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What makes people accept carbon capture and utilization products? Exploring requirements of use in the German population

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Carbon Capture and Utilization (CCU) is often referred to as an important cornerstone in the context of counteracting climate change. It aims to capture CO_2 from various sources and to store it in valuable products more or less permanently. While the environmental impact of this technology has already received much scientific attention, this work takes a social science perspective on the matter. Using an empirical mixed-methods approach consisting of an exploratory focus group study (N = 13) and a validating quantitative questionnaire study (N = 198), public perceptions and acceptance of CCU were assessed in Germany by identifying motivators, barriers, and usage requirements. As CCU products, clothing, cosmetics, and food packaging were under study. Potential cost savings from shortened supply chains or manufacturing steps were the biggest motivator for using CCU. However, environmental impacts resulting from the degradation and reuse of CO_2 were also recognized and the conservation of fossil resources was also acknowledged. The biggest barrier, in contrast, was the concern about possible manipulation of consumers through marketing. Participants feared that CCU would be publicly portrayed as better than it actually is. In addition, a high energy input in the production of CCU products was expected and doubts were expressed about the longevity of the positive environmental impacts of CCU. General acceptance within the sample was quite high, however, the level of CCU awareness was rather low. Our results show a considerable lack of public knowledge about and information regarding the environmental impact of CCU, among other factors, despite this very topic garnering plenty of scientific attention. A need for publicly accessible information materials uniquely tailored toward potential consumer target groups was revealed.

KEYWORDS

carbon capture and utilization, CCU, user requirements, acceptance, focus group study, survey

1 Introduction

The polar ice caps are melting and sea levels are rising resulting in increasingly extreme weather events in many places worldwide. Global warming concerns us all because it brings consequences that hardly anyone can escape. As the primary source of global emissions, the energy sector holds the key to responding to the world's climate change where novel or improved strategies are needed to mitigate the resulting consequences.

Governments around the world have been trying to set climate neutrality as a binding goal for some time now, with economic, financial, energy, and transportation policies all aligned with climate protection goals. However, to meet global targets of carbon dioxide (CO_2) emission reduction, the decarbonization of industrial processes needs to significantly accelerate (Wesseling et al., 2017). Reaching net zero emissions in the global energy sector is an ambitious intention, but it is still achievable if governments—working closely together as well as with companies, investors, and citizens—take serious actions and efforts in this direction from now on (IEA, 2023).

One possibility to reduce CO_2 emissions is to capture CO_2 at the point of its origin and to process it into carbon-containing products through appropriate treatment; this process is called Carbon Capture and Utilization (CCU). The CCU process involves first separating and, if necessary, purifying the CO_2 and then converting the CO_2 into a new substance or product using energy and other materials. The advantage of the CCU technology is that it can simultaneously reduce the CO_2 emissions and their negative impact on the climate and supply carbon for a range of different possible uses (Christensen and Bisinella, 2021). Moreover, using CO_2 as feedstock lowers the use and thus the dependence on fossil carbon resources (Arning et al., 2021).

Various technical approaches to CCU and as many practical applications of the resulting materials can be found in the literature to date. One major area of research in this context is mineral carbonation, which can be used in the production of building materials such as cement (Rashid et al., 2020). Furthermore, the industrial interest in the biological production of bulk chemicals, as well as biofuels from gases (CO, or CO_2 + H_2) as the sole energy and carbon source, has risen intensively. This is also the main topic within the European project CO_2SMOS, where researchers from different disciplines endeavor to develop technologies transforming CO_2 emissions produced by bio-based industries into a set of high added-value chemicals with direct use as intermediates for bio-based products. However, public acceptance is a fragile good which needs to be formed and publicly developed with care. The intention to use a novel product, as general part of public acceptance, requires information and knowledge about the product and the production in order to allow informed decisions for using these novel products (cognitive component) (van Heek et al., 2017b; Linzenich et al., 2019; Offermann-van Heek et al., 2020) on the one hand and affective components, for example, trust in the product and the production process, a balanced and informed risk handling towards the novel production routes, and the product quality (van Heek et al., 2017a; Arning et al., 2020; Simons et al., 2021a) on the other hand. Before effective and acceptance-related information and communication strategies can be developed, an understanding of the public's attitudes and the factors underlying acceptance and risk perceptions need to be assessed (Jones et al., 2017; Arning et al., 2018; Simons et al., 2021a).

The aim of the presented study was therefore to explore the levels of knowledge about the CCU technology as well as to analyze public perceptions and consumer requirements for exemplary chosen, biobased products from the social science point of view. In a two-step empirical approach, we examined the societal adoption of CO_2-based products, involving qualitative and quantitative measurement methods like focus group interviews and an online survey.

2 Background

To be able to comprehensively address the acceptance of CCU products, we first describe the technology and previous scientific work on its acceptance. Then, the context of the present study is briefly summarized and the operationalization of technology acceptance is discussed in detail.

2.1 Carbon capture and utilization (CCU)

Carbon Capture and Utilization (CCU) describes the process of converting CO_2 into a resource for manufacturing valuable products (Godin et al., 2021; Shah et al., 2021). It targets capturing CO_2 emissions from various sources to keep them from entering the atmosphere (Markewitz et al., 2012). According to Cuéllar-Franca and Azapagic (2015) there is not one single CCU technology that fits all of its possible applications. Therefore, a multitude of different CO_2 capturing systems have been developed to meet the specific use cases. The different approaches of CO_2 capture can be classified into pre-combustion, post-combustion, and oxyfuel combustion systems (Songolzadeh et al., 2014). Al-Mamoori et al. (2017) give an in-depth overview on the CO_2-capture technologies, their applications, advantages and disadvantages, which will not be elaborated on further here due to the socioeconomic focus of the study at hand. While CO_2 is mostly extracted from waste materials, it is still important to note that it is not a free resource, as the entire process of CCU comes with financial and energy expenses (Rajabloo et al., 2023). The specific amount of these costs, however, varies depending on different factors such as CO_2 and contaminations' concentrations (Van Dael, 2018; Abdelkareem et al., 2021).

While there are various works discussing the sustainability of CCU technology, social acceptance of its products has received less scientific attention. However, specific CCU use cases and products such as fuels (Offermann-van Heek et al., 2020), plastic products (van Heek et al., 2017b), and foam mattresses (Arning et al., 2018) have been examined. Lutzke and Árvai (2021) summarize that the public is unaware of CCU technology for the most part, but is often receptive to its use after an introduction due to anticipated environmental benefits. However, the true environmental impact of the technology is difficult for consumers to assess. This was noted by Jones et al. (2017), who observed that while CCU is generally seen as positive for the environment, its use for plastic products appears to work against meeting environmental goals. However, according to Arning et al. (2020), in addition to the awareness of environmental aspects, risks associated with the technology can have a negative influence on acceptance. The before-mentioned associated risks can affect different domains; van Heek et al. (2017a) observe, for example, that consumers are concerned about potential health effects of use. It is also important to note that perceived risks do not necessarily correspond to scientifically based risks. As van Heek et al. (2017a) explain, participants of their study reported a concern about CO_2 leaking from the products used, despite it being firmly bound in the products in question.

2.2 Context of the study: CO_2SMOS project

Biorefinery industries have the great potential to turn CO_2 emissions into added-value chemicals due to their ability to transform the biogenic CO_2 waste streams into bio-based chemicals integrated within their own processes in a circular way. Within the European project CO_2SMOS, researchers of different scientific fields aim to develop technologies for transforming CO_2 emissions produced by bio-based industries into a set of high added-value chemicals with direct use as intermediates for bio-based products. The intended result is a toolbox that combines intensified chemical conversions (electrocatalytic and membrane reactors) and innovative biotechnological solutions based on gas/liquid combined fermentation processes and organic/green-catalysts reaction processes, which allow versatile production, depending on the available resources and the targeted value chains. Technologies involved in CO_2SMOS strive for low energy use, low production cost, and high product yield, and they have an outstanding greenhouse gas abatement potential, which will strengthen the sustainability and cost competitiveness of the integrated conversion processes.

In practical terms, the overall goal of the CO_2SMOS project is to boost the development of a set of innovative, cost-competitive CO_2 conversion technologies to transform biogenic CO_2 emissions produced by bio-based industries (e.g., in fermentation processes) into a set of high added-value chemicals with direct use as intermediates for bio-based products within the value chain of the bio-based industries. The use of industrially emitted or atmospheric CO_2 as a raw material offers many opportunities for the industry and at the same time has a desirable side effect of sustainability. It is not only one of the key means for fighting climate change but it also supports the circular economy by converting waste CO_2 into commodities, opening new ways of environmental protection, resource-saving, and economic growth. Certainly, optimal production routes and mere feasibility, however, do not currently assure a successful adoption of these products by end consumers. Therefore, a meaningful purpose of this study is a comprehensive analysis of societal perceptions considering requirements, concerns, or risks, and also an exploration of prerequisites for adoption and wide usage of bio-based products from CO_2 conversion by different user/consumer groups.

2.3 Public perception and acceptance in the context of renewable energy technologies

For a successful implementation of biogenic CCU products, such as the ones described within the context of the CO_2MOS project, technical and economic feasibility are essential though not the only prerequisites. Much more, the adoption of such CCU products also largely depends on public perception and social acceptance of the potential or future users. The public's reaction towards a novel technology has an enormous impact on the implementation, not only applying high pressure to policy and industry but also influencing or even thwarting the further development and roll-out (e.g., controversy against genetically modified foods (Bloomfield and Doolin, 2013), protests against nuclear energy (De Groot and Steg, 2010; De Groot et al., 2013) or hydraulic fracturing (Boudet et al., 2014)). Assessing the social acceptance of CCU solutions and promoting awareness of their environmental, social, and economic benefits is an indispensable component for an effective engagement of stakeholders and setting appropriate policies in the smooth implementation of these products on the market. Thus, to get insights into current public perceptions of this issue, the question arises as to what constitutes social acceptance and how it is studied.

Wüstenhagen et al. (2007) contributed to the clarity of understanding social acceptance of renewable energy technologies by distinguishing between three dimensions of social acceptance, i.e., sociopolitical, community, and market acceptance. Referring first to sociopolitical acceptance, the authors describe acceptance on a general level and claim that many barriers to achieving successful implementation can be considered a manifestation of a lack of social acceptance. Here, besides public acceptance, i.e., broad majorities of individuals in a society, the acceptance also concerns key stakeholders and policy actors of effective policies which have considerable influence on institutionalized frameworks fostering market and community acceptance. Concerning the current research, the sociopolitical acceptance thus on the one side refers to the general acceptance of the reuse of CO_2 by converting it into products like clothing, cosmetics, and food packaging, and on the other side, it bears on an accepted use of these products. The second dimension of social acceptance of renewable energy innovation—community acceptance—describes the specific acceptance of siting decisions and renewable energy projects by local stakeholders (Wüstenhagen et al., 2007). The acceptance of stakeholders depends on the personally experienced proximity to the industrial conversion of CO_2 (e.g., located near the residents) or involvement as a local authority. Typically, community acceptance has a time dimension that follows a pattern of a U-curve before, during, and after a particular project, where after the initial high acceptance the local acceptance falls to relatively low acceptance (siting phase) and again to higher acceptance once the project is running. Important factors in this context are also questions of shared costs and benefits, fair decision-making, involvement of all relevant stakeholders, and the local community's trust in the intentions of the investors and other external actors. In addition, research has shown that cognitive and affective assessments of risk perceptions, such as sustainability, health, and environmental risks, and their perceived uncontrollability reliably predict and are significantly related to CCU acceptance Arning et al. (2020). Huijts et al. (2012) claim that acceptance is motivated by the different goals towards which people strive. Based on Lindenberg and Steg (2007), they distinguish three important motives that influence behavior: gain (the choice is made by weighing the costs, risks, and benefits of options), normative goals (the choice is based on moral evaluations), and hedonic goals (a decision is based on what feels best). An accepting attitude towards a technology reflects behavior that enables or promotes the use of it and can be expressed in proclaiming the technology or purchasing and using the technology. On the other side, resistance can be expressed in not purchasing and using or even in taking protesting actions against the technology—as the authors continue. Besides an active acceptance or rejection of a technology, individuals can also adopt an indifferent position, where no attitude has been developed yet (Arning et al., 2019). Furthermore, it was shown that social acceptance reactions towards CO_2-based products are not only relevant when it comes to marketable end products (Arning et al., 2021; Simons et al., 2021b), but the production process was also impacted by acceptance factors (Camacho-Otero et al., 2019; Evans, 2019; Simons et al., 2021a). Apparently, consumers do not only consider the final product but try to gauge the way it is produced. Therefore, the assessment of public acceptance and the measuring of risk perceptions should be launched quite early in the developmental process in order to incorporate social factors, like acceptance and usage requirements, in the life-cycle assessment of the production process and the final product (Offermann-van Heek et al., 2020; Simons et al., 2021a).

Even though research on renewable technologies still mostly focuses on technical and economic factors, it is increasingly understood that the adoption of these technologies and efforts connected to a circular economy as a pathway towards sustainability has strong social, policy, and governance components (Sovacool et al., 2018; Hartley et al., 2020; Simons et al., 2021a). Involving potential and/or future users from the beginning in the development, design, and deployment of novel sustainable energy systems has many advantages for successful implementation. It enables the disclosure of (potential) consumers' perceived benefits and motives but also risks and pitfalls connected to the use of such technologies (Huijts et al., 2012; Arning et al., 2020; Emmerich et al., 2020). However, it is important to note that these perceptions do not necessarily correspond to scientific reality. For example, van Heek et al. (2017b) mention that participants considered the possibility of CO_2 escaping from solid products to be a health risk, although this was not a realistic concern with the products under discussion. Based on the empirical results of social perception and acceptance of the technology to be developed, technical and industrial efforts can be iteratively supported by reporting early on in the development process about the revealed obstacles so expenditures can be kept to a minimum. Also, guidelines can then be issued and legal regulations can be adopted. In this way, optimally adapted communication strategies for disseminating the products in society can also be developed (Offermann-van Heek et al., 2020; Kluge et al., 2021)—all factors that consolidate the successful adoption of the products. Last but not least, the social science research on energy technology acceptance enables not only tailoring of public education to consumers' needs (Hartley et al., 2020) but also spreading awareness about the economic and ecological necessity to systematically rethink technology development in line with sustainability (Simons et al., 2021a).

2.4 Research aim and questions

Based on the scientific background regarding general technology acceptance just presented and the objective of the CO_2SMOS project four research questions for understanding the rationales of (potential) users with respect to the adoption of the CCU products arise for the present study. The focus group study was guided by the following exploratory questions:

RQ1: What are motivators regarding CCU adoption?
RQ2: What are barriers regarding CCU adoption?
RQ3: What are user requirements for CCU products?

Subsequently, the resulting findings were validated in a quantitative study guided by the following research question:

RQ4: Does the general public accept CCU products?

3 Empirical approach

A mixed-methods approach was chosen for a holistic consideration of the research questions present. First, we performed an exploratory study in order to identify the acceptance-relevant factors that drive the social acceptance of CCU products and the adoption process. Subsequently, based on the results of the qualitative study, we designed a validating study. Both studies were performed consecutively in Germany within the period from August 2022 to March 2023. Figure 1 depicts design of the empirical process. The methodological approach to both studies will be provided below.

3.1 Exploratory study: identification of acceptance-relevant factors

To gain insights into the public's perception and acceptance of CCU-based products, an exploratory qualitative study was performed in the first step. A focus group design was chosen to allow observations on trade-offs and discussions between participants with different attitudes and perspectives on the matter. In order to cover as broad a spectrum of prior knowledge as possible, both laypersons and experts in the field of energy were interviewed on this topic. In the following, the focus group design will be presented, further information on data collection as well as preparation and the performed analysis will be given, the sample will be described, and finally, the main results will be summarized.

3.1.1 Focus group design

To help participants organize their thoughts and also record them independently of their participation in the discussion, everyone was asked to maintain a workbook throughout the focus group to take notes on the relevant topics. Before the group discussion began, all participants filled out a short questionnaire about demographic data and personal attitudes. Then, as a conversation starter, interviewees were asked about their prior knowledge regarding CCU. If they indicated to know nothing about the topic, they were encouraged to guess what it could be, based on the term itself. Experts were inquired regarding their professional involvement with CCU. Subsequently, a formal definition of CCU was presented by the interviewers to provide all parties involved with a basic understanding of the technology. Respondents were then asked for their initial assessment of CCU. They were asked to state what advantages and disadvantages they saw in the introduction of the technology and what they had to say about products manufactured using this process. Finally, the CO_2SMOS bio-based products, clothing, cosmetics and food packaging were introduced and participants were asked to assess them regarding benefits, risks, and conditions of use.

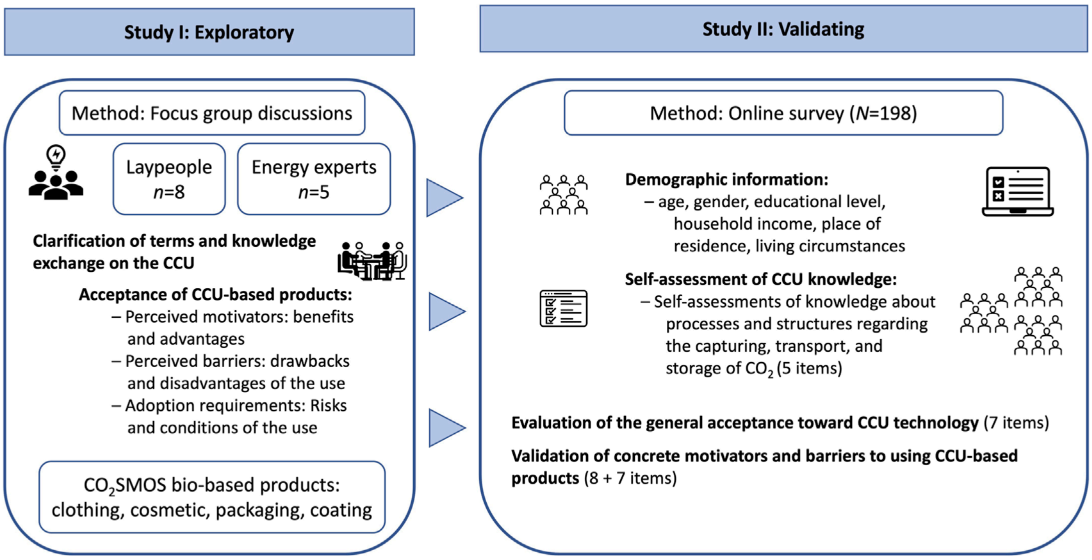

FIGURE 1
Design of the empirical approach detailing the exploratory study (n = 8 laypeople and n = 5 experts participating) and the validating study (N = 198 participants).

3.1.2 Data collection, preparation, and analysis

Beforehand, the interviewees were informed that they were free to quit the interview at any time, were encouraged to express their thoughts freely, and were told that none of their statements would be right or wrong. The participants were then informed that the focus groups would be recorded and gave their consent. Afterwards, the audio recordings were transcribed and pseudonymized through independent third parties so that no conclusions could be drawn about individual participants on the basis of the raw data material. Subsequently, a qualitative content analysis according to Mayring (2014) was performed. For this purpose, a category system was derived from the generated data material and iteratively adapted.

3.1.3 Sample

The focus group study was conducted in the German language as all participants spoke and understood German. A total of N = 13 participants—laypeople and experts—volunteered to take part in the focus group study. No financial incentives were given. The expert focus group consisted of 5 participants and 8 individuals participated in the laypeople focus group. Interviewees' age ranged from 18 to 67 with a mean of 39.09 years (SD = 16.84). With 6 males and 7 females, gender was equally distributed among the sample. The level of education among participants was comparatively high. Every layperson had attained at least a university entrance qualification, and experts all had university degrees. In a self-assessment, participants indicated that they tended to be environmentally conscious (M = 4.77, SD = .83; on a Likert scale with min = 1, max = 6). Furthermore, participants reported to behave environmentally friendly (M = 4.00, SD = .39; min = 1, max = 6) and felt a rather strong control over environmental effects (M = 4.24, SD = .54; on a Likert scale with min = 1, max = 6).

3.1.4 Results

In the following section, the main results of the qualitative focus group study will be presented. The results will be reported using the derived category system. For better comprehensibility, an illustration of the complete derived category system is depicted in Section 1 of the Supplementary Material. For a preliminary attempt at answering the research questions, the perceived motivators, barriers, and user requirements of CCU that emerged from the focus group study will be introduced.

3.1.4.1 Perceived motivators regarding CCU adoption (RQ1)

In the laypeople group, CCU was rather unknown. However, after being introduced to the technology, participants expressed a positive attitude towards it. As an important and one of the main motivators to use CCU products, participants mentioned sustainability (*"We see the sustainability aspect as a big advantage: You just do not throw the products away and cannot use them anymore […] but you can recycle them and use it in a new form again."*; Layperson, 48, male) and the reuse of climate-damaging CO_2 (*"The most important motivator is reusing, i.e., the aspect that the waste CO_2 is recycled into clothing. And that applies to all these CCU products."*; Layperson, 64, female). The possibility to 'permanently' bind CO_2 in long-term CCU products is perceived as a further driver to use CCU technology, where one of the laypersons mentions *"the idea that CCU is implemented for products that are preferably very durable and CO_2 will always be bound or at least very long"*; (Layperson, 18, male). In this context, also the reduction of climate-damaging CO_2 played an important role in the focus group discussions (*"It is not a resource that is really renewed by nature, but an unwanted by-product that we, as humans, emit in the environment. And in the end, we actually take this garbage that is in the air and make something good out of it. So, it is somehow good for the environment."*;

Layperson, 66, male). Regarding the environment, interviewees appreciated the relief brought by CCU-based manufacturing of the bio-products as well as saving of fossil resources (*"A decisive aspect is an environmental impact, i.e., how much CO_2 emissions can be avoided or saved by the processes? And also, what does the saving of fossil raw materials look like?"*; Layperson, 36, female).

In addition, respondents perceived it as an advantage that the CO_2 emissions are significantly reduced in comparison to conventional production and products (*"Transparent evaluation of the process [CCU] or the product in comparison to the classic manufacturing route or alternative available options. So that as a consumer I can really be sure when buying the product that this is not just marketing […] but that this process has indeed resulted as the ecologically best"*; Expert, energy economist, 35, male). The discussion partners in the expert group also addressed potential cost savings through fewer manufacturing steps (*"It matters how efficient or how energy-intensive these [CCU] processes are: Economic acceptance can play an important role against the current background, where we are facing energy shortages and high energy costs"*; Expert, sustainability in construction, 29, female) and shortened supply chain (*"If we look at the different energy requirements, which are then probably covered by renewables, we then have fewer or smaller trade-offs in the processes that have a lower energy requirement"*; Expert, life cycle assessment, 30, female).

3.1.4.2 Perceived barriers regarding CCU adoption (RQ2)

While respondents generally viewed CCU technology as sustainable, barriers to its adoption could also be identified. The perceived barriers concerned health, economic decisions, and the factual environmental impact of CCU. Regarding health, interviewees were concerned that CCU products may not be safe to use, especially over a prolonged period of time (*"So a health risk, which is just unexplored, just because it would last for a long time or because the scientists overlook something."*; Layperson, 22, male). They mentioned, for example, potential threats to one's health by direct contact with CCU products, especially in the context of clothing (*"On the one hand, if there are these risks for the skin, as we had just discussed, that there are chemicals or the like that are not so good for the skin. Then, garments that are on the first layer, such as T-shirts or undershirts or underpants, socks, all of that. They would just bring risks with them and might not be so much recommended accordingly."*; Layperson, 18, male). These concerns were based on the fact that the technology was perceived as innovative and thus unexplored.

Economic decisions proved to be a barrier in this context in two different ways. Respondents expressed concern that CCU products may be of inferior quality compared to conventional products, making them less economical to purchase (*"But then, of course, there are concerns that are nevertheless associated with it, such as questions about product quality, is that also comparable to conventional products?"*; Layperson, 22, male). In addition, the interviewees found it difficult to assess how CCU products are priced. They assumed that they would be more expensive than conventionally manufactured products due to the novel production method and its sustainability (*"The only disadvantage we see is that products will likely get more expensive"*; Layperson, 22, male).

Finally, environmental aspects regarding the production process from start to finish constituted barriers to the acceptance of CCU products. The question of where the required CO_2 would be sourced already posed a problem for respondents. It was discussed whether the CO_2 gained from fermentation processes, generated during waste recycling, would meet the amount of resources required in the future. Accordingly, concerns were raised about artificial adherence to CO_2 sources which would be inconsistent with meeting environmental goals (*"In principle, the question of CO_2 sources is of course super interesting, because the classic CO_2 sources should no longer be there in the long term in the ideal case."*; Expert, life cycle assessment, 30, female). In addition, the final disposal of the products after use was discussed. Respondents were apprehensive that the CO_2 would be re-emitted in the recycling of the product, making CCU only a temporary solution (*"When I no longer need the product and it is disposed of, so to speak, then the CO_2 is created again"*; Expert, life cycle assessment, 34, female). Further, interviewees noted that the use of CCU could supplant other solutions that already exist and are more sustainable, especially in the context of product packaging (*"We fear that once this happens and it works well, people will no longer pay so much attention to whether plastic is used or not. That means [we use] less paper or less glass packaging, because plastic is so easy to make now, which would then be something worse again"*; Layperson, 25, female). Ultimately, respondents were generally uncertain about the actual environmental benefits of using CCU in the contexts discussed here. They suggested that there were other industrial applications where CCU could achieve greater effects (*"If we only talk about plastics, for example, how big is the potential there and can it really be measured against the climate targets to some extent or are there completely different sectors in which something has to be done first?"*; Expert, acceptance research, 34, female).

3.1.4.3 User requirements regarding CCU products (RQ3)

Regarding user requirements for the adoption of CCU products, the focus group discussions revealed various factors concerning the quality of the products and the tangible characteristics of the materials used. Material fastness and the resistance of the materials used were discussed. In particular, respondents wished for compliance with existing quality standards (*"The conditions that would have to be met in order for us to use it, we had said that we wanted to see the common quality standards of such a product fulfilled"*; Layperson, 22, male). In order to satisfy this requirement, a quality assessment issued by an independent trustworthy authority was considered to be sufficient for laypeople (*"If the new products, if the new packaging is also rated as very good by the TÜV [German Technical Inspection Association], not by the TÜV, but I do not know, by Stiftung-Warentest [German Consumer Organization], then that would be enough for us at this point."*; Layperson, 22, male). As long as it could be ruled out that the quality of the respective CCU product was lower than that of a conventionally manufactured product, the respondents uniformly assessed CCU products positively.

Additionally, participants requested a guarantee for products' health compatibility. An interviewee mentioned that it was *"quite essential that it is not harmful to health"* (Expert, acceptance research, 34, female). Furthermore, it was consistently demanded that any contamination of products by chemicals seeping from the packaging must be prevented at all costs. Testimony suggests that laypeople may consider CO_2 as harmful to one's health or even toxic (*"As*

10.3389/fenrg.2023.1248555

for requirements, that it is absolutely sure that the food that is stored in there does not get anything from the packaging"; Layperson, 25, female). Health concerns hold for conventional materials like regular plastic as well.

Interviewees frequently remarked on difficulties with an isolated examination of CCU's environmental benefits. The researchers observed the need for "a bigger picture" providing insights into the impact of CCU in combination with other environmentally friendly technologies (*"It is also important that the technology is located within the overarching environmental and climate goals. For the population, these are all individual solutions, and it must be made clear how different technologies or products can work together to ultimately have an effect on the environment and climate.*"; Expert, acceptance research, 34, female). Assessing the sustainability of CCU technology was particularly difficult for the laypeople in the sample. In the focus groups, they accordingly mentioned possible independent impact certification (*"I think that, for example, such an independent certification or the audit of the ecological assessment could be interesting.*"; Expert, life cycle assessment, 30, female). However, which authority should issue such certification was not specified. Additionally, non-experts expressed a desire to create information material that explains the advantages and disadvantages honestly, transparently, and in detail to support the formation of opinions (*"I would also go with a transparent, correct in content, and understandable for laypeople communication.*"; Expert, acceptance research, 34, female).

Regarding the communication of informational material to consumers, focus group respondents demanded careful tailoring and deliberate phrasing in order to meet the target groups' individual needs. Particular emphasis was expected to be placed on finding the correct wording because the context was assumed to trigger undesired associations, especially in people unfamiliar with the subject (*"I could imagine that when the word bacteria alone is mentioned, which per se does not necessarily have to be something negative, but there is a danger that it will be negatively associated and perhaps linked with, also perhaps not necessarily rationally, but pathogens or harmfulness, the subject of diseases, etc.,*"; Expert, acceptance research, 34, female). According to respondents, negative associations generated by inconsiderate wording could influence CCU acceptance (*"If this wording is included, this could influence acceptance.*"; Expert, acceptance research, 34, female). Providing suitable informational material was therefore requested to be a joint effort from experts of all disciplines participating in the CCU production process.

3.1.4.4 Insights from the qualitative study

Methodologically, we can conclude that qualitative results from the interview study allowed to identify both, experts and laypeople's argumentation lines with respect to the perceived benefits of CO_2-based products and also potential barriers and critically evaluated aspects. These factors will form a rich and empirically collected base for the validating quantitative study.

Two major points are highlighted here: First, one could have expected that technical experts and laypeople do have different narratives, argumentation lines and evaluations, simply because experts can rely on domain knowledge which is mostly missing in the laypersons' group. Astonishingly, however, the argumentation structures of the experts did not differ fundamentally from those of the laypersons. While experts naturally went into more detail about individual production steps and addressed potential weaknesses regarding the environmental impact of CCU more specifically, the main motivators, barriers and user requirements identified remained the same in both groups. Second, it is interesting to note that there was little difference in the perception of the different CCU products (clothing, cosmetics, and food packaging). The only indication in this respect related to underwear, where the respondents were more cautious due to direct body contact.

3.2 Validating study: determining the level of acceptance and the relation between barriers and motivators

The results of the qualitative preliminary research offer a first insight into public perception and acceptance of CCU products. However, no general validity can be attributed to them. We therefore subsequently derived and conducted a validating quantitative study (N = 198). In the following, we present the questionnaire design, explain data cleaning and analysis, describe the sample, and finally display the main results of the quantitative study. In line with the target group of the study, the questionnaire was available in German. Prior to running the survey, the ethical acceptability of the study's aims and procedures was checked and approved by the ethical board of the Faculty of Humanities at RWTH Aachen University (Ethics Approval No.: 2022_17_FB7_RWTH AACHEN).

3.2.1 Questionnaire design

The online questionnaire used the main findings of the previous focus group interviews to identify the main acceptance drivers for biobased CCU products, i.e., motivators, barriers, as well as general acceptance conditions. An overview of all items, constructs, and the respective Cronbach's α, as well as means and standard deviations, can be found in Section 2 of the Supplementary Material.

In the beginning, we provided participants with a proper background for this study describing the global situation and the growing need for novel strategies mitigating the effects of global warming and the resulting consequences of current climate change. In the introduction, we outlined that employing modern technical solutions enables us to capture CO_2 at the point of origin and to process it through a proper treatment into carbon-containing products (e.g., clothes, cosmetics or packaging). Before starting the online questionnaire, participants were asked to consent to the terms of data protection and indicate being of legal age. In the first part, respondents provided demographic information (i.e., age, gender, educational level, household income, place of residence, and the circumstances under which they lived). The second part of the questionnaire briefly introduced the term *Carbon Capture and Utilization* that reduces CO_2 emissions and simultaneously uses CO_2 as a raw material to manufacture different products. Given this explanation, participants self-assessed their current general knowledge about the CCU technology, i.e., they rated their know-how about the capturing, transport, and storage of CO_2 on 10-point Likert scales ranging from 1 (=very low) to 10 (=very high). After that, participants evaluated their general attitude toward CCU technology and answered questions regarding the utilization of CO_2-based products. For that purpose, they (dis)agreed to statements like "I support the use of CO_2-based products" or "I am quite unsure about the quality of the $CO2_2$ products" on a 6-point Likert scale ranging from 1 (=I fully disagree) to 6 (=I fully agree). Subsequently, participants validated the concrete motivators and barriers to using CCU-based products according to the results of the previous focus group study. Here, respondents evaluated concrete perceptions regarding the benefits (e.g., sustainability, reuse of climate-damaging CO_2, environmental relief, etc.) and drawbacks of using such CO_2-based products (e.g., negligible impact on the environment, high energy effort, etc.) on a 6-point Likert scale as above. The questionnaire concluded with a final question about acceptable prices for the biobased CCU products.

3.2.2 Statistical analyses

Satisfying quality of the constructs used to measure perceived motivators, barriers, general acceptance, and personal attitudes was ensured by testing for internal consistency according to Cronbach's Alpha ($\alpha \geq .70$). Descriptive statistics were conducted by calculating means *M*) and standard deviations (SD). Differences from means to scale mid-points were tested for significance using one-sample t-tests and effect sizes were estimated by means of Cohen's *d*. The level of statistical significance was set to 5%.

3.2.3 Sample

In order to get an unbiased and representative sample regarding age, gender, education and geographical region within Germany, we used the service of an independent marketing research institute for the data collection. The online survey was distributed via link by the market research institute among the German population, which allowed a census representative sample (N = 198) to be gathered. With n = 99 women and n = 99 men participating, gender was perfectly balanced within the sample. The mean age was 47.06 years (SD = 16.69), with the youngest participant being 18 and the oldest being 74 years old. One-third of the participants (n = 66, 33.3%) stated to have reached primary education, n = 70 (35.4%) attained secondary education and n = 62 (31.3%) had graduated tertiary education. Thus, schooling was also quite evenly dispersed among the sample. Participants indicated behaving rather environmentally friendly (M = 4.03, SD = .86, min = 1, max = 6). With regard to the statement whether they specifically bought products whose production and use had a low impact on the environment, more than half of the sample was in agreement. 17 (8.6%) people reported to "fully agree", n = 36 (18.2%) to "agree" and n = 78 (39.4%) to "tend to agree". However, n = 44 (22.2%) indicated to "tend to disagree", n = 17 (8.6%) to "disagree" and n = 6 (3.0%) to "fully disagree". Finally, respondents felt to be fairly open to innovations (M = 3.73, SD = 1.05, min = 1, max = 6).

3.2.4 Results

This section summarizes the main results on the acceptance of CCU products from the quantitative online study (*RQ4*). Since acceptance was assessed using both motivators and barriers derived from the exploratory study, as well as items regarding the general acceptance of CCU products, the results well be presented accordingly. First, perceived motivators will be discussed, then perceived barriers will be presented and finally, general acceptance of bio-based CCU products will be outlined.

3.2.4.1 Perceived Motivators

The motivators that emerged from the qualitative study were found to be valid within the examined sample of the quantitative study. Figure 2 illustrates the resulting mean values for the evaluation of motivators. The benefits of using CCU were uniformly recognized by respondents, with all means lying significantly above the scale mid-point, indicating agreement. It can be observed that participants assume that using CO_2-based products would result in a relief for the environment ($t(197) = 10.95$, $p < .001$, $d = 1.14$), degradation of climate changing CO_2 ($t(197) = 8.25$, $p < .001$, $d = 1.13$), and reduction of CO_2 emissions compared to conventional

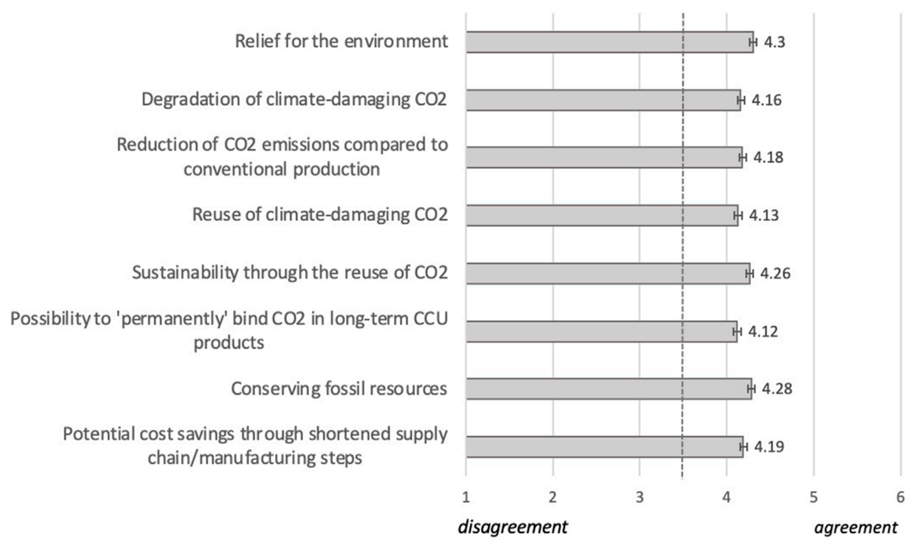

FIGURE 2
Means and corresponding standard errors resulting for motivators regarding CCU adoption (N = 198).

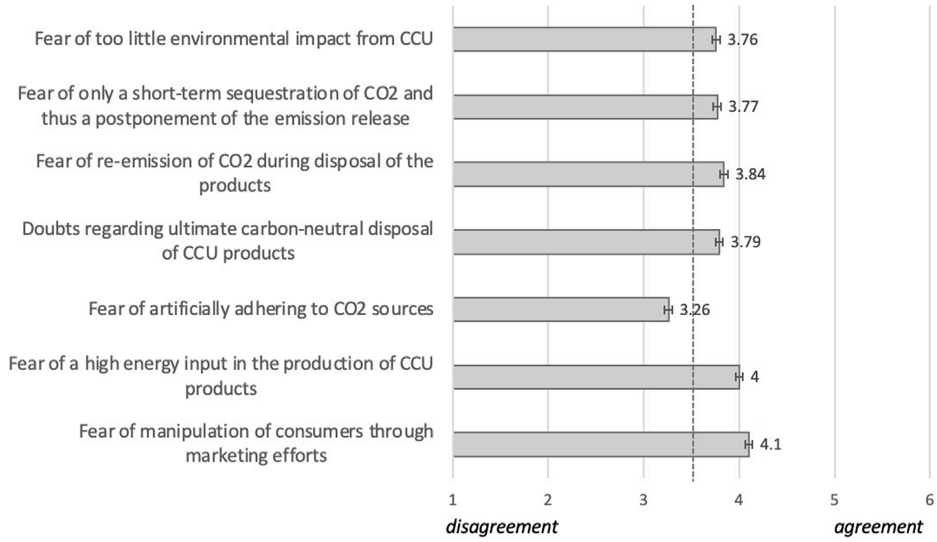

FIGURE 3
Means and corresponding standard errors resulting for barriers regarding CCU adoption (N = 198).

production processes ($t(197) = 7.80$, $p < .001$, $d = 1.10$). Additionally, participants estimate that CCU offers the possibility to permanently bind CO_2 in products ($t(197) = 8.23$, $p < .001$, $d = 1.07$). Thus, there is a consensus on the benefits of reusing climate-changing CO_2 and the sustainability provided by said practice. Furthermore, an agreement regarding the conservation of fossil resources ($t(197) = 9.73$, $p < .001$, $d = 1.16$) and potential cost savings through shortened supply chains and manufacturing steps ($t(197) = 7.27$, $p < .001$, $d = 1.13$) could also be detected.

3.2.4.2 Perceived barriers

As for perceived barriers, participants agreed with the derived statements to varying degrees, an overview of resulting means can be found in Figure 3. Here, most means are significantly higher than the scale mid-point, with the only exception concerning fear of CCU having too little environmental impact. However, statistically significant doubts concerning the ecological effects of the technology can still be observed. Respondents indicate a fear of re-emitting CO_2 during the final disposal of the products after use ($t(197) = 3.31$, $p = .001$, $d = 1.16$), and only a short-term sequestration of CO_2 which would only postpone the release of emissions ($t(197) = 2.37$, $p < .05$, $d = 1.02$). Participants also showed concerns regarding an artificial adherence to CO_2 sources through using CCU ($t(197) = -6.27$, $p < .001$, $d = 1.14$) and doubted ultimate carbon-neutral disposal of the CCU products ($t(197) = 2.47$, $p < .05$, $d = 1.10$). However, the biggest concerns revealed in the statistical analysis were the fear of high energy input into the production of CCU products ($t(197) = 5.68$, $p < .001$, $d = 1.04$) and the potential manipulation of consumers through marketing efforts ($t(197) = 5.93$, $p < .001$, $d = 1.20$).

3.2.4.3 General acceptance

Before acceptance requirements will be discussed in further detail, first, a closer look is directed to the effects of the prevailing CCU technology knowledge on the acceptance of CCU technology.

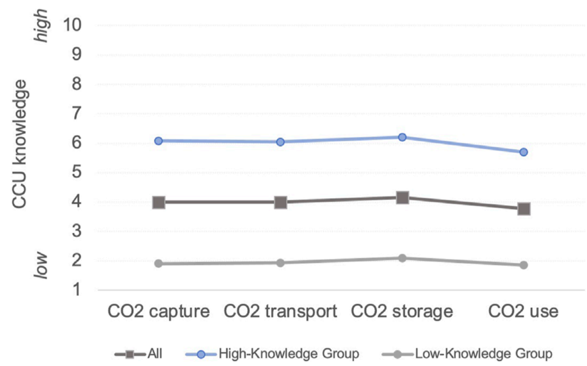

FIGURE 4
Self-assessments of knowledge about processes and structures regarding CO_2 use for the whole sample (N = 198), high CCU knowledge group (n = 99) and low CCU knowledge group (n = 99).

In a self-report, participants indicated rather low knowledge of CCU and the involved processes ($M = 3.98$, SD = 2.42, min = 1, max = 10, $t(197) = -8.85$, $p < .001$, $d = 2.42$). Figure 4 provides an overview of the respective assessments of the individually surveyed processes and further depicts the overall rather low level of CCU knowledge within the sample.

To determine whether perceived knowledge about CCU influenced general acceptance, a median split was performed (*Mdn* = 4.0). Respondents were thus split into a group of low knowledge and a group of medium to high knowledge, for ease of reading, from now on referred to as high CCU knowledge group. The results of general acceptance are presented based on these groups and depicted accordingly in Figure 5. For the group with low CCU knowledge, all values but the mean for supporting the use of CO_2-based products were significantly above—or for negatively

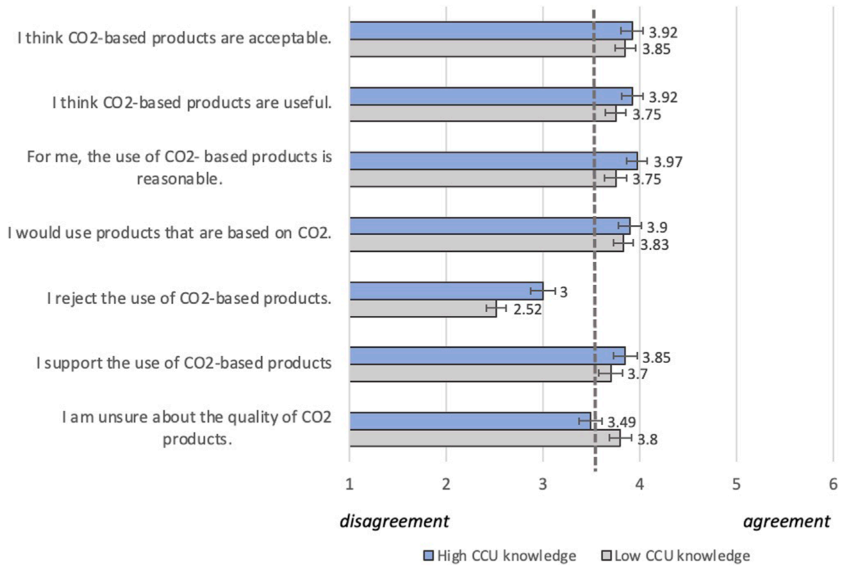

FIGURE 5
Means and corresponding standard errors resulting for the general acceptance of using CO_2-based products for high CCU knowledge (n = 99) and low CCU knowledge groups (n = 99).

phrased items respectively below—the mid-scale point, indicating acceptance. The values for the group with high CCU knowledge differ, however, with all calculated means but the one representing uncertainty regarding the products' quality being significantly above—or below—the mid-scale point. Interestingly, the group with high CCU knowledge shows higher acceptance values than the group with low CCU knowledge regarding most items, but is also more likely to reject the use of CO_2-based products. However, both groups view CO_2-based products as acceptable, useful and reasonable. Moreover, both groups support the use of CO_2-based products and are willing to use them. However, the group with low CCU knowledge is more uncertain about the quality of CO_2-based products. Overall though, the calculated mean value for general acceptance of the low-knowledge group (M = 3.79, SD = .76, $t(98)$ = 3.86, $p < .001$, d = .76) is only slightly below the high-knowledge group's (M = 3.87, SD = .83, $t(98)$ = 4.38, $p < .001$, d = .83).

4 Discussion

Climate change has multiple impacts on nature, society, and the economy, transforming step by step the world we live in. Currently, many scientists around the world are researching different solutions to this problem. CCU is one approach that naturally needs to be implemented in combination with multiple other environmentally protective technologies, rather than stand-alone. For a successful market launch of products manufactured using this environmentally friendly process, the general acceptance of these must first be carefully investigated. In order to investigate general acceptance in an all-encompassing manner, in the present study a mixed-method approach was applied. An exploratory study in the form of focus groups was conducted to gain first insights into the matter and generate a framework for the validating quantitative study that followed.

4.1 Discussion of key results

While there has been little prior research on this specific topic, Lutzke and Árvai (2021) found that the general public was rather unaware of CCU but showed a positive attitude towards it after introduction. The same could be observed in both studies present. While participants in the focus groups reported not knowing anything about CCU and the prior knowledge regarding CCU was rather low in the quantitative sample, both reported positive attitudes towards the technology after being informed about the process. Furthermore, the quantitative study measured a relatively high general acceptance of the use of CCU products. Here, primarily the willingness to use, and positive associations with, CCU products were examined as a measure of acceptance. Additionally, potential consumers' gain was examined to assess general acceptance based on the research of Lindenberg and Steg (2007). Motivators, barriers, and user requirements were discussed at great length during the focus groups. Respondents in the qualitative study explained to view CCU as a form of recycling of CO_2 which would be accompanied by positive impacts on the environment. These expectations were verified in the quantitative study.

However, there were also concerns about the longevity of these benefits. Some barriers that emerged from the focus group discussion, dealt with the fact that the CO_2 could only be bound in products for a short period of time or it could be re-released as soon as products were disposed of. However, the concern that the environmental benefits were too small could not be confirmed to be significant. Hence, several uncertainties regarding the CCU process were revealed to hinder participants' ability to estimate the overall environmental impact of CCU. While expectations were high, there was little knowledge of the scientific background which caused participants to be insecure in their assessments. These findings are in line with previous research by Jones et al. (2017) who likewise described that the environmental impact of CCU was difficult to evaluate for potential consumers. One of the previously mentioned uncertainties was related to the cost of manufacturing, regarding both monetary and energy costs. The focus groups' participants expected an all-encompassing evaluation of the production process compared to conventional manufacturing methods before adopting CCU, however, they lacked a neutral assessment from a competent, independent entity, whose judgement they would trust in this regard. Results of both studies revealed the participants' fear of manipulation by marketing that would portray the technology more positively than it actually is.

In addition to environmental impacts, the exploratory study also addressed potential health hazards. While the environment-related barriers affected all product evaluations equally to a considerable extent, the health-related barriers emerged to be particularly relevant for contexts involving close contact with the consumer's body, e.g., underwear and cosmetics.

It was also possible to confirm findings from Offermann-van Heek et al. (2020) concerning participants' fear of damage to their health caused by CO_2 leaking from CCU products. In their study, as well as in the present study, only solid products were examined, from which the CO_2 cannot actually escape. Furthermore, humans produce CO_2 themselves, which is released into the air around them through their breath. Accordingly, it remains to be clarified why health restrictions are suspected as a result of CO_2 leakage. Furthermore, this demonstrates that there is a public need for information on the concentrations of CO_2 in the environment that could be potentially hazardous to human health.

4.2 Implications for public education, information and communication

As Hartley et al. (2020) mention, social science research allows us to align public education with potential users' needs. We identified generally accessible, independent sources of information regarding environmental and health-related aspects of CCU that consumers can trust as an indispensable need to build confidence in CCU adoption. From the exploratory study, it is evident that these information materials must be precisely adapted to the needs of the respective consumer target group in order to prevent misunderstandings and negative connotations (Arning et al., 2018; Linzenich et al., 2019; Offermann-van Heek et al., 2020; Simons et al., 2021a).

Echoing other studies respecting CCU acceptance (Offermann-van Heek et al., 2020; Lutzke and Árvai, 2021), we also identified a low information level in the general public about CCU processes and approaches. From this, a clear call to action for public education and creating awareness for CCU technology can be derived. Surely, effective, far reaching information and communication strategies as well as a transparent science communication is urgently needed to increase public knowledge, to familiarise the public with novel products in general, and CCU technology in particular. It is also mandatory that information and public communication is tailored to the different consumer groups and to transparently address the prevailing acceptance, the individual knowledge gaps, but also potential misinformation and specific information needs (Arning et al., 2020; Simons et al., 2021a; Kluge et al., 2021). While these claims - transparent science communication and tailoring of information and communication to the needs of consumers - are undisputed for an effective risk communication and management, the role of information and domain knowledge for the acceptance of novel products needs a closer look. As found here, people with a higher self-reported knowledge show slightly higher acceptance rates for both, CCU technology and products. At first sight, this finding mirrors the common assumption that more information fosters domain knowledge and, finally, leads to a higher acceptance. If so, then the strategy should be to simply provide more publicly available information, as information and domain knowledge have a strong tie with acceptance.

However, as reality shows, the mere providing of information does not necessarily lead to higher knowledge and public understanding (Brunsting et al., 2013; Dowd et al., 2014; Lee et al., 2021). As a result, an increase of acceptance is not granted, but can also lead to considerable public protest activities (Walgrave et al., 2013; Valdez et al., 2018; Liebe and Dobers, 2019). Empirical evidence suggests that people who already have an elaborate knowledge profit from additional information as they are able to integrate the new information into their existing cognitive models (de Best-Waldhober et al., 2009). In contrast, those who do not have as much technical knowledge, like, e.g., laypeople, policymakers or communal deciders, often cannot benefit from the technical information in the same manner (Frewer, 2004; Karimi and Komendantova, 2017). Zaunbrecher et al. (2016); Offermann-van Heek et al. (2018) suggest that product acceptance in laypersons without a deep technical knowledge is mediated by the trust in the information, the trust in the technology and, also, the trust in the information provider (Offermann-van Heek et al., 2018; Kluge et al., 2021). Hence, it is not primarily the cognitive knowledge gaps that need to be addressed, but rather the affective preconditions—public trust—in order to make information effective.

To put the key messages in a nutshell: What can be done to address the needs of the public on the one hand and to get an independent reviewer or authority that is generally regarded as neutral to validate and certify the processes involved in CCU on the other hand? As a managerial recommendation for public education, innovation management and communication policy, the following key advice on different dimensions should be respected and implemented.

4.2.1 Public information

- Information should be based on empirically assessed information needs and acceptance by the public. No assumptions should be made on what the public should know or not know. Previous knowledge, expectations, fears and concerns should previously be assessed to allow the public to systematically learn from well tailored information.
- Laypeople should not be confronted with isolated technical information that is not connected to their specific information needs. Before any information campaign is launched, it is

important to understand where the "information" problem lies: If information is designed in such a way that it is tailored to the existing knowledge needs, is understandable, and it is, in addition, honestly communicated, where the risks of an innovation are in relation to the added value, then trust can develop among people who do not have the initial advantage of a high level of domain knowledge.

4.2.1 Procedural fairness

- A potent way to enhance trust in CCU products is the early integration of the public during technology development and early prototypes and allowing them to get hands-on experience with the CCU products. By getting to know the CCU materials, the quality of the products and the ease of using on the one hand, and an open discourse about the infrastructural requirements and the sustainability of the CCU approach on the other hand, the public can lose potential concerns and potential misconceptions, adjust risk perception and can form trust, and an informed knowledge base.
- Beyond the consumer groups, there are other stakeholders with potentially complementary interests in the CCU industry, for example, *policymakers and communal deciders.* Their knowledge is presumably equally as low as that of the consumers, but they might face another reality—they might have personal interests, such as successful election campaigns, which might lead to different decision preferences. Another group is *industry leaders and companies.* Their knowledge about (or interest in) the end-user's requirements is also usually rather low. Industry and companies are mostly interested in market success and financial reward, thus seeking policy support to get their interests realized. And finally, the *science-community* which might also have different stakes in the CCU technology: Natural scientists and engineers primarily focus on technical, economic, and increasingly ecological indicators. The social aspect of CCU technology with all its impacts and consequences for the people and the societal frameworks is mostly unknown or -seen, and thus not included in the evaluation procedures.

4.2.3 Requirements for multiperspectivity and integrated metrics

What is missing to date but needs to be developed is:

- An awareness of the fact that such technologies can only succeed if the multiperspectivity of the evaluation is taken into account, including technical feasibility, the financial implementation, but also the social and fairness claims that the innovation brings.
- A balanced orchestration of different goals and motivations of the partners involved, for which we need an established evaluation process.

In this context, research efforts should be fostered by universities, research institutions, and funding authorities that test and validate integrative evaluation instruments for different usage scenarios and stakeholder preferences, through which the feasibility of CCU scenarios will be evaluated from a technical, economic, ecological, regulatory, and/or social-acceptance viewpoint. Such application-oriented integrative assessment frameworks could help to inform decision-makers and support managerial decisions.

4.3 Limitations and future work

Besides the compelling results of the present studies, there are, of course, some limitations that need to be discussed. First of all, it should be noted that the underlying sample originates from Germany, so any conclusions drawn from it do not necessarily have to be universally valid. Technology acceptance and adoption could very well include a cultural component, for example, whereby a respondent's background could have an impact on their views. Therefore, it is necessary to conduct international research on this topic in the future to reveal possible differences between countries or further validate our findings.

Furthermore, the present work dealt with a general acceptance of CCU and resulting products. While the exploratory study discussed specific products by way of example, the quantitative study referred to CCU in general, without explicitly addressing exemplary products. However, it is quite possible that the perception and acceptance of different types of products differs. As observed by (Arning et al., 2020), the proximity to the user's body can be a fundamental pivot for health-related concerns. Such differences could not be examined in the quantitative study. Furthermore, in the formation of acceptance, consumers always have to consider various product properties and eventually settle for a trade-off. In the future, it will be necessary to investigate which properties are important in this context and how they are weighted.

Finally, it is important to mention that the exploratory study revealed a need for publicly available information about CCU and the processes involved. For this purpose, it is first necessary to identify possible target groups and determine what information is needed for the respective groups. Then, it must be examined on which distribution channels the information must be made available to the public. Furthermore, it has not been determined yet which institution can provide information sources in order for the public to have confidence in them. In addition, it was explicitly mentioned that special attention must be paid to wording when phrasing information materials. Thus, it must also be determined which phrases or words have to be avoided in order to avoid faulty negative associations with CCU.

5 Conclusion

The goal of this work was to investigate motivators, barriers, conditions of use, and general acceptance of CCU and the resulting products. Conserving fossil fuels and saving costs in comparison to conventional manufacturing processes were seen as incentives for CCU adoption. Moreover, environmental advantages resulting from the degradation and reuse of climate changing CO_2 were perceived as major benefits of adopting CCU. However, it must be noted that the respondents expressed doubts about the longevity of the positive environmental impacts. Furthermore, respondents were concerned that consumers could be manipulated by skilful marketing that could portray CCU as much better than it actually is.

These concerns arose because the technology is not particularly well known among the general population to date despite it being well-researched among the scientific community. Through our work, we disclosed a general need for information, regarding the technology itself, the environmental impact of the whole process, the expenses, and regarding the health consequences for users. In particular, the environmental impact of the technology must be holistically assessed and published in a way that is understandable and accessible to laypersons. Moreover, the public must be educated about the concentrations of CO_2 in their environment up to which there is no danger to their health so that they can realistically estimate the dangers to their health in dealing with CCU. In spite of this lack of public awareness and information, rather high levels of general acceptance were established in the sample present. Consequently, it can be assumed that the public will be open to CCU as soon as the necessary information and communication steps have been implemented.

Data availability statement

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

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

Conceptualisation: IH, WW, and MZ; methodology: IH, and WW; software: IH, and WW; validation: IH, and WW; formal analysis: IH; investigation: IH, and WW; resources: IH, and WW; data curation: IH, and WW; writing-original draft preparation: IH and WW; writing-review and editing: IH, WW, and MZ; visualization: IH, and WW; supervision: MZ; project administration: MZ; funding acquisition: MZ. All authors contributed to the article 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1248555/full#supplementary-material

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