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RESEARCH ARTICLE

A participatory and multi-actor approach to locally support crop diversification based on the case study of camelina in northern France

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Abstract

Despite the acknowledged benefits of crop diversification, the transition towards more diversified cropping systems needs to be supported, mainly due to socio-technical lock-ins favoring major dominant crop species. This calls for the development of new approaches to support the design of locally tailored diversified cropping systems. This paper aims to present an original participatory and multi-actor design approach, developed to support the introduction of camelina (*Camelina sativa*) into the cropping systems of northern France and to provide some insights about the characteristics, the specificities, and the limits of this approach to support its use and adaptation to other contexts. For 3 years, and in connection with the development of an oilseed biorefinery, we gathered a variety of actors (farmers, advisors, engineers in agronomy, researchers, and industrialists) to locally support the introduction of camelina in the cropping systems. First, we illustrate the diversity of the modalities that have been collectively imagined to introduce and manage camelina in the local cropping systems. Then, we describe the originality and the diversity of the knowledge produced on camelina, especially during the assessment of some of these modalities within on-farm experiments. Finally, drawing on concepts and theories from design sciences, we show that (i) the pre-existence of networks of actors, (ii) the rationale involvement of the actors, (iii) the implementation of a situated design process fueled by action and distributed among actors, (iv) the sharing and the circulation of knowledge among a diversity of actors involved in the production and use of the new crop, and (v) the implementation of an effective network management contributed to foster the three key elements that we identified as crucial to support crop diversification, namely, the production of actionable knowledge, the exploration of new ideas/concepts, and the active participation of a diversity of actors of the agri-food system.

Keywords Camelina sativa · Innovative design · Open innovation · On-farm experiment · Participatory design

1 Introduction

In the past six decades, the evolution of agriculture has led to simplified and input-intensive cropping systems, with acknowledged negative impacts on environmental (Tilman et al. 2002; Schott et al. 2010) and human (Mostafalou and Abdollahi 2013; Coutts and Hahn 2015; Gordon et al. 2017) health. For instance, the loss of planned as well as associated biodiversity has resulted in lower biological pest regulation, higher pesticide use, and consequently in the development of pest and weed resistances (Elzen and Hardee 2003; Gould et al. 2018; Dainese et al. 2019) and also in a higher demand for N fertilizer and fossil energy and thus higher greenhouse gas emissions (Mignolet et al. 2004). Therefore, more diversified cropping systems are needed to enhance the agroecological transition towards more sustainable agriculture (Lechenet et al. 2014; Duru et al. 2015; Liebman and Schulte 2015; Liu et al. 2019; Beillouin et al. 2020). For instance, lengthening crop rotations through the introduction of diversifying crops has been shown to be relevant to, among others, reducing pesticide use, as a result of a better biological control of weeds, diseases, and pests (Colbach et al. 2010; Lin 2011; Wezel et al. 2014). Building on the acknowledged benefits of crop diversification, the transition process towards more diversified cropping systems has already begun in various regions of the world but remains slow due to many obstacles (Roesch-McNally et al. 2018;

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Burchfield and Poterie 2018; Audouin et al. 2018; Weituschat et al. 2022), including socio-technical lock-ins favoring major dominant crop species. Indeed, several European studies showed that the development of diversifying crops is hindered by a combination of interconnected barriers at the various levels of the value chain (e.g., breeding, farming systems, collection and storage, processing) (Magrini et al. 2016; Meynard et al. 2018; Gomiero et al. 2019; Morel et al. 2020). Therefore, consistent and disruptive innovations at the production, process, and consumption levels, also requiring changes in public policies, are needed to break out agriculture and food sectors of this lock-in (Kuokkanen et al. 2017; Meynard et al. 2017; Magrini et al. 2018). However, only few studies have reported success stories in introducing diversifying crops and developing the associated value chains (Colombo et al. 2020; Cholez et al. 2020; Smadja and Muel 2021), thus calling for the development of new approaches to promote and support locally tailored crop diversification (Périnelle et al. 2021).

To build up such approaches, studies in agronomy, ergonomy, and design sciences provide significant inputs, especially to outline some characteristics that these approaches should have in order to address challenges raised by crop diversification. It is acknowledged that introducing a diversifying crop requires re-designing, at least partially, the cropping system in which this crop would take place. Yet, cropping system design towards agroecology is known to rely on renewed scientific knowledge (Caron et al. 2014) and its hybridization with expert knowledge (Doré et al. 2011; Toffolini et al. 2017). Therefore, lack of scientific and technical knowledge on diversifying crops, whether it concerns biological processes or agricultural practices and crop performances, as well as the lack of farmers' and advisors' expertise and know-how on these crops were identified as crucial barriers impeding their cultivation (Zimmer et al. 2016; Meynard et al. 2018; Muoni et al. 2019). As a result, supporting crop diversification requires a deep change in the ways of producing, formalizing, and sharing among actors various forms of knowledge (Catalogna et al. 2018; Quinio et al. 2022; Verret et al. 2020; Salembier et al. 2021). In addition, the double interconnected challenge of re-designing cropping systems and of producing and sharing knowledge on diversifying crops should be addressed to support crop diversification. With this aim, the concept-knowledge (C-K) theory, which describes the interactions between concepts (i.e., ideas), exploration, and knowledge use and production, within a design activity (Le Masson et al. 2006; Le Masson and Weil 2010) appears as a relevant framework to be mobilized. Moreover, to face the systemic lock-in described above, crop diversification would gain to rely on multi-actor approaches involving not only farmers, but also breeders, advisors in extension services, collectors, and engineers specialized in food processing and in machinery development (Pigford et al. 2018; Meynard et al. 2018; Puech et al. 2021). Finally, it appears relevant to actively involve these various actors of the supply chain from the beginning of the design process, within a participatory approach, as they will be the main "users" of the diversified cropping systems and for some of them in charge of their implementation and their adaptation to the local pedo-climatic and socio-economic-cultural conditions (Béguin 2003; Cerf et al. 2012).

This paper aims to (i) present an original participatory and multi-actor approach, combining knowledge production and design activities, developed to support the introduction of camelina (*Camelina sativa*) into the cropping systems of northern France and (ii) provide some insights about the characteristics, the specificities, and the limits of this approach in order to support its use and adaptation for other diversifying crops and territories (Fig. 1). After describing the four steps of the approach and the way we analyzed *a posteriori* our approach (Section 2.), we expose the outputs of this transversal analysis of the results obtained for the case study (Section 3). Finally, as discussion, we draw lessons from the case study to support the development of similar approaches in other contexts (Section 4).

Fig. 1 An original participatory and multi-actor approach combining design workshops (**a**) and on-farm experimentations (**b**) to support the introduction of camelina in northern France.

2 Materials and methods

2.1 Overview of the case study

In strong link with the emergence of a local oilseed biorefinery in northern France (Oise department), a research program covering topics from production to processing of a diversity of biomass sources coming from various crops was launched in 2012 (https://sas-pivert.com/). Among others, this program aimed to explore how to sustainably supply the biorefinery with a local production of biomass (50 km around the city of Compiègne, where the biorefinery was located). From this perspective, based on a previous analysis of candidate crops, camelina was identified as a promising diversifying crop, due to its agronomic and industrial characteristics. Camelina is a short cycle (around 1200 growing degree-days with a 5°C base temperature) oilseed crop that can be grown under a wide range of environments (Berti et al. 2016), including the pedo-climatic conditions of northern France, with 5000 hectares cultivated in this area at the beginning of the twentieth century, and trials reported during the 1990s (Bonjean and Le Goffic 1999). Camelina is also acknowledged for the diversity of the ways it can be integrated into cropping systems, as main crop or as double crop (Gesch et al. 2014; Berti et al. 2017) and for its promising potential in terms of seed yield and oil quality under low-input management (Putnam et al. 1993; Avola et al. 2021). Finally camelina is considered an interesting alternative raw material for biofuel production (Fröhlich and Rice 2005; Moser 2010; Shonnard et al. 2010; Ciubota-Rosie et al. 2013) but also for other applications in food, feed, cosmetics, or chemical derivatives (Waraich et al. 2013; Berti et al. 2016). However, re-designing the cropping systems of the study area to introduce camelina was challenging, mainly because of lacks of scientific knowledge, technical references, and farmers' experience on this little-known crop (Leclère et al. 2018). Indeed, although literature reviews showed a regain of interest in this rustic oilseed crop during the last decade (Zanetti et al. 2013; Berti et al. 2016), scientific knowledge remained limited, compared to the major crops of the study area, namely, wheat, rapeseed, and barley. Concomitantly, local conventional farmers had little expertise on this crop because of the limited cultivation areas under camelina in the region (less than 100 hectares in 2016 for organic camelina).

Based on this initial diagnosis, a 3-year project was initiated in 2016 by our research team to locally support the introduction of camelina in the cropping systems, in narrow collaboration with an advisor of the local Chamber of Agriculture, a group of motivated farmers from a local group of rural development within the area, and researchers and engineers from various fields involved in the biorefinery project.

2.2 Description of the general approach

The general approach proposed was based on four main steps (Fig. 2). Each step relied on specific devices and methods detailed in the following sub-sections and involved different types of actors (Table 1). Participation was on a voluntary basis, which means that on the one hand, participation to one specific device did not commit the participants for the rest of the process, and on the other hand, for each new device set up, an invitation was extended to the actors involved in the biorefinery project and to the 80 farmers of the agricultural development group.

2.2.1 Step 1: Identification of knowledge gaps hindering the design of locally tailored camelina-based cropping systems

The first step of our approach aimed to identify and prioritize the gaps in knowledge that were specifically hindering the design of camelina-based cropping systems in the study area, in order to sustainably supply the local biorefinery. To do so, on one hand, we cross-referenced a literature review on camelina with biorefinery expectations, defined both by literature and through meetings with key stakeholders of the biorefinery project. On the other hand, we organized a multi-actor workshop, gathering seven farmers, two local advisors from the Chambre of Agriculture, three engineers in agronomy from national technical institutes or rural associations, two researchers specialized in oilseed crops extraction and processing, two members of oilseed industrial groups, and two representatives from the biorefinery (Table 1). This workshop aimed to identify (i) the knowledge that appeared needed to design and implement camelina-based cropping systems but that was not available at that time and (ii) the assessment indicators derived from the various participants' expectations (Leclère et al. 2018). Based on KCP method (Le Masson et al. 2009), we asked farmers to imagine how they would grow camelina in their own cropping systems, thus bringing to light the knowledge lacking to feed this situated design. Concomitantly, we asked advisors, engineers, researchers, and representatives from industries to react on opportunities or warnings linked to farmers' proposals.

2.2.2 Step 2: Knowledge production from field assessment of designed camelina crop management routes

The second step consisted in producing knowledge, specifically to fill the main knowledge gaps identified in the first step. It was based on the design, the implementation, and the assessment of various camelina crop management routes (CMRs), both as spring and summer crop (Fig. 2). More precisely, two on-farm experimental devices were set up: (i) a

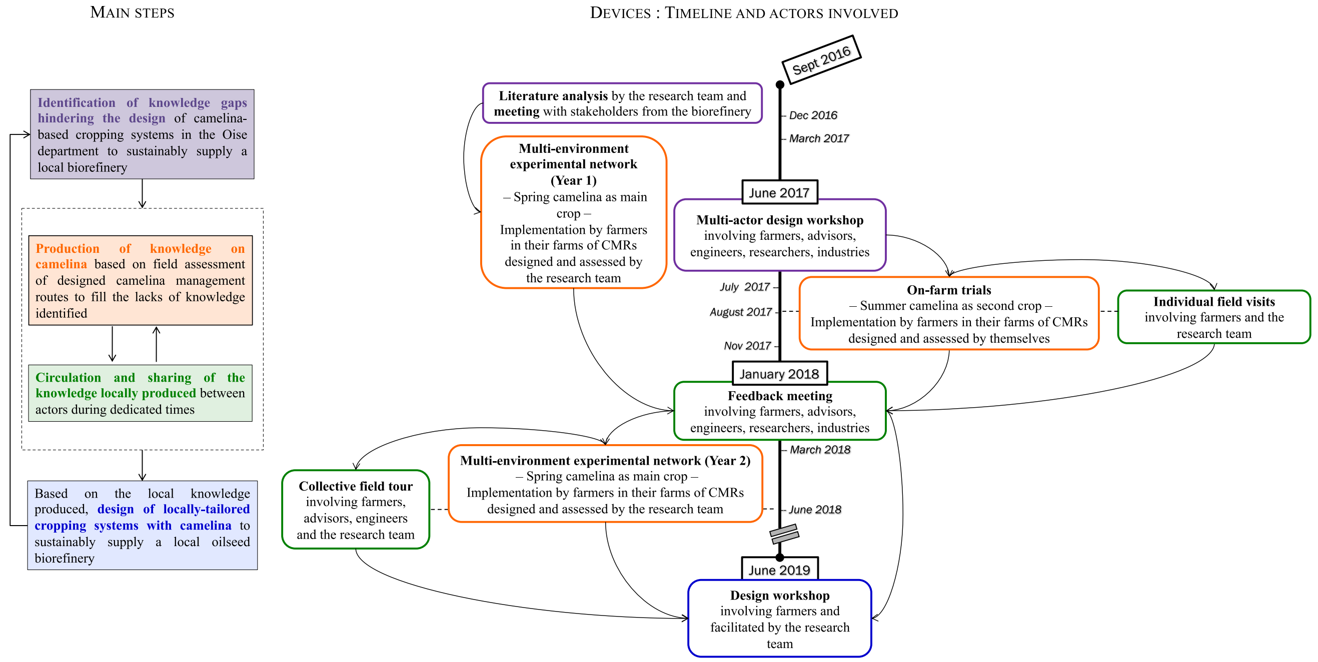


Fig. 2 General approach developed and implemented to support the introduction of camelina into the cropping systems of the Oise department to sustainably supply a local oilseed biorefinery. The four steps of the approach are detailed on the left side. The devices implemented, the actors involved, and the timeline are described on the right side. CMRs, crop management routes.

multi-environment experimental network, including CMRs designed and assessed by our research team (researchers in agronomy), and implemented by farmers, and (ii) on-farm trials, i.e., CMRs designed and implemented on their own by the farmers themselves (Fig. 2, Table 2). Farmers involved in each on-farm experimental device were not necessarily the same (Table 2), but all were chosen because they were interested and motivated by the topic and the objective of each experimental device. In total, in the multi-environment experimental network, four CMRs, with camelina as spring main crop, were tested across nine environments. Besides, in the on-farm trials, thirteen CMRs, with camelina as second crop grown during summer, were implemented by four farmers (Fig. 4). In the multi-environment experimental network, the assessment of the modalities was performed by our research team and relied on the measurement of several variables during and at the end of the crop cycle, the statistical analysis of the data (Leclère et al. 2019), and the implementation of an agronomic diagnosis to identify the causes of seed yield and quality variability (Leclère et al. 2021b). In the on-farm trials, knowledge production was mainly based on the formalization and the analysis of a qualitative assessment carried out by the farmers and collected through interviews (Leclère et al. 2018) (Table 2).

2.2.3 Step 3: Circulation and sharing of the knowledge locally produced

This step was related to the circulation of the knowledge produced and its sharing among actors (Fig. 2). Indeed, as the experimental devices did not always involve the same farmers, and did not involve the other type of actors (Table 1), we set up formal exchange times with various actors to share and discuss the results obtained or the observations made.

First, as part of the monitoring of the on-farm trials, individual field visits were performed in August 2017 (Fig. 2) by one researcher with each of the four farmers involved (Table 2). During these visits, farmers' observations and appraisal were discussed together with the researcher. Then, during the following winter (January 2018, Fig. 2), we organized a 1-day feedback meeting, the objectives of which were to share the results of the first year of experiment and to prepare the second year of the multi-environment experimental network. Apart from the research team, this meeting involved eighteen people: eight farmers, four of whom had implemented on-farm trials (F3, F5, F7, F9), two advisors from the Chamber of Agriculture, four engineers in agronomy from national technical institutes or rural associations, three researchers specialized in oilseed crop extraction and processing, and one representative of the biorefinery project. This group was formed by people who had

Table 1 Actors involved in the devices implemented during the four steps on the general approach. Devices are mentioned in chronological order from left to right. MEE network means multi-environment experimental network. Step 1 refers to "Identification of knowledge gaps"; Step 2 refers to "Production of knowledge on camelina"; Step 3 refers to "Circulation and sharing of the knowledge locally produced"; Step 4 refers to "Design of locally tailored cropping systems with camelina." "X" means that the considered actor has been involved in the device.

Type of actors	Meeting with biorefinery actors (Step 1)	MEE network 1st year (Step 2)	Multi-actor design workshop (Step 1)	On-farm trials (Step 2)	Feedback meeting (Step 3)	MEE network 2nd year (Step 2)	Collective field tour (Step 3)	Farmers' design workshop (Step 4)
Farmers (F)								
F1		X	X					
F2		X	X					
F3		X	X	X	X	X	X	X
F4		X	X		X	X	X	X
F5			X	X	X			
F6			X					
F7			X	X	X	X	X	X
F8		X			X	X		X
F9				X	X			X
F10					X			
F11					X			
F12								X
F13								X
F14								X
F15								X
Local advisors (A)								
A1			X		X		X	
A2			X		X			
A3								X
Engineers in agronomy (E)								
E1	X		X		X		X	
E2	X		X					
E3					X			
E4			X					
E5					X			
E6	X				X			
E7							X	
Researchers in oilseed extraction and processing (R)								
R1			X		X			
R2			X		X			
R3					X			
Oilseed industrial groups (I)								
I1	X		X					
I2			X					
Biorefinery (B)								
B1	X		X		X			
B2			X					
Research team (T)								
T1	X	X	X	X	X	X	X	X
T2		X	X		X	X	X	X
T3	X	X	X			X	X	X

Table 2 Main characteristics of the two experimental devices in terms of modalities tested, methods of assessment, actors involved, and knowledge produced. More details on both devices are available in Leclère et al. (2018) and Leclère et al. (2019) respectively for the on-farm trials and for the multi-environment experimental network. For the actors involved, the IDs in brackets refer to the list of actors presented in Table 1.

	On-farm experimental device	
	Multi-environment experimental network	On-farm trials
General description	4 spring camelina crop management routes tested across 9 environments (3 soil types; 2 years of experiments: 2017 and 2018)	13 summer camelina crop management routes as second crop, spread over 4 farms; 1 year of experiment (2017)
Actor(s) involved		
Design	Researchers in agronomy (R1, R2, R3)	Farmers (F3, F5, F7, F9)
Implementation	Farmers (F1, F2, F3, F4, F8 in 2017; F3, F4, F7, F8 in 2018)	Farmers (F3, F5, F7, F9)
Assessment	Researchers in agronomy (R1, R2, R3)	Farmers (F3, F5, F7, F9) jointly with a researcher in agronomy (R1)
Assessment		
Data collection	Measurements (crop and weed biomass at flowering and harvest; N content; yield; oil and protein contents; mineral nitrogen in the soil)	Measurement (only camelina yield); Farmers interviews during and after the experiment
Analysis	Statistical analysis of the data; agronomic diagnosis	Qualitative analysis of the assessment performed by the farmers
Formalization of the knowledge produced	Bar charts Graphs describing correlation between variables	Verbatim Table synthesizing indicators used by farmers to assess their trials and the result of the qualitative assessment using different colors

attended the multi-actor workshop but also new ones (e.g., F10, F11, E3, R3) (Table 1). The reporting of the results relied on (i) the presentation of a first analysis of the experimental data (emergence rate, weed biomass, camelina yield) from the multi-environment experimental network and (ii) the testimonies of the four farmer-experimenters who had designed and implemented on-farm trials. All the exchanges between the participants during this meeting were recorded. Finally, during the second year of experiment (June 2018, Fig. 2), a collective field tour was organized in the four fields of the multi-environment experimental network. Three of the four farmers involved in the experimental device this year, as well as one advisor from the Chamber of Agriculture, two engineers in agronomy from national technical institutes or rural associations, and the research team (researchers in agronomy) attended this field tour (Table 1). During the visit, in each field where a trial was implemented, exchanges between participants were driven by the following questions: “What do we see? Does the modality observed is satisfying regarding its initial objectives?” If yes, why? If no, why and what proposals could we make to improve the situation next year?”. Again, all the exchanges were recorded for further analysis, and a detailed report including pictures was produced and shared with the participants but also with the actors involved in the other meetings.

2.2.4 Step 4: Farmers’ design of site-specific cropping systems including camelina

After the 2 years of experiment, a final design workshop was organized to support the design, by nine farmers, of camelina-based cropping systems adapted to their own farms, always with the goal to sustainably supply the biorefinery (Fig. 2). As proposed by Reau et al. (2012; 2015; 2018), the design workshop was organized around an ambitious and shared target, defined as: “Where and how would you grow a pesticide-free, low-input, and profitable camelina in your farm?”. Nine farmers attended this design workshop, including four farmers who had never been involved in the approach before (Table 1). After a time period dedicated to share knowledge, during which the locally produced knowledge was presented by the research team, every farmer was asked to design at least one proposal of cropping system to introduce camelina into his own farm. More precisely, farmers designed (i) the new crop sequence including camelina, and (ii) the main components of the camelina CMR, from the harvest of the previous crop to the implementation of the following crop. Farmers were asked to shape their prototype on a "crop information sheet." This document, designed by the research team to collect data, is comprised of two sections, one in which the crop sequence including camelina is presented and compared to the current one and another in which the main features of the crop management steps are mapped on a timeline and detailed (Leclère et al. 2021a). All the proposals were collectively debriefed: after the presentation and the explanation by each farmer of his technical choices, proposals were discussed by the whole group. All the comments, explanations, and new proposals were added in live on the crop information sheet, and exchanges were recorded to allow further analysis.

2.3 Ex-post analysis of the approach

In order to draw lessons from this case study and contribute to the development of similar approaches for other crops and territories with different objectives and characteristics, an ex-post analysis of the approach and its outputs was performed by the research team. The analysis was organized around three topics of interest. First, special attention was paid to the various design processes that took place all along the project. Especially for each design process, drawing on the C-K theory (Hatchuel and Weil 2009), we analyzed the design reasoning meaning that we identified, described, and mapped, when possible, the actors involved, the modalities explored, the knowledge mobilized by the actors, and the knowledge gaps to be filled identified by the actors. Second, we performed a cross-cutting reading of the knowledge produced during the project. Each device (on-farm experiments, workshops, etc.) led to a distinctive production of actionable knowledge, i.e., knowledge that is produced in action and that "specifically supports stakeholder decision making and consequent actions" (Geertsema et al. 2016), that have been published in scientific papers (Leclère et al. 2018, 2019, 2021a, 2021b). Therefore, the objective of this ex-post analysis was to look at all these results with a new eye to highlight the nature of the knowledge produced and illustrate its diversity and originality. Finally, drawing on concept and theories from design science and on literature about participatory design approaches in agriculture, we identified, analyzed, and discussed the specificities, the conditions of success, and the limits of the approach. To do so, we asked ourselves which characteristic of the approach enabled or hindered (i) the production of actionable knowledge, (ii) the exploration of new ideas/concepts, and/or (iii) the active participation of a diversity of actors of the agri-food system which are the three key elements that we identified as crucial to support crop diversification.

3 Results

3.1 Design reasoning of the on-farm experimental devices

3.1.1 A multi-environment network focused on weed control and on the quantitative and qualitative performance of camelina as spring crop

Based on the literature review (Step 1), we identified that (i) weeds were a major problem for growing camelina, (ii) chemical weeding was not fully effective to control weeds and only few pesticides were available, and (iii) only a few studies investigated zero-herbicide alternatives to control weeds. In addition, during the exchanges, biorefinery industrialists mentioned they expected low-input crops, able to limit environmental impacts at the production chain level. This target bolstered the fact that knowledge on herbicide-free CMRs for camelina was missing to design cropping systems adapted to our case study. Thus, to fill this knowledge gap, the research team designed three herbicide-free CMRs with camelina as main spring crop, in the view to assess and understand both the effect of these CMRs on weed biomass and the variability of camelina quantitative (yield) and qualitative (oil composition) performance, under various pedo-climatic conditions. Beyond mobilizing agronomic knowledge on already existing herbicide-free strategies to manage weeds in other crops or on crops' functioning, designing CMRs took into account (i) the local pedo-climatic conditions and cropping systems characteristics, (ii) the technical feasibility for farmers, and (iii) the biorefinery expectations (Fig. 3). For instance, no CMRs using mechanical weed control were designed because no farmer had the required equipment. Besides, intercropping with food crops was favored because of the "food first" stated objective of the biorefinery project leaders (Fig. 3).

3.1.2 On-farm trials focused on summer camelina as second crop to answer specific and situated knowledge gaps

During the multi-actor design workshop, the participants identified a diversity of ways to introduce camelina into the cropping systems of the Oise department: as spring or summer crop, in pure stand or intercropped with a diversity of food and non-food crop species (Fig. 4). Linked to this exploration, a lot of questions and uncertainties were raised by the participants, leading to the identification of knowledge gaps on camelina management, on camelina crop functioning (ecophysiology, growth, and production),

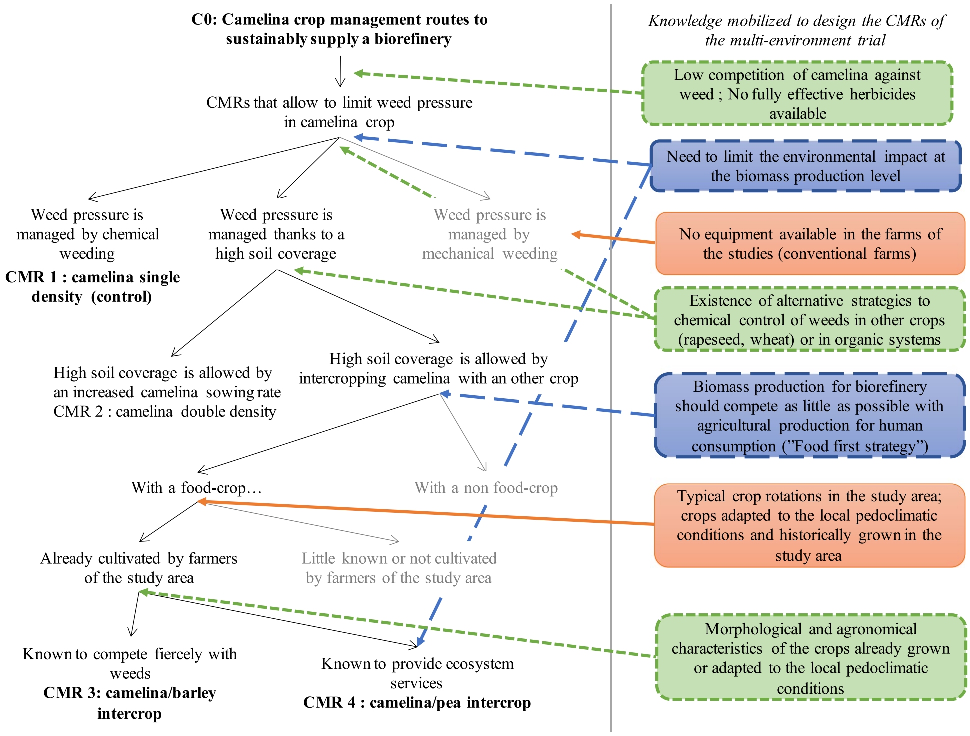


Fig. 3 Formalization, using a C-K (concept-knowledge) map, of the design reasoning conducted by the research team to imagine the crop management routes (CMRs) that were assessed in the multi-environment network. In this representation, the exploration of ideas (concepts) is presented on the left side, and the associated exploration of different pockets of knowledge is shown on the right hand. Links between knowledge and concepts are identified with arrows, as proposed by Hatchuel and Weil (2009). Gray arrow and text refer to non-explored path during the exploration (C space). The colors refer to the categories of knowledge mobilized during the design process: green with small dots, agronomic knowledge; blue with large dots, knowledge on biorefinery expectations and constraints; orange with full traits, knowledge on the local agriculture (cropping and production systems).

and on camelina preceding effects, for camelina both as spring and summer crop. Fostered by this collective reflection, four farmers (Table 1) decided to test and appraise camelina as a second crop in the specific context of their farms. More precisely, each farmer designed his own camelina CMRs, and the experimental design to be implemented, all with the aim of answering specific questions they had in their own farm. Overall, three trials took the form of a "feasibility test" in which farmers tried to see if the CMRs tested were technically feasible and were answering their expectations in terms of performances or services. For instance, one of these farmers assessed the feasibility of growing camelina after canned pea by specifically looking at the ability of camelina to reach maturity before the sowing of the following winter crop and at the effect of herbicide residuals from canned pea on camelina. The fourth trial was designed as a factorial trial which objective was to test the effect of different combinations of practices (sowing rate, tillage systems, and fertilization rate) on camelina growth and yield when grown as double crop after winter barley.

3.2 A diversified knowledge production throughout the approach

3.2.1 Knowledge produced about camelina introduction and management, farmers' expectations, and monitoring and assessment criteria used by farmers

A wide range of ways to introduce and manage camelina, adapted to a diversity of local and unique situations (defined by the combination of a specific environment and farmer's objectives and constraints), were identified and described during the workshops (Step 1 and Step 4) and the design of the CMR assessed in both on-farm experiments (Step 2) (Fig. 4). The explanation of the farmers' logic of action underlying these modalities, during the workshops or during the interviews with farmers (about their on-farm trials), made it possible to identify (i) a variety of farmers' expectations regarding the crop and (ii) assessment and monitoring criteria used by farmers (some of them being unexpected). For example, for some farmers, the introduction of camelina

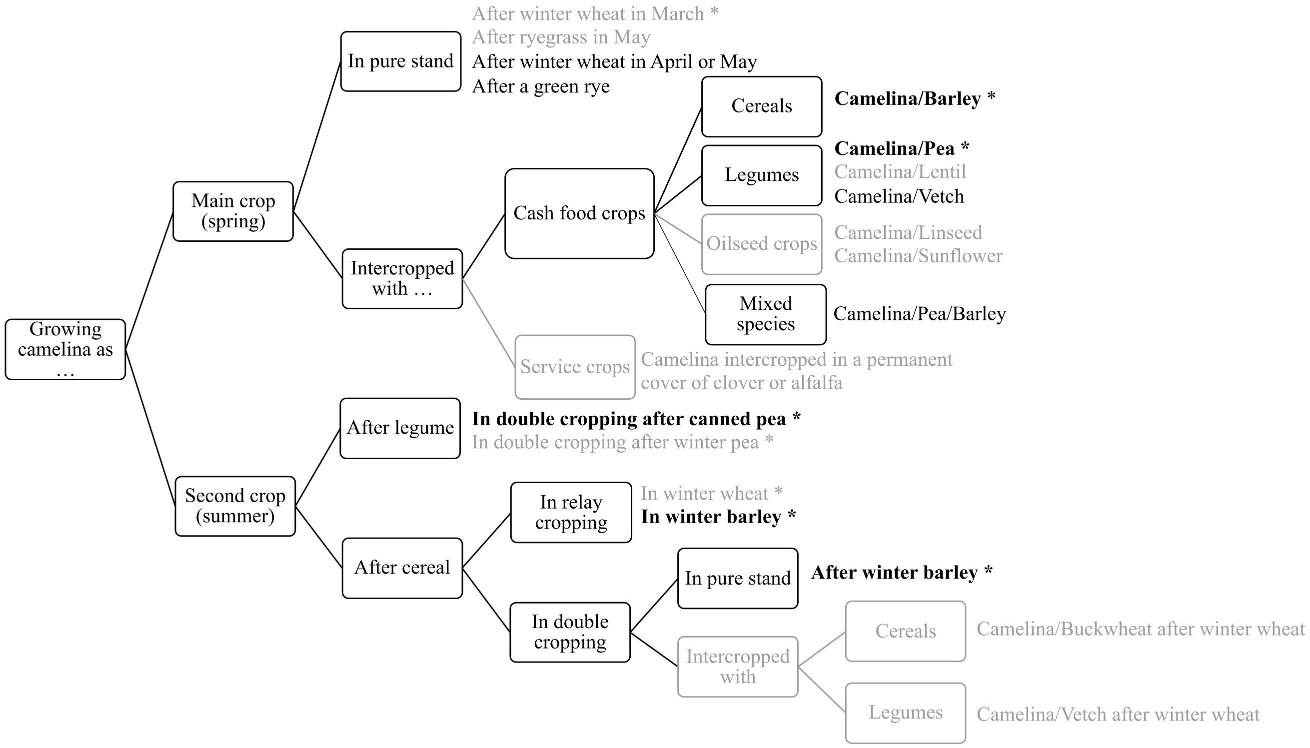


Fig. 4 Mapping the exploration of ways to introduce camelina into the cropping systems of the study area during the two design workshops. Overall, 17 paths were explored during the multi-actor design workshop and 9 during the farmer design workshop. In gray: paths only explored during the multi-actor design workshop. In black: paths only explored during the farmer design workshop. In bold: paths explored during both the multi-actor and the farmer design workshop. Modalities that have been tested in the on-farm experimented are marked with a star. Relay cropping means that camelina is sown before the harvest of the previous crop. Double cropping means that camelina is sown right after the harvest of the previous crop.

was expected to be a lever to reduce weeds in their crop sequence, exclusively composed of winter crops. For others, the introduction of camelina—as second crop—was a lever to increase profitability in soils with low-yield potential for major crops (e.g., sugarbeet, wheat, rapeseed) (Leclère et al. 2018). We also identified that weed species, and not only weed abundance—highly used in scientific studies including ours (see Leclère et al. 2019)—was an indicator used by farmers to monitor and assess the crop (Fig. 5).

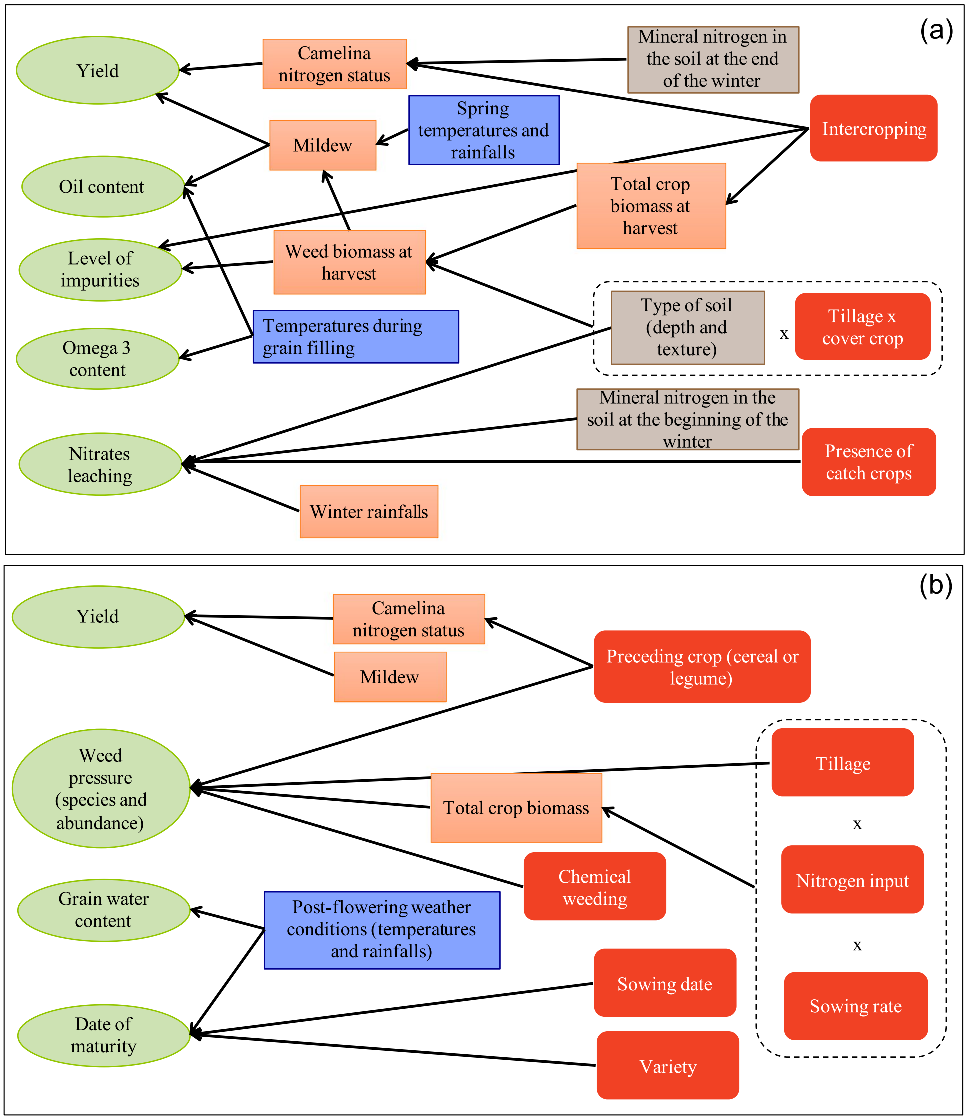
3.2.2 Knowledge produced about biological processes of regulation and competition at stake in camelina stand

Although using different analytical approaches, both experimental devices were used to identify and describe several major biological processes during camelina development. On one hand, the analysis of the quantitative data from the multi-environment experimental network helped to understand and quantify biological processes for weed regulation in camelina. For instance, the evidence of a negative correlation between weed biomass and total crop biomass at maturity—and not at flowering—allowed us to highlight a post-flowering competition for resources, mainly explained by higher species growth rates in the intercrop modalities after flowering (Leclère et al. 2019). On the other hand, farmers' hypotheses to explain observations made on their on-farm trials, and collected during the individual interviews, gave first insights on possible processes involved (even if they had not been scientifically proven). For example, one farmer, who implemented eight different camelina CMRs as second crop after winter barley, combining two types of soil tillage, two sowing rates and two nitrogen rates, explained the low yields achieved (lower than 1.5 t/ha) as a consequence of a nitrogen deficiency due to the barley straw decomposition in the tilled modalities: "*In my opinion, the decomposition of the straw pumped nitrogen, whereas in the no-till part, the degradation was slower. You can see that, as soon as it's not tilled, it's better. In my opinion, when I till the soil, nitrogen will destroy the straw at the expense of the plant.*" (Excerpt from F7 interview, 06/09/2017).

3.2.3 Knowledge produced about factors and practices affecting camelina performances in the study area

The analysis of the quantitative and the qualitative data from both experimental devices also led to the production

Fig. 5 Functional schemes linking practices (red inset), crop (orange inset), and soil (brown inset) characteristics, climatic conditions (blue inset), and variables of interest for farmers, agronomists, and/or biorefinery representatives (green circle) based on the results of the multi-environment experimental network (**a**) and the on-farm trials (**b**).



of knowledge about factors (e.g., soil and crop characteristics, climatic conditions) and agricultural practices influencing camelina quantitative, qualitative, and environmental performances in on-farm conditions within the study area (Fig. 5). For instance, the agronomic diagnosis performed on the multi-environment experimental network (Leclère et al. 2021b) showed that camelina yield variability was mainly explained by the nitrogen crop status at flowering and downy mildew, while climatic conditions (cumulative temperature and high temperatures during grain filling duration) explained oil composition variability (Fig. 5a). Accordingly, the qualitative assessment performed by the farmers during the individual field visits and interviews also led to identify nitrogen crop status as factor influencing camelina yield, when grown as second crop (Fig. 5b). More precisely, by comparing the various situations, farmers identified that the nature of the preceding crop was a key factor influencing camelina status and yield: "*After canned pea, it is good for the nitrogen supply, you have better yield than after winter cereal*" (Excerpt from F9 interview, 26/10/2017).

3.2.4 Acquisition of know-how and expertise by the farmers

The implementation of the trials by the farmers themselves, for both experimental devices (Table 2), enabled them to acquire know-how on camelina management: they learned how to manage the sowing or the harvest of this small-seed crop with their own equipment, and they developed means to dry the harvest, etc. Simultaneously, they also acquired expertise on this little-known crop illustrated by their ability to provide some characteristics about camelina functioning ("*It is a plant that likes heat, so the problem in the off-season is that I feel that it had trouble for growing*", excerpt from F7 interview, 06/09/2017) or to formalize some decision rules for the management of camelina in the future ("*This year, I harvested my peas on the 12th of June and I sowed camelina on the 24th: I lost time. As soon as I harvest peas, I have to sow the next day because 15 days is huge for the daily temperature*", excerpt from F9 interview, 26/10/2017).

3.3 Design of locally tailored camelina-based cropping systems based on the locally knowledge produced during the second design workshop

3.3.1 A renewed exploration of the ways to introduce camelina into the crop sequence

As for the multi-actor design workshop (Step 1), a wide range of ways to introduce camelina into the cropping systems was explored during the design workshop dedicated to farmers (Step 4) (Fig. 4). However, the exploration slightly differed from the first workshop with the loss of some paths previously explored (e.g., the oilseed intercrops) and the emergence of new paths (e.g., spring camelina as pure crop after an unripe rye) (Fig. 4). The ex-post analysis of the farmers' proposals showed that this renewed exploration could be explained by:

(i) The presence of new farmers (i.e., who had never participated to any devices of the approach, F12 to F15, Table 1), with new objectives and constraints. For instance, the proposal of introducing camelina after green rye was specifically linked to a methanization project carried out by F12 to answer the obligation of having at least one cash crop per year within a crop sequence with dedicated energy crops.

(ii) The mobilization of the knowledge previously produced during the Steps 1 to 3. For example, F8 justified his choice of introducing camelina in intercrop with a legume (pea) and a cereal (barley), both with low sowing rate, as a way to reduce nitrogen competition with camelina and limit weed pressure, based on some results of the multi-environment experimental network summarized in Fig. 5.

3.3.2 Detailed camelina CMRs designed by farmers

All farmers proposed prototypes of the management they would apply on camelina (even though uncertainties remained) (Leclère et al. 2021a). As previously, the ex-post analysis of the farmers design workshop outputs (Step 4) showed that this resulted from the mobilization, by farmers, of the knowledge produced during the Steps 1 to 3 but adapted to their local situations. For instance, in the case of the introduction of camelina as double crop after winter barley (Fig. 4), for which many questions about sowing rate, nitrogen fertilization, and weeding had been raised during the multi-actor design workshop (Step 1) (Leclère et al. 2018), three different CMRs were designed by farmers F3, F7, and F15 during the farmers design workshop (Step 4) (Table 3). All three proposals were justified by farmers as strategies to limit (i) barley volunteers in camelina crop and (ii) nitrogen deficiency due to barley straw decomposition, which were the two major factors limiting yield, identified from the on-farm trials (Step 3) (Fig. 5b). These proposals relied on a high sowing rate (between 8 and 10 kg·ha^{-1}) combined either with the removal of the straws of the preceding crop or an application of nitrogen fertilizer, and a chemical or mechanical weeding, if needed (Table 3). The design of these specific combinations of techniques was mainly justified by what the farmers learned from the implementation and the appraisal of the on-farm trials (Step 3) and shared at the beginning of the farmers design workshop (Step 4).

3.3.3 Identification of new knowledge gaps to be filled

As a result of (i) the exploration of new ways to introduce camelina in the cropping systems and (ii) the design of camelina CMRs, the farmer design workshop (Step 4) also led to refresh the knowledge gaps to be filled to support the introduction of camelina in the Oise department. For instance, several farmers mentioned the need of investigating the effect of camelina on different possible following crops (e.g., wheat, sorghum, sunflower), and especially its possible allelopathic effect, to be able to design a crop sequence suited to these characteristics. During the multi-actor design

Table 3 Description of the three combinations of agricultural practices designed by farmers during the design workshop to limit barley volunteers and nitrogen deficiency due to barley straw decomposition when introducing camelina as double crop after winter barley.

	Barley straw removal	Camelina sowing rate (kg ha^{-1})	Weeding technique	Fertilization
F15	Yes	8 to 10	Mechanical	0
F3	Yes	8 to 10	Chemical (broadleaf herbicide)	0
F7	No	8 to 10	Chemical (broadleaf herbicide)	80 kg ha^{-1} of 18–46 NP fertilizer at sowing

workshop (Step 1), these knowledge gaps had already been identified, but were not mentioned as a priority. Regarding the N fertilization of camelina, which was also one of the topics discussed during the multi-actor design workshop (Step 1), the possibility and modalities of using organic matter as a source of N fertilization was a new question raised as well as the needs of camelina in different other mineral elements (phosphorus, boron, and sulfur in particular).

4 Discussion: lessons from the case study to support the development of similar approaches in other contexts

The participatory and multi-actor approach presented in this paper was successful to initiate a dynamic around the cultivation of a diversifying crop, Camelina sativa, in northern France. From zero, around one hundred hectares of non-organic camelina were sown in summer 2019, right after the end of this 3-year process, to test at wider scale the possibility to use this crop as raw material for biorefinery. In 2022, trials are still running: seven farmers (including F4 and F12) are producing camelina at large scale in the study area (respectively 170 and 130 hectares in 2021 and 2022) to supply an emerging biokerosene value chain. What are the specificities of the approach that contributed to support crop diversification in that area? What are the conditions of success of this approach? What would be the limitations to overcome and the possible areas of improvement? This section aims to draw lessons from this experience and discussed them to support the development of similar approaches in other contexts. First, we better characterized the main traits of a generic approach to support crop diversification. Then, we emphasized the main challenges that the adaptation to other contexts can raised and discussed how the approach could be improved in the future.

4.1 Characteristics of a participatory and multi-actor design approach to support crop diversification

4.1.1 A multi-actor approach based on pre-existing actor networks

Beyond being part of our project, some of the actors were already linked with each other within two pre-existing networks, which has fostered and stimulated innovation within the group. First, all the farmers involved in our study were part of a local group of development of about 80 farmers, facilitated by a local advisor of the Chamber of Agriculture (a French advisory structure). In France, such groups usually gather farmers of a same geographic area and aim to support agricultural development through exchanges during meetings or visits or the setting up of collective projects to share risks (Esposito Fava 2015). Therefore, all the farmers involved in our project were already used to share experiences and work together and were engaged in a relation of trust, which is a key element for innovation (Skardon 2011). As shown in several studies (Kroma 2006; Goulet et al. 2008; Dolinska and d'Aquino 2016), this pre-existing network also increased farmers' ability to innovate by highly favoring the exploration of new ideas and the circulation and sharing of the knowledge produced within and outside our case study. For instance, without any intervention of the research team, the entire group of 80 farmers decided to organize their annual field trip of the year 2019 in Spain, to visit a seed company working on new varieties of camelina, and meet Spanish camelina producers. This initiative, which happened before the second design workshop (Step 4), motivated new farmers to attend this workshop and resulted in the exploration of new paths linked to their own situation (see 3.3.1). In addition, this trip also contributed to expand the knowledge base of the farmers mobilized during the design process, as shown by this quotation: "In Spain, they talked about swathing camelina 8 days before maturity, so it might be a solution for me" (Excerpt from farmer design workshop, 06/06/2019). A part from this farmer network, the pre-existence of the "PIVERT ecosystem" network, gathering different actors from the value chain who shared a common ambition to develop a local oilseed biorefinery, also played a central role in facilitating interactions and collective actions. Jointly with the existence of a juridic structure (SAS PIVERT) owning physical space to meet, this has contributed to create a favorable environment for systemic and integrated thinking on innovation, similarly to what have been called "innovation platforms" in the literature, increasingly used in agricultural research for development, particularly in Africa (Schut et al. 2016; Angbo Kouakou et al. 2017; Dabire et al. 2017; Davies et al. 2018). Especially, the ability of these multi-stakeholder platforms to foster knowledge exchanges and co-creation has been recently demonstrated (van Ewijk and Ros-Tonen 2021).

4.1.2 A participatory approach characterized by a rational involvement of the actors

Many studies showed the need and the value of actively involving a diversity of actors from various sectors or organizations (farmers, advisors, researchers, processors, local community, or non-profit organization representatives) in the design process to support the agroecological transition (Bos et al. 2009; Chantre et al. 2016; Sautier et al. 2017; Puech et al. 2021). According to the situation, the involvement of various actors can help to identify a blocking situation linked to different actor's perceptions (Berthet et al. 2014), define collectively some assessment indicators (Le

Bellec et al. 2012), or co-design shared scenarios for the future (Pelzer et al. 2020) or coupled innovations (Salembier et al. 2020). However, such participatory approaches often raise the question of the long-term engagement of the actors. In our approach, not all the actors were always present in the different devices, but they were involved according to the objectives to achieve. This rationale involvement of the actors in time, which was an intentional choice of the research team, contributed to the establishment of fruitful and long-lasting interactions among the diversity of actors involved. For instance, as we dedicated some time specifically to farmers' exchanges (as field tours) in which a lot of technical discussions took place, we were able to organize the multi-actor devices (multi-actor design workshop and feedback meeting) around topics of interest for all the actors, including the laymen in agronomy. This highly helped the actors to share their visions, understand each other's expectations, and build a common ambition.

4.1.3 A design activity distributed among the actors

Drawing on the C-K theory and nine case studies in research, Toffolini et al. (2020) showed the ability of a design process to produce original scientific knowledge. In our case study, the distributed aspect of the design (meaning that the actors have been engaged simultaneously but not jointly in separate design activities (Falzon and Darses 1996)) played a significant role in the originality and the diversity of the knowledge produced. Indeed, the design of the experimental devices was driven by distinct motivations (produce knowledge on biological processes for researchers in agronomy, answer technical and situated questions, and acquire know-how for the farmers) and mobilized different knowledge pockets (see 3.1). Thus, the two complementary experimental devices, resulting from these design activities, led to the production of original scientific knowledge on one hand and of empirical knowledge on the other, both known to be useful to design agroecological cropping systems (Girard and Navarrete 2005; Faugère et al. 2010; Doré et al. 2011).

4.1.4 A design process fueled by action

Together with the design activities, experimentation—in our case, the on-farm implementation of the theoretical CMRs designed—also played a crucial role, both in producing actionable knowledge and in stimulating the exploration of new ideas. First, several authors showed that, by managing experiments in their farms—as it has been done in our approach—, farmers acquire know-how and situated knowledge about crop management and performances that support them in their continuous process of change of their cropping systems (Leitgeb et al. 2014; Catalogna et al. 2018). Similarly, in our approach, the empirical knowledge produced during on-farm experimentation, formalized by researchers and then shared among actors through testimonies or other form of representation (functional scheme), was helpful for other farmers to design cropping systems suited to their own farm (Leclère et al. 2021a). In addition, design studies emphasize the fact that design process should not be narrowed only to the step of invention, as the implementation of the solution is also a key step to refine the properties of the object to be designed and to make new questions and ideas emerge (Schön 1992; Visser 2010). Until now, researchers in agronomy have mainly developed approaches and methods to support the invention step, as with the design workshops (Reau et al. 2012), but have given little consideration to the implementation phase, as part of design and not only of an evaluation step (Prost et al. 2018). In our case study, this crucial role of the implementation step to feed a design process can be illustrated with the example of the introduction of camelina as second crop. This way to introduce camelina was indeed presented, during the multi-actor design workshop, as a very promising option by the farmers to meet their objectives (Leclère et al. 2018). However, the difficulties for camelina to reach maturity in several on-farm trials implemented by farmers (Step 2) led them to propose to refine and adapt the management of camelina during the second design workshop (Step 4): e.g., using early varieties, earlier sowing or even relay-sowing, swathing camelina before harvest (Leclère et al. 2021a). Combining different types of experimental devices (implementation step) with other methods as on-farm tracking innovation or design workshop (invention step) is more and more used in participatory approaches and has shown some promising results to support the design and the implementation of agroecological practices and cropping systems (Navarrete et al. 2017; Périnelle et al. 2021; Aare et al. 2021)

4.1.5 A situated design to allow a dialogue between the desirable and the achievable

Whether for the multi-actor (Step 1) or the farmers (Step 4) design workshops, actors were always asked to design cropping systems or CMRs adapted to their own situation, expectations, and objectives. This choice of having a situated design during the workshops allowed a dialogue between the desirable and the achievable, which is crucial to the design of agroecological systems (Prost et al. 2018). Indeed, on one hand, design studies highlight the need to define and share among actors an ambitious target to simulate creativity and avoid fixation effects (Dorst and Cross 2001; Le Masson et al. 2009; Agogué et al. 2014). This is why, for example, Reau et al. (2018) proposed to carry out non-situated and long-term design to support the design of innovative cropping systems during design workshops. According to the authors, this is essential for a good exploration of new concepts as "each person carries out the exercise with a certain detachment and openness of mind insofar as it does not concern them directly or immediately" (R. Reau, pers. comm.). But, on the other hand, the adaptive management approach, required to manage the links between desire and reality, also advocates the flexible and adaptive nature of the target to fit real situations and thus support change processes (Béguin 2007). Especially, the constant adaptation of the design target is presented as a key element to keep the ambition and the energy high within system innovations projects (van Mierlo et al. 2010). As mentioned above, in our case study, situated design allowed to put these two levels in dialogue. Each workshop was organized around an ambitious target ("Producing camelina to sustainably supply an oilseed biorefinery" for the multi-actor workshop (Step 1) and "Growing a pesticide-free, low-input and profitable camelina" for the farmer design workshop (Step 4), but, during the design process, these targets were specified and adapted based on the contribution of each actor regarding his own situation. For instance, during the multi-actor workshop (Step 1), we were thus able to define what would be a "sustainable supply" in our case study, with, for example, criteria linked to the quantity and the quality of the seeds or the agronomic and environmental performances of the crop (Leclère et al. 2018) that were then used to design and assess the CMRs of the multi-environment experimental network (Fig. 4a).

4.1.6 An open innovation approach based on the circulation and sharing of knowledge between actors throughout the entire process

Initially defined in the field of industry (Chesbrough 2003), open innovation has been defined in agronomy as approaches that support the empowerment of farmers in the design, through the development of (i) news channels for the circulation of knowledge and know-how, (ii) new spaces for exchanges, (iii) new resources to support design, and (iv) new links between farmers-designers (Chesbrough et al. 2014; Salembier et al. 2018). In our approach, we formalized a specific step about the circulation and sharing of knowledge (Step 3). More precisely, in addition to the dedicated devices to share knowledge (field tours, meetings), an effort was also made by the research team to formalize and make available the knowledge produced using various formats (exploration trees as in Fig. 4, functional scheme as in Fig. 5), known to stimulate exploration during design process (Brun 2017; Quinio et al. 2022; Leclère et al. 2021a). In our case, the implementation of such an open innovation approach played a significant role in support to the design by farmers of locally adapted camelina-based cropping systems. Although we did not put in place a specific monitoring of farmers individual learning in time, we indeed observed and illustrated that the farmers—even new ones—mobilized locally produced knowledge during their design process (see §3.3 and Leclère et al. 2021a). In addition, we also consider that favoring open innovation in our approach contributed to foster collective learning on camelina and the hybridization between scientific and empiric knowledge—both useful to support cropping system design—, as it has been also observed in other participatory and multi-actor approaches (Specht et al. 2016; Girard and Magda 2018; Navarrete et al. 2018).

4.1.7 An effective network management

Several authors identified that effective network management is required to allow participatory approaches achieving their full potential (Meier and O'toole 2001; Giest and Howlett 2014; Berthet and Hickey 2018). Especially in agriculture, Berthet and Hickey (2018) showed that, beyond initiating and facilitating interaction processes between actors ("Connecting"), network management should also play a significant role in guiding interactions through process agreement ("Framing"), facilitating knowledge transfer and capitalization ("Knowledge brokering"), and searching for goal congruency by creating new content ("Exploring") to support agroecological transition. In our case, the management of the multi-actor dynamic across time was under the responsibility of the research team. The effectiveness of the network management, i.e., combining the four aspects, was achieved because of the multiples roles that the research team endorsed within this multi-actor dynamic. In all device, at least one researcher of the research team was involved (Table 1) whether as designer (Steps 1 to 4), knowledge producer (Step 2), facilitator (Steps 1, 3, and 4), interviewer (Step 2), or observer (Steps 1 to 4). The endorsement of these multiples roles of researchers is part of the paradigm shift from a lineal and diffusionist model towards an interactive and participative one currently at stake in the agricultural sector that has been identified as crucial to support agroecological transition (Doré et al. 2011; Le Gal et al. 2011).

4.2 Towards the transposition of the approach: challenges, points of vigilance, and areas of improvement

4.2.1 Developing a tailored approach adapted to the specificities of the context

While the seven characteristics listed before must be taken into account during the design of an approach to support crop diversification, their translation into steps, articulating various devices, remains, on the contrary, really open to allow adaptation to different contexts. For instance, in our case, the choice of camelina as study crop was a determining factor for the implementation of the on-farm trials by farmers (Step 2). Indeed, when looking at the activity of experimentation by farmers (Leitgeb et al. 2014; Catalogna et al. 2018), the risk associated with experimentation, and in particular the economic risk, is decisive (determination of the area dedicated to experimentation, acquisition of specific equipment, etc.). In the case of camelina, the possibility of experimenting with a double crop (where camelina could, in the worst case, have the role of a cover crop) with a reduced investment (in connection with low-input management due to the hardiness of the species) contributed to creating a favorable context (i.e., with a limited risk) for implementing these experiments, despite the absence of a concrete local outlet for this crop. However, not all the diversifying crops are showing similar agronomic characteristics than camelina, suggesting that new forms of experimentation actively involving farmers should be developed to support crop diversification (Lechenet et al. 2017; Lacoste et al. 2022). In addition, we also recognize that the success of approach relied partly on the involvement of a small number (<10) of motivated and innovative farmers, thus questioning the ability of the approach to support transition towards more diversified cropping systems at a wider scale. To overcome this limit, we assume that other types of devices should be imagined, especially to organize collective exploration. More broadly, this means that adaptation to other contexts would therefore need the realization of adequate diagnoses beforehand to reveal the specificities in terms of pedo-climatic conditions, agronomic issues, or even in terms of actor networks and skills in the studied area where the crop diversification will occur (Colombo et al. 2020; Morel et al. 2020).

4.2.2 Moving from a research-led towards an actor-led network management to better support transition towards diversified cropping systems

Even this study contributed to initiate a local dynamic around this new diversifying crop, as illustrated before, the capacity of this approach, characterized by a full research-led network management, to support a transition process towards more diversifying cropping systems, that are known to be complex and last over time (Duru et al. 2015; López-García et al. 2021), is a real limitation we identified. Indeed, in our case, the design and the implementation of the approach as part of 3-year-funded research project forced us to focus mainly on the issue of knowledge production to support design of camelina-based cropping systems without really addressing the question of the trajectories of change that the farmers should follow to achieve these cropping systems—which is a central question when looking at the question of the transition process. Therefore, in our opinion, it is crucial, in the future, to work towards the development of governance systems that are not fully dependent on funding or on the timeframe of research projects, often too short or binding (DeLonge et al. 2016). More precisely, at a time when the agroecological transition is reexamining the role of the various actors in the agricultural sector (Coquil et al. 2018; Aare et al. 2021), we argue that during the process, it would be useful to reflect on how to move from a research-led towards an actor-led network management. This would imply to better identify the skills needed to support and manage such multi-actor and participatory design approaches and develop adapted training or toolbox to support actor in this new role (Baccar et al. 2022).

4.2.3 Addressing simultaneously lock-ins at various level of the value chain

Focusing on 11 diversifying crops in France, Meynard et al. (2018) highlighted the interconnected impediments to crop diversification occurring at every link of the value chain. Referring to this study, we assume that our approach mainly contributed to remove existing barriers at the farming production level through the coordinated development of agronomic and organizational innovations. However, we also identified that building on our approach and its outputs, it would be possible to also address simultaneously existing lock-ins at other levels of the value chain, upstream or downstream, that would require to better reconnect agriculture, food, and environment sciences (Lamine 2015; Jordan et al. 2016; Brun et al. 2021). This would imply, among others, to involve the actors from the value-chain in a more active way than we did in our case study, in which their participation was rather "consultative" (using Pretty (1995) typology of participation in development programs and projects) thus hampering effective transformations at their own level. For instance, in the case of camelina, we succeeded in prioritizing breeding traits answering farmers needs in the local context of northern France, namely, the need of early varieties to increase the chances of reaching maturity in double-cropping modalities and the need of varieties with higher thousand grain weight to facilitate the establishment of broadcast seeding, also in double-cropping. However, we hypothesize that involving breeders more actively in the process—what we did not do—would have contributed to ease the adoption of these criteria in the selection process and the creation of a sales market for the seeds that are main impediments identified for now at the upstream production level (Magrini et al. 2016; Meynard et al. 2018; Parenty 2018).

4.2.4 Analyzing the approach with a dedicated and reflexive monitoring

In this paper, we analyzed ex-post a participatory and multi-actor design approach. This analysis was performed by our research team (researchers in agronomy) and was based on the data produced during the approach (scientific papers, audio recordings, workshops, meetings, and interview reports) and on informal exchanges with the actors involved. In other terms, it means that no specific data collection was imagined at first to feed this analysis. Therefore, we argue that it would be valuable, in the future, to add a reflexive process as part of the approach. As it has been done in other participatory approaches, this could include the evaluation of the overall process by the actors using surveys (Boulestreau 2021) or the analysis of the learning process through time (Braun et al. 2021). In our opinion, the added value of such reflexive process would be twofold. First, it would contribute to strengthen a theoretical framework to support crop diversification by extending and deepening the list of characteristics we proposed in this study. Second, including such reflexive activity as full part of the approach will also support the actors in their transition towards more diversified cropping as it contributes to social learning (Blackstock et al. 2007; Rossing et al. 2021).

5 Conclusion

This paper presents the results of an ex-post analysis of an original participatory and multi-actor design approach that was performed to identify to what extent the implementation of the four steps of this approach contributed to (i) the production of actionable knowledge, (ii) the exploration of new ideas/concepts, and/or (iii) the active participation of a diversity of actors of the agri-food system which are the three key elements that we pre-identified as crucial to support crop diversification in the literature. Drawing on concepts and theory from design sciences, we outline what the characteristics needed to support crop diversification are. We expect that sharing the learnings from this case study could be helpful for other actors from the agricultural sector (especially advisors from extension services), to develop their own approaches to support crop diversification in other situations (other crops, other regions). This article reaffirms the observation made by Prost (2021) about how useful it can be to put in dialogue agricultural and design sciences to support transition towards sustainable agriculture.

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