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Beyond knowledge-based target group identification: The role of risk perceptions for biofuel risk communication

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ABSTRACT

The transition to sustainable mobility is a key component of global efforts to defossilize energy systems, with biofuels playing a strategic role alongside electrification. However, public responses to biofuels are heterogeneous and shaped by subjective risk perceptions rather than knowledge alone. This challenges traditional communication approaches based on the knowledge-deficit model and highlights the need for more differentiated, perception-based audience segmentation. Therefore, this study investigates how knowledge, risk perception, and information need jointly structure communication-relevant target groups for biofuel risk communication. We conducted an online survey with $N = 508$ German laypersons in 2024 to analyze their knowledge levels, information needs, and perceived risks regarding biofuels. Using cluster analysis, three distinct target group segments were identified: “Concerned Curious,” “Concerned Avoiders,” and “Calmly Curious”. The results reveal that knowledge alone is insufficient to explain differences between groups. The Calmly Curious exhibited high information needs but low risk perceptions, while the Concerned Curious reported elevated risk perceptions alongside high information needs. The Concerned Avoiders showed low knowledge and high risk perceptions. Although the clusters did not differ in socio-demographic variables and attitudinal variables, they yielded different patterns of risk- and benefit perceptions. The findings demonstrate that risk communication should be designed explicitly target-group oriented to address the specific beliefs and knowledge needs of each group, particularly those with heightened concerns about biofuels. By systematically including risk perceptions in addition to knowledge variables in the segmentation of target groups, this study provides insights into the interplay between knowledge levels and risk perceptions.

1. Introduction

A significant challenge in the mitigation of climate change is the reduction of fossil fuel usage [1]. Especially the transportation sector, accounting for approximately one quarter of overall EU GHG emissions [2], offers considerable potential for decarbonization. Since the private transportation sector contributes more than 70% of transportation sector emissions, and overall, 12% of EU carbon dioxide (CO₂) emissions, sustainable fuels and alternative driving technologies are essential for reducing emissions from light-duty cars.

Among these options, biofuels are frequently discussed as a relevant pathway to reduce greenhouse gas emissions in the short to medium term, as they can be integrated into existing infrastructures and vehicle technologies [3]. At the same time, their societal perception and evaluation remain complex. While biofuels are often associated with environmental benefits, public debates - such as the “food versus fuel”

controversy [4] - have raised concerns regarding land use, food security, and overall sustainability, contributing to ambivalent public perceptions. These concerns are expressions of risk perceptions, i.e., individuals' subjective interpretation and evaluation of potential risks, which have consistently been identified as a central determinant of public acceptance of energy technologies, often outweighing the influence of factual knowledge [5]. At the same time, public knowledge about biofuels is often limited [6,7], while interest in further information remains comparatively high, suggesting that knowledge and information needs do not necessarily align (e.g., [8]). This indicates that the public cannot be considered a homogeneous audience, but rather differs in how they perceive, evaluate, and relate to biofuels.

In this context, communication plays a key role in shaping how biofuels are understood and assessed. In particular, risk communication aims to support informed decision-making by addressing both potential risks and benefits [9]. However, effective communication depends on

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how different groups interpret information, which concerns they consider relevant, and which information needs they have. Traditional approaches have largely relied on the knowledge deficit model, assuming that differences in attitudes primarily result from differences in knowledge levels and that providing factual information from experts to lay audiences would be sufficient to reduce these gaps [10,11]. This perspective has been increasingly challenged by research showing that public responses cannot be explained by knowledge alone. Consequently, risk communication is now understood as an interactive process that needs to account for perceptions, concerns, and information needs of the target audience [12]. This implies that communication cannot follow a one-size-fits-all approach but requires target-group-oriented strategies. Tailored communication that considers the heterogeneity of audiences is more likely to resonate and address the specific barriers that different audience segments face [13].

Therefore, the identification of target groups has become an important approach for addressing heterogeneity in communication about innovative technologies. Existing segmentation studies in the context of biofuels have provided first insights by focusing on specific aspects such as trust in information sources, communication preferences, or knowledge levels (e.g., [7,8,14]). However, these approaches often focus on isolated dimensions and do not systematically consider how different factors interact. This raises the question of how target groups for biofuel communication can be identified in a way that captures this complexity more adequately. In particular, it remains unclear how central dimensions such as knowledge, risk perception, and information need jointly structure differences between audience groups and how they can be used to derive communication-relevant target groups.

Therefore, the present study aims to identify communication-relevant target groups for biofuel risk communication by integrating knowledge, risk perception, and information needs. More specifically, the study pursues the following research objectives: (1) to analyze how knowledge, risk perception, and information needs of biofuels are distributed within the population, (2) to identify distinct communication-relevant target groups based on these dimensions, and (3) to examine how these groups differ with regard to characteristics relevant for biofuel risk communication.

In doing so, the study advances the understanding of audience heterogeneity in the context of sustainable mobility and delivers a differentiated basis for designing effective communication strategies to support the societal acceptance of biofuels.

2. Theoretical background

2.1. Biofuel introduction: technology, implementation, and challenges

Biofuels are defined as renewable energy carriers derived from biological sources, including crops, waste, or oils. Biofuels can be used across a wide range of applications, including power generation and as liquid fuels in transportation, enabling the familiar use of internal combustion vehicles (ICV). While first-generation biofuels mainly relied on feedstock like sugary or high-fat plants, second- to third-generation advanced biofuels include advanced production processes with micro-organisms, e.g., algae, producing biofuels from waste, oils, or byproducts [15]. As a substitute for fossil fuels, biofuels have been shown to make a significant contribution to energy diversification and greenhouse gas (GHG) reduction efforts [16]. The capacity of these systems to demonstrate versatility and contribute to the objective of carbon neutrality signifies their status as a substantial component in the transition towards a low-carbon energy system [17].

In 2023, Germany produced approximately 3.9 million tons of biofuels for its domestic market, with waste materials constituting a significant proportion of the feedstock [18]. According to the Federal Office for Agriculture and Food (BLE, [18]), the utilization of biofuels has resulted in an average greenhouse gas (GHG) emissions reduction of approximately 90% when compared to their fossil fuel counterparts.

This represents a total reduction of approximately 12 million metric tons of CO₂ equivalents, thereby underscoring the sector's considerable climate benefits. In Germany, in 2023, biodiesel dominated biofuel consumption, accounting for 60% of the total biofuel usage. Bioethanol contributed 24%, and hydrogenated vegetable oils (HVO) made up approximately 12% [18]. These fuels are produced from a mixture of raw materials, with 60% originating from waste and residues and 40% from cultivated biomass, predominantly rapeseed and maize.

Notwithstanding the aforementioned benefits, the production of biofuels is confronted with several challenges, including technological barriers, economic viability, sustainability of feedstock, and competition with food production (particularly concerning first-generation biofuels). As Agrawal et al. [19] point out, the long-term viability of biofuels is contingent upon overcoming limitations inherent to supply chains, the enhancement of conversion efficiency, and establishing a sustainable feedstock base. Globally, the International Energy Agency [20] projects that to meet the decarbonization targets of the transport sector by 2050, current renewable fuel production capacity—including biofuels and synthetic fuels (e-fuels)—must grow more than fivefold.

Advanced biofuels, often derived from non-food biomass such as lignocellulosic materials, show particular promise as sustainable energy carriers. However, their development and market penetration are still limited (0.8% in Europe in 2021 vs. 4% first-generation biofuels [15]). Panoutsou et al. [3] argue that supportive and stable policy frameworks are essential to encourage investment and innovation in advanced biofuels. Additionally, the lack of a coherent long-term strategy to promote these next-generation fuels within the European Union has been criticized [15]. While policy is critical, it is not the only factor driving biofuel adoption. Public perception and acceptance also play a crucial role [21]. The extent to which a technology is accepted by society is influenced by a combination of regulatory frameworks and societal attitudes and concerns regarding that technology [22]. Addressing these public concerns through communication about the technology, based on specific insights into beliefs of threats and benefits, is crucial for widespread deployment.

In summary, biofuels are a technically feasible and environmentally beneficial part of the future transportation energy mix. However, their broader adoption depends not only on how they are perceived by the public but also on how these perceptions are addressed through communication. Therefore, the following section examines key factors that allow the identification of communication-relevant target groups.

2.2. Individual factors as basis for target group segmentation in biofuel risk communication

Public responses to energy technologies such as biofuels are shaped by multiple interrelated individual factors, leading to heterogeneous patterns of perception and evaluation across the population. The following section reviews key determinants of public perceptions of biofuels and their role for understanding differences between audience groups in the context of risk communication.

Previous research has identified a range of factors influencing *public perception and acceptance* of energy technologies [23]. Research on acceptance of renewable energies and alternative fuels proved the interplay of perceived risks and benefits, trust in institutions, and economic risk and benefit considerations such as fuel price costs or switching costs [24,25]. Perceived environmental benefits are often positively associated with acceptance, while concerns about indirect land-use change, food security, and sustainability can reduce support [23,26]. In addition, contextual factors such as media coverage and public debates further affect how individuals perceive and evaluate biofuels [27,28]. Public evaluations of biofuels are therefore not uniformly negative: perceptions of biofuels are often positive [6], although public debates such as the “food versus fuel” controversy continue to shape ambivalent attitudes [4]. Importantly, these findings already indicate that public perceptions are not homogeneous but vary

systematically across the population. For example, Balogh et al. [14] identified groups such as biofuel skeptics, who reject biofuels and endorse critical statements, alongside more supportive or undecided segments. This heterogeneity poses a central challenge for communication: if publics differ systematically in how they perceive and evaluate biofuels, communication cannot assume a uniform audience but must be tailored to different target groups. However, existing research often focused on single explanatory dimensions such as trust in communicators [29] or communication preferences [8], rather than systematically integrating multiple perception-related factors. As a result, these approaches provide only a partial understanding of how different determinants of public perceptions interact and how they contribute to differences between audience groups.

Early perspectives addressed this challenge by focusing on *knowledge* as a central variable for defining target groups and assumed that differences in knowledge levels (“experts vs. laypeople”) led to differences in attitudes and acceptance (e.g., [30]). This view is closely linked to the knowledge-deficit model, which attributes low acceptance and heightened risk perceptions to a lack of knowledge and assumes that these can be mitigated by providing factual information [31]. However, this knowledge-focused perspective has been increasingly challenged, as it neglects the role of additional factors that shape public acceptance, such as individual risk and benefit perceptions, affective responses, or social norms [32,33]. Despite these limitations, knowledge remains a relevant variable in the context of risk communication, as it is linked to individuals’ ability to interpret information and articulate information needs (e.g., [34]). In the context of biofuels, empirical studies indicate comparatively low levels of public knowledge [6,29]. Subjective self-assessed and factual knowledge align relatively well [14], yet both subjective and factual knowledge levels remain limited. At the same time, interest in obtaining more information is often high despite these low knowledge levels [7,35], suggesting that knowledge deficits do not necessarily lead to disengagement. This indicates that information needs cannot be directly inferred from knowledge levels alone but represent a distinct dimension that varies across individuals.

From a *risk communication perspective*, this limitation is particularly relevant, as information-seeking behavior is not only driven by knowledge but also by perceived risks and affective responses, as highlighted in models such as the Risk Information Seeking and Processing Model (RISP) [36]. Risk communication is an interdisciplinary field that examines how communication influences the perception and evaluation of risks across domains such as health, environmental hazards, and emerging technologies [9,37]. Its primary objective is to enable informed decision-making under conditions of uncertainty by addressing both potential risks and benefits.

The effectiveness of risk communication depends on several factors, including the definition of the target group and its characteristics, such as how audiences process information [13] or which mental models they hold about risks [11]. Additional factors include the role of (trust in) the communicator [7], as well as the framing, content, and presentation of messages [38,39]. Understanding differences between audience groups is particularly crucial, as it allows communication strategies to be tailored to specific perceptions, needs, and concerns.

Consequently, *segmentation approaches* have been applied in the context of biofuel communication to account for heterogeneity in public responses. Previous studies have used different criteria for segmentation, including trust in information sources, communication preferences, and knowledge. For example, Van de Velde et al. [7] segmented audiences based on perceived trustworthiness of information sources, identifying four clusters with distinct trust levels in science, journalism, or industry, along with differences in content and channel preferences. More recently, Offermann et al. [8] combined communication preferences and information needs in a segmentation approach, testing for differences in trust levels. Building on the more traditional knowledge deficit approach, Balogh et al. [14] clustered audiences based on objective knowledge of and interest in biofuels. Interestingly, they

identified biofuel skeptics with increased environmental and social sensitivity but strong rejection of biofuels. Taken together, the audience for biofuel communication is far from homogeneous and that segmentation is an essential prerequisite for effective risk communication. However, the studies also reveal a key limitation: previous segmentation approaches did not include *risk perceptions*, even though theoretical models such as the Risk Information Seeking and Processing model (RISP) [13] and the Planned Risk Information Seeking Model (PRISM) [40] highlight affective and cognitive risk perceptions as central drivers of information-seeking and avoidance.

This highlights the importance of perception-based approaches in risk communication, extending beyond knowledge-focused explanations [12]. Emerging evidence further emphasizes that distinguishing between affective and cognitive dimensions of risk perception is essential for understanding public responses to alternative fuels [41,42]. In addition, previous research has shown that segmentation can be based on various individual characteristics, including trust in institutions [29], communication preferences [8], or environmental awareness [14]. The role of sociodemographic variables, however, remains inconsistent. Baral [43] found gender to be a significant predictor for biofuel knowledge, with men showing higher knowledge than women. Similarly, Velde et al. [7] identified group differences for gender and education, whereas Offermann et al. [8] reported no specific cluster characteristics related to sociodemographic factors. This further underscores that single variables are insufficient to capture the complexity of public responses.

Overall, these findings demonstrate that public responses to biofuels are structured along multiple dimensions. However, despite this heterogeneity, existing segmentation approaches have rarely integrated knowledge, risk perceptions, and information needs in a unified framework. Addressing this gap provides the basis for a more comprehensive and theoretically grounded identification of target groups for biofuel risk communication.

2.3. Research questions and research approach

Following the identified research gaps, this study follows a two-step research approach (see Fig. 1).

First, the perception of biofuels among the German public remains largely unexplored, despite the long-standing use of biofuels in transport. While studies from other countries reveal low knowledge levels and increased information needs, there is a lack of data for potential German consumers. Additionally, little is known about specific risk perceptions (cognitive and affective) regarding the use of biofuels, even though, in theory, risk perceptions strongly affect the acceptability of sustainable technologies. Therefore, our first research goal was to assess

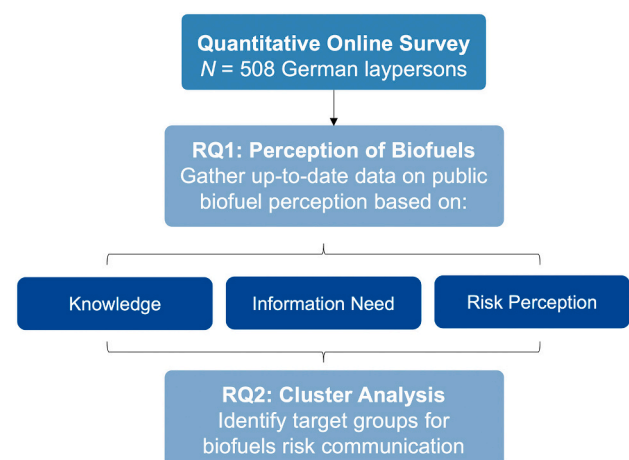


Fig. 1. Research approach.

up-to-date data on public perception in Germany regarding biofuels, including knowledge levels, information needs, and cognitive and affective risk perception.

RQ1: What are the current levels of knowledge, information needs, and risk perceptions regarding biofuels among the German public?

Second, theoretical and empirical work in risk communication highlights that individual perceptions, not knowledge alone, shape responses to communication efforts. Segmentation approaches in the biofuel context have revealed heterogeneity but have so far neglected risk perceptions as a criterion. Therefore, the second research goal was to identify distinct target groups for risk communication, integrating knowledge, information needs, and risk perceptions.

RQ2: Which communication target groups can be identified based on these variables, and how do they differ in their characteristics?

Based on the findings of our research questions, of general biofuel perception and the specific cluster characteristics, recommendations for target-group-oriented risk communication will be derived. These recommendations especially target communicators from different areas, either political or scientific, and especially with a background in sustainable transportation alternatives, as well as risk communication researchers. Therefore, the identified audience segments will be translated into recommendations for target-group-oriented risk communication in the discussion section.

3. Methods

3.1. Data collection and survey instrument

Data collection: To address the research aims, a quantitative online survey was conducted targeting laypersons residing in Germany who were aged 16 and above. The questionnaire was reviewed and endorsed by the Ethics Committee of the Empirical Human Sciences department at RWTH Aachen University (2022_10_FB7_RWTH Aachen). The study followed all institutional and local regulations, and the participants had provided their written informed consent to participate in the study. Data collection took place in February 2024 and was carried out by a market research company.

Survey instrument (see Fig. 2): The survey began with socio-demographics and mobility behavior. Following that, participants received introductory technical information about biofuels, including current research on production from alternative feedstocks that do not compete with food production. The introductory information was developed with the support of experts from the FSC to ensure factual correctness. The exact wording of the introduction and all survey items is available in the Appendix. Readability and understanding were ensured with $N = 3$ Pretests by German native speakers.

The main part of the questionnaire included the following measures:

- Subjective *knowledge* (1 item) and *information need* (1 item) about biofuels.
- *Risk perception of biofuels*, including *affective* (5 items, Cronbach's $\alpha = 0.91$, source: [44]) and *cognitive* (7 items, Cronbach's $\alpha = 0.94$, source: [45]) dimensions.
- Climate -change-related attitudinal constructs: *environmental consciousness* (EC, 5 items, Cronbach's $\alpha = 0.89$, source: [45]), and the general *climate change awareness* (CCA, 5 items, Cronbach's $\alpha = 0.84$, source: [46]).
- Institutional trust (science, governments, NGOs, industry) “to make good and correct decisions in regard to the mitigation of climate change”, with a seven-item *institutional trust* scale (IT, Cronbach's $\alpha = 0.89$, source: [47]).
- General risk propensity was measured with five items of the General Risk Propensity Scale (GRIPS, Cronbach's $\alpha = 0.92$) by Zhang et al. [48].
- Biofuel-specific perceptions and attitudes: *willingness to use* biofuels (WTU, 1 item) and risk perceptions of different *impact factors* (IF, 8 items) associated with biofuel usage in road transport, such as health implications and financial considerations. These attitudes were designed either as a benefit or a threat, for example, a *financial benefit* “I benefit financially”, or a *health threat* “My health or that of my family is at risk”. These items were developed based on prior qualitative interviews and subject-related literature [49,50].

All items in the survey were measured using a 6-point Likert scale ranging from 1 (low agreement) to 6 (high agreement), which reduces central tendency bias and allows participants to make fine-grained distinctions [51]. Risk perception items (cognitive and affective) were measured on a 6-point semantic differential [52] with opposing adjective pairs, e.g., from “not threatening” to “threatening” or “senseful” to “senseless”.

A total of $N = 738$ datasets were collected. Data cleaning included the exclusion of incomplete data sets or removal of conspicuous answering patterns, as well as screening for speeders (response time's median by half). Reverse-phrased items were recoded before scale construction. The internal consistency was proven with Cronbach's α for each scale consisting of more than one item, revealing satisfactory results for reliability (Cronbach's alpha > 0.8 [53]). The median completion time was Mdn. = 16:28 min (SD = 14:23 min).

3.2. Sample

The final sample after data cleaning of $N = 508$ showed a census-representative distribution of the German public regarding the socio-demographic factors of age, gender, federal state, and level of education (see Table 1). Of the participants, 50.2% ($n = 255$) were female, 49.2% ($n = 250$) were male, and 0.6% ($n = 3$) identified as another gender. The average age was 47.9 (SD = 16.3) years, ranging from 16 to 85 years. For

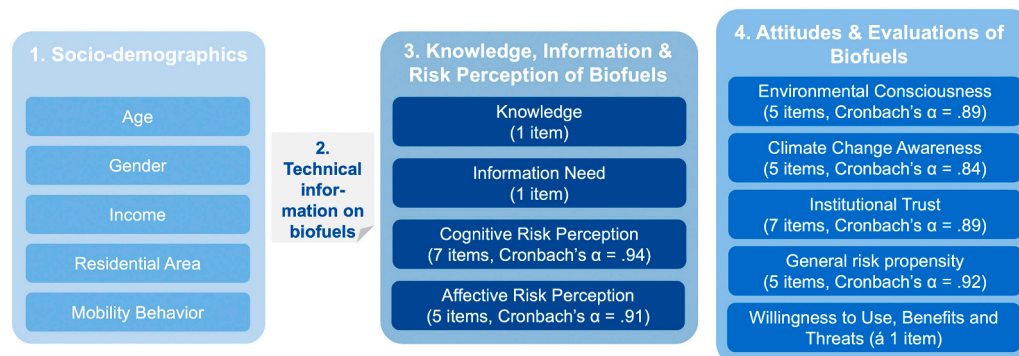


Fig. 2. Survey structure.

Table 1

Sample characteristics including sociodemographic and attitudinal variables; $N = 508$.

Variable	N	%	M	SD
Gender				
Male	250	47.2		
Female	255	50.2		
Other	3	0.6		
Age			47.9	16.3
16–29	73	14.4		
30–44	155	30.5		
45–64	149	29.3		
>65	131	25.8		
Area of living				
City	136	26.8		
Suburbs	209	41.4		
Rural	163	32.1		
Income				
<1.050 €	54	10.6		
1.050 € - < 2.000 €	111	21.9		
2.000 € - < 3.000 €	113	22.2		
3.000 € - < 4.000 €	88	17.3		
4.000 € - >5.000 €	92	18.1		
n.a.	50	9.8		
Education*				
Low education	344	65.7		
Medium education	85	16.78		
High education	89	17.5		
Mobility				
Car owner	337	66.3		
Monthly to daily car user	437	86		
Willingness to use biofuels			3.8	1.3
Attitudinal variables				
Environmental consciousness			4	1.2
Climate change awareness			4.2	1.1
Institutional trust			3	1
General risk propensity			2.5	1.1

*Level of education according to the ISCED guidelines

further analysis, the participants were grouped into four age categories: 16–29 years (14.4%, $n = 73$), 30–44 years (30.5%, $n = 155$), 45–64 years (29.3%, $n = 149$), and 65–85 years (25.8%, $n = 131$). Educational attainment was classified according to ISCED guidelines [54]. Most participants were at a low educational level (65.7%, $n = 334$), followed by the higher education tertiary level (17.5%, $n = 89$), and the least amount were secondary level (16.7%, $n = 85$). Most respondents (44.1%, $n = 214$) estimated their net income to be between 1050 and 3000 Euros. The majority of the sample lived in suburban areas (41.1%, $n = 209$), followed by rural areas (32.1%, $n = 163$) and the city center (26.8%, $n = 136$). Regarding mobility-related characteristics, most participants were car owners (66.3%, $n = 337$) or had regular access to a car (86%, $n = 437$). Concerning a user intention for biofuels, the sample showed slightly elevated willingness to use (WTU) biofuels ($M = 3.8$, $SD = 1.3$; $t = 5.1$, $p < .001$) (see Table 1). Insights into specific attitudinal variables revealed elevated environmental consciousness (EC, $M = 4$, $SD = 1.2$, $t = 8.3$, $p < .001$) and climate change awareness (CCA, $M = 4.2$, $SD = 1.1$, $t = 14.5$, $p < .001$) among the participants, as well as lowered institutional trust (IT, $M = 3$, $SD = 1$, $t = -11.5$, $p < .001$) and general risk propensity (GRIPS, $M = 2.5$, $SD = 1.1$, $t = -21.2$, $p < .001$).

3.3. Statistical analysis

Statistical analyses were conducted with SPSS (Version 29.0.1.1) and jamovi (Version 2.3). To address the second research question, we performed a cluster analysis based on the core variables of subjective knowledge, information need, and risk perceptions (cognitive and affective dimensions). These variables were chosen because they directly reflect the constructs most relevant for risk communication and audience segmentation. The cluster analysis followed a two-step procedure. First, a hierarchical cluster analysis was conducted to explore the potential number of clusters. The scree plot and dendrogram suggested a

three-cluster solution. Accordingly, a K-means clustering was applied, specifying three clusters. After the cluster solution was established, additional variables were analyzed to characterize and differentiate the clusters. These included *attitudinal constructs* (environmental consciousness, climate change awareness, institutional trust, general risk propensity), as well as *biofuel-specific attitudes* (willingness to use, perceived benefits, and perceived threats). One-sample t -tests were applied to prove scale midpoint (3.5) deviations, and group comparisons between the clusters were tested with non-parametric independent sample Kruskal-Wallis tests to test mean score differences between the clusters.

4. Results

The results are presented in two parts. First, general attitude results towards biofuels among the overall sample are presented, providing recent data on public perceptions of biofuels in Germany. Second, the main results of the cluster analysis and third, specific results regarding cluster characteristics are reported.

4.1. General attitude towards biofuels

Although biofuels have been used for transport in Germany for over two decades, public familiarity with the fuel solution remained low in the sample. The self-assessed knowledge of biofuels was relatively low among the sample ($M = 2.6$, $SD = 1.3$; $t = -15.8$, $p < .001$; see Fig. 4), with 75.2% indicating they would “tend to disagree” to “do not agree at all” on having knowledge about biofuels (see Fig. 3). However, participants reported a moderate information need ($M = 3.3$, $SD = 1.6$; $t = -2.3$, n.s.; see Fig. 4), with a slightly higher percentage expressing a desire to be better informed about biofuels (52.9%, $n = 268$) than those reporting no such need (47%, $n = 240$) (see Fig. 3).

Overall, the study revealed lowered risk perceptions, both affective ($M = 2.8$, $SD = 1.1$; $t = -15.7$, $p < .001$) and cognitive ($M = 2.8$, $SD = 1.1$; $t = -14.9$, $p < .001$) towards biofuels (see Fig. 4). No significant difference was found between affective and cognitive risk perceptions ($z = -1.0$, n.s.).

4.2. Segments based on cluster analyses

The cluster analysis based on subjective knowledge, information need and cognitive and affective risk perceptions revealed three different clusters (see Fig. 5). The three clusters were verbally labeled according to their profiles in the clustering variables: 1) *Concerned Curious* ($n = 165$), 2) *Calmly Curious* ($n = 168$), and 3) *Concerned Avoiders* ($n = 175$).

The “*Concerned Curious*” ($n = 165$) and “*Calmly Curious*” ($n = 168$) were identified as *curious* due to their medium to low knowledge levels (*Concerned Curious*: $M = 3.1$, $SD = 1.1$, $p < .001$; *Calmly Curious*: $M = 3.2$, $SD = 1.2$, $p < .01$) combined with high information needs (*Concerned Curious*: $M = 4.1$, $SD = 0.9$, $p < .001$; *Calmly Curious*: $M = 4.4$, $SD = 0.9$, $p < .001$). In contrast, the “*Concerned Avoiders*” ($n = 175$) were characterized as *avoiding*, with the lowest knowledge levels ($M = 1.5$, $SD = 0.8$, $p < .001$) and the lowest information need ($M = 1.6$, $SD = 0.8$, $p < .001$). Risk perception levels further differentiated the clusters: While the *Calmly Curious* cluster showed the lowest affective ($M = 1.9$, $SD = 0.7$, $p < .001$) and cognitive ($M = 1.8$, $SD = 0.6$, $p < .001$) risk perception, the *concerned* cluster *Concerned Avoiders*, expressed lowered to moderate risk perception (affective: $M = 2.9$, $SD = 1.2$, $p < .001$; cognitive: $M = 3$, $SD = 1.1$, $p < .001$). Interestingly, the *Concerned Curious* cluster reported the highest risk perception levels (affective: $M = 3.4$, $SD = 0.9$; cognitive: $M = 3.5$, $SD = 0.8$), even though these values remained within the moderate range (n.s. vs. midpoint).

Group differences between the clusters were further tested with nonparametric Kruskal-Wallis tests and post hoc tests with the Bonferroni correction. As expected, given the clustering procedure [55], all

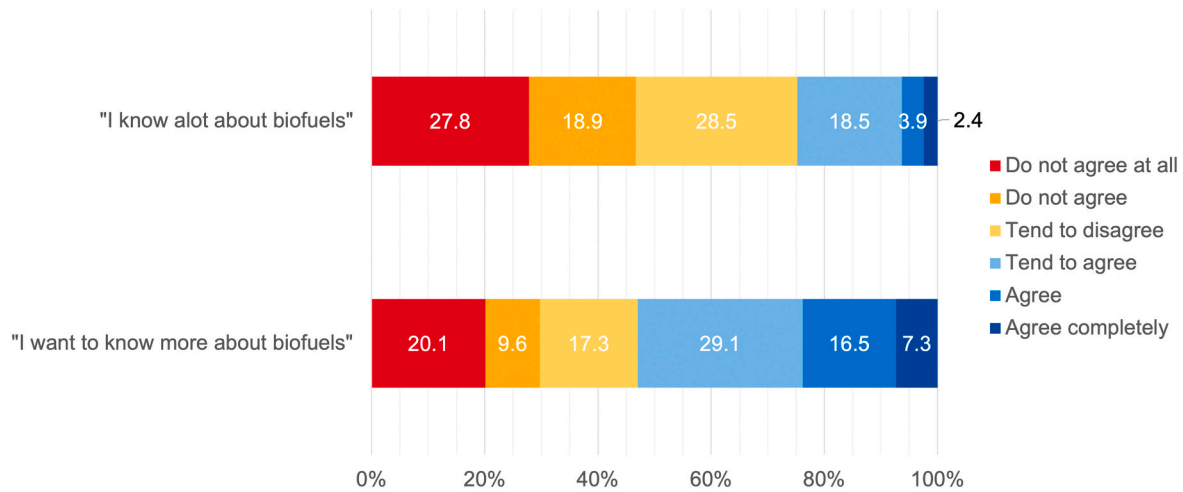


Fig. 3. Self-assessed knowledge (top row) and information need (bottom row) regarding biofuels of the German public; $N = 508$.

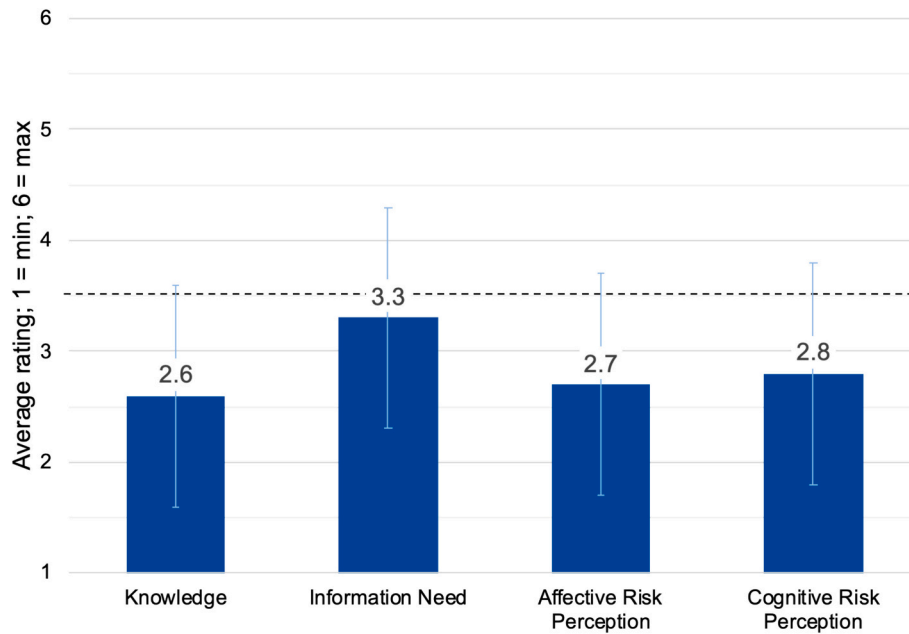


Fig. 4. General attitude (Mean and Standard Deviations) towards biofuels regarding knowledge and information need, as well as affective and cognitive risk perception of biofuels among the German public; $N = 508$.

differences on the origin variables were significant ($p < .01$), except for knowledge between *Concerned Curious* and *Calmly Curious* (n.s.; see Table 2).

4.2.1. Cluster differences in individual factors

Apart from the major goal—the identification of cluster groups—we examined individual factors to identify group-specific characteristics relevant to risk communication. The identified clusters were investigated for differences in individual factors, including socio-demographic characteristics and attitudinal variables (Environmental consciousness, EC; Climate change awareness, CCA; Institutional trust, IT; General risk propensity scale, GRIPS).

The comparative analysis of *sociodemographic factors* in the three clusters revealed only one significant effect: a slightly higher proportion of females in the *Concerned Avoiders* (58.3%) cluster compared to both *curious* clusters (*Concerned Curious*: 44.2%; *Calmly Curious*: 47.6%). No other socio-demographic differences emerged (see Appendix).

Attitudinal factors, by contrast, revealed clear differences between the

three cluster groups. The *Concerned Avoiders* scored significantly lower on environmental consciousness ($M = 3.4$, $SD = 1.3$, $\chi^2(2) = 44.32$, $p < .001$), climate change awareness ($M = 4.0$, $SD = 1.2$, $\chi^2(2) = 12.95$, $p < .01$), institutional trust ($M = 2.6$, $SD = 1.0$, $\chi^2(2) = 39.35$, $p < .001$), and general risk propensity ($M = 2.1$, $SD = 1.0$, $\chi^2(2) = 21.18$, $p < .001$) compared to both *curious* clusters (*Concerned Curious* and *Calmly Curious*). The difference in climate change awareness between *Concerned Avoiders* and *Concerned Curious* was not significant in post-hoc comparisons (see Fig. 6 & Table 2).

Interestingly, despite these group differences, all clusters displayed similar overall patterns regarding the observed variables in terms of increased (>3.5), decreased (<3.5), or moderate levels ($=3.5$). All clusters demonstrated increased levels of CCA ($p < .001$), as well as decreased levels of IT ($p < .001$) and GRIPS ($p < .001$). Only the *Concerned Avoiders* displayed moderate levels of environmental consciousness (n.s. vs. midpoint) (see Table 2).

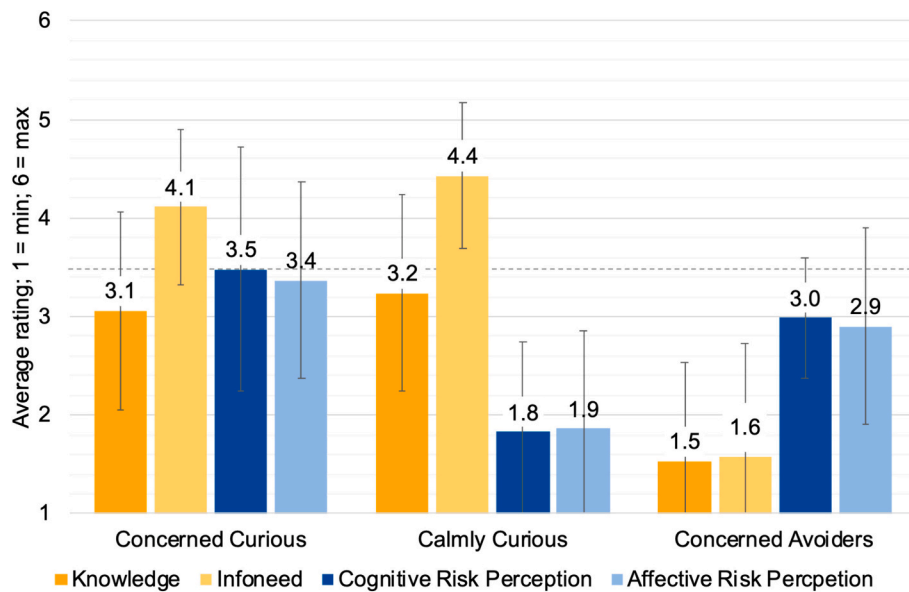


Fig. 5. Results of the cluster analysis based on knowledge, information need and cognitive and affective risk perception of biofuels, revealing three different clusters as target-groups for risk communication: Concerned Curious ($n = 165$), Calmly Curious ($n = 168$) and Concerned Avoiders ($n = 175$); dashed line represents midpoint of scale (3.5) and error bars indicate standard deviation (SD); $N = 508$.

4.2.2. Cluster differences in biofuel perceptions and willingness to use usage evaluation

In the final step, the clusters were examined with regard to their evaluations of biofuel use, including overall *willingness to use biofuels* as well as *perceived threats and benefits* (see Fig. 7 & Table 2).

The analysis indicated that the *Calmly Curious* expressed the most favorable views. They reported the highest WTU ($M = 4.7$, $SD = 1$, $t = 16$, $p < .001$) and the highest evaluations of perceived benefits ($M = 4.4$, $SD = 1.1$ – 1.3 , $t = 5.2$ – 9.7 , $p < .001$). They consistently showed lowered perceptions of potential threats ($M = 2.3$ – 2.6 , $SD = 1.1$ – 1.2 , $t = -14$ to -10 , $p < .001$). The only exception concerned the perception of financial benefits ($M = 2.8$, $SD = 1.4$, $t = -6.2$, $p < .001$) which were rated below the midpoint, ($M = 2.8$, $SD = 1.4$, $t = -6.2$, $p < .001$). Overall, the *Calmly Curious* demonstrated the strongest opposition to all potential threats posed by biofuel usage while simultaneously expressing the highest level of support for biofuel benefits (except financial benefits), contrasting sharply with the *concerned* clusters ($\chi^2(2) = 13.9$ – 113.5 , $p < .01$ – <0.001 ; see Table 2).

The *Concerned Avoiders* represented the most skeptical segment. They reported the lowest willingness to use biofuels ($M = 3.2$, $SD = 1.4$, $t = -2.7$, $p < .01$) and reported the lowest financial benefit perceptions ($M = 2.1$, $SD = 1.3$, $\chi^2(2) = 26.8$, $p < .01$). Their risk perceptions were consistently lowered, both affective ($M = 2.9$, $SD = 1.2$, $p < .001$) and cognitive ($M = 3.0$, $SD = 1.1$, $p < .001$).

The *Concerned Curious* were characterized by an ambivalent position. They expressed a medium willingness to use biofuels ($M = 3.6$, $SD = 1.2$, n.s.), but simultaneously reported the highest threat perceptions, especially regarding health and environmental risks ($\chi^2(2) = 59.4$ – 64.9 , $p < .001$). Both affective ($M = 3.4$, $SD = 0.9$) and cognitive ($M = 3.5$, $SD = 0.8$) scores were moderate (n.s. vs. midpoint).

Despite these significant cluster profile differences, the two *concerned* clusters (*Concerned Avoiders* and *Concerned Curious*) both reported a comparatively lower willingness to use biofuels than the *Calmly Curious* (*Concerned Curious*: $M = 3.6$, $SD = 1.2$, n.s.; *Concerned Avoiders*: $M = 3.2$, $SD = 1.4$, $t = -2.7$, $p < .01$). In both groups, financial benefits received the lowest ratings (*Concerned Curious*: $M = 2.8$, $SD = 1.4$, $t = -6.2$, $p < .001$; *Concerned Avoiders*: $M = 2.1$, $SD = 1.3$, $\chi^2(2) = 26.8$, $p < .01$). Moreover, both clusters perceived biofuel use as more threatening than beneficial, with elevated risk perceptions compared to the *Calmly Curious*. While the *Concerned Curious* perceived moderate health and

environmental threats, the *Concerned Avoiders* showed lowered, consistent risk perceptions across dimensions.

Across all clusters, financial benefits were consistently rated as the least favorable aspect of biofuel utilization. Among the decreased to medium perception of potential threats, the ecological threat was the highest perceived threat by the clusters.

5. Discussion

Overall, this study aimed to investigate the importance of considering public perceptions next to knowledge levels when setting up effective risk communication attempts in the context of sustainable fuel alternatives. Linking a conceptual approach for general risk communication insights with practical implications for biofuel risk communication, we focused our study on insights from a representative sample of German laypersons. The highlights of our study embedded in the theoretical background can be found in the following chapter.

5.1. Public knowledge, information needs, and risk perception of biofuels

Supporting the findings of other cultural and national backgrounds [14,56], our results confirm that public knowledge about biofuels in Germany remains low. Despite this, we found a relatively positive perception of biofuels in terms of decreased cognitive and affective risk perception, as well as a moderate willingness to use biofuels. This indicates that limited knowledge does not necessarily lead to negative perceptions and attitudes. This is consistent with earlier research showing that laypeople often hold favorable views of biofuels despite limited knowledge and familiarity (e.g., [7]). Interestingly, the information need was lower than suggested by prior research [57], which may reflect the overshadowing of biofuel debates, for example, by other alternative driving technologies like electric vehicles (EVs) or e-fuels. Scherrer [24] found EVs to be the most covered topic in a media analysis on alternative fuel vehicles between 2018 and 2020 in Germany, likely to raise public awareness and positive perception. In contrast, biofuels received limited attention in the media debate so far, which may explain why the German public expressed moderate willingness to use them but only limited demand for further information.

Our results suggest that biofuels occupy a paradoxical position. While they are already part of the fuel mix and are considered an

Table 2

Characteristics of the three clusters (Mean, Standard Deviation, and deviation from midpoint of scale tested with one-sample *t*-tests) and test statistics of group differences tested with independent sample Kruskal-Wallis tests; *N* = 508.

Variables	Cluster (% , number of cases)												Group differences				
	Concerned curious (33%, <i>n</i> = 165)				Concerned avoiders (35%, <i>n</i> = 175)				Calmly curious (33%, <i>n</i> = 168)				Test statistic		Concerned curious vs. concerned avoiders	Concerned curious vs. calmly curious	Calmly curious vs. concerned avoiders
	<i>M</i>	<i>SD</i>	Deviation from 3.5		<i>M</i>	<i>SD</i>	Deviation from 3.5		<i>M</i>	<i>SD</i>	Deviation from 3.5						
			<i>t</i>	<i>p</i>			<i>t</i>	<i>p</i>			<i>t</i>	<i>p</i>	χ^2 (df)	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Cluster variables																	
Knowledge	3.06	1.1	−5.28	<0.001	1.53	0.8	−33.21	<0.001	3.24	1.2	−2.74	<0.01	193.08 (2)	<0.001	<0.001	0.372	<0.001
Information Need	4.11	0.9	8.59	<0.001	1.58	0.8	−34.12	<0.001	4.43	0.9	13.09	<0.001	339.32 (2)	<0.001	<0.001	0.019	<0.001
Cognitive Risk																	
Perception	3.48	0.8	−0.31	0.761	2.99	1.2	−5.85	<0.001	1.83	0.6	−35.39	<0.001	185.72 (2)	<0.001	<0.001	<0.001	<0.001
Affective Risk																	
Perception	3.38	0.9	−1.80	0.073	2.90	1.2	−6.61	<0.001	1.86	0.7	−32.00	<0.001	223.7 (2)	<0.001	<0.001	<0.001	<0.001
Individual factors																	
Attitudinal variables																	
Environmental																	
consciousness	4.17	1.0	8.02	<0.001	3.43	1.3	−0.672	0.503	4.27	1.1	9.164	<0.001	44.32 (2)	<0.001	<0.001	0.278	<0.001
Climate change																	
awareness	4.23	1.0	8.385	<0.001	4	1.2	5.423	<0.001	4.46	1.1	−3.634	<0.001	12.95 (2)	0.002	0.107	0.052	<0.001
Institutional trust	3.12	1.0	−4.989	<0.001	2.61	1.0	−11.61	<0.001	3.24	0.9	11.743	<0.001	39.35 (2)	<0.001	<0.001	0.116	<0.001
General risk																	
propensity scale	2.59	1.0	−11.44	<0.001	2.14	1.0	−17.48	<0.001	2.63	1.2	−9.19	<0.001	21.18 (2)	<0.001	<0.001	0.805	<0.001
Biofuel evaluation																	
Willingness to use	3.6	1.2	0.6	0.568	3.22	1.4	−2.7	0.008	4.65	0.9	16.02	<0.001	113.45 (2)	<0.001	0.104	<0.001	<0.001
Health threat	3.19	1.0	−4	<0.001	2.7	1.3	−8.28	<0.001	2.29	1.1	−14.22	<0.001	59.38 (2)	<0.001	<0.001	<0.001	<0.001
Ecological threat	3.56	1.1	0.766	0.445	2.91	1.2	−6.44	<0.001	2.55	1.2	−10.31	<0.001	64.85 (2)	<0.001	<0.001	<0.001	0.004
CO2 benefit	3.31	1.1	−2	0.021	3.35	1.3	−1.45	0.148	4.35	1.1	9.72	<0.001	75.65 (2)	<0.001	0.428	<0.001	<0.001
Industry benefit	3.22	1.0	−4	<0.001	3.1	1.3	−4.19	<0.001	3.96	1.1	5.19	<0.001	53.49 (2)	<0.001	0.669	<0.001	<0.001
Finance benefit	2.47	1.2	−11	<0.001	2.09	1.3	−14.40	<0.001	2.82	1.4	−6.23	<0.001	26.79 (2)	<0.001	0.002	0.047	<0.001
Jobs benefit	3.43	1.0	−0.878	0.381	3.23	1.2	−2.92	0.004	4.11	1.1	6.88	<0.001	50.19 (2)	<0.001	0.241	<0.001	<0.001
Fossil import benefit	3.53	1.2	0.304	0.761	3.53	1.4	0.24	0.808	4.36	1.3	8.42	<0.001	46.27 (2)	<0.001	0.904	<0.001	<0.001
Import benefit	3.68	1.2	2	0.057	3.55	1.3	0.55	0.585	4.04	1.3	5.42	<0.001	13.86 (2)	<0.001	0.508	0.005	<0.001

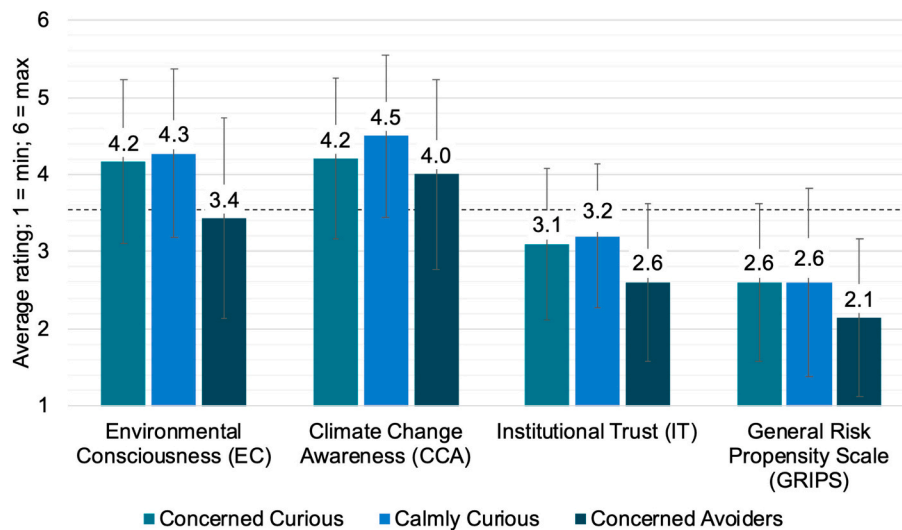


Fig. 6. Cluster Characteristics based on the individual factors environmental consciousness, climate change awareness, institutional trust, and general risk propensity (GRIPS); dashed line represents midpoint of scale (3.5) and error bars the standard deviation (SD); $N = 508$.

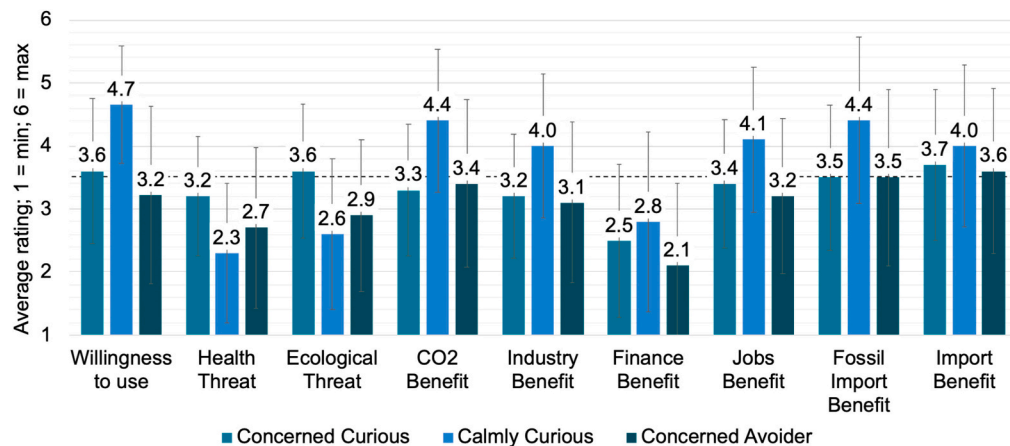


Fig. 7. Cluster characteristics based on willingness to use biofuels, and perceived risks (threats) and benefits with the usage of biofuels; dashed line represents midpoint of scale (3.5) and error bars the standard deviation (SD); $N = 508$.

important transitional technology, they remain comparatively invisible in public discourse. From a risk communication perspective, this highlights the importance of first raising public awareness of biofuels as a relevant option before more detailed communication strategies can address specific information needs or adoption barriers.

However, the low visibility of biofuels and limited public awareness and information-seeking behavior may also pose risks for future adoption. If public awareness remains low, misinformation and a lack of trust in political or scientific institutions—which was consistently observed across all clusters—could amplify concerns and ultimately lead to a rejection of biofuels [40]. Subgroups that actively avoid information about biofuels represent a particular challenge in this regard [e.g. on the effect of affect as in 58]. Their disengagement reduces the effectiveness of traditional communication approaches focused on knowledge transfer. Future research should therefore examine the motives behind such avoidance in greater detail to inform strategies that can mitigate polarization and information uptake resistance.

5.2. Target groups for biofuel risk communication

Contrary to the identified public knowledge gap and positive perceptions, our cluster analysis revealed a diversified pattern in the

underlying cluster groups. Three distinct segments were identified, each with different levels of knowledge, information needs, and risk perceptions, underlining that the public is not a homogeneous audience.

The *Calmly Curious* group was found to be the most supportive of biofuels. They had moderate knowledge levels, high information needs, and low risk perceptions, as well as the highest willingness to use biofuels. This segment appears receptive to communication that highlights the benefits of biofuels, particularly the ecological and climate-related advantages. However, financial benefits were consistently rated low, suggesting that monetary benefits may be less persuasive than environmental or societal benefits of biofuel usage.

The *Concerned Avoiders* represented the most skeptical group. They were characterized by very low knowledge, very low information needs, lowered risk perceptions, and the lowest willingness to use biofuels. Their low information need poses a particular challenge, as communication efforts may not reach or resonate with them. Information might even be avoided, a concept described by Kahlor [40], which suggests that some individuals actively disengage from risk-related communication. For this group, misinformation and low institutional trust could further amplify skepticism and hinder acceptance.

The *Concerned Curious* displayed an ambivalent profile. They reported moderate knowledge and high information needs, but

simultaneously expressed the highest (moderate) risk perceptions, particularly regarding health and environmental threats.

Comparing the clusters against theoretical assumptions reveals important insights. The *Calmly Curious* and *Concerned Avoiders* broadly support the assumptions of the knowledge-deficit model, which posits an inverse relationship between knowledge and risk perception [10]. However, the *Concerned Curious* challenge this relationship: despite higher self-reported knowledge, this group reported increased information needs and moderate but elevated risk perceptions. Similar findings have been reported for other emerging technologies, where higher knowledge levels were associated with stronger concerns [59–61]. This highlights that knowledge and risk perception are not linearly related but interact in complex ways.

From a theoretical perspective, the integration of risk perceptions into audience segmentation adds an important additional layer to target-group specification and shows that including knowledge deficits alone is not sufficient for target-group definition. Risk perceptions—even though no difference was found between the affective and cognitive dimensions—are essential to consider when developing communication strategies, as they can vary across different target groups and exhibit unpredictable dynamics in relation to self-assessed knowledge. This is in line with models of risk communication, such as the Risk Information Seeking and Processing Model (RISP; [13]), which explicitly highlights the role of affective and cognitive perceptions as predictors of information seeking or avoidance.

While risk communication is considered effective when risk perception has developed in a predefined manner among the target audience (either decreased for overrated risks or increased for underestimated risks), our results highlight the importance of considering risk perceptions additionally prior to communication efforts.

Our cluster solution extends previous work on target-group segmentation in the context of risk communication of biofuels. Balogh et al. [14] identified three groups (*supporters*, *irresolute*, and *skeptics*) based on objective knowledge and interest. Their clusters broadly differentiated positive, neutral, and negative orientations, but did not account for risk perceptions as an additional explanatory factor. Offermann et al. [8] proposed two segments (*car lovers* and *public transport enthusiasts*), focusing on mobility behavior, communication preferences, and trust in information sources. While these approaches provided valuable insights, they either emphasized knowledge and attitudes [14] or lifestyle-related characteristics [8].

In line with these studies, our cluster characteristics could not be differentiated on sociodemographic variables such as age, gender, or income. This suggests that socio-demographics are not essential predictors for communication efforts. Instead, consistent with prior work on alternative fuel perceptions [62], individual characteristics such as environmental consciousness, trust, and risk perception are a more reliable basis for segmentation, especially for the avoider group. While our avoider group showed moderate environmental awareness and higher climate change awareness, revealing similar results to those of Balogh et al. [14] regarding increased environmental awareness among biofuel skeptics, this group was clearly distinct from the curious clusters. Regarding these environmentally motivated attitudes, as well as institutional trust and risk propensity, the avoiders expressed significantly lower levels.

Our study contributes to this line of research by introducing risk perceptions as a central segmentation variable alongside knowledge and information needs. This approach revealed a previously overlooked ambivalent group—the *Concerned Curious*—that would not have been captured in knowledge- or preference-based typologies alone. The identification of this group underscores that heterogeneity within “concerned” publics is important to consider, since not all skeptics disengage. Some of them remain information-seeking and thus addressable in communication efforts.

While novel studies generally challenge the concept of relying on knowledge deficits for communication efforts (e.g., [33,63,64]), and

highlight the need for considering perceptions, including those in target group segmentation, was—to our knowledge—a novel approach. This methodological approach enabled us to obtain a diversified picture of perception and knowledge at an early stage of target group analysis for biofuel risk communication. While the *Concerned Avoiders* and *Calmly Curious* indicate the contrasting relationship between perception and knowledge in terms of the knowledge deficit approach, the *Concerned Curious* emerged with counteracting specifics, as already outlined before. The interplay of knowledge, information need, and public (risk) perceptions, therefore, does not seem to be universally determinable, but varies on an individual level and must therefore be constantly monitored and observed when considering related research approaches.

Taken together, our findings emphasize that target-group definitions in risk communication should not rely solely on knowledge levels. Instead, perceptions—and their interplay with information needs—provide valuable insights into how audiences engage with technologies such as biofuels.

5.3. Implications for target-group-specific risk communication

The identification of three distinct audience segments has important implications for the design of biofuel communication strategies. Our results indicate that each segmented target group requires a differentiated communication approach that accounts for their specific knowledge levels, information needs, and patterns of risk perception.

With high willingness to use biofuels, high information needs, and low risk perceptions, the *Calmly Curious* represent a generally supportive audience. Communication could build on their openness by emphasizing ecological and climate benefits, positioning biofuels as a meaningful complement to other sustainable technologies. It can be theorized that this group will prove to be relevant for industry and developers, since these may represent earlier adopters, who can be engaged through transparent product information and sustainability certification or labels (e.g., label for CCU by [65]). Policy communication should strengthen this group's role as potential adopters by providing clear long-term policy commitments.

The ambivalent segment of the *Concerned Curious* combines moderate knowledge and high information needs with elevated risk perceptions. They are critically interested and require balanced, transparent communication of risks and benefits. For developers, this could mean specifically addressing risks and uncertainties about feedstocks, environmental trade-offs, and long-term impacts in a credible way, rather than focusing on benefits or promotional narratives. Industry actors should also avoid framing communication exclusively around benefits, as this may increase mistrust. Instead, engaging in dialogue formats or participatory initiatives could be more promising to address the needs of this group. Policymakers can support this group by providing evidence-based, independent information platforms and by acknowledging controversies in debates (e.g., food vs. fuel debates) to reduce skepticism.

The group of *Concerned Avoiders* is disengaged, with low knowledge, very low information needs, and low willingness to use biofuels. They are unlikely to respond to conventional communication campaigns. For developers and the industry, direct communication efforts might have little effect; instead, indirect strategies are needed, such as embedding biofuels into broader sustainability narratives (e.g., mobility transitions) or working with trusted intermediaries (NGOs, consumer associations). Policy communication should not prioritize detailed knowledge transfer here, but focus on building long-term trust through transparent regulation, third-party certification, and highlighting societal benefits in practice.

Across all groups, two cross-cutting findings are further important. First, institutional trust was generally low. Communicators should therefore know about trust-promoting factors and rely on independent, credible messengers, such as scientists, NGOs, or consumer organizations, rather than industry alone. Second, financial arguments were consistently rated low. Instead, communication should highlight the

environmental, health, and societal benefits of biofuels, which might be persuasive across clusters.

In sum, the results suggest that effective risk communication for biofuels must be audience-specific, transparent, and trust-oriented. Rather than one-size-fits-all approaches, communication should recognize the diversity of the public.

5.4. Considerations for future research

Our study provided new insights into target group segmentation and the importance of knowledge, information needs, and risk perception for risk communication. Future research can build on the foundations laid in this study regarding several aspects. Based on one of the main results, the importance of including perceptions in target group segmentation, risk perception should be examined in more detail, for example, by including perceived relevance of threats and benefits of laypersons as segmentation variables. Additionally, our research approach for identifying target groups based on knowledge and perceptions for risk communication should be tested in other application fields (e.g., health risks or natural risks) or with other sustainable technologies (e.g., other alternative fuels or innovative production steps like CCU), revealing further insights into the proposed diversified interplay between these variables.

Regarding our methodological approach, it may be advantageous to expand the attitudinal factors used to identify cluster characteristics by adding further variables, such as subjective norms [58] or the distinction between factual and subjective knowledge [14]. Beyond that, since we have chosen to employ 6-point Likert scales without a neutral midpoint, it would be worthwhile to examine whether equivalent findings would be obtained by employing scales with a neutral midpoint, such as the five- or seven-point Likert scale. Lastly, although we were able to reveal distinct communication target groups, in the future, empirical research should test whether specified communication efforts significantly affect perceptions of the targeted audience.

6. Conclusion

This study examined how knowledge, risk perceptions, and information needs can be used to identify communication-relevant target groups for risk communication on biofuels. Based on a representative sample of the German public, three audience segments were identified that differ significantly in subjective knowledge, information needs, and risk perceptions: *Calmly Curious*, *Concerned Curious*, and *Concerned Avoiders*.

Overall, self-assessed knowledge about biofuels was low in all groups, while risk perceptions were low to moderate, and willingness to use biofuels was positive to neutral. The segmentation results demonstrated that including affective and cognitive risk perceptions provides substantial added value, as it allows for the identification of distinct subgroups that would remain concealed under a knowledge-based segmentation: two groups with similarly high information needs could only be distinguished by their perception of potential risks: the *Calmly Curious* with low risk perceptions and the *Concerned Curious* with moderate risk perceptions. The third group, the *Concerned Avoiders*, showed very low knowledge levels, very low information need, and the lowest willingness to use biofuels, indicating a disengaged subgroup that is difficult to reach with information-based communication approaches.

These findings contribute to research on risk communication and audience segmentation by showing that knowledge alone is insufficient for identifying meaningful target groups. In line with theoretical models such as the Risk Information Seeking and Processing Model (RISP) [13] and the Planned Risk Information Seeking Model (PRISM) [40], the results demonstrate that risk perceptions are a central and distinct dimension that shapes how individuals interpret information and whether they engage with it. By integrating risk perception as an additional factor, the study extends existing segmentation approaches

beyond knowledge-centered perspectives.

These findings show that audience heterogeneity must be considered when designing biofuel communication. Rather than assuming a homogenous audience, communication strategies should be based on systematically derived target groups that reflect segment-specific combinations of knowledge, information needs, and risk perceptions. In particular, communication addressing the *Concerned Curious* should include transparent information on risks and environmental trade-offs, whereas for the *Calmly Curious*, benefit-focused communication is recommended. For the *Concerned Avoiders*, conventional knowledge provision appears less suitable due to their low information motivation.

While this study focuses on biofuels, the findings are transferable to other innovative energy technologies that raise heterogeneous public perceptions, such as hydrogen technologies or carbon capture and storage. The proposed approach, therefore, provides a generalizable basis for identifying communication-relevant target groups in the context of sustainable energy transitions.

However, several limitations must be considered. First, the cross-sectional design does not allow for conclusions about causal relationships between knowledge, risk perceptions, and information needs. Second, the use of self-reported measures may be subject to biases such as social desirability or subjective misestimation. Third, the study focuses on the German population, which may limit the generalizability of the results to other socio-cultural contexts. Finally, the cluster analysis follows an exploratory approach, and the identified group structures should be validated in future studies.

Based on these findings, future research should investigate how communication strategies tailored to identified target groups affect engagement, trust, and behavioral intentions. Experimental and longitudinal designs are needed to examine whether segmentations based on knowledge, risk perceptions, and information needs improve the effectiveness of risk communication over time.

By integrating risk perceptions into segmentation, this study advances existing approaches by demonstrating how communication-relevant target groups can be systematically derived from multiple perception-related dimensions. This provides a more differentiated and theoretically grounded basis for developing targeted risk communication strategies that extend beyond knowledge-based approaches.

CRedit authorship contribution statement

Regina Gimpel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katrin Arning:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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

During the preparation of this work, the authors used an AI language model from OpenAI to improve language quality and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Regina Gimpel reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2026.104793>.

Data availability

Data will be made available on request.

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