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Harmful or Beneficial to Humans and the Environment? An Empirical Study on the Social Acceptance and Risk Perception of CO_2-Based Fuels

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Risk analysis and assessment of toxic effects are important elements to be considered in the development of renewable fuels, such as CO_2-based fuels made from CO_2, water, and renewable energy. However, the successful introduction of CO_2-based fuels could also be affected by public concerns about possible risks and adverse effects on health and the environment. In order to examine risk perceptions of laypeople for CO_2-based fuels and to understand if they can act as a barrier for the public acceptance of these fuels, we carried out an online survey with German laypeople. A special focus was placed on perceptions of toxic effects such as beliefs about exposure pathways and resulting health impacts, but also on participants' openness towards CO_2-based fuels. Results showed that CO_2-based fuels were seen as an acceptable and beneficial technology and risks were perceived to be low. By tendency, lower risk perceptions were related to a higher acceptance of CO_2-based fuels. The overall risk judgment was impacted by fears about toxic effects, concerns about environmental pollution, and the perceived general harmfulness of CO_2-based fuels. The general openness towards CO_2-based fuels was revealed to affect risk perceptions and beliefs about toxic effects: A higher openness towards the topic was linked to less severe concerns about CO_2-based fuels. The findings from this study provide valuable insights on how to develop communication concepts to inform laypeople about possible risks and benefits of CO_2-based fuels to address their concerns and information demands and give them a better understanding of the effects of toxic substances on different risk targets.

Keywords: social acceptance, risk perception, CO_2-based fuels, perceived toxic effects, user diversity

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1 INTRODUCTION

CO_2 emissions are major contributors to climate change and cause high pollutant emissions such as NOx that deteriorate air quality. For a decarbonization of the transport sector (Edenhofer et al., 2014; United Nations Environment Programme, 2019), the consequent reduction of emission types is an urgent challenge for research and industry efforts. Alternative fuels have the potential to reduce CO_2 and pollutant emissions in road transport, shipping, and aviation (Ramachandran and Stimming, 2015; Yilmaz and Atmanli, 2017; Gilbert et al., 2018). They can be produced from biomass (biofuels) or CO_2, water, and renewable electricity (e-fuels or CO_2-based fuels). Both approaches can also be combined in the production of bio-hybrid fuels

(König et al., 2019; Lehrheuer et al., 2019). Factors considered in the selection of fuel candidates and their production processes are their technical and economic feasibility and environmental effects, such as the global warming impact (König et al., 2020).

Though CO_2-based fuels can have favorable environmental effects compared to conventional fuels, e.g., contributing to defossilization in the transport sector and lowering greenhouse gas and pollutant emissions, especially when renewable energy is used for fuel production (Deutz et al., 2018; Albrecht and Nguyen 2020), the high production costs could be an obstacle to their economic viability and competitiveness to conventional diesel and gasoline (Ueckerdt et al., 2021).

Moreover, potential toxicity is an important parameter to be taken into account in the selection of fuel candidates (Heger et al., 2018). Another aspect that may impact the successful uptake of innovative fuel solutions is their social acceptance: At least a passive tolerance of the fuel production infrastructure and the active willingness of drivers to use these fuels is required (Chin et al., 2014).

Thus, the roll-out of alternative fuels will not only depend on their actual toxicity and effectiveness as evaluated by ecological and technical experts but might also be affected by laypeople's social acceptance, their risk perceptions and concerns, e.g., on human health and the environment (Neil et al., 1994; Slovic, 2015) as well as their willingness to use alternative fuels. So far, little is known about the drivers and barriers that influence the social acceptance of alternative fuels. Past research in the mobility and energy sector has identified lay risk perceptions as a vital barrier to the favorable reception of novel technologies [e.g., hydrogen technologies (Itaoka et al., 2017; Ono and Tsunemi, 2017) and biofuels (Fung et al., 2014)]. Therefore, in the present study we examine if laypeople's risk perceptions with regard to feared toxic effects might act as a barrier to the acceptance of CO_2-based fuels. In this paper, we focus on risk perceptions regarding CO_2-based fuels because they allow for a lower global warming potential although their production is more expensive than for biofuels (König et al., 2019).

Based on the results, recommendations for fuel and toxicity research are derived on how the needs and concerns of the public can be considered in the selection of fuel candidates for a more sustainable road transport. Also, guidelines for information and communication concepts can be developed to make the public familiar with CO_2-based fuels and address laypeople's concerns appropriately.

2 STATE OF RESEARCH ON CO_2-BASED FUELS

In this chapter, the state of research on CO_2-based fuels regarding toxic effects (**Section 2.1**) and regarding acceptance and risk perception (**Section 2.2**) is described.

2.1 Potential Toxicity Risks of Fuels on the Environment and Human Health

Fuels are produced and burned to produce energy for our modern life, and we pay money for fuels to make our lives more comfortable, lighting our house and driving cars around. However, there are hidden costs of fuels not included in their market price, referring to significant impacts on human health and the environment. There are serious consequences at every point of the fuel supply chain. Fuels production could generate pollutants into air and water, harming the local ecosystem. Fuel transportation can lead to severe accidents and spills, contaminating drinking water and affecting human health. Burning fuels can release toxic chemicals and greenhouse gases into the air, causing asthma and cancer as well as global warming (Union of Concerned Scientists, 2016). Moreover, occupational high-level exposure to fuel vapors or exhaust could cause cytogenetic damages in peripheral lymphocytes and chromosomal aberrations (Carere et al., 1995; Cavallo et al., 2006). Thus, it is urgent to develop sustainable and less harmful alternative fuels for meeting future energy challenges.

To avoid dangerous chemicals getting into the environment, the potential risks of alternative fuels on the environment and human health should be taken into considerations in early product development. This is important not only for the economic and environmental perspective but also for public acceptance. For humans, there are three possible exposure routes to fuels–inhalation, ingestion and dermal exposure–which can affect human health. Ingestion exposure can occur *via* biotic uptake and accumulation from fuel-contaminated water or livestock (fish and vegetables); dermal exposure can result from skin contact with fuels or fuel-contaminated environmental media; inhalation exposure occurs *via* breathing air contaminated with fuel exhaust or fuel vapors (Reese and Kimbrough, 1993). The primary exposure route to fuels for most humans is inhalation, and air pollution related to fuel exhaust has been linked to respiratory infections, acute vascular dysfunction, heart disease and lung cancer (Lucking et al., 2008).

2.2 Public Perception and Acceptance of CO_2-Based Fuels

For a successful development of innovative sustainable fuel solutions, social acceptance and risk perceptions by laypeople are an essential element. Especially in the field of renewable energy development (e.g., wind farms or Carbon Capture Storage projects), local protests showed that the transformation of the energy and mobility system can only succeed if all actors–from the local to the global level–accept it (Terwel et al., 2012; Wolsink, 2018).

Characteristically, (non-)acceptance contains an attitude-dimension (ranging between a positive and a negative pole) and can take the form of approval, tolerance, indifference, or rejection of a technical innovation (Schweizer-Ries, 2008). It can also include a behavioral dimension, e.g., the purchase or use of a product or the protest against the roll-out of an infrastructure (Davis et al., 1989). In the acceptance model by Huijts et al. (2012), developed and validated in the context of renewable energy technologies, acceptance is influenced by a variety of factors such as perceived risks, perceived costs, and benefits, as well as positive and negative feelings towards the energy technology. Also, person-related factors affect acceptance and the willingness to use renewable energy technology, e.g., the experience and the previous knowledge in the context of the respective technology, but also affective factors and felt risks, as the fear of harm, or the concern of extra costs by long-term technology usage. Such risk perceptions can vitally affect the acceptance of a technology (Bearth and Siegrist, 2016; Itaoka et al., 2017). However, the evaluation of risk is different for laypeople and technical experts (Renn, 2004): Whereas experts apply criteria quantifiable in numbers such as the probability with which a negative outcome might occur and the number of annual fatalities (Slovic et al., 1982), risk and benefit perceptions of laypeople are less fact-based and contain both, cognitive and affective components (Slovic and Peters, 2006; Linzenich et al., 2019; Arning et al., 2020).

2.3 Risk Perception and Acceptance of CO_2-Based Fuels

'Risk perceptions' are subjective assessments of risks, i.e., the perceived probability and the potential (negative) outcome of an adverse event (Slovic, 1987) in contrast to the concept of 'risk,' i.e., the probability distribution of an adverse event and the magnitude of its consequences (Renn and Benighaus, 2013). In line with Slovic et al. (1982), laypeople base their risk perceptions on evaluations how dreaded (catastrophic or fatal consequences), controllable, and voluntary for those exposed these risks are and if they are well-known and observable, how immediately possible negative consequences occur, and regarding the number of individuals affected (including how much oneself is exposed to the risk). In case of CO_2-based fuels perceived toxic potential can have an influence on perception and acceptance, if, for example, the mental model prevails that damage is caused to various risk targets due to increased levels of harmfulness of CO_2-based fuel usage compared to conventional fuels (e.g., Engelmann et al., 2020). A study by Offermann-van Heek et al. (2017) found low risk perceptions since CO_2-based fuels were not seen as harmful for the environment. Also, Arning and Ziefle (2020) revealed a basically positive perception of alternative fuels, even though conventional fuel drivers evaluated alternative fuels less positively than early adopters, who already use new fuel types.

As the knowledge on CO_2-based fuel acceptance is still scarce, a look should be taken on studies from related contexts, e.g., biofuels and CCU (Carbon Capture and Utilization). CO_2-based fuels and biofuels are both made from alternative, renewable feedstock and might evoke similar concerns. Previous research on biofuels has investigated perceived risks for the environment and humans (e.g., Van de Velde et al., 2011; Winden et al., 2014). Considered environmental effects included concerns about sustainability, e.g., suitability as long-term solution to challenges in the energy sector, a possible competition to renewable energies, the resource use for producing biofuels, and negative effects on plants/wildlife and the quality of air, land, and water (e.g., Binder et al., 2012; Winden et al., 2014). Examined risk perceptions for humans referred to health and social impacts (e.g., Van de Velde et al., 2011; Winden et al., 2014). Moreover, economic risks in terms of higher food and fuel prices in acceptance have been studied (Binder et al., 2012). Winden et al. (2014) found that people were even willing to pay surcharges for biofuels if risks for the environment and human health were reduced. On top of that, results showed that people would pay a higher surcharge for lower health impacts compared to lower environmental effects.

Also, studies on public perceptions of Carbon Capture and Utilization (CCU) might yield insights for the perception of CO_2-based fuels because in both cases products made from CO_2 are focused. Studies on CCU risk perceptions have revealed a moderate to low risk associated with CCU production plants and CCU products (e.g., Perdan et al., 2017; Arning et al., 2019; Linzenich et al., 2019). Laypeople's concerns were related to a release/leakage of CO_2 during its transport to the production plant, the usage and the disposal of the CCU product, and to the possible resulting environmental and health effects (e.g., Van Heek et al., 2017; Perdan et al., 2017). Higher risks were seen for the production of CO_2-derived products, especially for the short-term storage of CO_2 before it is used in the manufacturing process as well as for the disposal of the CO_2-derived product compared to the product use (Arning et al., 2019).

2.4 Risk Perceptions Regarding Toxic Impact

Risk perceptions can refer to different targets perceived at risk, e.g., nature, wildlife, society, risks for human health in general, for family, friends, and oneself (McDaniels et al., 1995; Sjöberg, 2000). These risk targets, which from a technical point of view are to be evaluated as the entities to be protected from toxic influences, are an important factor in risk perception research. An effect of 'risk denial' was revealed in previous risk perception research (Sjöberg, 2000) with individuals thinking they are less at risk when exposed to a technology compared to other people. Furthermore, perceived overall risk can evolve from different risk sources, e.g., accident risks, negative health effects, environmental damage, financial, social, and sustainability risks, as found, for example, for Carbon Capture and Storage (CCS) (L'Orange Seigo et al., 2014; Upham and Roberts, 2011) and transmission lines (Nelson et al., 2018). Another risk-relevant aspect can be fear of toxic effects of a substance. This even often irrationally fear caused by chemicals in daily goods is described as 'chemophobia' (Gribble, 2013). Regardless of whether these fears of toxic substances are justified or not, those risk perceptions can influence the acceptance and adaptation of technologies or products. There is already a broad knowledge base on perceived harmfulness of products and technologies (e.g., feared harmfulness of leaking CO_2 with health impacts such as allergies or problems caused for one's circulatory system in case of CCU (van Heek et al., 2017), but so far only one study has investigated feared toxic effects in the context of CO_2-based fuels (Engelmann et al., 2020).

Perceptions of toxic impacts can be broken down along two dimensions. On the one hand there are the entities or *sources* (object, consumer good, or technology) from which a toxic effect emanates or appears to emanate (dimension 1). For example, in the field of consumer goods, genetically modified crops and contaminants that enter food during the production process were found to cause concerns for human health (Hallman et al., 2003; Kher et al., 2013). Another field from which a toxic effect can be assumed is polluted air. It was found that laypeople often assume that in case of air pollution due to fires the toxic effects of inhaling smoke depend on the type of burning material and that they overestimate the possible consequence of developing cancerous diseases subsequently (Greven et al., 2018). Finally, perceived air pollution was found to significantly influence perceived health consequences (Orru et al., 2018).

On the other hand, the focus is on those risk *targets* that might be affected by perceived toxic impacts (dimension 2), most notably human health and the environment. Environmental threats which are perceived to be a consequence of the spread of harmful substances were, for example, found in a study focusing on plug-in electric vehicles (Axsen et al., 2017). Trade-offs were identified since electric vehicles were perceived to be more environmentally friendly due to the fact that their usage causes no direct air pollution; at the same time, the potential toxic effect and difficult recycling of the batteries used was identified as a perceived disadvantage. A second relevant risk target is human health. Health impacts are feared due to contact with contaminants through food (Hallman et al., 2003). Another area in which a number of results have been obtained is the feared consequences for human health caused by the use of fossil fuels and resulting air pollution. It was found that for parents of young children an increase in knowledge about health effects of air pollution for children impacts attitudes regarding fossil resource use negatively (Hanus et al., 2018). This perception of possible consequences for human health as a risk target is emphasized by findings of connections between public's knowledge and the willingness to reduce personal car use (Wang et al., 2019). The fear of adverse health effects has proven as an important reason for opposition to novel technologies across a variety of technologies, e.g., mobile phone base stations (Drake, 2006), wind farms (Reusswig et al., 2016), and transmission lines (Nelson et al., 2018).

2.5 Research Questions

To investigate the perception of CO_2-based fuels by laypeople specifically focusing on toxic effects, the present paper pursued the following research questions.

Q1. How are CO_2-based fuels perceived in terms of risks and benefits for human health and the environment (especially their toxic potential)?

Q2. Which factors (technology-related perceptions, user factors) impact the social acceptance and risk perception of CO_2-based fuels?

Q3. How does openness towards CO_2-based fuels impact the perception of risks and benefits for human health and the environment?

Q4. How does openness towards CO_2-based fuels impact laypeople's beliefs about exposure pathways and resulting health impacts caused by toxic effects of CO_2-based fuels?

3 MATERIALS AND METHODS

Benefit and risk perceptions regarding health- and environmental effects from CO_2-based fuels were assessed by means of an online questionnaire which was distributed in December 2019 in Germany. Prior to participating in the study, respondents were informed that their participation was completely voluntary and that they could terminate their participation any time. The participants were not reimbursed for taking part in the study. A high standard privacy protection was ensured and data collection and analysis were carried out completely anonymously so that none of the answers can be referred back to individuals. Ethics approval from an ethics committee was not sought, as the study falls in the category of non-invasive, non-clinical research on human subjects with reasonably low risks, that transparently provides subjects with information about the purpose, aim, and risks of the conducted studies, in the case of which no such approval is necessary in Germany.

3.1 Questionnaire

The questionnaire was structured in five parts (see **Figure 1**). The complete list of questionnaire items can be found in the **Supplementary Appendix**. Item analysis statistics are displayed in **Table 1**.

In the first part of the questionnaire respondents were surveyed for person-related factors (demographics, car use behavior, and attitudinal variables). As attitudinal variables participants' environmental awareness (with a special focus on mobility) and their attitude towards car use in general were assessed. Environmental awareness was measured by seven items (Diekmann & Preisendörfer 1998; Dunlap et al., 2000; Schahn 2000; Heath and Gifford 2006; European Commission 2008; Spence and Pidgeon 2010) that capture attitudes towards environmental protection and climate change as well as environment-related mobility behavior. The general attitude towards car use was assessed by four items adapted from Steg (2005).

The second part of the questionnaire aimed at eliciting persons' general evaluation of the toxic impact of fuels on the environment and human health (without referring to any specific type of fuel). This was done to identify the personal 'baseline' of concerns towards toxic effects linked to fuel-based mobility for each respondent using ten items from a study by Saleh et al. (2019) on toxicity perceptions of chemical substances, which were adapted to the fuel context.

The third and fourth part of the questionnaire focused on perceptions and openness towards CO_2-based fuel in specific. First, knowledge and interest in CO_2-based fuels were assessed by three items (see **Supplementary Appendix**). Next, perceptions of CO_2-based fuels were measured using the semantic differential technique (Osgood et al., 1957). CO_2-based fuels had to be evaluated on eleven different evaluative dimensions–each represented by a bipolar adjective pair (e.g., inefficient/efficient) relating to acceptance, perceived benefits, costs, and risks (see **Figure 2**)–on a scale from 1 (= negative adjective) to 10 (= positive adjective). The adjectival scales were selected based on previous literature (Chin et al., 2008; Zaunbrecher et al., 2016; Linzenich et al., 2019; Jansen et al., 2020) and an interview pre-study on alternative fuel perceptions. Six of the adjectival scales were directed at

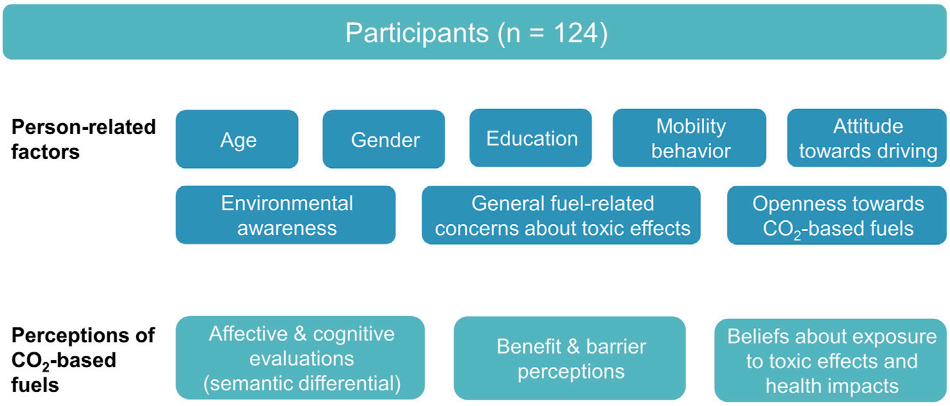

FIGURE 1 | Structure of the online questionnaire.

TABLE 1 | Item analysis for constructs regarding perceived impact by fuels on human health and the environment (See **Supplementary Appendix** for all items included in listed constructs).

Construct	Number of items	Cronbach's alpha
Attitude towards driving a car	4	0.73
Environmental awareness	7	0.77
Perceived toxicity of fuels in general	10	0.92
Openness towards CO_2-based fuels	8	0.95

capturing perceived risks linked to toxic effects (i.e., risky/safe, dangerous/harmless, polluting/eco-friendly, toxic/nontoxic, dirty/clean, harmful/not harmful).

In a next step, respondents were asked whether they expect more benefits respectively risks from these new fuels compared to conventional fuels for eight different risk targets (own health, childrens' health, nature, wildlife, climate etc., see **Figures 6**, **7**). The items for measuring perceived benefits and risks were taken from Bronfman et al. (2012), while risk and benefit targets were chosen based on acceptance-relevant target groups (e.g., Howe,1990; Klein and Weinstein, 1997; McDaniels et al., 1995).

In order to deepen the study of risk perceptions for CO_2-based fuels, respondents were asked to indicate contact situations that they believe to create or amplify toxic effects of CO_2-based fuels based on three items developed by Jansen et al. (2020) (see **Figure 8**). Also, they were asked if and which specific health effects they expect from the two fuels, ranging from allergic reactions and respiratory ailments to cancer and genotoxic effects (see **Figure 9**), by evaluating the frequency with which they occur compared to conventional fuels on a five-point scale ranging from 1 = 'much less frequently' to 5 = 'much more frequently.' The six considered health effects were selected based on previous literature (e.g., symptoms used in Howe, 1990 and Greven et al., 2018).

In the fifth part of the questionnaire, the general openness and intention towards the use of CO_2-based fuels was assessed by eight items (see **Supplementary Appendix**) to investigate the general support for a transition to CO_2-based fuels in the transport sector and the willingness to switch to alternative fuels.

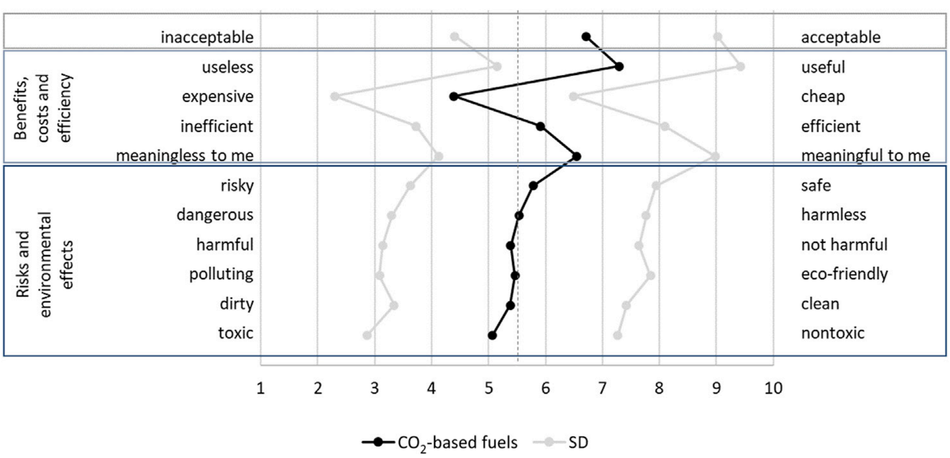

FIGURE 2 | Semantic differential for evaluating CO_2-based fuels (n = 124).

If not indicated otherwise, the items used to measure attitudes towards CO_2-based and conventional fuels had to be answered on six-point Likert scales (1 = 'do not agree at all,' 6 = 'fully agree'). Thus, mean values <3.5 signify rejection and values >3.5 approval of a statement.

3.2 Sample

A total of n = 204 respondents took part in the survey which was distributed in web forums and *via* social media. After data cleaning (removal of incomplete datasets, of speeders below a processing time of 35% of the median, and of cases with inconsistent/contradictory response behavior), a sample of n = 124 car-driving laypeople remained for statistical analysis. All participants volunteered to take part and were not gratified for their efforts. In the beginning of the survey, they were informed that we are interested in their opinions and perspectives on CO_2-based fuels and that there are no 'incorrect' or 'wrong' answers. We thus motivated them to honestly share their personal views. Participants were also informed that a high privacy protection in handling their data is assured.

In order to give laypeople participants an adequate neutral information background with respect to the purpose and the application field of CO_2-based fuels, all participants were informed at the beginning of the survey that the overall goal of this study is to capture personal and laypeople assessments of conventional and CO_2-based fuels. We further informed them that alternative–in contrast to conventional fuels–are fuels produced on the basis of CO_2. This involves capturing and processing CO_2, which is an industrial by-product that would otherwise be emitted into the atmosphere. New fuels can then be produced from CO_2, renewable electricity, and water. When the CO_2-based alternatives are used, the previously bound CO_2 is released back into the atmosphere.

The resulting sample consisted of 60.5% female and 39.5% male participants in an age range between 20 and 70 years [mean age was 34.7 years (SD = 14.0)]. Overall, 62.9% of the sample held a university degree. A major part of participants stated to live in the city center (44.4%). As regards people's attitude towards driving (see **Table 1**), respondents had a rather negative than positive attitude towards driving cars (M = 2.97, SD = 1). Environmental awareness was rather high (M = 4.55, SD = 0.87). Respondents were asked to give information on their perception of the toxic impact of fuels in general. As found, the perceived negative impact on human health and on the environment caused by toxic impact of fuels was moderate (M = 3.39, SD = 0.96).

3.3 Data Analysis

Data was analyzed using descriptive and inference statistics. Mean values were calculated for all constructs measured by multiple items. Cronbach's α for these constructs was $\alpha > 0.7$, which indicates a satisfactory internal consistency (see **Table 1**). The structure of public perceptions of CO_2-based fuels was investigated by principal component factor analysis. Next, impact factors on acceptance and risk perceptions of CO_2-based fuels were identified by stepwise regression analyses to understand how laypeople form their risk and acceptance judgments and which role concerns about toxic effects play in this regard. The role of user factors (demographics and attitudinal variables) on perceptions of CO_2-based fuels was examined by correlation analyses and MANOVAs. To gain insights into laypeople's beliefs about what influences fuel toxicity, descriptive statistics as well as t-tests were conducted. The level of significance was set at 5%.

4 RESULTS

In the following, the results for perceptions and concerns about toxic effects of CO_2-based fuels are presented.

4.1 Public Perceptions of CO_2-Based Fuels (Q1)

Knowledge about CO_2-based fuels was rather low (M = 2.33, SD = 1.27). At the same time people's interest was moderate (M = 3.1, SD = 1.33). Nevertheless, for both knowledge and interest in CO_2-derived fuels mean values were all below the middle of the scale (<3.5).

A semantic differential was used to assess how CO_2-based fuels are perceived by laypeople on different evaluative dimensions represented by eleven bipolar adjective pairs (e.g., inefficient/efficient). As depicted in **Figure 2** the dimension rated highest was the fuels' perceived usefulness (M = 7.29, SD = 2.14), followed by acceptance of CO_2-based fuels (M = 6.71, SD = 2.31) and meaningfulness for oneself (M = 6.55, SD = 2.43). The dimension evaluated most negatively was 'expensive–cheap' (M = 4.39, SD = 2.1), indicating that this carbon-based fuel is thought to be associated with higher costs (whether in production or in the final price). Looking at absolute values, attitudes towards CO_2-based fuels were rather neutral since mean values for the other evaluative dimensions, with the exception of 'inefficient–efficient' [M = 5.91, SD = 2.18, $t(123) = 2.1$, $p < 0.05$] and 'toxic–nontoxic' [M = 5.07, SD = 2.2, $t(123) = -2.16$, $p < 0.05$], did not differ significantly from the middle of the scale.

4.2 Technology-Related Impact Factors on Acceptance of CO_2-Based Fuels (Q2)

First, we report on how acceptance and risk perceptions are composed, and which evaluative dimensions contribute to the perceived riskiness of a CO_2-based fuel. A Principal Component Factor Analysis (PCA) was conducted together with item reliability analysis for the adjective pairs in the semantic differential to detect the underlying factor structure of public perceptions of CO_2-based fuels. The pair 'inacceptable–acceptable' was used as criterion variable in the regression analysis. Checking the quality criteria for PCA (Hair, 2011), the data matrix and sampling adequacy were found to be sufficient (Bartlett's test of sphericity $p < 0.001$, KMO = 0.873). According to the results of the factor analysis public perceptions consisted of two factors (see **Supplementary Table A1**). The factor structure implies that laypeople did not only distinguish benefits and risks but also the target of evaluation.

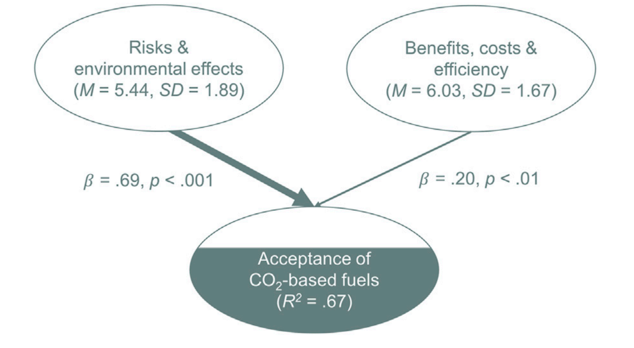

FIGURE 3 | Regression model for the acceptance of CO_2-based fuels (n = 124). Only factors with significant impact on acceptance are displayed.

The first factor '**risk and environmental effects'** (Cronbach's alpha = 0.93) contained assessments of the general riskiness, danger, and harmfulness associated with CO_2-based fuels as well as evaluations of environmental effects (environmental friendliness, evaluation as 'clean' or 'dirty') and toxic effects.

The second factor **'benefits, costs, and efficiency'** (Cronbach's alpha = 0.75) was related to assessments of the general usefulness of CO_2-based fuels and concrete evaluation criteria related to the usage of CO_2-based fuels in terms of expensiveness and performance. The factor was related to the drivers themselves because costs and efficiency are direct and observable affecting drivers in their daily lives. Also, the benefits were worded as 'meaningful to me' and as 'useful,' therefore drivers are assumed to have related the statements to themselves.

In a next step, it was investigated if and to which extent these factors impact the acceptance of CO_2-based fuels. A stepwise regression analysis was run with the two factors as independent variables and acceptance (the adjectival pair 'inacceptable–acceptable') as dependent variable. The resulting regression model (see **Figure 3**) accounted for 66.6% in acceptance of CO_2-based fuels [$F(2,121) = 120.41$, $p < 0.001$]. Risks and environmental effects (note that a higher value means lower perceived risks) had the highest impact on acceptance ($\beta = 0.69$, $p < 0.001$), followed by evaluations of benefits, costs, and efficiency ($\beta = 0.20$, $p < 0.001$). Acceptance was increased by lower perceived risks and concerns about environmental effects as well as more positive evaluations of the general usefulness and efficiency of CO_2-based fuels and lower costs.

The identified factor structure reveals that the 'general' riskiness that laypeople associate with CO_2-based fuels lies on the same evaluation dimension as environmental and toxic effects. In order to better understand risk judgments of laypeople, it is important to identify their constituent parts or 'building blocks.' We conducted a stepwise regression analysis with the overall riskiness (mean value over the two adjective pairs 'risky–safe' and 'dangerous–non-dangerous'[1]) as dependent variable and the other adjective pairs contained in the factor 'risks and environmental effects' as independent variables[2] (**Figure 4**). The resulting regression model explained 62.3% of the variance in perceived general riskiness [$F(3,120) = 66.23$, $p < 0.001$] and contained the adjectival scales 'polluting–eco-friendly' ($\beta = 0.31$, $p < 0.01$), 'harmful–not harmful' ($\beta = 0.23$, $p < 0.05$) and 'toxic–non-toxic' ($\beta = 0.34$, $p < 0.001$). The adjective pair 'dirty–clean' had no significant impact and was thus excluded from the model.

As can be seen, higher concerns about toxic effects and (environmental) harmfulness were associated with a higher general risk perception and all three factors had a similar impact on risk. The result shows that concerns about toxic effects should be investigated further to better understand risk perceptions and ways of addressing and decreasing perceived risks.

4.3 Correlations Between User Factors and Risk Perceptions of CO_2-Based Fuels (Q2)

Not only technology-related evaluations can impact perceived risks of CO_2-based fuels but also user factors (demographics and attitudinal variables) might play a role. To look into the effect of user factors we ran correlation analyses between the general risk perception score (risky/dangerous) and the demographic (age, gender, education) and personality characteristics (environmental awareness, attitude towards driving, openness towards CO_2-based fuels, general fuel-related concerns about toxic effects). As shown in **Figure 5**, there was a weak negative correlation of risk perception with education, a moderate negative correlation with the openness towards CO_2-based fuels, and a moderate positive correlation with general fuel-related concerns about toxic effects. That means, a higher formal education level and a higher openness towards CO_2-based fuels were related to a lower risk perception and higher concerns about toxic effects from fuel-based mobility in general were linked to a higher risk perception of CO_2-based fuels. All other user factors were not significantly correlated with perceived risks.

The impact of openness towards CO_2-based fuels on benefit and risk perceptions of CO_2-based fuels is now analyzed in greater detail as this was the factor showing the highest correlation with perceived risk. By understanding if and how people with a higher and a lower openness towards CO_2-based fuels differ in their perceptions of advantages and risks and in their beliefs how toxic effects are caused, diverging requirements and concerns for the rollout of these fuels and thus vital topics for information and communication can be unveiled. In order to understand the impact of 'openness' towards CO_2-fuels, the sample was divided into two equally sized groups by median split: respondents with a comparably lower openness (mean value ≤ 4.2, $n = 63$) and respondents with a comparably higher openness towards CO_2-based fuels (mean value of >4.2, $n = 61$).

In the following, differences between these groups for benefit and risk perceptions of CO_2-based fuels are analyzed.

4.4 Impact of Openness Towards CO_2-Based Fuels on Risk and Benefit Perceptions for Human Health and the Environment (Q3)

The knowledge whether risk and benefit perceptions vary for different risk targets is vital to understand how evaluations of CO_2-based fuels are developed and if there are groups of people or

[1]Items were recoded that a higher value corresponds to a higher perceived risk.
[2]These Items were also recoded.

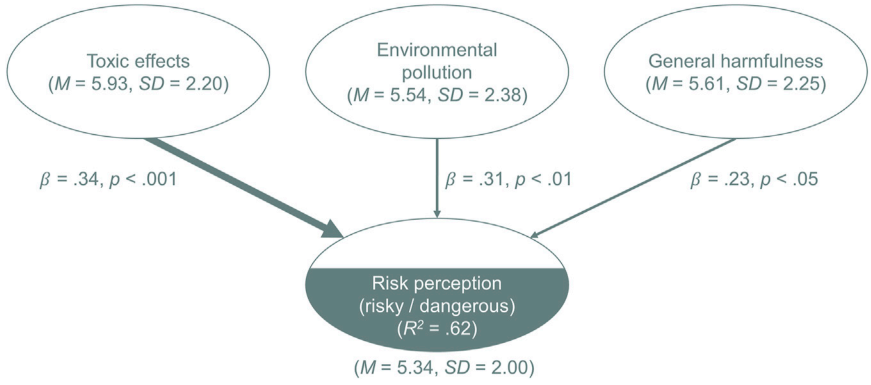

FIGURE 4 | Regression model for general risk perception of CO_2-based fuels (n = 124). Only factors with significant impact on risk perception are displayed.

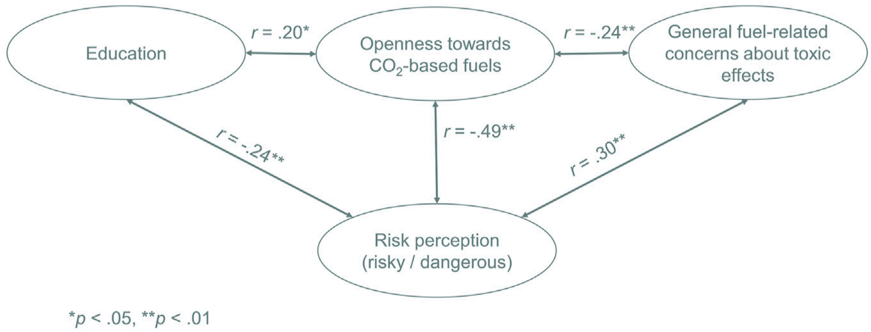

FIGURE 5 | Correlation analyses of user factors and general risk perception of CO_2-based fuels. Only factors with significant correlations are displayed.

ecosystem goods that are especially feared to be affected by these fuels. Respondents were asked to evaluate if they believed that CO_2-based fuels had a more positive or negative effect on different risk targets (humans and the environment, see **Figures 6**, **7**) compared to conventional fuels.

Repeated-measures ANOVAs with the between factor ‘risk targets’ yielded no significant differences: the mean values for risk perceptions varied between $M = 2.66$ for the climate ($SD = 1.14$) and $M = 2.80$ for (one’s own) children ($SD = 1.1$). When looking at the perceived benefits, the picture changes. Significant differences between risk target evaluations were revealed, e.g., between the climate ($M = 4.15$, $SD = 1.11$), which was perceived to benefit from CO_2-based fuels more than all other objects {e.g., the vegetation [$M = 3.84$, $SD = 1.16$; $F(1, 122) = 11.53$, $p = 0.001$] or between one’s own health ($M = 3.57$, $SD = 1.11$) and the wildlife [$M = 3.72$, $SD = 1.17$; $F(1, 120) = 7.06$, $p < 0.01$]}.

Regarding perceived positive impacts of CO_2-based fuels there were significant differences between participants with higher openness and those that are less open to their utilization for all analyzed risk targets (see **Figure 6**). The greatest difference between the two groups was in case of perceived positive effects for the climate, which were perceived to be significantly higher for people that are more open to CO_2-based fuel use ($M = 4.63$, $SD = 1.03$) than for those that have a less positive attitude on this topic ($M = 3.68$, $SD = 1.0$, $t(121) = -5.22$, $p < 0.001$). The slightest but nevertheless significant difference existed for one’s own health which was rather perceived to benefit from the use of CO_2-based fuels in the opinion of those who were more open towards CO_2-based fuels ($M = 3.85$, $SD = 1.21$) than those who were rather not ($M = 3.31$, $SD = 0.94$, $t(120) = -2.79$, $p < 0.01$).

A similar picture emerged for the perceived disadvantages of CO_2-fuel usage: Although all mean values for both groups were below the middle of the scale (3.5), the perceived negative impacts were evaluated significantly more negatively by those that show a lower openness towards CO_2-based fuels [e.g., ‘the wildlife’: $M = 3.25$, $SD = 1.05$, $t(122) = 6.5$, $p < 0.001$; ‘(one’s own) children’: $M = 3.3$, $SD = 1.72$], whereas people who are more open evaluated the negative impacts for all risk targets significantly less negative [e.g., ‘the wildlife’: $M = 2.16$, $SD = 0.8$; ‘(one’s own) children’: $M = 2.28$, $SD = 0.86$, $t(122) = 5.85$, $p < 0.001$] (see **Figure 7**).

4.5 Impact of Openness Towards CO_2-Based Fuels on Beliefs About Exposure Situations Causing Toxic Effects and Resulting Health Impacts (Q4)

In this section, we aimed for a deeper understanding of which factors are believed to increase toxic effects of CO_2-based fuels by investigating the negative impacts of exposure types. To do so,

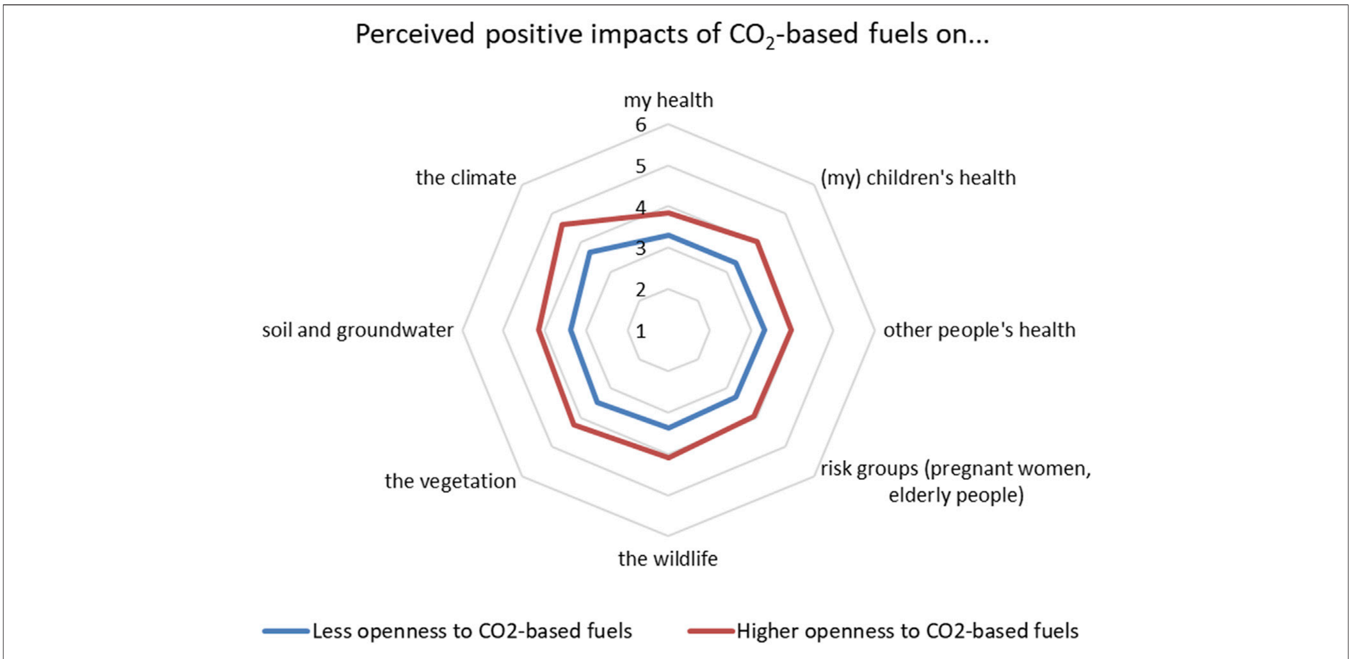

FIGURE 6 | Perceived positive impacts of CO_2-based fuels on risk targets. Displayed are mean values for perceived benefits (min = 1, max = 6).

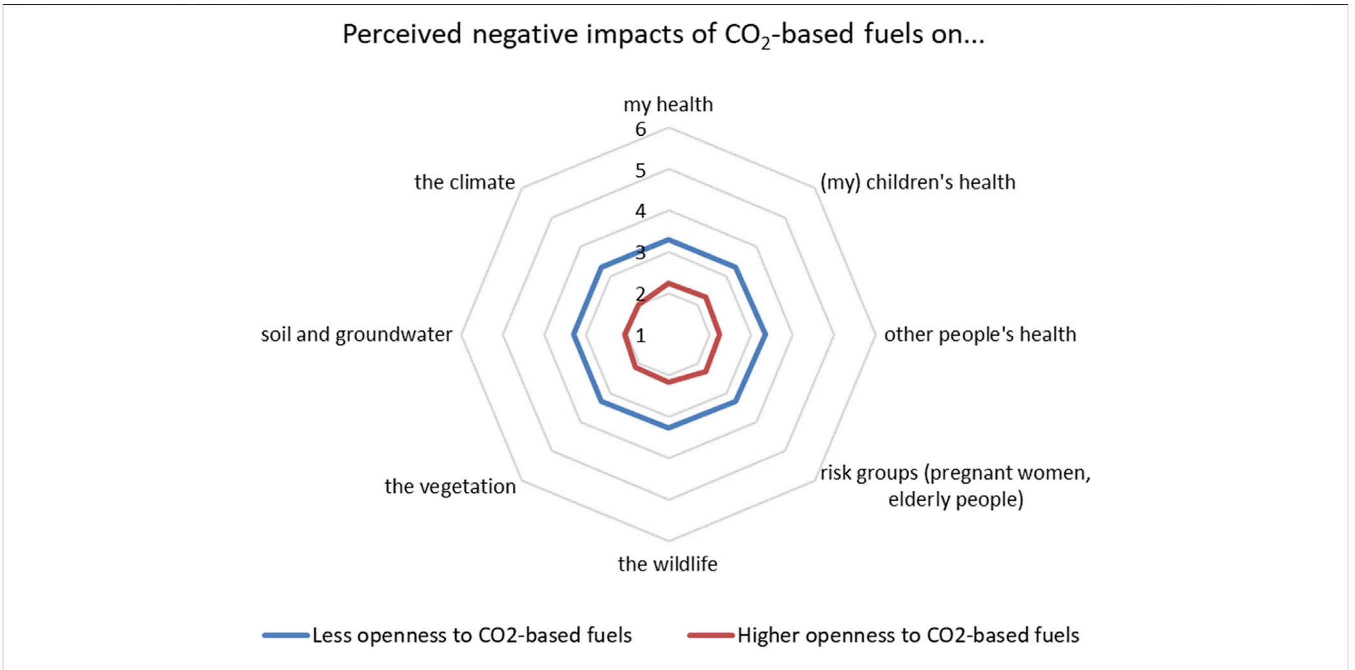

FIGURE 7 | Perceived negative impacts of CO_2-based fuels on risk targets. Displayed are mean values for perceived disadvantages (min = 1, max = 6).

t-tests were used again to investigate whether there were differences in terms of openness to use CO_2-based fuels as an alternative propulsion technology.

In general, all three types of exposure to a fuel (inhalation of fuel vapors or exhaust fumes as well as skin contact) significantly differed from the mean value of the scale (3.5). It can be concluded that damaging effects by different types of exposure to CO_2-based fuels were perceived to be rather low. However, there were significant differences between the two groups of diverging openness to the technology (see **Figure 8**). For all three types of exposure respondents with higher levels of positive attitude towards CO_2-based fuels feared significantly less negative

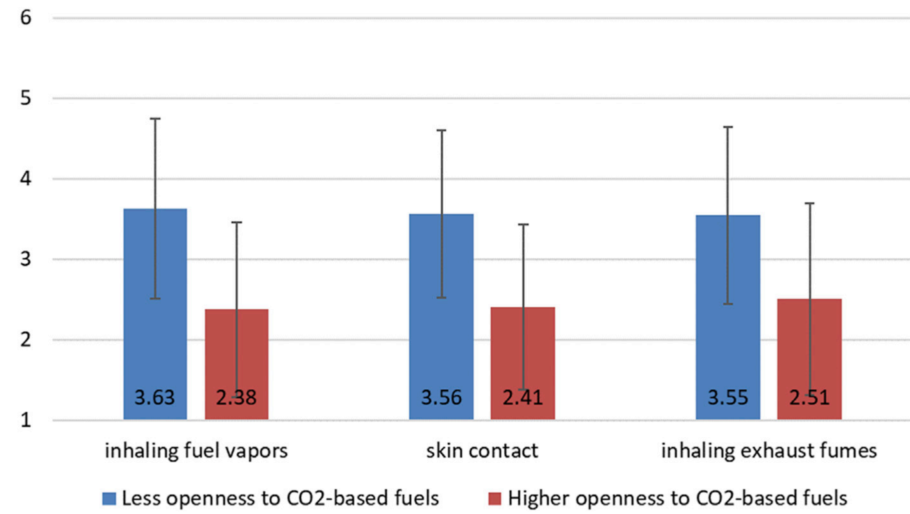

FIGURE 8 | Differences in perceived impact by exposure types (n = 123).

impacts (e.g., 'inhaling fuel vapors': $M = 2.38$, $SD = 1.08$) than people that showed lower openness in this regard [$M = 3.63$, $SD = 1.12$, $t(121) = 6.3$, $p < 0.001$].

Finally, significant differences were found for respondents wither lower vs. higher levels of openness towards CO_2-based fuels regarding their perception of the occurrence of health impacts caused by contact with the more sustainable fuel alternative. When asked about the perceived frequency of several possible health effects they indicated whether they estimated their occurrence to be more or less frequent (on a scale from 1 to 5) than would be the case with conventional fuels. All analyzed impacts on human health were significantly perceived to be scarcer in direct comparison with conventional fuels by people who were more open towards the technology (see **Figure 9**). The smallest gap between means of the two groups existed in case of 'irritation of the eyes' [higher openness towards CO_2-based fuels: $M = 2.62$, $SD = 0.61$, lower openness towards CO_2-based fuels: $M = 2.95$, $SD = 0.82$, $t(112.78) = 2.53$, $p < 0.05$]. The biggest difference between the group with higher ($M = 2.49$, $SD = 0.65$) and lower openness towards CO_2-based fuels ($M = 2.98$, $SD = 0.76$) persisted in the case of perceived frequency of cancer [$t(118.76) = 3.87$, $p < 0.001$].

5 DISCUSSION

Alternative fuels such as CO_2-based fuels have the potential to contribute to the decarbonization of the transport sector. Despite the environmental benefits that CO_2-based fuels have for our society, the adoption of alternative fuels can be slowed down or even stopped by a lack of societal readiness. In this study, an online survey was used to investigate whether heightened risk perceptions, especially regarding the perceived toxicity of CO_2-based fuels, can affect their acceptance. In addition, it was investigated which benefit perceptions exist and whether perception patterns are associated with individual user characteristics. In this chapter, the results are discussed, recommendations for fuel research and information concepts are formulated and an outlook on the future research duties is given.

5.1 Risk Perceptions of CO_2-Based Fuels

Overall, CO_2-based fuels were perceived as rather useful, meaningful for oneself, and efficient, and most important as acceptable, confirming recent studies' findings. For instance, Hackbarth & Madlener (2016) were able to show that alternative fuels are an acceptable option, under the premise that they can also keep up with the conventional benchmark on other levels (e.g., price). Their ability to do so was most recently proven by Engelmann et al. (2020) in a direct comparison of risk perceptions (including perceived toxicity) for both CO_2-based and conventional fuels.

It has to be taken into account though that respondents' evaluation cannot (yet) be based on real-life experience like it is the case with handling, e.g., gasoline or diesel when refueling one's own car. Therefore, yet, perceptions of a CO_2-derived alternative can only be gathered by informing people about the product and its production, bearing in mind that this approach may involve the evaluation of mental models which are not equivalent to a knowledge or experience-based evaluation.

Still however, it is important to understand the public perceptions prior to the entering of the novel product to the market as information and communication strategies can be steered quite early in the implementation and roll-out process. The overall positive perception of CO_2-based fuels in the current study with low perceived risks shows that the public is not only open to green fuel innovations but can also handle the risk perceptions. These are often connected to novel and 'unpredictable' product innovations (Wood and Moreau, 2006; Jaw, 2014) and have been documented in a broad number of technological fields [e.g., food technology (Siegrist and

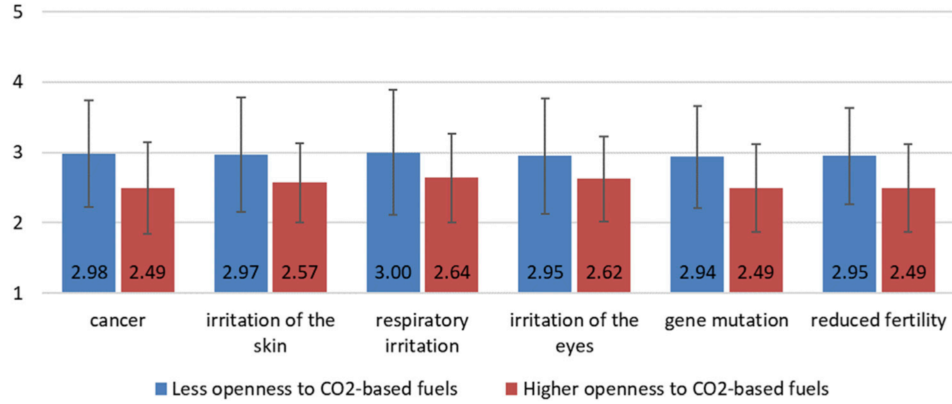

FIGURE 9 | Differences in perceived frequency of health effects in comparison to conventional fuels (n = 123).

Hartmann, 2020), autonomous driving (Brell et al., 2019), or medical technology (Ziefle and Schaar, 2011)].

5.1.1 Impact Factors on the Acceptance of CO_2-Based Fuels

When investigating the structure of public perceptions of CO_2-based fuels, two factors were revealed–'risks and environmental effects' and 'benefits, costs, and efficiency'–which entail the most crucial impact factors on large-scale technology acceptance revealed in past research (e.g., Huijts et al., 2012). In the present study, perceptions of risks and environmental effects were more influential than perceptions of benefits, costs, and efficiency. Openness towards CO_2-based fuels was more relevant to perceptions of CO_2-based fuels than other user factors such as demographics which (except for education) showed no significant correlation to risk perceptions of CO_2-based fuels. This does not mirror findings from previous technology acceptance research, which found benefits to be more influential than risks for a broad variety of technologies, including CCS and CCU (Linzenich et al., 2019) and automated driving (Liu et al., 2019). This can be reasoned by different points. First, the investigated benefits factor did not contain only perceived benefits but also evaluations of costs and efficiency. Moreover, the risks factor had a more general target (effects on the environment respectively harmful effects in general). In contrast, the benefits factor was rather related to the drivers themselves with dimensions that directly affect the driver (costs, efficiency of the fuel, meaningfulness of fuels for the own person). Second, previous research revealed that the relationship between perceived benefits, risks, and acceptance is not universal with always the same components. Instead, it is influenced by a variety of different evaluation factors and depends on the researched technology context (Huijts et al., 2012; Visschers and Siegrist, 2018).

Although the impact of user factors on risk perceptions was low and acceptance judgments were mainly shaped by benefit and risk perceptions, user factors might have had an indirect impact through benefit and risk perceptions on acceptance (e.g., Linzenich et al., 2019), which should be investigated in future studies for CO_2-based fuel perceptions.

5.1.2 The Role of Toxic Effects and Different Risk Targets for Risk Perceptions for CO_2-Based Fuels

In the risk assessment of chemicals, there is a product-related approval that ensures comparable standards for all products. Fuels are excluded from this standard procedure. Due to the regulation of the toxicity of individual components and the diversity of fuel types, for example, in their composition, it becomes complex to establish a standard procedure. The perceived general riskiness of CO_2-based fuels was characterized by higher concerns about harmfulness, environmental pollution, and toxic effects of these fuels. Fears of toxic effects are thus an integral part of risk perceptions of CO_2-based fuels and could be a barrier to the implementation of these fuels given the high importance of risk perceptions for acceptance. Although risk perceptions and concerns about toxic effects were 'neutrally pronounced' in the present study, perceived risks might increase or fade over time with the market entrance and beginning diffusion of CO_2-based fuels (e.g., due to personal experience with these fuels, media reports, and public debates). This makes it important to fully understand laypeople's beliefs and concerns linked to CO_2-based fuels and possible hazards. In the current study, risk perceptions did not substantially differ for different elements of the ecosystem (human health, wildlife, soil and groundwater quality, and climate stability). In contrast, benefit perceptions were found to vary between some of the targets. We assume that laypeople make more general, universal risk judgments for CO_2-based fuels without a distinction between who and what is affected by possible risks, underlining once more the well-known affective nature (Slovic and Peters, 2006) of risk perceptions in terms of a felt general 'hazardousness' or 'dreadfulness'. Still, one has to bear in mind that respondents did not evaluate benefit and risk perceptions on an absolute basis but relatively to conventional fuels. It could be that on an absolute level laypeople actually see differences in hazards for the different risk targets but that the 'relative distance' to conventional fuels is the same throughout all targets. Thus, the way risk perceptions were measured might have caveated possible differences.

Human health and environmental effects were identified as important risk targets in risk perceptions for a variety of technologies, e.g., in the context of CCU (van Heek et al., 2017) and biofuels (Winden et al., 2014). Moreover, exposure has been revealed as a relevant factor for risk perceptions and more specifically for toxicity concerns in previous research (Slovic et al., 1982; Pumarega et al., 2017). Without a distinction between CO_2-based and conventional fuels, a higher level of perceived toxic effects and resulting harm was identified for the environment than for effects on human health. One possible explanation for this finding is the now widespread awareness of the link between emissions and climate change (Shi et al., 2015) and the comparably low level of laypeople's knowledge regarding risks posed by toxicity (Stahlmann and Horvath, 2015) as well as laypeople's missing conception of dose-response relationships of chemicals and conditions of harmful effects by substances (Bearth and Siegrist, 2016).

Previous results regarding higher risk perceptions for children's health (Asensio and Delmas, 2015; Kotcher et al., 2019) could not be confirmed in the course of this study, since in direct comparison with other risk targets (e.g., one's own health, risk groups such as pregnant women, the climate) no stronger increased risk perception compared to conventional fuels could be determined.

5.2 Concerns About Toxic Effects of CO_2-Based Fuels as Factors in Risk Perceptions

The aspect of differences in perception of harm due to varying exposure situations needs to be placed into the context of inhalation of exhaust fumes being the most frequent and daily route of exposure to a fuel, which is 1) applicable both for users and non-users of vehicles and 2) most likely out of a person's own control. Regarding this second aspect, further investigation based on this study's findings needs to be done, since risk perceptions are a possible consequence of perceived uncontrollability (Slovic, 1987). It has been shown before that increased perceived uncontrollability of CCU technologies can be related to lower levels of benefit perception and higher levels of perceived risks for the environment and human health (Arning et al., 2020). Since it has been found that increased openness to the utilization of CO_2-based fuels impacts the risk perception connected to diverging exposure types it should be investigated in future research if the trait of 'openness' is connected to elevated levels of perceived control of one's surrounding conditions.

Despite the significant differences between the two groups with diverging levels of openness, the participating laypeople did not evaluate one of the exposure pathways to be more harmful regarding arising health effects. Again, the missing differentiation by laypeople between exposure types can be explained by two possible reasons: Due to a low level of knowledge, laypersons are unable to differentiate, or they perceive all three types of contact with a CO_2-based fuel as–in this case–being rather harmless to health. A further explanation is that people were more concerned about other types of exposure not captured in the current study, for example, ingestion (contamination of drinking water or crops caused by fuel spill), which needs to be investigated in further studies.

When it comes to health impacts, no higher frequency of health concerns compared to conventional fuels was feared. Also, people with higher openness towards CO_2-based fuels did even fear less frequent health effects than laypeople with a lower openness. However, perceptions might change when these fuels enter the market due to public discussion or media reports and previous research has shown the high relevance of health-related concerns (e.g., cancer) for resistance against planned projects in the context of mobile base stations and transmission lines (Drake, 2006; Cotton and Devine–Wright, 2013).

5.3 Putting the Results into Practice: Implications for Stakeholder Groups

5.3.1 Implications for Toxicity Research and Screening of Fuel Candidates

Traditionally, technical, economic, and greenhouse gas-related considerations dominate the discussion about novel alternative fuel design (König et al., 2019). Findings from toxicity research, as usual in the registration, evaluation, and authorization of chemicals, and social acceptance are currently not directly integrated into fuel design processes, which might represent valuable addenda to achieve both environmentally friendly and accepted fuel innovations. Future research should thus enhance the methodology and directly integrate toxicity-related and acceptance parameters in the selection of suitable fuel candidates in order to create fuel innovations that are both environmentally and health friendly and socially accepted. If, for example, a toxic effect is highly relevant in toxicity research and from acceptance perspective, it might be all the more serious for the successful roll-out of alternative fuels. On the other hand: Even if a dimension is subordinate from toxicology perspective, it could still be a barrier to the favorable acceptance of alternative fuels. The current study revealed such a divergence in perceptions for laypeople and toxicity research in terms of exhaust gases. Whereas laypeople were afraid of exhaust (inhaling exhaust and getting sick), toxicity research emphasizes a more profound effect on the environmental quality. Integrating knowledge on toxic effects of alternative fuels and their perception by the public early on as weighted parameter in fuel design can help decisionmakers as a 'lightning signal' to identify socially accepted pathways for alternative fuels and their production routes with low toxic impact. For example, optimization-based fuel design could include toxic effects and social acceptance as target functions besides costs and environmental effects to find the optimal fuel for different applications.

5.3.2 Implications for Information and Communication Concepts

The findings yield valuable insights on how to develop information and communication concepts for the roll-out of alternative fuels.

Laypeople need to be informed neutrally and comprehensibly about possible adverse effects on environment and human health so that they feel that their concerns and information needs are acknowledged and properly addressed. This can also help to resolve prevailing misconceptions about alternative fuels. The information provided should include how potential toxicity risks from fuels are investigated, how the fuel can be safely handled, and which measures fuel production companies take to select fuel types of low toxic impact and to monitor and safely operate the production of a fuel. The communication concepts should compare toxic effects of new fuels to established fuel types to help laypeople to put risks into perspective.

The results can also be used to inform education concepts for fuel developers (e.g., engineers, chemists) as the findings highlight that laypeople's concerns can deviate from experts' perspective: Whereas laypeople see exhaust gases as source for toxic effects, toxicity research does not focus on exhaust but makes a more holistic assessment of toxic impacts. Although only relevant from laypeople's view, this belief could still negatively affect the adoption of alternative fuels. An education concept for social innovations in mobility needs to convey the complexity of criteria that may affect the successful roll-out of these innovations to prevent a late failure on the market. If an acceptance problem is detected only in the market entering stage, basic decisions are already set since large investments are made and production and refueling infrastructure is installed. Then, the roadway to more accepted solutions might be blocked and attempts to increase acceptance of the rejected innovation might be futile because a negative opinion on this technology is already prevailing.

6 OUTLOOK

Since the questionnaire focused mainly on risk perceptions regarding toxic effects of CO_2-based fuels, results might overestimate the importance of toxicity in laypeople's perceptions as they were forced to take it into account although they might not have spontaneously associated possible toxic effects when thinking of CO_2-based fuels. To get a broader picture, future studies should therefore also assess laypeople's free associations of benefits and risks of alternative fuels.

A further methodological constraint refers to the circumstance that the perception of toxic effects was for some aspects (e.g., risk and benefit targets and concerns about adverse health effects) only evaluated relatively to conventional fuels but not on an absolute basis. This had the advantage that we were able to sound out whether concerns about toxic impact were a particular acceptance barrier for CO_2-based fuels or whether concerns were similar to those of conventional fuels. However, as a result, we now only know the relative distance between CO_2-based fuels and fossil fuels, and this does not allow us to identify which was the highest feared risk for CO_2-based fuels. Also, it proved difficult to measure risk perceptions regarding toxic effects. Some of the constructs and items used did not distinctly represent toxic characteristics but referred to more general risk aspects.

Finally, the convenience sample used for this study was rather small. Yet, for the testing of the research questions at hand and the identification which risk perceptions laypeople might have regarding CO_2-based fuels, the sample size is appropriate to test valid relations. Also, it is sufficient to understand if they can act as a barrier for the public acceptance of these fuels. Still however, on the base of this first insight into the topic, further and larger samples should be targeted, pursuing different goals. This regards an understanding of user diversity in risk perceptions of CO_2-based fuels. Young and highly educated people–as examined here–often have a higher affinity towards technology, are more open to technical innovations (early adopters) and less anxious as previous research on technology adoption has shown (e.g., Mohamed et al., 2016; Hardman and Tal, 2018; Berliner et al., 2019). In this context, more and more diverse people with regard to different education levels and socio-economic status, but also regarding sustainability attitudes and mobility habits should be integrated to get a full picture. Moreover, in future studies the limited focus on CO_2-based fuels in road transport should be extended, to examine if concerns about toxic impact differ with the application context that alternative fuels are used for (aviation, shipping, road traffic).

When it comes to other possible future research topics that can be derived from our results, the following areas should be considered as well (e.g., impact of user factors on acceptance of CO_2-derived fuels or investigation of the development of risk judgments of CO_2-based fuels). As this study has shown, the investigation of perceived risks from harmful effects of CO_2-based fuels is not trivial, as laypersons perceive differences, e.g., in comparison to the harmfulness of contact with conventional fuels.

Apart from that, it is promising to look at what results can be obtained for the development of new technologies and fuels if interdisciplinary work is done. For this reason, a closer integration of the two disciplines involved in this study, being social sciences and toxicology, should be sought. On a methodological level, this could mean drawing on the knowledge of environmental toxicologists as early as the layperson questioning stage, in order to develop survey instruments that also give non-experts a better understanding of the effects of toxic substances on various risk targets and, in a next step, to find out whether people can differentiate between different potentially harmful substances. In addition to the examination of risk perceptions regarding fuel as an end-product, risk perceptions directed on the production process should also be considered. In our study we only referred to possible contact situations with the end product. Possible hazardous situations with negative consequences, caused by toxic effects that may occur during production (e.g., toxic by- or waste products), should also be evaluated by laypeople (e.g., in the context of local acceptance) and stakeholders involved in the production process (production workers, site operators). This is especially relevant since the successful roll-out of alternative fuels will not only require the adoption by end-users but also the acceptance of various stakeholders involved in the implementation of these fuels (e.g., policymakers, fuel and automobile industry, and–if used in heavy-duty transport or aviation–also forwarding agencies and airlines).

Finally, the current developments with the Ukraine war in line with the raising public awareness of the strong dependency on fossil energy across countries could also have a strong impact on the significance of the urgent need for novel technologies that foster renewable energy development and deployment. It is advisable to repeat studies on risk perceptions and to catch the current view of public's acceptance and their assessment of prevailing risks. A perceived more urgent exit from certain energy sources could lead to a change in the perception of more sustainable technologies from the energy sector such as CCU and CO_2-based fuels.

7 CONCLUSION

The present study investigated laypeople's risk perceptions of CO_2-based fuels with special regard to toxic effects. It was found that CO_2-based fuels were evaluated as rather beneficial and acceptable and were associated with a low risk. Risk perceptions were inversely related to acceptance of CO_2-based fuels with perceived toxic impact being a constituent part of risk perceptions alongside environmental pollution and general harmfulness. Openness towards CO_2-based fuels was identified as a user characteristics impacting risk perceptions and beliefs about toxic effects. The findings highlight the importance of transparent information and communication concepts informing the public about possible risks from alternative fuels and about the process of selecting, producing, and monitoring CO_2-based fuels including how standardized information about toxicity is integrated in the process. This helps to appropriately consider laypeople's concerns and information needs and to address possible misconceptions and might inform decision-makers regarding the potential acceptance issues in different stakeholder groups which could be addressed by individually tailored public educative formats. Future research should aim for integrating toxicity research and social acceptance as weighted parameters in fuel design, e.g., as a 'lightning signal' to identify pathways towards non-toxic and socially accepted fuel solutions or, even more, as a target function in the selection of fuel candidates.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AL and LE were responsible for conceptualization, data curation, formal analysis, investigation, methodology, validation and visualization of the described study as well as for the writing of the original draft, and the revision. KA was responsible in conceptualization, data curation, investigation, methodology, validation and writing as well and furthermore for supervision. MD and SH were involved in the conceptualization and writing of this study and MD moreover was involved in validation. MZ and MR-N were responsible for funding acquisition and project administration as well as writing of the manuscript. Additionally, MZ was involved in supervision, validation, and revision.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.737070/full#supplementary-material

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