Private sector	U + F	UDDT + DU	Public access building	<10	2021
Jeanne d'Arc elementary school	Paris	Île-de-France	Public sector	U + F	DT	Public access building	<10	2022
Lot C15B (office building with university restaurant)	Palaiseau	Île-de-France	Public sector	U	DU	Office + public access building	10 to 100	2023
Saint-Vincent- de-Paul neighborhood	Paris	Île-de-France	Public sector	U	Urine diversion flush toilets (UDFT)	Different types of buildings	>500	2024
Olympic village experimental building	Saint-Denis	Île-de-France	Private sector	U/F	UDFT	Public access building	10 to 100	2024
Seine Aval campus of the SIAAP	Achères	Île-de-France	Public sector	U	UDFT	Office building	100 to 500	2020, but not yet in service
Au Clair du Quartier participatory housing	Grenoble	Auvergne-Rhône-Alpes	Residents	F	UDDT	Housing building	<10	2017
Ecoravie participatory housing	Dieulefit	Auvergne-Rhône-Alpes	Residents	F	UDDT	Housing building	<10	2017
Cinema UTOPIA	Pont-Sainte-Marie	Grand Est	Private sector	U + F	DT + DU	Public access building	<10	2022 or 2023
La Fumainerie	Bordeaux	Nouvelle Aquitaine	Non-profit	U/F	UDDT	Housing buildings (network)	10 to 100	2020 > 2022
Toopi Organics	La Réole	Nouvelle Aquitaine	Private sector	U	DU	Public access buildings (network)	<10	2021
Maison de l'Economie Solidaire	Ramonville	Occitanie	Non-profit association	U + F	DT	Housing buildings (network)	10 to 100	2017
L'Ôôôberge participatory housing	Dol-de-Bretagne	Bretagne	Residents	U/F	UDDT	Housing buildings	10 to 100	2022

Author: OCAPI – École des Ponts Paris Tech2022.

terms of environmental impacts and for agricultural valorization, compared to conventional sanitation systems (Vinnerås and Jönsson, 2001; Winker et al., 2009; Lam et al., 2015; Kjerstadius et al., 2017; Harder et al., 2019). Life-cycle analyses show a real environmental gain in the case of urine source separation systems where nitrogen is: 1) separated from wastewater and no longer treated biologically by nitrification/ denitrification; and 2) valorized in agriculture as fertilizer (Bisinella de Faria et al., 2015; Martin, 2020; Besson et al., 2021; Hilton et al., 2021). Greenhouse and field trials have also shown that the effectiveness of urine-based fertilizers is close to that of synthetic nitrogen fertilizers (Martin, 2020; Martin et al., 2020). A growing number of actors now consider that excreta source separation can contribute to ecological transition, but also potentially to the other challenge highlighted in the current situation: food security. In the last year, there has been strong upward pressure on nitrogen fertilizer prices.[5] Since February 2022, the war in Ukraine has also heavily squeezed supplies and prices for gas, nitrogen fertilizers, and foodstuffs, affecting many countries, especially European

5 The price of nitrogen fertilizers rose fourfold between April 2021 and April 2022.

countries that are heavily dependent on Russian gas and ammonitrate for their agriculture. This situation has fed into debates in Europe on how to increase food security, a goal that the use of urine-based fertilizers could help to achieve. Under these circumstances, the subject has attracted growing media attention. For the year 2022, out of 26 French media documents identified by the OCAPI program on source separation, 9 of them mention the interest of the practice in view of the risks of shortage induced by the war in Ukraine. It should be noted that articles tackled with the subject were published not just in the specialist press, but also in the national media, thus beyond the usual circle of initiates.[6]

The three projects analyzed in this article (see part 4) were motivated by these environmental and food security issues. Au Clair du Quartier was initially motivated by the desire to protect water resources. La Fumainerie wishes for its part "to participate in the effort to reduce the pollution of waterways" and "to promote a sustainable and circular management of excreta"[7]. Finally, Saint-Vincent-de-Paul eco-neighborhood forms part of a public policy of Paris municipality, aimed at creating a pilot site for ecological transition, with a strategic objective of "zero carbon, zero waste, zero discharge." The urine diversion project emerged at the crossroads of local water resource protection issues on the one side,[8] and of sustainable fertilizers, circular economy and food security issues on the other side.

At the "landscape" level, therefore, different environmental and food security challenges have cast doubt on the nutrition/excretion system currently operating in the industrialized world. As a result, source separation is gradually attracting interest as an alternative practice that could help to resolve these problems, with projects emerging with this aim, such as those studied.

3.2 The development of source separation in French cities

Larsen et al. (2021) describe the progress of the practice of source separation, distinguishing between three phases of development: Phase 1: "Local innovation in eco-villages and research projects" (1990–2000), Phase 2: "Local validation in demonstration projects in different countries" (2000–2010), and finally Phase 3: "global diffusion taking-off" (2010-today). Therefore, the authors take the view that the practice is now entering the take-off phase at a global scale, and notably in Europe, with possibilities of larger-scale diffusion. While highlighting some steps taken for this purpose, as the "breakthroughs in toilet design and treatment processes, enabling the technology's value chain to reach the brink of maturity" (*Ibid.,* p.1161), the authors mention a series of obstacles to overcome, notably for the economic viability of the systems and the legitimation of the urine-based fertilizers for their use in agriculture. On this point, steps are beginning to be taken for the European market. A first urine-based fertilizer, the Aurin, produced in Switzerland by Vuna Nexus,[9] has indeed been approved and licensed for sale in this country since 2018, and in Austria since 2022.

What is the situation in France? The practice of urban source separation has started later than in some other European countries. It has not yet reached the "global diffusion taking-off" phase described by Larsen et al. (2021), and would rather be in the phase of "local validation in demonstration projects."

In Scandinavia and in the German-speaking countries, some first projects were developed in the 1990s at a relatively significant scale (eco-neighborhoods) (Larsen et al., 2013; Esculier, 2018). Over the past 15 years, new pilot projects have emerged in Switzerland or Germany. The Jenfelder Au district of Hamburg is currently Europe's biggest urban source separation project (ultimately 835 dwellings)[10]. By contrast, in France, existing projects were limited up to the 2010s to individual household initiatives in rural areas, isolated sites not connected to a public sewer, or one-off events such as music festivals. In urban spaces, a very small number of projects were initially implemented outdoors: dry toilets in public spaces, parks and gardens, etc. Since the mid-2010s, a new dynamic has emerged. Pilot projects in collective buildings are now being implemented in cities as well.

Our inventory of collective urban source separation projects identified 17 projects that have emerged in the last 15 years—12 of them up and running, and 5 under construction or in the design phase (see Figure 2)—as well as many others that have been proposed but not implemented. This inventory also shows the gradual emergence of larger scale projects—office and public access buildings, apartment blocks, and in one case an entire neighborhood (Saint-Vincent-de-Paul, Paris 14th).

Table 2 shows that the identified projects are led by a variety of actors: 6 projects are run by public structures, 6 by private

6 In an article published on 5 June 2022 in the national newspaper Les Échos, the journalist Stefano Lupieri notes that "the use of urine as a fertilizer is re-emerging with the explosion in the price of nitrogen fertilizers caused by the Ukraine conflict". https://www.lesechos.fr/weekend/business-story/fertilisants-lurine-retrouve-des-couleurs-1412090 [consulted on 13 June 2022]. To look up other articles recently published in France on the subject, see: https://www.leesu.fr/ocapi/ocapi-dans-les-medias

7 https://www.lafumainerie.com/les-ambitions [consulted on 14 October 2022].

8 See below the ongoing challenges to preserve the water quality of the river Seine.

9 A spin-off of the Swiss Federal Institute of Aquatic Science and Technology (Eawag).

10 In this project, the sewage is collected in a vacuum, separately from domestic wastewater, and transported to a local methanation unit to produce biogas.

actors, 3 by residents and 2 by non-profit associations. The cases we studied illustrate this diversity. The feces separation project at Au Clair du Quartier in Grenoble originated with the residents themselves, who oversaw the construction of the building in which they live. The project of La Fumainerie in Bordeaux was also instigated by citizens, who in this case set up a non-profit association to trial an urban excreta collection and valorization system. For its part, the urine separation project at Saint-Vincent-de-Paul is run by the city of Paris, in concert with the public development company Paris & Métropole Aménagement (P&MA). There are also private initiatives, like the installation of dry toilets at the Fondation pour le Progrès de l'Homme and at the Restaurant 211 in Paris. Figure 2 also highlights the specific development of source separation projects in Île-de-France, as well as experiments extending to other French regions.[11]

3.3 The beginning of an institutionalization

As our inventory shows, the first urban collective source separation projects appeared in the 2010s in urban "niches" (Geels, 2002), integrating groups of individuals with strong ecological convictions. At the end of the 2010s, source separation began to be incorporated into larger scale urban development projects, instigated by conventional city making actors: the City of Paris for the Saint-Vincent-de-Paul project, the Paris-Saclay Public Development Establishment for the C15B project in Palaiseau (Essonne department), with dry urinals and urine valorization on the neighboring farmland.

Going further, many projects identified have benefited from the support of institutions and local authorities to their implementation. La Fumainerie's experiment over the period 2020–2022 is receiving financial support from the local authorities[12] to the tune of 90% of the project's cost. The investments associated with the urine separation project in Saint-Vincent-de-Paul is subsidized by the Agence de l'Eau Seine-Normandie (AESN—Seine-Normandie water agency) to the tune of 80% for the public facilities and 40% for the private facilities. Other projects in the region of Île-de-France (Restaurant 211 in Paris, C15B in Palaiseau…) also benefit from subsidies of the AESN.

Therefore, what we see here is the development trajectory of an innovative practice as theorized in the MLP current, with experiments appearing in specific "niches" before being diffused to a larger scale. It is foreshadowed by recent projects led by conventional actors, such as the City of Paris. Other signs of this beginning of institutionalization can be listed. Firstly, the financial support of the AESN and certain local authorities reveal a new commitment—although still modest—on the part of public actors. Secondly, the topic is gaining importance in the scientific research community, as shows the evolution of the OCAPI program. Initially developed at the Ecole Nationale des Ponts et Chaussées, it has been fostered along the last years through national projects involving not only other French research centers (such as Institut national des sciences appliquées, Centre national de la recherche scientifique and Institut national de recherche pour l'agriculture, l'alimentation et l'environnement), but also the collaboration of public instances (such as the Chambre d'agriculture d'Île-de-France), associations and private companies. Finally, professional networks dealing with this topic also emerge. The first one is the Réseau de l'assainissement écologique (RAE). Created in 2009 by ecological sanitation pioneers, it was, at first, focused on rural places and one-off events and is now booming in terms of numbers of actors and variety of projects. More recently and with an urban purpose, a working group on "source separation of domestic wastewater" was created in 2016 in Île-de-France within the association ARCEAU. It gathers some 60 members from local authorities and public institutions, researchers, and practitioners involved in urban production, sanitation and excreta management. Source separation has also started to be a topic in events and workshops organized by professional networks of local authorities and the water and sanitation sector.

We can conclude from this general analysis that source separation is gradually spreading in France, but is still in a phase of "local validation in demonstration projects" (Larsen et al., 2021).

4 Cross-analysis of three source separation projects

As Larsen et al. (2021, p.1165) point out, source separation is "a systemic innovation challenge." On the one hand, it disrupts the representations and practices central to the dominant socio-technical sanitation and nutrition regimes. On the other hand, far from being solely technical, this new approach demands various orders of change (acquisition of new knowledge, adoption of new practices, changes in rules and markets…) (Bergek et al., 2008a). In addition, there is the need to bring different actors into alignment for the implementation and success of the processes.

11 The inventory conducted, based on the information gathered by the OCAPI team, is not necessarily comprehensive. Since the research program is located in Île-de-France, it is easier to identify projects arising in that region compared with the other regions.

12 Bordeaux Métropole, Département de la Gironde and Région Nouvelle Aquitaine.

10.3389/fenvs.2022.976624

TABLE 3 Configurations of actors and systems of collection and valorization in the case studies.

Case studied		Au Clair du Quartier (Grenoble)		Saint-Vincent-de-Paul (Paris 14th)		La Fumainerie (Bordeaux)	
Materials collected		Separate feces collection, urine to sewers		Separate urine collection, feces to sewers		Separate collection of urine and feces	
Project scale		Participatory housing block (5 families)		Neighborhood (600 homes) + various shops and amenities		Urban excreta collection and valorization network (60 participants: 34 households +4 other structures)	
Progress status		Operating since 2017		Under construction. Commissioning in 2024		Experiments underway (2020-2022)	
Project initiator(s)		Residents of the building		City of Paris + Paris Métropole Aménagement		La Fumainerie association	
		System	*Run by*	*System*	*Run by*	*System*	*Run by*
Existing or planned process	**User interface**	Urine diversion dry toilets	Residents	Urine diversion flush toilets and dry urinals	Different public and private actors	Urine diversion dry toilets	Installation: La Fumainerie association Day-to-day operation: participants
	Collection and transport	Manual, in a bucket, to the garden	Residents	By separate network to a plant located in the neighborhood	Ville de Paris (the right management)	By delivery tricycle to the Maison de la Matière Organique (MAMMO—organic matter center), place jointly managed with the Récup Bokashi Association	La Fumainerie association
	Type of treatment and valorization	Composting in the garden	Residents	Production of a fertilizer (concentrated nitrified urine)	Operation of the plant, owned by the City of Paris, outsourced to a private company	Feces: 1/composting on an industrial platform 2/experiments in swath co-composting with bio-waste, then by electromechanical composting at MAMMO	1/The Pena Environnement Company 2/La Fumainerie and Récup Bokashi associations
						Urine: was to be used to produce biostimulants. Following conformity problems with the process, the partnership was stopped	Stopped partnership with the firm Toopi. Looking for new partnerships
	End uses	Use of compost in the garden (for trees only)	Residents	Use of the fertilizer on the City's green spaces	City of Paris	Feces: use of the compost: 1/by farming specialists 2/by a local structure for a teaching garden and by individuals	1/Customers of Pena Environnement 2/Local structure and individuals (distribution by La Fumainerie association)
						Urine: Currently no valorization	
System Funding		Self-funding by the inhabitants		City of Paris, public and private actors, subsidies by the Water Agency		Subsidies from local authorities and central government: 95%, participatory funding and association memberships: 5%	

Author: OCAPI – École des Ponts Paris Tech, 2022.

This part seeks to highlight the implementation dynamics of the three studied projects: Au Clair du Quartier (ACQ) in Grenoble, La Fumainerie (LAFUM) in Bordeaux and Saint-Vincent-de-Paul (SVP) in Paris. We analyze their temporal processes, the reasons for socio-technical choices, the challenges encountered and the responses to them, as well as the stakeholder alignment issues. We also study the various forms of "territorial embeddedness" of the projects. Finally, we wonder about the sustainability, as well as the possibilities of diffusion of these different kinds of projects.

4.1 Defining and implementing projects: A long-term process

Defining and implementing source separation projects is a long-term process. It implies adjustments in response to urban constraints. It also depends on changes in the relative engagement of actors in the project and the problems they collectively encounter. Different key topics came out of our qualitative cross-analysis of the case studies and the interviews linked to them: first, socio-technical options are highly driven by

urban constraints (spatial and logistical); second, project implementation relies on the possibility to make choices along the way; third, this long-term process is notably marked by regulatory negotiations and progressive partnership development.

4.1.1 Urban constraints driving socio-technical options

A dense urban environment may seem conducive to source separation, given the quantities of excreta that can be collected and valorized. Nonetheless, this context carries its own constraints. The three projects (see Table 3) had to accommodate these constraints, which influenced some choices made.

At ACQ, the residents opted for urine diversion dry toilets (UDDT) with only feces being collected and valorized, a decision motivated by logistic and spatial constraints. It reduced the storage volumes and facilitated handling,[13] in the context of a building with no elevator and no basement, with small apartments and a small attached garden of 200 m^2. Here, residents have chosen to manually carry their feces in a bucket to the garden for composting, the urine reaching the public network. In the LAFUM project, the organization installs dry toilets in individual homes and collects the materials by delivery tricycle. LAFUM association has chosen UDDT to facilitate not just the valorization of urine and feces, but also handling and transportation by the collector. At SVP, the urine produced from all the dwellings will be collected *via* urine diversion flush toilets and transported by a separate network to an on-site plant. Urine will be treated by nitrification-distillation to produce a concentrated fertilizer (5% of the initial volume), the Aurin. The aim is to reduce the volumes transported off site for valorization, since SVP is right in the center of Paris where movement is difficult.

Urban source separation projects thus bring constraints, in particular spatial and logistic constraints, which are specific to dense urban environments, but also to each site (Legrand et al., 2021). These constraints partly steer the technical choices, though without determining them. The cases studied illustrate the variety of possible options (collection of urine and/or feces, transportation by hand, *via* a network, or by delivery tricycle, valorization of materials *in situ* or off-site in different forms. . .) and show that the range of possibilities is actually very wide. The socio-technical options chosen also depend on the characteristics, motivations and aspirations of the actors involved (see Section 4.2.2).

13 Collecting urine and feces would have entailed storing and managing 10 times the volume of material.

4.1.2 Project implementation dynamics: Making choices along the way

The three projects studied share the trait of being largely constructed "as they went along," with decisions taken and changes and rearrangements made along the way.

The system set up at ACQ was the outcome of step-by-step design over the period 2012–2015 within a sustained dialogue between the inhabitants and the architect, made possible by the participatory housing approach. Once the building was commissioned in 2017, the residents continued to adjust their practices in areas such as toilet maintenance or compost management over the subsequent years (Joveniaux et al., 2021). In the case of LAFUM, the task in 2020 was to find volunteer households prepared to trial dry toilets in their homes. Similarly, partner firms ready to valorize the urine and feces collected were gradually identified. As we will see, these partnerships also evolve during the experimentation in 2020–2022 (see Section 4.1.3).

As concerns SVP, the experiment was part of a larger urban development project, which imposed its timetable for the decision-making process. During the consultation phase in 2019, real estate operators who applied to develop the ten plots in the district were thus required to include the possibility of separate urine management in their projects, even though the option was still on the drawing board and there was no certainty of implementation. To this end, they were asked to set aside spaces and passages in the buildings so that the project could be implemented if approved. It was only subsequently, in 2019–2020, that a feasibility study on urine separation was conducted, with four scenarios of varying ambition (from a single plot to the entire neighborhood). At the end of 2020, the City's municipal councilors approved the most ambitious scenario. Following this, other choices had to be made, notably about the methods of managing the system.

It is also worth pointing out one factor that favored action: the reversibility of the project. Given the uncertainty regarding the real-world success of the experiments, the systems chosen in all three cases are reversible, offering the possibility of reverting to flush toilets and the public sewage network. This condition made it easier to convince the different actors to join the project.

Finally, this ongoing process sometimes took place in dialogue with a community of researchers. LAFUM experiment was supported by a monitoring committee made up of researchers from different backgrounds. As for the SVP operation, the idea of adopting urine source separation was proposed by a researcher (Fabien Esculier) at the design phase, and followed in an observational capacity by researchers from the OCAPI team.

In the three cases, the projects' implementation appears as an open and evolving process. It is inherent in an experimental approach that has its own burden of unknowns and requires dealing with uncertainties, notably in terms of technologies, markets and regulations (Bergek et al., 2008b). In this process,

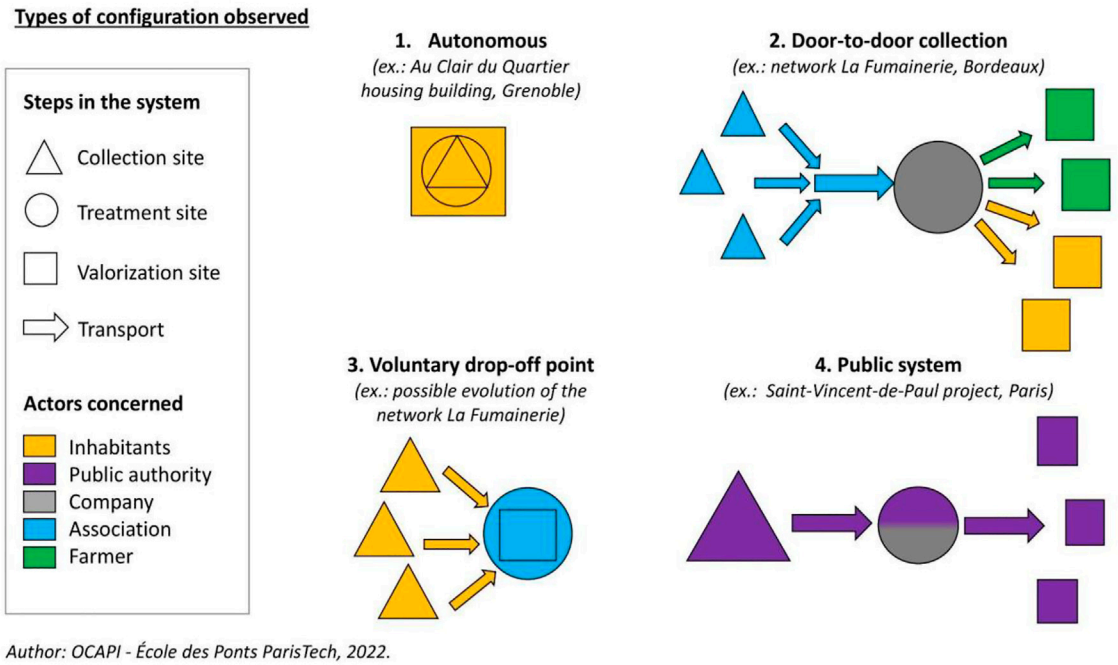

FIGURE 3
Types of system configuration observed in the three case studies.

the projects' sponsors sought to leave some possibilities open, while accommodating the need to take decisions based on a timetable imposed from outside.

4.1.3 Putting a new sanitation paradigm in practice: Challenges encountered

At first sight, the ACQ project might seem simpler than the other two projects studied, in that it involves a single apartment building and only a small number of actors. Indeed, the five families involved in the project designed and now manage the system themselves. The main challenge here was to convince all the residents of the pertinence of the project, which was initially proposed by a few of them. One essential step was to take the time for discussion, which continued over 3 years (2012–2015). This process led to a collective decision on a system that matched the constraints and possibilities of each household. These factors, along with the strong and shared involvement of the residents in the running of the system, may explain why it has worked smoothly since 2017 (Joveniaux et al., 2021). On a regulatory level, the ACQ project respects the existing legal framework in France, while playing on its ambiguities. The regulations require that buildings located in a collective sanitation zone be connected to the sewer, without however imposing the evacuation of excrement into it. At ACQ, we are in a hybrid situation: the urine goes to the sewer, but not the feces. Maintaining a sewer connection has avoided regulatory difficulties.

LAFUM association had on its side to tackle various challenges in order to carry out its experiment. The association had to obtain support from the local authorities to fund its experiment and also to obtain the agreement of the relevant government departments to implement it, which entailed numerous discussions in 2019–2020. As well as for the ACQ project, the installation of dry toilets in a collective sanitation zone takes place in an unclear legal framework. Furthermore, the regulations which enable obtaining a license for excreta collection do not take into account the possibility of a tricycle transport. Proposing an out-of-frame project, LAFUM association decided to lead its experimentation despite a legal vacuum, with the consent of local authorities. Partnerships also had to be formed for the valorization of the excreta. Since 2020, feces recovery has been carried out by an industrial composting platform, Pena Environnement, on the outskirts of Bordeaux. In parallel, LAFUM association is also conducting experiments in the combined composting of feces and biowaste with another association, Recup'Bokashi,[14] in the Maison de la Matière Organique (MAMMO)[15] in Bordeaux. For the urine management, a partnership was set up in 2021 with Toopi

14 Association which collects biowaste.

15 Structure created in 2021 by LAFUM and Recup' Bokashi associations, in order to pool their resources.

Organics, a Gironde start-up created in 2019 with the aim of producing agricultural biostimulants from urine using an industrial fermentation process. However, following problems of pH conformity in the urine collected with the process utilized,[16] this partnership was terminated and LAFUM association is looking for other valorization solutions. This situation prompts two observations: it is difficult, when collecting from multiple micro-contributors, to meet the "quality" requirements of an industrial firm. It is also difficult to find partners for excreta valorization, since this is still an emerging sector.

During the design phase of the urine separation project in SVP (2018–2020), the project's initiators also had to tackle a series of challenges. Three stages in particular were fundamental, and gave rise to key decisions in 2020 in favor of moving forward with the project.

- A first challenge was to identify a project coordinator at Paris municipality to manage an innovative project that raised crosscutting problems involving multiple departments, notably the Waste Management and Water Department (DPE) and the Green Spaces and Environment Department (DEVE). The entry of the Mission Résilience[17] into the play of actors was an important step in opening up the closed silos of the municipal departments. In 2020, this structure oversaw a collective process of discussion and decision-making around a municipal-scale project, in concert with the public development company P&MA. It is worth noting here that the source separation project received high-level political support at Paris municipality, which led to the process being backed by the Mission Résilience, an offshoot of the City's General Secretariat. As a result of this situation, a project involving several different departments could be effectively coordinated.
- A second priority was to establish a system of governance that would ensure integrated management. In 2018–2019, there were debates about whether the collection network and urine treatment plant should be public or private entities, and over the type of management to adopt. Paris municipality finally decided to set up a publicly controlled urine collection network, and to outsource the management of the treatment plant, which would remain a municipal property, to a private company. The DPE agreed to run the urine collection network, despite an initial lack of information about the potential costs to the department.
- A third key step was to find outlets for the urine-based fertilizer, which is not yet licensed for sale in France. Given the circumstances, Paris municipality decided in 2020 to use the urine-based fertilizer internally, on the City's green spaces,[18] pending the issue of a license that could open up new outlets. The involvement of the DEVE meant that the latter's questions about the agronomic qualities and health risks associated with urine-based fertilizer had to be answered. Financial questions were also raised. According to an assessment by the City, if DEVE buys the urine-based fertilizer from the DPE at the price it pays for its liquid fertilizer, the operation (urine collection, treatment, and valorization) should break even. This financial assessment proved to be an important factor in favor of the involvement of the two departments concerned (DPE and DEVE).

In the three case studies, the implementation of the source separation projects thus represented a long term process. It entailed overcoming challenges, finding answers to new questions (technical, regulatory, financial...) raised by an untested practice, and gradually bringing the necessary actors into alignment. In line with the work of Kerber et al. (2015), our analysis shows that organizational aspects and new forms of cooperation between actors of different sectors appear fundamental for the implementation of such transversal projects. It implies that the different actors involved manage to share among themselves the roles, responsibilities, investments and risks associated with these innovative projects.

4.2 Forms and dynamics of the projects: Lessons and questions

A cross-analysis of the cases brings out the diversity of the forms of territorial embeddedness, not just in terms of scale, but also in terms of configurations of actors. After having highlighted this diversity, we will question the projects' dynamics and sustainability, as well as their possibilities of diffusion.

4.2.1 Diversity of scales and actors' configurations

At ACQ, the project, implemented in a single apartment building, is entirely managed by the residents. For its part, the LAFUM experiment, which encompasses a network of collection sites scattered around the city, involves residents, a non-profit that installs the dry toilets and collects the excreta, and partner companies for their valorization. The SVP project is the one that brings the largest number of actors into play. Paris municipality plays an essential role, since it has decided to manage a large part of the system in-house (urine collection and use of the urine-

16 Obtained by adding acid to the urine, an operation carried out by the households participating in the experiment.

17 Structure created in 2015 to coordinate the urban resilience strategy adopted in 2017 by Paris municipality.

18 An approach that does not require a commercial license, only certain checks before use.

based fertilizer). On the other hand, the running of the treatment plant is to be outsourced to a private company. The future system will also involve many other actors at the scale of individual buildings: developers and landlords, maintenance operators for the pipes and toilets, and—essential actors for the successful operation of the system—residents and users, who will need to adapt their practices to the toilets. The three cases studied thus outline new forms of sanitation system territorialization. Figure 3 provides a schematic of the different types of system configurations observed.

ACQ is an "autonomous" project, with the feces being collected, treated, and valorized on site by a single set of actors: the residents (type 1).

The LAFUM project involves both non-profit and private actors, a system of door-to-door collection on multiple urban sites, then several types of treatment and location, both urban and periurban, for the materials collected (type 2). The outlets are also varied—private gardens in the city and farms in rural areas—and the scale regional. The LAFUM network could ultimately evolve (see next section) in its methods of collection towards voluntary drop-off points (type 3).

For its part, the SVP project (type 4) is primarily run by a public actor, Paris municipality, although the operation of the urine treatment plant is outsourced to a private company. In SVP, urine will be collected *via* a public network and treated on site, but looking forward it is conceivable that a neighboring district could be connected to the treatment plant, with the urine being transported and treated off-site. The method of operation adopted in SVP could be seen as a continuation of the conventional centralized sanitation system managed by local authorities, possibly in partnership with private companies. However, the scale of management is more decentralized than is currently the case in Île-de-France, where wastewater treatment is concentrated in a handful of plants run by SIAAP across the region. In this case, the fertilizer produced will be valorized not on site, but across the city of Paris.

In the projects described here, we see the outlines of new forms of excreta management, undertaken by new actors. It reveals the beginning of a circular approach to flow management, in some cases at local level, in others at the regional scale.

4.2.2 Sustainability and possibilities of dissemination of the projects studied

The analysis carried out shows the diverse forms of territorial embeddedness of source separation projects currently implemented in French cities. What are the development possibilities of these different projects?

The socio-technical choices made in the ACQ and LAFUM projects are based on "low-tech" options and require a relatively strong involvement of inhabitants and/or workers involved in excreta collection and transport. The "autonomous" project set up at ACQ is in line with the values of the group of inhabitants, wishing to get involved in the management of their habitat, in favor of the environment. It is based on a dry toilet model that is more expensive than a conventional toilet, but the absence of flush water generates savings. The system is self-managed by the residents. It has been running for several years. However, it requires a significant investment in time on the part of its users, and could run into problems if current or future residents lose commitment. The LAFUM experimentation is less demanding for the inhabitants, since collection and treatment are supported by the association and partner companies. It nevertheless implies that the inhabitants choose to use dry toilets. They must also warn LAFUM association when the toilets have to be discharged and they must be at home when the collector comes. After 2 years, the results of the experiment are very positive in terms of dry toilets acceptability. The 40 or so participating households are keen to continue using dry toilets in their homes, and LAFUM association has received around a hundred requests from other families. The experiment shows that there is a real demand from people interested in the idea of having dry toilets in an urban environment. However, logistical and economic issues are raised for the sustainability of the network. The weekly home collection service by delivery tricycle is expensive: 200 euros a month for each collection site, an unviable model in the long term. LAFUM association is therefore considering the possibility of changing its collection model. One option is for people to take excreta to a voluntary drop-off point, which would make collection less expensive. This is more demanding for inhabitants: will they be ready to do so? Whatever options are chosen, the LAFUM project will need to find new sources of funding to continue.

The choices made by Paris municipality at SVP are based on more "high-tech" options than at ACQ and LAFUM, with urine diversion flush toilets that seem very similar to conventional flush toilets, a collection by a dedicated sewer, and a nitrification-distillation treatment facilitating the external transport and use of the fertilizer. The SVP project is based on recent technological developments, both in terms of toilets and treatments. Concerning economical aspects, the investments in the urine separation system are highly subsidized by the AESN (regional water agency). The assessment carried out by Paris municipality seems to show that, once the system is up and running, the municipality will be able to fund the operation through the savings it makes on the purchase of fertilizer for the city's green spaces (see Section 4.1.3). If a commercial license is issued in France in the coming years for the type of urine-based fertilizer produced in SVP[19], this fertilizer could then be sold and the valorization system opened up to external markets (farmers, etc.).

19 Which could soon be the case, since it has been approved in Switzerland since 2018 and in Austria since 2022.

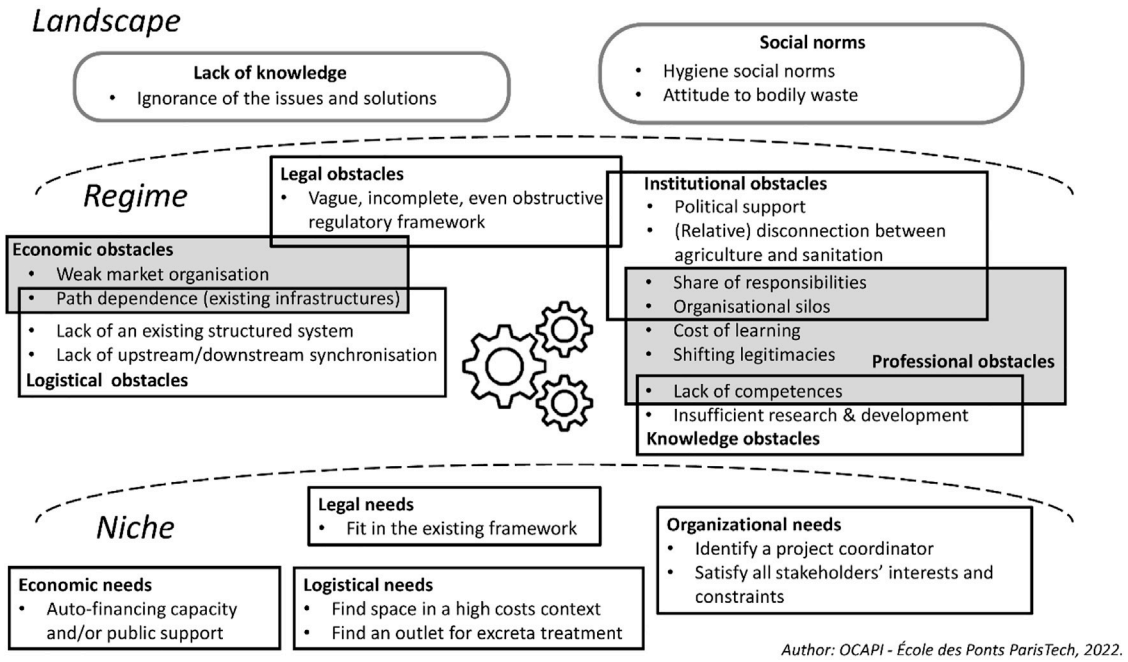

FIGURE 4
Different kinds of constraints hindering the spread of source separation in France.

The three cases differ in their forms and are still evolving. The projects' diversity first responds to the diversity of territorial contexts, generating specific constraints and possibilities. But it also depends on the conceptions, motivations and expectations of local stakeholders. Concerning the diffusion of source separation, the dissemination of configuration types 1 and 2 (Figure 3) beyond their current niches is not guaranteed, since they currently involve toilet users with a strong environmental sensitivity. However, they respond to the values and aspirations of certain citizens and can therefore develop further as values evolve. The SVP project is based on technical options that seem more easily transposable to other sites. It is a large-scale flagship project, carried by a major player (Paris municipality). The success of this project could therefore contribute to the legitimization of the practice and inspire other actors in urban areas. Failure would have the opposite effect. Widerly, the sustainability of the projects, the forms they will take in the future, as well as the possibilities of wider diffusion of the practice will depend on multiple factors, discussed in the following part.

5 Towards the spread of source separation in France?

The cases presented in this study represent, in terms of innovation trajectories, niches of emergence for alternative practices. Two of them (ACQ and LAFUM) are grass-roots initiatives, led by groups of environmentally sensitive citydwellers, whereas the third one (SVP) is led by a collectivity pioneer on urban source separation projects in France. It is not easy to infer from these cases the possibility of scaling up for source separation. Based on results of our case studies, we discuss in this last part existing obstacles and possible levers to the diffusion of the practice. To do this, we will draw on the TIS framework and analyze the state of development and the functional dynamics of source separation in France, in the light of the critical functions put forward by Bergek et al. (2008a).

5.1 From niche experiments to wider implementation: Insights from a TIS perspective

As stated in Part 3, the development of the practice in France is only emerging. Concerning TIS structural components, the techniques associated with source separation have reached a certain degree of maturity, enabling projects such as SVP, based on recent technical proposals for the collection and treatment of materials. New private and public actors are also getting involved, including large ones (Paris municipality). Networks are beginning to structure themselves (RAE since 2009, ARCEAU working group since 2016). Institutional actors are beginning to support the practice, both on the sanitation side (AESN on its territory), and on the agricultural side (Chambre d'agriculture d'Île-de-France). But the actors,

networks and institutions within the TIS are still weakly developed and linked to each other. They will have to strengthen and connect together in order to be able to influence the evolution of the sanitation system.

If we take up the different key functions for the diffusion of an innovation mentioned by Bergek et al. (2008b), these functions are in our case still weak and unevenly developed. We evaluate below the dynamics of each of them.

5.1.1 Development of knowledge and field experimentation

Among the key functions for the development of an innovation is the development of knowledge. For the moment, this function appears to be insufficiently fulfilled, the lack of knowledge acts as a bottleneck for the diffusion of source separation. Most interviewees pointed out this lack of knowledge, both on the environmental issues associated with excreta management, and on the solutions available to move towards more virtuous practices. There is still a general ignorance among the different actors involved in the "making of the city"[20] about these two topics. Current nutrition/excretion systems are a problem, but the complexity of the systems prevents the problem being grasped. In addition, the conventional method of managing urine and feces makes it invisible and shifts the problem downstream, out of the city. Many problems are familiar to the actors concerned: the growing costs of sanitation, pressure on water resources, pollution of aquatic environments, greenhouse gas emissions, etc. But these clusters of problems are not consciously linked together and connected with the methods used to manage human urine and feces.[21] The lack of knowledge concerning the different techniques available for the separate collection, treatment and recovery of excreta also appears to be an obstacle to the emergence of alternatives. In response, an encouraging trend is the clearly growing media interest in the subject: it participates in knowledge diffusion, concerning both scientific research, technical options and project implementation. Apart from the working group created into the Arceau association in Paris region in 2016, expanding, or creating new networks of actors in other regions on the topic would contribute to the dissemination of knowledge and the sharing of experiences between actors.

The functions "influence of the direction of search", "resource mobilization" (both for research and field projects) and "field experimentation" are interrelated and influence knowledge creation and dissemination. They have been developing for about 15 years in France, without however having yet acquired enough strength. Field experimentation and community-based research projects emerged in the 2000s, led by NGOs, firms and citizens, members of the RAE. This led to the emergence of efficient ecological sanitation systems, both in rural and urban contexts, generally at a small scale. Going further, public actors have been funding research since the mid-2010s and around ten academic research teams are now involved in projects on source separation. Some local authorities are now providing financial support for field experimentation in urban contexts at a larger scale, and a minority carry them out directly (case of the City of Paris). Finally, private investors are starting to provide funds in the development of industrial processes for the treatment and valorization of excreta. This is the case, for example, of the start-up Toopi Organics, created in 2019, working on a urine fermentation process to produce bacterial strains for the agricultural market. Note that the company also benefits from public subsidies.

Although the field of source separation has been developing over the last 10 years, the research conducted, the experiments carried out and the resources invested in this field are still very low compared to the resources mobilized and the research and experimentation activities carried out in the conventional sectors of the nutrition/excretion system.

5.1.2 Finding economic and logistic models

Another critical function mentioned in the TIS framework is market creation. Markets for fertilizers derived from excreta are indeed emerging in some European countries. One example is the authorization of Aurin in Switzerland in 2018 and in Austria in 2022. Beyond the question of the market, in our sense there is a need for an economic model in a broader sense, since excreta management represents above all a service to the population. From this point of view, one major obstacle is the current phenomenon of path dependence, since investments in the conventional sanitation system may act as a disincentive to new investment in alternative systems.

In France, source separation projects are currently based on different options: direct recovery of materials, on site (in the case of ACQ) or within the structure (in the case of SVP), or recovery of materials by other actors (composting platforms, farmers, etc.). The latter occurs in an informal[22] or sometimes through a formal framework, or through experimental channels (in the case of LAFUM). Some actors claim the choice of an autonomous management of excreta at the scale of the dwelling. Nevertheless, many urban configurations are incompatible with on site treatment and reuse of urine and/or feces.

Beyond economic aspects, the creation of excreta management chains also raises professional and logistical

20 Private actors (sanitation engineering offices, architects, spatial planning and construction firms, etc.) and public actors (local authorities, water authorities, etc.).

21 This situation is in sharp contrast with the intense debates around methods of managing urine and feces during the second half of the 19th century in France (Jacquemet, 1979).

22 Many companies renting dry toilets for festivals have established agreements with farmers for the recovery of materials.

issues. Indeed, the absence of already structured chains hinders the interplay of supply and demand. The development of the practice requires the involvement of actors at every step of the process. It also requires adapting the management chains to the needs and habits of the territorial actors involved, with a synchronization between current possibilities for the collection of human excreta on the one hand, and agricultural fertilization practices on the other hand (the tools, the timeframes, the technical approaches, the volumes, the forms of products preferentially used. . .). Public policies have a decisive supporting role to play in this development, through institutional and financial support.

5.1.3 Building legitimacy

Another function, and undoubtedly the most important for the dissemination of source separation on a larger scale, remains largely to be built: that of the legitimacy of the practice. Legitimacy can be defined as "the perceived consonance of an entity with its institutional environment, i.e., a socially constructed set of norms, values, beliefs and practices in its context" (Markard et al., 2016, p.330). As concerns source separation, the legitimation process is just beginning in France, and the involvement of more actors depends on the joint evolution of legislation and social norms.

In the first place, the standard conceptual and legal framework governing the management of human excreta at present is transportation by water and treatment in centralized plants, for urban and rural areas belonging to collective sanitation zones. Excreta treatment systems associated with source separation are therefore developing in France within a legal framework that is unclear and subject to interpretation (see Section 4.1.3). This situation prevents the involvement of new actors, beyond the pioneers. Likewise, the use of excreta-based fertilizers in agriculture, although legally possible (except in the case of organic farming), is hampered by the absence of a specific framework. To date, agricultural recovery is possible using the category of sewage plant sludge, a category that is particularly constrained due to the specific environmental risks associated with sludge. A clarification of the regulatory context, and at least an explanation of the possibilities offered by the existing framework, would make it possible to remove some of the existing legal uncertainties, and at the same time to legitimize the practice by explicitly integrating it into the legal texts.

Furthermore, the legitimation of the practice implies a commitment of political and institutional actors. In Part 3, we showed the decisive role played by local authorities and local or regional institutional actors in experimental source separation projects, whether in the form of direct control, political support, or financial subsidy. A wider dissemination will require increasing political and institutional support, at national and regional levels. For example, through the financial support of source separation by water agencies on other territories than Seine-Normandie. More broadly, ecological transition in the nutrition/excretion system calls for global change in the national and international rules and policies that underpin the operation of the current nutrition/excretion system, from both a regulatory and an economic perspective (for example, the evolution of the EU's Water directive, or again of the rules, taxes and subsidies regarding fertilization practices).

Finally, the legitimation of source separation also implies a transformation of social norms. Indeed, the practice collides with social norms that have so far been little discussed: the disgust for the excremental sphere, combined with a form of denial over the production of bodily waste. This is facilitated by flush toilets and sewers that make excrement disappear, both materially and symbolically (Hawkins, 2004). What can be done to raise awareness of these issues, and thereby to change practices? This is one of the essential questions regarding the development of source separation. Rather than developing systems with the logic of hiding excreta from the users, making the question of nutrient pollution and excreta recovery visible in public spaces, without sacrificing comfort of use, is a road that has been taken by several actors, such as LAFUM association and other members of the RAE, with a certain efficiency.

To conclude, the development of source separation in France is still facing a series of constraints (Figure 4). Setting up a niche operation involves meeting a series of practical needs. Development on a larger scale comes up against a series of intertwined obstacles (at the regime level) that must be overcome. It also calls for deeper mutations (at the landscape level) regarding in particular social norms and cognitive frames. Bergek et al. (2008b) note that what is legitimate may shift in response to changing problem agendas at the societal or landscape level. For the past 15 years, the dominant regimes of the nutrition/excretion system have been increasingly challenged by environmental and food security issues. These issues have, on the contrary, favored the development of source separation. Will the growing tensions in Europe lead to a real questioning of the dominant regime? For example, the historic drought that affected France during the summer of 2022 led to critical water shortages in many territories. In this context, alternative sanitation practices such as dry toilets may acquire more legitimacy and disseminate on a larger scale.

5.2 Exploration of possible development paths

The process of extending source separation beyond niches of innovation faces a series of obstacles. Nonetheless, having considered them, it may be helpful to think, from a territorial perspective, about the pathways of development that are currently emerging. We find ourselves at a moment where there is an accumulation of local experiments. Each one seems unique in its kind and specific to its territory. How can these initiatives fit more broadly into the making of the city, how can they connect with a more generic model of urban development? In the rest of this article, given the current state of knowledge, we

will restrict ourselves to advancing hypotheses that may serve as a basis for future research on the subject.

Let us begin by asking the following question: is the contingent nature of the experiments observed in the emergence of source separation in France a temporary phenomenon, pending the development of generic systems, or is it irreducible, necessary for the solutions to be sustained?

The cases studied show possible points of entry for source separation implementation. The 4 types described in Figure 3 constitute alternatives to the conventional connection between sanitation systems and real estate development. Other surveys conducted with source separation stakeholders have shown the possibility of even more alternatives (Crolais et al., 2016; Brun et al., 2020), which could lead to defining additional types. The transition to larger scales depends on political choices, which may lead to changes in legal and economic rules and facilitate certain types of projects rather than others.

The analysis undertaken here brings out the diversity of possible source separation projects, of their forms of territorial embeddedness and actors configurations. In France, certain authors have looked at the question of the dynamics and territorial reconfigurations that might promote the energy transition (Rumpala, 2013; Tabourdeau and Debizet, 2017; Defeuilley, 2018; Lapostolle, 2021) or else the farming and food transition (Lamine, 2012; Bognon and Marty, 2015; Verhaeghe, 2020). Following on from these studies, it is noteworthy that the source separation systems studied, if disseminated more widely, could have a "transformative potential" (Fontaine, 2017) for the governance and territorialization of the nutrition/excretion system. Indeed these systems are managed by the residents at ACQ and by members of a non-profit citizen group in the case of LAFUM. In SVP, the municipality has decided to manage the system at its own scale, which could be perceived as a reterritorialization of urine management compared with that of waste water, which is currently managed at the scale of the agglomeration. The projects studied thus entail a reappropriation of the management of resources in their territory by citizens or local authorities. While these projects vary in scale, in each case they represent forms of relocation of resource management, with the beginnings of circular resource loops operating within cities or between cities and the surrounding countryside. New links and mutualisms are created between actors and territories, relocated by comparison with those underpinning the current nutrition/excretion system.

It is nevertheless difficult to imagine that the pioneering experiences described in this study will spread very rapidly without a disruption or break in the established socio-technical regime. Indeed, a considerable and necessarily long-term effort will need to be made to change professional practices, but also social norms, before human excreta management can become a circular process. It is therefore reasonable to also consider the prospect of an expansion in source separation based on opportunistic responses by territorial authorities to external proposals, and a preference for turnkey solutions. On top of this, there is the inertia of the current system of urban services, which are often outsourced to private actors that are part service providers and part public service contractors. The nature of the current system might favor the development, by the big urban service contractors, of generic, industrial scale solutions that can be reproduced everywhere.

These big urban service contractors are playing a wait-and-see game on this issue, and have not yet taken a position in terms of service offerings, even if it is likely to happen quickly. Moreover, in the last 15 years in France, there has been a trend for water and sometimes sanitation services to be brought back under municipal control, with some local authorities deciding to break with the practice of outsourcing to the private sector and to revert to public control (Chiu, 2013). This is the case for the cities in our study: Grenoble brought its drinking water system back under municipal control in 2000, Paris in 2009, and Bordeaux is planning to resume direct management of water in 2023 and of sanitation in 2026.

Beyond the big urban service contractors, it is worth considering another type of industrial actor here, those that view human excreta as a resource and that have positioned themselves in the collection market in order to ensure efficient access to this raw material. One example of this is the French start-up Toopi Organics. This company, which has just obtained a license for their urine-based bacterial strains for agriculture, is hoping to create a large-scale market for the resulting products *via* local partnerships with agro-industrial actors (the 20 biggest French cooperatives). It is thus seeking to develop an integrated market. In this case again, the tendency is towards a generic type of rollout based on a small number of industrial type actors operating at national level.

Hence, very contrasting development paths could be taken, from local collection and valorization of excreta through various small-scale projects, to mass collection and redistribution. This observation raises the question of the potential need to adapt projects to the specificities of each territory. Studies on water management (de Gouvello, 2001) have shown that territories are to some degree irreducible when it comes to importing an imposed model, which instead needs to be reinterpreted each time. Will this be true of the collection and valorization of human excreta, resulting in the coexistence of a diversity of systems, or will it be erased over time? These issues around adaptation to territorial specificities need to be tackled in parallel with issues of environmental footprints. as well as socio-technical and economic feasibility. The future of source separation will also be strongly determined by the landscape developments and the evolutions of the socio-technical regimes of sanitation and food. Global change will modify the landscape and the impact on sanitation and food regimes could be tremendous. World War Two, for instance, created a huge interest in urban organic fertilizers in France in a context of tension on fossil resources (Dufour and Barles, 2021). In a context where all regions are committed to make their socio-technical regimes evolve rapidly in order to maintain the stability

of the Earth-system (United Nations, 2015), the development of source separation seems coherent with a systemic shift in the various socio-technical regimes that organize life in industrial countries (sanitation, food, housing, mobility, energy, etc.). Such systemic shift, scrutinized in the case of the food regime in a context of massive source separation (Billen et al., 2021), needs to be further explored to analyze the adequacy of the various source separation development pathways in a context of global socio-ecological transition.

6 Conclusion

In this article, we analyzed the development of source separation of human excreta in France, which in recent years has moved into the urban environment. Our work led on a territorial approach, based on a cross-sectional analysis of experimental projects in three cities (Paris, Bordeaux and Grenoble) and complemented by the mobilization of the "multi-level perspective" and the "technological innovation systems" frameworks.

Source separation has not reached yet in France the "global diffusion taking-off" phase described by Larsen et al. (2021). It is still in a phase of "local validation in demonstration projects." However, we showed that the situation has been evolving quite rapidly these last years, with the growing development of pilot projects in urban areas. The context is indeed favorable to source separation for both environmental and food security reasons.

We analyzed the implementation dynamics and the challenges encountered in three source separation projects in French cities. The conclusions of our case studies are in line with those made by other authors, as Kerber et al. (2015), in their analysis of obstacles and levers to the deployment of source separation projects in Germany. It appears that beyond the technical issues, stakeholder alignment issues and organizational challenges are fundamental. The emergence and sustainability of these pilot projects imply that the interests and constraints of the different actors involved are taken into account. It is also necessary that these actors produce answers together to the questions of roles, responsibilities and risks' distribution, as well as to funding issues. We have specially shown that alignment issues are different depending on territories. Actors can make various socio-technical choices, leading to source separation projects with different kinds of territorial embeddedness. Finally, the three case studies enabled us to identify different niches of emergence conducive to these practices, such as participatory housing and eco-neighborhoods, along with resident groups working together to develop separation excreta collection networks in existing housing.

We wondered about the potential for source separation to develop beyond these niches, pointing out a number of obstacles to its diffusion. To enable scaling-up, big changes are still needed, notably on social, legal, economic and logistic levels. This analysis leads to the following recommendations. First of all, political and institutional actors should continue to support the implementation of pilot projects, both financially and politically. Indeed, as Huguenin and Jeannerat (2017, p.633) underline it, pilot projects are "specific and concrete stages of inquiry through which future social values can be problematized, debated, co-constructed, recognized and justified—democratically and iteratively." At the same time, it is necessary to encourage regulatory changes in order to facilitate both the implementation of source separation projects in urban areas and the use of excreta-based fertilizers in agriculture. Changes in social values must also be favored, in particular through the dissemination of knowledge on the topic. Finally, it is necessary to make links between issues which, for the moment, are dealt with in a sectoral manner (urbanism, sanitation and agriculture), through meetings between actors, professional sectors and territories.

We also discussed the potential for development of different excreta separation methods, in connection with territorial configurations. In our view, a challenge, here, is not to think of scaling up as a homogeneous dissemination of a practice, but as the production of contexts allowing its deployment in different territories. Ultimately, it conversely leads us to think about the territorial reconfigurations that could be brought about by the development of source separation, and their "transformative potential" (Fontaine, 2017) in terms of governance of nutrient flows.

What would happen if source separation were to develop? The pathways currently emerging in France are very disparate, and there is no way to predict which will rise to the top. The nutrition/excretion system can incorporate new practices at the margins, without generally moving away from the industrial regime, and broadly retaining the key existing actors and processes. Conversely, these new practices may participate in transforming this system with reconfigurations that affect not only the circulation of nutrient flows but above all how decisions are made about their future, ultimately leading to political, social, economic, and territorial transformations.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

AJ, ML, FE, and BG contributed to conception and design of the study. AJ wrote the first draft of the manuscript. AJ, ML, FE, and BG wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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