Cleaner and Responsible Consumption 19 (2025) 100355

Contents lists available at ScienceDirect

Cleaner and Responsible Consumption

journal homepage: www.journals.elsevier.com/cleaner-and-responsible-consumption

Who's willing to take the green leap? Consumers' preferences and their willingness to use different carbon capture and utilization products

Wiktoria Wilkowska *, Imke Haverkämper, Martina Ziefle

RWTH Aachen University, Chair of Communication Science, Human-Computer Interaction Center, Campus-Boulevard 57, Aachen, 52074, Germany

ARTICLE INFO

Keywords:
Consumer diversity
CCU products
Social acceptance
Risk perception

ABSTRACT

The accelerating pace of climate change demands decisive action, particularly through technologies that mitigate carbon dioxide (CO_2) emissions. Carbon capture and utilization (CCU) technology represents a promising approach requiring both technical optimization and societal acceptance. To achieve this, technology developers must tailor applications to align with the specific needs and expectations of diverse consumers. This study examines how sociodemographic and attitudinal factors shape individuals' perception of risk and their willingness to adopt various CCU-derived products, such as clothing, cosmetics, aviation fuel, and food. Based on survey data ($N = 827$), participants were categorized as either Hesitants (42 %) or Enthusiasts (58 %) according to their attitudes towards CCU, technical commitment, risk disposition, and innovation interest. The results show that the perceived risks of CO_2-based products are influenced by both demographic and attitudinal variables, with the latter being the strongest predictor of willingness to use products across categories. Among all applications, aviation fuel was perceived as offering the most notable environmental benefits with the lowest health-related risks. By integrating behavioral insights into the evaluation of CCU technologies, this research provides a nuanced understanding of consumer acceptance processes, emphasizing the importance of aligning technological innovation with user expectations to foster socially embedded and economically viable pathways toward climate neutrality.

1. Introduction

In light of accelerating climate change and pressure to decarbonize industrial systems, Carbon Capture and Utilization (CCU) has gained attention as a strategy for emission reduction. By transforming captured carbon dioxide (CO_2) into marketable products—such as textiles, cosmetics, fuels, or food—CCU technologies integrate circular economy principles into carbon management. While technological advancements in this field are progressing rapidly, the successful deployment of CCU-based products ultimately depends on their acceptance by consumers (=end users). Consumers, as key actors in shaping market demand and policy legitimacy, play therefore a critical role in determining the societal viability of such innovations.

Previous research emphasizes the importance of consumer trust in the quality of the technical innovation, the reliability of industry (Offermann-van Heek et al., 2020), and the trust in public and political communication (Simons et al., 2021). Additionally, perceived benefits and risks as well as familiarity influence the willingness to adopt sustainable innovations (Wang et al., 2024; Raimi et al., 2024; Arning et al., 2020; Jones et al., 2017). However, studies on consumer responses to CO_2-derived consumer goods remain limited. Moreover, there is growing recognition that acceptance varies across populations; rather, it has been shown that the adoption and (anticipated) use is product-specific and depends on individual and contextual factors (Wilkowska et al., 2024; Nielsen et al., 2022; Oltra et al., 2022). There are several arguments in favor of developing a profound understanding of the needs and requirements of potential consumer groups of different CCU products, in order to address target groups effectively through adapted design and communication strategies. As it is known from previous research, different consumers vary in their needs and face different barriers in using CCU-based products (Pieri et al., 2023; Lutzke and Árvai, 2021; Offermann-van Heek et al., 2018). Thus, tailoring products and marketing strategies to diverse groups increases total uptake and accelerates the total impact. To this end, acceptance is likely to be shaped by sociodemographic characteristics, including age and gender, as well as attitudinal dispositions toward environmental technologies. As such, a differentiated understanding of consumer perspectives is essential for designing effective market strategies and

* Corresponding author.
E-mail address: wilkowska@comm.rwth-aachen.de (W. Wilkowska).

https://doi.org/10.1016/j.clrc.2025.100355
Received 12 August 2025; Received in revised form 6 November 2025; Accepted 9 November 2025
Available online 11 November 2025

communication frameworks that foster public support.

The present study investigates consumer risk perceptions and willingness to use CCU-based products across multiple application domains. Drawing on empirical data, we explore how user diversity affects acceptance and examine the market implications of these findings in the context of European sustainability goals.

2. Theoretical background

2.1. Acceptance of CCU-based products

The deployment of CCU technologies is pivotal in addressing climate change, yet it is contingent on public acceptance. Acknowledging public concerns is essential for facilitating these technologies' adoption (Arning et al., 2020; Raimi et al., 2024). The social dimension plays a critical role in this process, as acceptance from local communities can determine the success or failure of CCU projects and addressing public concerns can ensure community support (Grecu, 2015; Meehan, 2024). To comprehend technology acceptance in the context of environmental innovations like CCU, several theoretical models have been developed. Two prominent frameworks are the Theory of Reasoned Action (TRA; Ajzen and Fishbein, 1980) and the Technology Acceptance Model (TAM; Davis, 1989).

The TRA posits that individuals' behaviors are primarily determined by their intention to perform that behavior, influenced by two key components: attitudes towards the behavior and subjective norms surrounding it. Attitudes represent psychological predispositions to evaluate an object – e.g., an energy technology – by weighing its perceived advantages and disadvantages, including associated risks (Ajzen, 1985). TAM provides a framework for explaining and predicting individual acceptance of new technologies. In recent years, many conceptual models based on TAM have been developed and extensively employed in academic research. The model illuminates mechanisms underlying technology acceptance by examining users' psychological perceptions and behavioral intentions. At its core is the notion that users' perceptions, particularly perceived usefulness and ease of use, are pivotal in determining their adoption of new technologies.

Exploring the practical implications of these theoretical models is imperative for understanding technology acceptance. In the context of CCU technology, it is necessary to examine consumer perceptions and behaviors towards CCU products. A wide range of products can be derived from CCU processes, including plastics, building materials, chemicals, fuels, clothing items, carbonated beverages, and food storage containers. Regarding general acceptance of CCU products, favorable perceptions regarding environmental benefits such as a perceived reduction in CO_2 emissions and fossil resource savings significantly impact consumer acceptance (Arning et al., 2021a; Wilkowska et al., 2024; van Heek et al., 2017a;van Heek et al., 2017b). Moreover, economic advantages alongside environmental serve as strong predictors for product adoption since consumers are motivated by potential cost savings (Averdung and Wagenfuehrer, 2011; Arning et al., 2020; Offermann-van Heek et al., 2018; Haverkämper et al., 2023). Social influences also play a significant role (de Groot et al., 2020). While potential health risks and safety concerns critically affect consumers' willingness to adopt CCU-based products (Wilkowska et al., 2024; van Heek et al., 2017a,b), public acceptance of scientific and health-related recommendations is susceptible to being shaped by trust in relevant experts (Liu et al., 2021; Simons et al., 2024). Furthermore, consumer trust in companies producing CCU products and the credibility of information sources are essential for gaining confidence (Liu et al., 2021; Offermann-van Heek et al., 2018). Additionally, intention to utilize CCU products is influenced by perceived benefits, associated risks, and overall trust in information provided about these products (Liu et al., 2021; Offermann-van Heek et al., 2018). Ultimately, a balance between perceived benefits and risks affects overall acceptance levels (Arning et al., 2020). Moreover, several attitudinal factors influence acceptance in this context. Numerous studies have demonstrated the role of environmental awareness (Arning et al., 2018, 2021b, 2023), indicating that individuals with a heightened awareness of environmental issues exhibit a higher level of acceptance towards these technologies. However, individual health and safety concerns also shape attitudes towards CCU products since perceived risks related to health implications during production or disposal conditions significantly impact acceptance (van Heek et al., 2017a; van Heek et al., 2017b; Arning et al., 2018, 2021b). The influence of demographic factors, like age and gender, on product acceptance is another significant consideration. Research indicates that younger individuals exhibit more positive attitudes towards CCU products compared to older demographics, but male respondents generally show less willingness to pay for them (Pieri et al., 2023). Sociodemographic factors like education level and income correlate with higher levels of acceptance among individuals with greater awareness or understanding of environmental issues (Arning et al., 2018, 2023).

2.2. The context and objects of the study

To achieve market competitiveness for CCU-derived products relative to conventional alternatives, it is essential to explore individual requirements and integrate consumers' preferences into the development process from the outset. This requires early investigations into public perceptions and acceptance levels to anticipate potential adoption barriers, informing technical innovation and refining outreach strategies. Consequently, this study examines how exemplary but representative CCU-derived products (see below) are perceived by different societal groups and which potential they have to be adopted in the market in the long term.

In our study, we have chosen four different product categories as examples that not only represent diverse market sectors but also illustrate the broad applicability and transformative potential of CCU technology—from high-energy applications and everyday consumer goods to innovative sustainable solutions across industries.

- *Cosmetics* serve as an ideal candidate to demonstrate the versatility of CCU technology in producing high-value, consumer-oriented products. CCU-derived ingredients can create innovative, sustainable cosmetic formulations, addressing consumer demand for eco-friendly and ethically produced goods while showcasing the technological adaptability of CO_2 conversion processes.
- *Clothing* exemplifies how CCU-derived products can extend into everyday consumer goods. The development of bio-based fibers or polymers through CCU offers a sustainable alternative to conventional synthetic materials, potentially reducing the environmental footprint of the fashion industry. This application highlights the potential for CCU to contribute to both environmental sustainability and circular economy strategies.
- *Aviation fuel* represents a high-impact application of CCU technology due to significant emissions associated with air travel. By converting CO_2 into synthetic aviation fuels, CCU can directly contribute to decarbonizing a sector that is notoriously difficult to electrify, making it a critical test case for reducing greenhouse gas emissions on a global scale.
- The inclusion of *food*, whether through novel packaging materials or food additives derived via CCU, illustrates the broader potential of this technology to permeate vital sectors of the economy. In the context of a circular economy, CCU-based food products underscore how CO_2 can be transformed into essential commodities, thereby fostering sustainability in a sector closely linked to human well-being and resource efficiency.

2.3. Research objectives

In this paper we aim to investigate whether—and in what ways—the characteristics of specific consumer segments influence the social

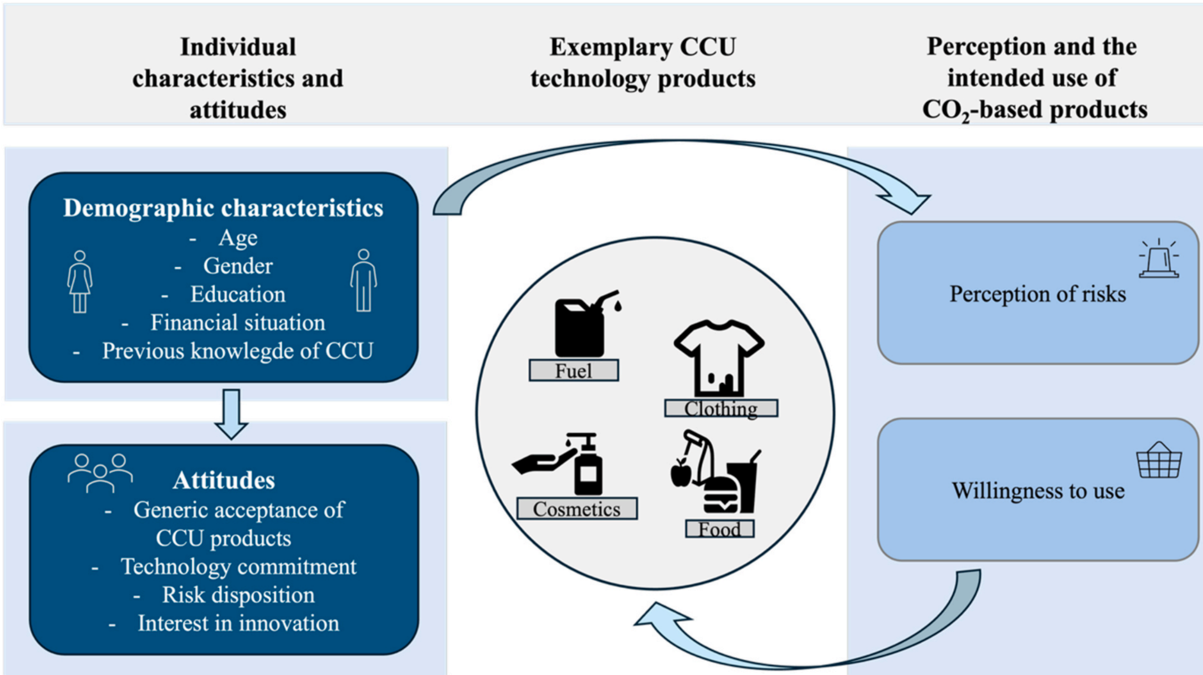


Fig. 1. Design of the empirical approach.

perception and long-term adoption of these everyday products manufactured using the CCU approach. Given the well-documented role of risk perception in shaping consumer attitudes and behaviors toward energy-related innovations (e.g., Siitonen et al., 2024; Arning et al., 2020, 2024; Linzenich et al., 2020, 2021), the first research objective (RQ1) is to examine the extent to which demographic attributes and attitudinal profiles of consumers significantly affect their perceived risks regarding various CO_2-based products. Building on this and considering consumers' willingness to use such products as an indicator of potential market acceptance, the second research question (RQ2) addresses whether meaningful differences in the willingness to adopt CO_2-based products exist across distinct consumer groups. In a final analytical step, the study explores consumer preferences among the four aforementioned CCU-derived product categories to identify which product types hold the greatest potential for public acceptance and use (RQ3).

In summary, this paper seeks to answer two central questions: 1) Who are the consumer groups most likely to embrace CCU-based products? 2) Which types of CCU-derived products are most likely to be accepted and integrated into everyday use?

3. Methodology

3.1. Study design

An online survey was conducted according to the stratified sampling method (Hankin et al., 2019). The quantitative data collection was supported by a research agency on a German consumer panel. After data cleaning, a total of $N = 827$ complete data sets were included in the statistical analyses. Participants were paid by the panel institute for their participation and took an average of 12–15 minutes to complete the survey. Participation was voluntary and participants could not proceed with the online survey unless they agreed to participate at the outset of the survey.

In this study, the dependent variables were *perceptions of risk* associated with the aforementioned exemplary CCU-based products, i.e., aviation fuel, clothing, cosmetics and food, and the assessments of the *willingness to consume or use* them. In addition, the online survey investigated the *general preferences* of potential consumers for products manufactured using CCU technology. The selection of these variables was grounded in their relevance to understanding market acceptance of such sustainable innovations. Perceived risk is a critical determinant of consumer decision-making, particularly for emerging technologies where uncertainties regarding safety, quality, and long-term impact may arise (Engelmann et al., 2024; Linzenich et al., 2021; Arning et al., 2020). Willingness to consume or use serves as a direct behavioral indicator, shedding light on the likelihood of adoption and potential market penetration (Lutzke and Árvai, 2021; Venkatesh et al., 2003; Davis, 1989). Finally, exploring general product preferences allows for broader insights into consumer openness to CCU technology and the potential interest in the different product categories, informing strategies for targeted communication and policy recommendations to enhance acceptance and trust.

As independent variables, the study examined the influence of individual user characteristics on the adoption of CCU-based products. The first factor refers to the participants' *age* [three age groups: younger (18–38 years) vs. middle-aged (39–54 years vs. older (55+ years)], as environmental concerns and sustainability awareness often vary across age groups (Ágoston et al., 2024; Lee and Kim, 2024; Wang et al., 2021): Younger consumers may be more inclined to adopt CCU-based products due to greater exposure to climate change discourse and pro-environmental attitudes, whereas older consumers might prioritize traditional product attributes such as reliability and safety. The second potentially influencing factor is the participants' *gender* (female vs. male), which has been proven to affect individuals' opinions on carbon footprint awareness. Studies indicate that women, on average, demonstrate stronger pro-environmental attitudes and are more likely to engage in sustainable consumption behaviors than men (Raimi et al., 2024; Gökmen, 2021; Bloodhart and Swim, 2020). The third factor refers to participants' *attitudes* considered relevant for adopting products manufactured via CCU technology (enthusiastic vs. hesitating attitude regarding innovation interest, technological commitment and acceptance of CCU). Consumer adoption of sustainable products is often influenced by personal values (e.g., ecological responsibility), attributional style, and social expectations (e.g., peer behavior or cultural norms). Investigating attitudinal variations can thus reveal whether social acceptance plays a role in adoption decisions and how it may be

Table 1
Items used for the general attitudes towards and the internal consistency of the scales: general CCU technology acceptance, technical commitment, risk disposition, and interest of innovation.

Construct	Items	Internal consistency
Acceptance of CCU products (3 items)	*"I would use products that are based on CO_2."*	**α =.81**
	"I am in favor of using CO_2-based products."	
	"I reject the use of CO_2-based products." [recoded]	
Technical commitment (4 items)	*"Whether I am successful in using modern technology depends largely on me."*	**α =.84**
	"If I have difficulties in dealing with technology, it ultimately depends on me alone to solve them."	
	"It is up to me whether I succeed in using new technical developments - it has little to do with chance or luck."	
	"What happens when I deal with new technical developments is ultimately under my control."	
Risk disposition (6 items)	*"I am willing to take risks."*	**α =.85**
	"I am prepared to take risks."	
	"I am very careful when I make plans and execute them." [recoded]	
	"I follow the motto "Nothing ventured, nothing gained."	
	"I don't like adventurous decisions." [recoded]	
	"I like putting things on risk."	
Interest in innovation (4 items)	*"I regularly keep an eye out for new products."*	**α =.89**
	"I am usually the first in my circle of friends and acquaintances to try new products."	
	"I often look for information on new products that might interest me."	
	"I find it interesting to try out new products."	

leveraged to promote CCU-based products (Raimi et al., 2024; Haverkämper et al., 2023).

3.2. The structure of the online survey

Prior to the administration of the survey, participants were informed of the purpose and content of the study. Written consent was obtained from all participants prior to their involvement in the study, with their explicit permission for their data to be utilized for research purposes. The online survey, which was standardized for the purpose of this study, was conducted using the professional software platform Qualtrics XM.

The survey was divided into three parts as presented in Fig. 1. The first part covered the demographic characteristics of the participants, including age, gender, the highest level of education attained, and the financial situation. Furthermore, participants were invited to indicate their current knowledge of CCU technology ('yes'/'no' response). Prior to this assessment, participants were presented with a graphic and descriptive overview of CCU technology (for details see Appendix, Table 7).

In the second part of the survey, participants responded to questions related to their general attitude towards the acceptance of CCU products (based on TAM; Davis, 1989), technology commitment (Neyer et al., 2016), risk disposition, and interest in innovation. For statistical purposes, the items of each attitude were first checked for their internal consistency (=Cronbach's Alpha) and then combined into a corresponding construct; details are presented in Table 1. In addition, we examined and confirmed the convergent and discriminant validity of the scales, with the supporting evidence presented in Appendix (Tables 8 and 9).

In the last part of the survey, participants were confronted with four different CO_2-based products, i.e., fuel, clothing, cosmetics, and food, and their possible uses. For each of these products, they evaluated the *risks associated* with the particular CCU-based product (4 items) and stated to what extent they are *willing to use* such a product (3 items). All resulting scales for the specific CCU-based products manifested satisfactory internal consistency (see Table 2). Although we assessed convergent and discriminant validity, the willingness to use and risk perception measures did not meet standard thresholds, which we attribute to their inherent conceptual inseparability. All above-described items regarding the attitudes and evaluations of CCU-based products were assessed on six-point Likert scales ranging from "fully disagree" (=1) to "fully agree" (=6). We opted for six-point Likert scales rather than five- or seven-point versions because eliminating the neutral midpoint forces respondents to express a clear opinion, thereby reducing neutral bias (Joshi et al., 2015). According to Krosnick and Presser (2010), this approach enhances reliability and validity, particularly when the topic is familiar to respondents. Six-point scales also produce response distributions that are closer to normal, which facilitates parametric testing and improves model fit (Dawes, 2008). This enables finer trait differentiation in psychometric assessments than for instance five-point scales do.

3.3. Sample description

Overall, data from $N = 827$ German participants were collected via online. The sample was on average $M = 44.9$ years old ($SD = 14.8$; min = 16; max = 81) and consisted of a higher proportion of males (57.8 %, $n = 478$) than females (41.7 %, $n = 345$); 0.5 % of the respondents ($n = 4$) did not specify their gender. As their highest educational level, 27.3 % of the participants indicated to hold a university degree ($n = 226$) or a university qualification degree (21.2 %; $n = 175$), and 28.2 % ($n = 227$) reported a secondary school certificate. In

Table 2
Items evaluating the risk perception of and willingness to use the CO_2-based products used in the study, and the internal consistencies for the single products.

	Items	Internal consistency for specific scales
Willingness to use (3 items)	1. *Item variations*	*aviation fuel:* α = .82
	a) *"I would fly in a plane powered by CO_2-based aviation fuels."*	*clothing:* α = .86
	b) *"I would wear clothes made from CO_2-based fibres."*	*cosmetics:* α = .84
	c) *"I would use cosmetics containing CO_2-based ingredients."*	*food:* α = .86
	d) *"I would eat food containing CO_2-based components."*	
	2. *Item: "I am in favor of using CO_2-based {product}."*	
	3. *Item: "I am against the use of CO_2-based {product}." [recoded]*	
Perception of risk (4 items)	*"I consider the risks from CO_2-based {product} manageable."*	*aviation fuel:* α = .77
	"I think {product} made from CO_2 is harmless."	*clothing:* α = .84
	"{Product} made from CO_2 could have negative consequences for human health." [recoded]	*cosmetics:* α = .82
	"CO_2 could escape from {product}." [recoded]	*food:* α = .82

addition, 21.5 % indicated to have a vocational school diploma or master's degree and a small proportion of the sample indicated to hold a PhD (2 %, $n = 15$); less than 1 % ($n = 6$) had not yet graduated.

Most study participants reported a rather low monthly household income for German standards[1]: 18.4 % ($n = 152$) of the sample reported to earn less than 1000€ and 21.9 % ($n = 181$) between 1000 and 2000€ per month. More than 21 % ($n = 177$) had about 2000–3000€ per month available, and 23.7 % of the whole sample disposed of 3000–5000€ per month; 8 % indicated salaries of more than 5000€/month ($n = 68$) and more than 6 % had not specified their monthly household income.

When asked if they were already aware of CCU technology prior to this survey, over 80 % of participants responded that they were not aware of it, and just under 20 % stated that they had already heard about the CCU technology. This means that most participants were encountering CCU technology for the first time.

3.4. Statistical analyses

We report descriptive statistics using means (*M*) and standard deviations (*SD*) or frequencies. The reliability (=internal consistency) of the used constructs was examined using Cronbach's α; α-values ≥0.7 indicate a satisfactory internal consistency of the scale (see Tables 1 and 2). To examine differences regarding the potential consumer factors, we applied analysis of variance (ANOVA) for comparisons of three groups simultaneously or *t*-test for comparing the means between two groups. For effect size measures, the parameter partial eta squared (η^2) is reported when ANOVA is used, and the parameter Cohen's d (d) is reported for a *t*-test. According to Cohen's (1988) guidelines, the effect size of η^2 indicates that the effect is small when $\eta^2 \approx .01$, medium when $\eta^2 \approx .06$, or large when $\eta^2 \approx .14$. Accordingly, the *effect size of d* is small when $d \approx .2$, medium when $d \approx .5$, or large when $d \approx .8$. The significance level (p) was set at the conventional level of 5 %.

3.5. Relationships between demographic and attitudinal variables

Based on the results, we chose to study the demographic variables of age and gender, as well as the attitudinal factors relating to consumers' interest in innovation, technical commitment, and general acceptance of using CCU products. Conversely, we conducted our analyses without considering education and financial situation, as well as excluding previous CCU knowledge due to a high proportion of participants stating low previous knowledge of the CCU technology, and the different proportions of the education and financial levels within the sample.

To explore the moderating or mediating effects and contribute to segmentation for later intervention or communication strategy tailoring, we examined in the first step the associations between the demographic variables gender and age, and their influence on attitudinal constructs. The results of statistical analyses are summarized in Table 3.

Overall, we found significant effects of age ($F(8,1628) = 7.52$, $p < .001$, $\eta^2 = .04$) and gender ($F(4,813) = 3.79$, $p = .005$, $\eta^2 = .02$) on the attitudinal variables. In particular, the results reveal that age correlates negatively with interest in innovation, risk disposition, and acceptance of CCU, but not with technical commitment. These findings indicate that younger participants tend to report higher openness to innovation, risk-taking, and CCU acceptance. The corresponding ANOVAs support these associations, with significant effects of age on *interest in innovation, risk disposition*, and general *acceptance of CCU,* but not on *technical commitment.* Effect sizes suggest small but meaningful effects, particularly for *risk disposition* with younger ($M = 3.6$, $SD = 0.9$) people being more willing to take risks than middle-aged ($M = 3.3$, $SD = 1$) and older people ($M = 3.2$, $SD = 1$).

The results for gender show a small but statistically significant effect on interest in innovation and risk disposition, with males exhibiting slightly higher scores than females. No significant gender differences were found in technical commitment or acceptance of CCU. These small effect sizes suggest that, while gender may play a minor role in shaping openness to innovation and risk, it appears to be irrelevant to attitudes towards technical systems or specific technologies, such as CCU. Therefore, gender-based tailoring of communication may be unnecessary for CCU-related topics.

In the next step, we cluster the attitudes into high and low values to build consumer profiles. This allows us to examine the influence of attitudinal profiles, as well as demographic variables, on the acceptance and risk perception of different CCU products.

4. Results

4.1. Clustering and creation of attitudinal customer profiles

To investigate how attitudinal characteristics, in addition to demographic variables, influence perceived risk and willingness to use different CCU products, participants were first divided into two clusters based on their high and low mean scores on *general CCU technology acceptance*, *technical commitment*, *risk disposition*, and *interest in innovation.* We used two-step cluster analysis approach, which is well applicable to large data sets and allows classification of data with metric levels of measurement. It is a hybrid approach that first uses a distance measure to separate groups and then uses a probabilistic approach to select the optimal subgroup model (Gelbard et al., 2007). The number of clusters was determined based on a statistical goodness of fit measure (Bayesian information criterion).

The two clusters were significantly different from each other ($F(4,818) = 322.17$, $p < .001$; $\eta^2 = 0.61$) and from the midpoint of the scale ($t(822) = -120.79$, $p < .001$; $d = 0.49$). The smaller cluster consisted of $n = 346$ participants (42 %) who reached significantly lower means in all attitudes (=Hesitants), and the larger cluster consisted of $n = 477$ respondents (58 %) who scored on average higher on the specific attitudes (=Enthusiasts); the ratio between the clusters was 1.38. Regarding the relative predictive importance, *interest in innovation* scored highest (1.00), followed by *technical commitment* (0.71), *general acceptance of CCU products* (0.40), and finally *risk disposition* (0.10). In terms of content and effect sizes, this means that the Enthusiasts had a significantly higher interest in innovation and a higher technical self-efficacy, as well as a generally higher acceptance of CO_2-based products in comparison to the Hesitants of our sample; the latter also had a significantly lower risk disposition, although the differences were small. Descriptive and inferential statistics regarding the attitudes examined in the study are presented in Table 4.

4.2. Differences in risk perception for different CCU-based products

To investigate whether and to which extent the usage behavior of future consumers is influenced by their demographic and attitudinal characteristics, we first consider in our analyses the perception of risks for the respective exemplary CCU products.

Using oneway ANOVA, we calculated the effect of age on the perceived risks associated with CCU-based fuel, clothing, cosmetics, and food. All relevant statistical parameters used, including descriptive and inferential statistics, are summarized in Table 5 (top section). The analysis revealed a significant effect of ***age*** only for the CCU-based clothing, indicating a small effect size. This suggests that perceptions or evaluations of clothing made using CCU technology vary slightly but significantly between age groups, with the youngest adults on average having the highest confidence or perceiving the lowest risk in CO_2-enriched garments.

Unlike the isolated influence of age, participants' ***gender*** affected their perception of risk with regard to all CCU-based products tested. Table 5 shows that males scored on average higher on risk perception in

[1] According to Federal Statistical Office (2022), the average monthly salary in Germany equals to 4100€.

Table 3
The correlative relationships between, and effects of, demographics on attitudinal variables.

		Interest in innovation	Risk disposition	Technical commitment	Acceptance of CCU
Age	Pearson correlation	**−.18****	**−.22****	−.04	**−.10****
	ANOVA	$F(2,816) = 13.05$, $p < .001$, $\eta^2 = .03$	$F(2,816) = 21.42$, $p < .001$, $\eta^2 = .05$	$F(2,816) = 1.14$, *n.s*	$F(2,816) = 3.88$, $p = .021$, $\eta^2 = .01$
Gender	Spearman correlation	**.08***	**.08***	.02	.02
	ANOVA	$F(1,816) = 7.68$, $p = .006$, $\eta^2 = .01$	$F(1,816) = 11.70$, $p < .001$, $\eta^2 = .01$	$F(1,816) = 0.48$, *n.s*	$F(1,816) = 1.00$, *n.s*

correlation is significant at the $^{**}p = .01$ level; $^{*}p = .05$ level.

all the products, i.e., they perceived the CCU-based fuels, clothing, cosmetics, and food to be significantly more manageable, environmentally safe, and uncritical to health than the female respondents. According to the Common Language Effect Sizes (CLES), the small yet consistent gender differences suggest that male participants were less likely than female participants to perceive high risks associated with particular CCU products, with probabilities ranging from 55.7 % to 58.6 % (fuel = 0.586; clothing = 0.557; cosmetics = 0.577; food = 0.579).

In addition, we found a significant influence of the *clustered attitudes* on the perception of risks for the tested CCU product examples. The comparison of the attitudinal groups reveals that potential consumers who have a high interest in innovation and place a high value on technical commitment, and who also exhibit a high level of acceptance towards CCU technology, demonstrate significantly higher levels of trust and confidence in these products when compared to those who adopt a more cautious stance. In terms of CLES, the probability of Hesitants reporting higher perceived risks than Enthusiasts ranged from 63.4 % to 67.5 % (fuel = 0.658; clothing = 0.675; cosmetics = 0.642; food = 0.634). These medium-sized effects suggest that Hesitants consistently view CCU-based products as riskier than Enthusiasts, regardless of the specific application. The largest difference was observed for CCU-based clothing, whereas the smallest, though still significant, occurred for food products.

Based on the current findings, RQ1 can be addressed by concluding that consumers' risk perceptions of various CO_2-based products are significantly shaped by their demographic backgrounds and attitudinal dispositions. The analysis indicates that gender and attitudes significantly influence these perceptions. The observed means for risk perceptions oscillated around the midpoint of the six-point scale, indicating that the participants adopt rather reserved or neutral in their approach to CCU-manufactured products. It has been observed that, on average, participants exhibited a diminished level of trust in the CO_2-enriched products that are in close proximity to the body (i.e., cosmetics, food).

4.3. Differences in consumer willingness to use CCU-based products

The next step was to statistically assess whether there were meaningful differences between the distinct consumer groups in their willingness to adopt CO_2-based products. The relevant statistical values required for the descriptive and inferential parameters are summarized in Table 4 (bottom section).

An ANOVA assessing the impact of *age* on the willingness to adopt CCU-based products indicated a statistically significant effect with respect to the intention to use CCU-derived aviation fuel, clothing, and food. Considering descriptive values, the highest means resulted for the use of fuel followed by CO_2-based clothes and the highest willingness can be observed in the youngest group, while the lowest willingness among the age groups was achieved in the middle-aged group of study participants. For the CO_2-enriched food, on the other hand, the willingness to use it decreased steadily with increasing age and the overall willingness to use CO_2-based food was lower than for the other products. The effect sizes for these differences were rather small. In contrast, the mean scores for cosmetics tended to remain in the neutral range of the scale, with a slight tendency towards a positive willingness to use, and these were not affected by the age of the potential consumers.

Gender, as one of the demographic characteristics, had a significant influence on the willingness to buy or use these products: Small to medium strong gender effects were found for clothing, cosmetics and food (see Table 4). In terms of CLES, men were marginally more likely than women to report greater willingness to use CCU-based clothing (0.543), cosmetics (0.545), and food (0.572). The effect was strongest for food products, which may reflect differences in perceived risk or personal relevance of such applications. For CCU-based fuels, no meaningful difference emerged, suggesting that this product category is perceived comparably positive by both gender groups.

Moreover, a *t*-test examined the impact of *attitudinal characteristics* on the willingness to use the CCU-based products. Persons with high levels of interest in innovation, technical commitment and acceptance of CCU technology (=Enthusiasts) achieved significantly higher average scores than Hesitants for all the products analyzed, and these effects were medium to large according to the observed effect sizes. The probability that Enthusiasts would show greater willingness to use CCU-based fuels compared to the Hesitants was 69.4 % (CLES = 0.694), followed by clothing (70.2 %; CLES = 0.702), cosmetics (67.6 %; CLES = 0.676), and food (66.7 %; CLES = 0.667). It is even clearer here that the Enthusiasts are the most willing to use aviation fuel and clothing produced with CO_2, while their willingness to consume cosmetics and especially food via

Table 4
Descriptive (means and standard deviations) and difference statistics (ANOVA) between the two clusters: Enthusiasts ($n = 477$) and Hesitants ($n = 346$).

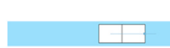
	Enthusiasts	Hesitants	Difference statistics
Interest in innovation (min = 1, max = 6)	$M = 4.31$ ($SD = 0.89$)	$M = 2.78$ ($SD = 0.89$)	$F(1,821) = 194.23$; $p < .001$; $\omega^2 = 0.42$
			
Technical commitment (min = 1, max = 6)	$M = 4.71$ ($SD = 0.72$)	$M = 3.62$ ($SD = 0.86$)	$F(1,821) = 387.58$; $p < .001$; $\omega^2 = 0.37$
			
General acceptance of CCU (min = 1, max = 6)	$M = 4.75$ ($SD = 0.97$)	$M = 3.78$ ($SD = 1.00$)	$F(1,821) = 595.52$; $p < .001$; $\omega^2 = 0.19$
			
Risk disposition (min = 1, max = 6)	$M = 3.55$ ($SD = 1.00$)	$M = 3.12$ ($SD = 0.85$)	$F(1,821) = 41.22$; $p < .001$; $\omega^2 = 0.05$
			

Table 5

Descriptive and inferential statistics for the effects of the user demographics and clustered attitudes on risk perceptions and acceptance of CCU-based products ($N = 827$; gender coding: female = 1, male = 2; clustered attitudes coding: Enthusiasts = 1, Hesitants = 2; *n.s.* = not significant).

			User demographics and attitudes [M (SD)]							Inferential statistics	
			Age Groups			Gender		Cluster Groups			
	Construct	**Item Examples**	**Young** (18-38y)	**Middle-aged** (39-54y)	**Older** (55 + y)	**Female** (1)	**Male** (2)	**Enthusiasts** (1)	**Hesitants** (2)	**Statistics of differences** (*F*-test, *t*-test)	**Effect size** [95 %-CI]
Risk perception for CCU-based …	… **fuel** (4 items; $\alpha = 0.77$; min = 1, max = 6)	*"CO_2 from aviation fuel could leak back into the atmosphere." [recoded]*	3.77 (1.0)	3.70 (1.0)	3.87 (1.0)	**3.59 (0.9)**	**3.90 (1.0)**	**4.00 (1.0)**	**3.45 (0.9)**	*Age:* $F(2,822)=1.91$, *n.s.* *Gender:* **$t(820) = -4.35$, $p \leq 0.001$** *Attitudes:* **$t(777.32) = 8.28$, $p \leq 0.001$**	– $d = -0.31$ [−0.45, −0.17] $d = 0.58$ [0.44, 0.72]
	… **clothing** (4 items; $\alpha = 0.84$; min = 1, max = 6)	*"I think clothing made from CO_2 is safe."*	**4.11 (0.9)**	**3.86 (1.0)**	**3.94 (1.0)**	**3.85 (1.0)**	**4.05 (1.0)**	**4.23 (1.0)**	**3.61 (0.9)**	*Age:* **$F(2,823) = 5$, $p = 0.007$** *Gender:* **$t(821) = -2.89$, $p = 0.004$** *Attitudes:* **$t(766.05) = 9.19$, $p \leq 0.001$**	$\eta^2 = 0.01$ [0.00, 0.03] $d = -0.20$ [−0.34, −0.06] $d = 0.64$ [0.50, 0.79]
	… **cosmetics** (4 items; $\alpha = 0.82$; min = 1, max = 6)	*"I think the risks of CO_2-based cosmetics are manageable."*	3.71 (0.9)	3.63 (1.0)	3.65 (1.0)	**3.51 (0.9)**	**3.78 (1.0)**	**3.87 (1.0)**	**3.38 (0.9)**	*Age:* $F(2,823)=0.5$, *n.s.* *Gender:* **$t(821) = -3.86$, $p \leq 0.001$** *Attitudes:* **$t(774.19) = 7.36$, $p \leq 0.001$**	– $d = -0.27$ [−0.41, −0.13] $d = 0.51$ [0.37, 0.65]
	… **food** (4 items; $\alpha = 0.82$; min = 1, max = 6)	*"Food made from CO_2 could have negative consequences for human health." [recoded]*	3.47 (1.0)	3.35 (1.1)	3.78 (1.1)	**3.23 (1.0)**	**3.52 (1.1)**	**3.61 (1.1)**	**3.11 (0.9)**	*Age:* $F(2,823)=1$, *n.s.* *Gender:* **$t(821) = -4$, $p \leq 0.001$** *Attitudes:* **$t(796.81) = 7.04$, $p \leq 0.001$**	– $d = -0.28$ [−0.42, −0.14] $d = 0.49$ [0.34, 0.63]
Willingness to use CCU-based …	… **fuel** (3 items; $\alpha = 0.82$: min = 1, max = 6)	*"I'm in favor of using CO_2-based fuels in aviation."*	**4.32 (1.1)**	**3.99 (1.2)**	**4.19 (1.2)**	4.08 (1.1)	4.22 (1.2)	**4.49 (1.1)**	**3.70 (1.1)**	*Age:* **$F(2,822) = 6$, $p = 0.003$** *Gender:* $t(783.97) = -1.62$, *n.s.* *Attitudes:* **$t(820) = 10.10$, $p \leq 0.001$**	$\eta^2 = 0.01$ [0.00, 0.03] – $d = 0.72$ [0.57, 0.85]

(*continued on next page*)

Table 5 (*continued*)

Construct	Item Examples	User demographics and attitudes [M (SD)] Age Groups: Young (18-38y)	Middle-aged (39-54y)	Older (55 + y)	Gender: Female (1)	Male (2)	Cluster Groups: Enthusiasts (1)	Hesitants (2)	Inferential statistics: Statistics of differences (F-test, t-test)	Effect size [95 %-CI]
… **clothing** (3 items; α = 0.86; min = 1, max = 6)	*"I would wear clothes made from CO_2-based fibers."*	**4.30 (1.1)**	**3.91 (1.2)**	**4.03 (1.2)**	**3.97 (1.2)**	**4.15 (1.2)**	**4.42 (1.1)**	**3.59 (1.1)**	*Age:* **F(2,823) = 8.36, p ≤ 0.001** *Gender:* **t(821) = −2.18, p = 0.029** *Attitudes:* **t(821) = 10.60, p ≤ 0.001**	η^2 = 0.02 [0.01, 0.04] d = −0.15 [−0.29, −0.01] d = 0.75 [0.61, 0.89]
… **cosmetics** (3 items; α = 0.84; min = 1, max = 6)	*"I reject the use of CO_2-based cosmetics." [recoded]*	3.74 (1.1)	3.61 (1.2)	3.58 (1.2)	**3.54 (1.2)**	**3.73 (1.2)**	**3.96 (1.2)**	**3.22 (1.1)**	*Age: F*(2,823)=1.45, *n.s.* *Gender:* **t(820) = −2.27, p = 0.023** *Attitudes:* **t(821) = 9.12, p ≤ 0.001**	– d = −0.16 [−0.3, −0.02] d = 0.64 [0.50, 0.79]
… **food** (3 items; α = 0.86; min = 1, max = 6)	*"I support using CO_2-based foods."*	**3.57 (1.1)**	**3.33 (1.2)**	**3.29 (1.4)**	**3.22 (1.2)**	**3.54 (1.3)**	**3.71 (1.3)**	**2.98 (1.1)**	*Age:* **F(2,823) = 4.05, p = 0.018** *Gender:* **t(821) = −3.63, p ≤ 0.001** *Attitudes:* **t(794.36) = 8.78, p ≤ 0.001**	η^2 = 0.01 [0.00, 0.03] d = −0.26 [−0.39, −0.12] d = 0.61 [0.47, 0.75]

CCU technology is more reserved, but still positive. On the other hand, the Hesitants on average rejected the latter products.

The results regarding the willingness to use and purchase CCU-based products also confirm that the decisions that lead to the long-term adoption of the products are largely influenced by the demographic and attitudinal characteristics of the potential users and the groups differ significantly in their intention to use these products in their everyday lives (RQ2).

4.4. Which of the CCU-based products is preferred most?

In the final step of the statistical analyses, we examined which of the CCU-based product types studied have the greatest potential for public acceptance and use.

In the study, participants were asked to rank the four CO_2-based products, i.e., aviation fuel, clothing, cosmetics, and food according to their likelihood of use, with the first rank representing the most preferred option. The results reveal substantial variations in consumer preferences across different ranking conditions. For instance, aviation fuel was most frequently chosen as the top preference in one instance (n = 465; 56.3 %), while in another, food (n = 129; 15.6 %) emerged as the most favored product. Clothing (n = 136, 16.5 %) and cosmetics (n = 96, 11.6 %) exhibited fluctuating positions across the rankings, indicating that consumers' evaluations are nuanced and context-dependent. Table 6 shows graphically which product was most frequently selected in 1st, 2nd, 3rd or 4th place overall and reveals a clear preference ranking.

For the second rank, clothing was selected most frequently, suggesting that although it is not the top preference, it is perceived as a viable and attractive alternative among the CCU-based products. In the third rank, cosmetics emerged as the most common choice, implying that while it may not be the preferred option overall, a substantial portion of respondents regards it as a moderately acceptable option. Data for the fourth rank, representing the product least likely to be used, reveals that food received the highest number of selections. This indicates that it is the least favored option among the CO_2-based products. This suggests that consumers may perceive significant barriers—-whether due to safety, quality, or cultural concerns—when considering CCU-based food products. Fig. 2 depicts the rankings of consumer preferences for the products tested in the study.

5. Discussion

Current CO_2 removal technologies, such as CCU, enable the reduction of greenhouse gases by capturing emissions and reusing of the CO_2 in everyday objects. However, public perception of such products plays a key role in the long-term adoption and thus success of climate change mitigation trough such approaches. In this study, four exemplary products—aviation fuel, clothing, cosmetics, and food—manufactured via CCU technology and representing diverse market sectors were examined considering the users' perceived risks and their willingness to use them as relevant indicators for the social acceptance. The main focus was to ascertain the extent to which demographic attributes, including age and gender, and attitudinal profiles of the consumers entailing the general CCU technology acceptance, technical commitment, risk disposition, and interest in innovation significantly affect social

Table 6
Ranking of four CCU-based products (aviation fuel, clothing, cosmetics, food) over four rankings with a frequency of occurrence each (N = 826).

Placement	Aviation fuel	Clothing	Cosmetics	Food
1st rank	465	136	96	129
2nd rank	243	435	116	32
3rd rank	44	163	485	134
4th rank	74	92	129	531

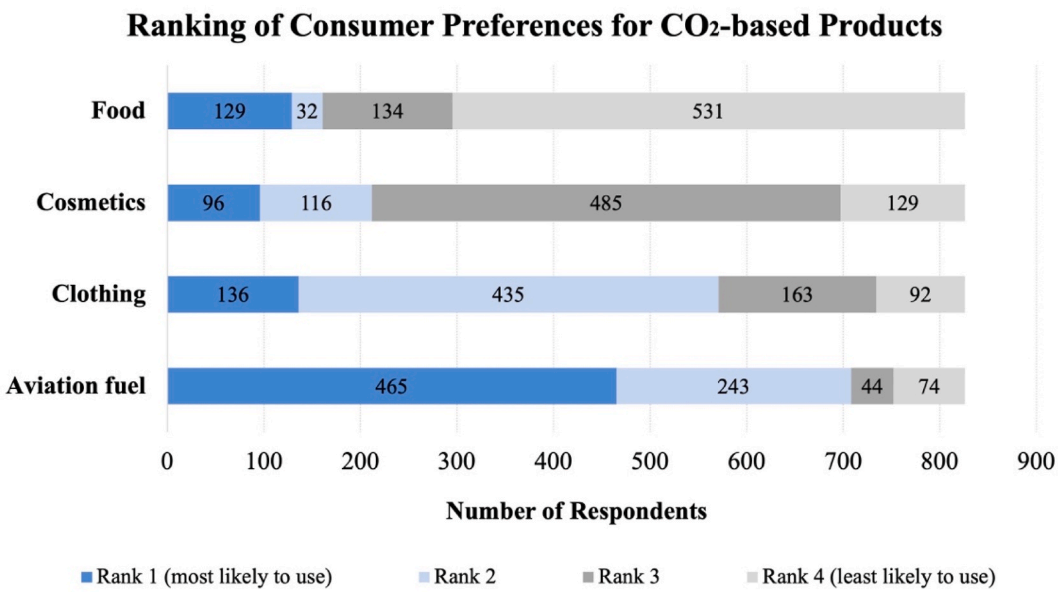


Fig. 2. Ranking of consumer preferences for the CCU-based products studied ($N = 826$).

perceptions and purchasing decisions. Considering consumer diversity is critical for the successful market of carbon-reducing technologies and products.

5.1. Summary of the key results

Based on the presented results, our first research question can be addressed by concluding that consumers' *perceptions of risk* associated with various CO_2-based products are substantially influenced by both demographic characteristics and attitudinal factors. Notably, gender and individual attitudes significantly impacted these perceptions, which means that in particular males with a high level of acceptance of CCU technology and those with a high level of interest in innovation and technical involvement in general showed a more positive assessment of the products than the hesitant group, especially females. The means for perceived risk tended to cluster around the midpoint of the six-point scale, suggesting that participants generally maintained a cautious or neutral stance toward CCU products. This result aligns with findings indicating that limited awareness, insufficient knowledge, and perceived risks contribute to participants adopting a predominantly cautious or ambivalent position toward CCU products, rather than exhibiting pronounced support or opposition (Kim and Ladenburg, 2024; Arning et al., 2019). Furthermore, our data indicate that, on average, participants expressed lower levels of trust in CO_2-derived products intended for close bodily use, such as food items and cosmetics. This appears to be a stable phenomenon, as this result confirms earlier findings (Haverkämper et al., 2023; van Heek et al., 2017a,b). In contrast to the more pronounced effects of gender and attitudinal factors, age demonstrated a comparatively weaker influence on risk perception. Significant age-related differences were observed only in relation to CCU-based clothing, with the youngest participants showing the highest level of trust in the product's safety. Nonetheless, the overall mean scores for perceived risk across all tested products clustered around the midpoint of the scale, indicating a generally cautious evaluation of potential risks. This suggests that, while age may shape perceptions in specific contexts, it does not appear to be a dominant factor influencing overall risk assessments of CCU products.

Moving further, we examined the *willingness to use* the CCU products as a direct indicator for social acceptance. The findings underscore the importance of understanding user diversity in shaping consumer willingness to adopt products derived from CCU technologies. Across various product categories, attitudinal dispositions have been shown to be the most significant predictor of acceptance. Participants who expressed more positive attitudes towards climate-related innovations and a high level of interest in innovation (i.e. those classified as "Enthusiasts") were found to be significantly more open to using CCU-based products, irrespective of the product type. The findings indicated that these effects were consistently robust, underscoring the pivotal role of psychological and value-based factors in shaping public acceptance of environmental technologies. In contrast, sociodemographic factors—-while still relevant—exerted more selective and context-dependent influence. Age showed significant effects in certain domains (notably clothing, fuel, and food), with younger participants generally expressing greater willingness to use CCU-derived products. This suggests a generational openness toward innovation and sustainability-oriented consumption practices. However, the magnitude of these effects was relatively small, indicating that age alone does not strongly determine acceptance. Gender differences were also observed but were modest and not consistent across all product types. Where significant, the results suggested that men tended to be slightly more accepting than women, particularly in product categories involving direct bodily contact, such as food and cosmetics. This may reflect differences in risk perception or trust in novel technologies, which are known to vary by gender in environmental and health-related domains (Brown et al., 2021; Zhao et al., 2021; Xiao and McCright, 2015; Hunter et al., 2004). Addressing thus the second research question (RQ2), we found meaningful differences across distinct consumer groups in the willingness to adopt CO_2-based products. Acceptance appears to be influenced by a dynamic interaction between individual attitudes and sociodemographic factors, with substantial variation observed both across and within these demographic segments (Offermann et al., 2025).

In addition, we explored consumer preferences among the four exemplary CCU-derived product categories to identify which product types hold the greatest potential for public acceptance and use (RQ3). The ranking data reveal clear patterns of consumer preference for different types of CO_2-based products, shedding light on perceived usefulness, risk, and acceptability. Among the examined product categories, aviation fuel was the most preferred, with most participants ($n = 465$) ranking it first. This pronounced preference is presumably rooted in the perception that such applications offer environmental benefits while posing minimal personal risk, as they do not involve direct bodily contact or consumption. Moreover, using sustainable aviation fuel does not demand changes in user habits, as the associated benefits are externalized yet socially valued. The second most prevalent ranking was for CO_2-enriched clothing, indicating a moderate level of acceptance. Participants may regard sustainable textiles as a familiar and low-risk innovation, particularly in light of the growing popularity of eco-friendly fashion. Although cosmetics were not wholly rejected, they were approached with a greater degree of caution and most frequently ranked third in terms of preference within the CCU product categories. This placement is likely due to concerns about applying novel materials directly to the skin. Cosmetics are often associated with personal care and safety, and the presence of unfamiliar ingredients may raise skepticism. However, the presence of first ($n = 96$) and second place ($n = 116$) rankings suggests that a segment of consumers is open to innovation, likely influenced by positive attitudes or prior knowledge. Finally, the findings indicated that CO_2-based food products received the least support overall, with the majority of respondents ($n = 531$) assigning them the lowest ranking. This outcome reflects profound and pervasive concerns regarding the ingestion of unfamiliar or synthetic substances, underscoring the pivotal role of trust, safety, and naturalness in food-related decision-making. The prevailing tendency is evidently shaped by the perceived proximity of the product to the body and the degree of perceived personal risk. Based on the findings, there is a higher level of acceptance for products used externally or indirectly, and a greater degree of hesitation for those involving ingestion or intimate contact. These distinctions in ranking underscore the heterogeneous nature of consumer preferences and emphasize addressing specific attributes driving each product's appeal in the CCU context. Consequently, these findings emphasize the necessity for additional research to be conducted into the underlying factors that influence acceptance, with a view to informing enhancements in product development and targeted marketing strategies.

5.2. Implications for the (european) market

Continuing with the ranking data, this study's results suggest that consumer acceptance of CO_2-based products in Europe varies significantly by application, with important implications for market strategy and policy development. Aviation fuel emerged as the most favored product, indicating strong public support for CCU applications perceived as low-risk and high-impact. This positions the aviation sector as a strategically viable entry point for CCU technologies. Similarly, CO_2-based textiles were received with moderate approval, especially among younger and sustainability-oriented consumers. This suggests market potential for integrating CCU materials into the growing eco-fashion sector, where storytelling and sustainability branding can be effectively leveraged. In contrast, cosmetics and particularly food were met with greater skepticism, likely due to their intimate or ingestive nature, which intensifies concerns about safety and naturalness. These findings indicate that such products should not be prioritized for immediate commercialization. Instead, they require gradual introduction, supported by transparent communication, regulatory oversight, and the establishment of consumer trust.

In addition, the aforementioned findings on risk perception and willingness to use CO_2-based products reinforce the necessity of a differentiated and trust-sensitive market approach. Products perceived as less risky, in particular aviation fuel and clothing, were found to elicit a higher level of usage willingness among potential consumers. This suggests that these categories offer lower barriers to market entry. European stakeholders should focus initial commercialization efforts here, where acceptance is not only higher but also less contingent on detailed product knowledge or regulatory reassurance. In contrast, products involving direct bodily contact, such as cosmetics and especially food, were associated with a higher perceived risk and a lower willingness to use. This finding suggests the presence of a trust deficit that must be addressed prior to the market introduction. In order to ensure the effective management of these categories, it is essential to proactively communicate potential risks, including transparent information about production processes, health safety, and environmental benefits. Moreover, the implementation of independent certification, endorsement by public health or consumer protection authorities, and the execution of pilot programs, including test markets and co-creation with consumers, has the potential to further facilitate and enhance the process of trust-building in a gradual manner. Last but not least, the persistent potency of individual attitudes underscores the significance of targeted consumer engagement. Public information campaigns, educational initiatives, and participatory formats should focus on shaping positive attitudes towards CCU technologies. It is recommended that policymakers and industry actors leverage EU Green Deal communication strategies and integrate CCU narratives into broader climate and circular economy discourses. In sum, it can be posited that aligning the release of products with the perceived risk, levels of trust, and consumer values will be pivotal in fostering a receptive and resilient European market for CCU innovations.

More broadly, the findings underscore the importance of user diversity in shaping acceptance. Market strategies must account for demographic and attitudinal differences, tailoring communication and product positioning to specific consumer segments. Building alliances with trusted scientific institutions and implementing certification schemes will further support the social legitimacy of CCU products. Ultimately, the commercialization of CCU technologies in Europe should begin with low-contact, high-acceptance applications, while developing long-term strategies to address concerns in more sensitive domains through trust-building and public engagement.

5.3. Limitations of the study and future research directions

Although this study provides new insights into the adoption of CCU technology and its innovative applications, it is important to acknowledge certain methodological limitations and highlight areas where further research is needed.

A key limitation of the present study lies in its reliance on stated preferences rather than observed behavior. While survey respondents reported willingness to use or purchase CCU-derived products, such hypothetical assessments may not accurately predict actual adoption patterns, particularly when respondents have limited real-world exposure to these technologies. Future studies should therefore incorporate behavioral data, such as revealed preferences in market-like settings or field experiments, to validate and deepen insights into consumer acceptance.

Additionally, the scope of assessed CCU products was necessarily limited, with a notable emphasis on aviation fuel, which may have shaped respondents' attitudes due to its higher public visibility and perceived environmental impact. Broader investigations should explore less familiar or lower-profile CCU applications, such as building materials or consumer goods, to uncover potential barriers to acceptance in other domains.

Another potential limitation is that the survey and introductory explanatory materials (see Appendix) may have influenced the participants, either by increasing their familiarity with the topic or by fostering more positive attitudes towards it. This aspect of the study design may have enhanced perceived comprehensibility and acceptance, suggesting that part of the observed effect could be attributed to these factors. Furthermore, because no attention or comprehension checks were included, we cannot be sure that participants actually understood the information provided.

Finally, the study does not address contextual or cultural factors that may influence perceptions, such as media discourse, regulatory frameworks, or regional climate policies. Future research should adopt comparative or longitudinal designs to examine how societal context and policy environments shape public attitudes toward CCU, thereby enabling more targeted and socially responsive deployment strategies.

6. Conclusion

Reaching net-zero targets as set by the European Union, requires maximizing market penetration with CO_2-reducing products and a broad adoption across all demographics. When examining public adoption of CCU-based products, it is important to recognize that consumer behavior is not uniform but shaped by various psychological, social, and demographic factors. Understanding these influences and differences between various (future) consumer groups is crucial for ensuring market acceptance and optimizing communication strategies. Importantly, this study reveals that no single user group can be treated as uniformly accepting or resistant. Instead, acceptance is shaped by an interplay of individual attitudes and sociodemographic background, with variability not only between, but also within, these groups. This highlights the need for targeted communication and engagement strategies that address specific concerns, values, and expectations of diverse consumer segments.

In conclusion, user diversity plays a critical role in shaping the market potential for CCU-based innovations. To enhance public acceptance and support broader deployment, it is essential to move beyond a one-size-fits-all approach and recognize the heterogeneous landscape of consumer perspectives. Tailoring communication, education, and product positioning to distinct user profiles—especially focusing on attitude-driven engagement—will be key to fostering trust and encouraging responsible uptake of CCU technologies.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and DeepL to improve the language and readability. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Wiktoria Wilkowska: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Imke Haverkämper:** Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Martina Ziefle:** Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank participants for their openness to share opinions on the CCU technology. This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101000790. Martina Ziefle thanks the Cluster of Excellence 2186, 'The Fuel Science Center' (ID: 390919832), for their valuable input. The Cluster is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy. The authors thank Lilian Kojan for the support in the survey operationalization and data collection.

Appendix

Table 7
Information about the CCU and its products presented to the survey participants, along with instructions on how to use them. All instructions were provided in German—the respondents' native language—in the order in which they are presented.

Placement in the survey	Information given to the participant
Introduction	Dear participants, Thank you for taking the time to participate in this survey. The aim of the survey is to gain insight into perceptions of products based on innovative, climate-friendly technologies. Climate-friendly products are crucial for achieving the difficult balance between meeting climate protection goals and maintaining high product quality. Until now, the development of such products has been driven primarily by technical and economic considerations. At the Chair of Communication Science at RWTH Aachen University, we focus mainly on the social scientific support of these innovative processes. We are particularly interested in understanding how end customers perceive these new products in terms of their perceived advantages and disadvantages. Completing the questionnaire should take approximately 10–12 min. There are no right or wrong answers — only your opinion matters. No prior knowledge is required either. Please respond as spontaneously as possible and be as honest as you can. Only through realistic evaluations of new product development can such efforts ultimately be sustainable and successful. *Information regarding data protection, consent and requests for demographic data.*
Introduction to CCU	The climate crisis is one of the major global challenges of our time. The CO_2 present in the atmosphere is considered to be a primary driver of climate change. This is why reducing CO_2 emissions is seen as an important way of mitigating climate change. One approach is to capture or sequester CO_2 directly at its source and utilize it as a raw material in the production of other goods. This technology is known as 'carbon capture and utilization' (CCU). The process involves the following steps: 1. First, the CO_2 is captured and, if necessary, purified. 2. Next, the CO_2 is transformed into a new substance or product using energy and other materials.

(*continued on next page*)

Table 7 (*continued*)

Placement in the survey	Information given to the participant
	This graphic illustrates the CCU process. It illustrates the possible sources of CO_2, the products resulting from its utilization, and the options for processing it at the end of its lifecycle. Sources of CO_2 include exhaust streams from industrial plants and gases produced during the fermentation of biomass. CO_2 can also be captured directly from the air. CO_2 can be utilized in a variety of ways and is categorized as an energy vector, for direct utilization, or material utilization. *Data collection regarding knowledge, general acceptance of CCU-based products and the attitudes of the participants.*
Introduction CCU products *(presented in random order)*	The following section of the survey will present you with four products and their potential applications, all of which are based on CO_2 and can be manufactured using CCU technology. **Aviation fuel** When energy is used, CO_2 can react with hydrogen to form numerous compounds. CCU therefore enables substances to be produced that previously required petroleum or natural gas. These include many chemicals and fuels; for example, CO_2 can be used to produce aviation fuel. *Questions on risks and acceptance of CCU-based aviation fuel* **Clothing** Thanks to CCU technology, it is possible to produce textile fibers from CO_2. This enables conventional fibers produced using fossil raw materials to be replaced. Clothing made using CCU technology resembles traditional polyester clothing in terms of its properties. *Questions on risks and acceptance of CCU-based clothing* **Cosmetics** CCU can also be used to manufacture CO_2-based products for the cosmetics industry. For instance, creams can be made using CO_2 as a base. This replaces conventional waxes, which are mostly derived from natural substances or paraffin, a by-product of petroleum. The creams produced through the CCU process contain CO_2-based waxes. *Questions on risks and acceptance of CCU-based cosmetics* **Food** CCU can also be used to produce CO_2-based products for use in food production. One example is synthetic starch derived from CO_2, which can be used to make bread instead of conventional starch. *Questions on risks and acceptance of CCU-based food*
Ranking of the CCU-based products	Finally, we would like to know how you would rank the four products when compared directly. Please arrange them so that the one you would most likely use is first, and the one you would least likely use is last. Please note that if you do not wish to change the order in which the products have been presented to you, you should still move one of the options slightly so that your response can be recorded. CO_2-based clothing, CO_2-based cosmetics, CO_2-based aviation fuel, CO_2-based food products *(presented in random order)*
Data cleaning	To ensure data quality, we excluded incomplete responses and those who provided incorrect answers to the attention check question (quality control). We also excluded 'speeders' (those who completed the task in less than 30 % of the group-specific median completion time). The minimum processing time for the test subjects was 380 s (=6.33 min; median processing time: *Md* = 575).

Convergent validity is supported when each scale shows internal consistency of at least $\alpha \geq .70$, standardized factor loadings mostly $\geq .50$, an Average Variance Extracted (AVE) of $\geq .50$, and a Composite Reliability (CR) of $\geq .70$. Discriminant validity is established when, for every scale, the square root of its AVE exceeds all absolute Pearson correlations with other scales (Fornell-Larcker criterion). All attitude-related scales satisfied the established thresholds for convergent and discriminant validity, as documented in the following two tables.

Table 8
Summary of convergent and discriminant validity indicators (Factor loadings, Cronbach's α, Average Variance Extracted, √AVE, Composite Reliability) for attitude-related scales.

Construct	Items	Factor loadings	α	AVE	√AVE	CR
Acceptance of CCU products (3 items)	*"I would use products that are based on CO_2."*	.85	.81	.62	.79	.83
	"I am in favor of using CO_2-based products."	.87				
	"I reject the use of CO_2-based products." [recoded]	.62				
Technical commitment (4 items)	*"Whether I am successful in using modern technology depends largely on me."*	.76	.84	.60	.77	.86
	"If I have difficulties in dealing with technology, it ultimately depends on me alone to solve them."	.81				
	"It is up to me whether I succeed in using new technical developments - it has little to do with chance or luck."	.73				
	"What happens when I deal with new technical developments is ultimately under my control."	.79				
Risk disposition (6 items)	*"I am willing to take risks."*	.87	.85	.52	.72	.86

(*continued on next page*)

Table 8 (*continued*)

Construct	Items	Factor loadings	α	AVE	√AVE	CR
	"I am prepared to take risks."	.82				
	"I am very careful when I make plans and execute them." [recoded]	.57				
	"I follow the motto "Nothing ventured, nothing gained."	.71				
	"I don't like adventurous decisions." [recoded]	.58				
	"I like putting things on risk."	.73				
Interest in innovation (4 items)	*"I regularly keep an eye out for new products."*	.99	.89	.71	.84	.91
	"I am usually the first in my circle of friends and acquaintances to try new products."	.91				
	"I often look for information on new products that might interest me."	.79				
	"I find it interesting to try out new products."	.65				

Table 9
Pearson correlation matrix for attitude-related scales.

		Acceptance of CCU products	Technical commitment	Risk disposition	Interest in innovation
Acceptance of CCU products	Pearson's *r*	–			
	df	–			
	p-value	–			
	upper 95 %-CI	–			
	lower 95 %-CI	–			
Technical commitment	Pearson's *r*	**.26**	–		
	df	825	–		
	p-value	<.001	–		
	upper 95 %-CI	.32	–		
	lower 95 %-CI	.20	–		
Risk disposition	Pearson's *r*	**.11**	**.17**	–	
	df	825	825	–	
	p-value	.001	<.001	–	
	upper 95 %-CI	.18	.24	–	
	lower 95 %-CI	.04	.10	–	
Interest in innovation	Pearson's *r*	**.20**	**.36**	**.36**	–
	df	825	825	825	–
	p-value	<.001	<.001	<.001	–
	upper 95 %-CI	.27	.41	.42	–
	lower 95 %-CI	.14	.29	.30	–

Data availability

Data will be made available on request.

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