



Risk Assessment Regarding Perceived Toxicity and Acceptance of Carbon Dioxide-Based Fuel by Laypeople for Its Use in Road Traffic and Aviation

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One approach to mitigate the emissions of carbon dioxide (CO₂) is the development of CO₂-based products, such as fuels for road traffic and aviation. Since the acceptance of sustainable product innovations such as CO₂-based fuels depends on an individual's acceptance decision based on perceived risks and benefits, this study focuses on subjective risk perceptions of fuel toxicity. An online survey was conducted to assess risk evaluations of CO₂-based fuels regarding various risk targets, exposure characteristics, negative outcomes for health and environment, and frequency of health impairments. CO₂-based fuels were significantly more positively perceived than conventional fuels and were found to be perceived to pose less risks regarding types of exposure and properties leading to toxic effects. For both aviation and road traffic the acceptance of CO₂-based fuels increased with decreasing fear of health and environmental consequences and the less frequently health effects were assessed. The findings allow to derive implications for risk assessment and communication strategies in the development and roll-out of CO₂-based fuels.

Keywords: carbon dioxide-based fuels, acceptance, toxicity, risk perception, carbon capture and utilization, public perception

INTRODUCTION

The continuous emission of carbon dioxide (CO₂) into the atmosphere, caused by the combustion of coal, oil, and gas, continues to drive climate change [Global Carbon Project (GCP), 2018]. Efforts to reduce emissions and resulting environmental effects are being made by working on technological solutions for areas which still rely heavily on fossil fuels, such as the transport and aviation sectors. In one of these approaches carbon is captured and used by reintroducing it into the consumption cycle [Carbon Capture and Utilization (CCU)] (Von der Assen and Bardow, 2014). This way, the CO₂ can be used for manufacturing goods such as plastic products (Iqbal et al., 2018) or CO₂-based fuels for transport and aviation (Deutz et al., 2018). Apart from the technological development of new procedures, such as CCU, the public's perception of such practices can be critical for a successful roll-out. Since previous studies show that a rejection by the general public can cause innovations to fail, it is crucial to know more about the factors that impact the evaluation and acceptance of new technologies (Wallquist et al., 2010). Acceptance-relevant factors, such as risk and benefit perceptions, can have an impact on how a technology is perceived by the public and on

whether people are willing to use new products. As for technical innovations in general, this also applies for CO₂-based products, their perception and acceptance by the public and their implementation (Venkatesh et al., 2003). We define the concept of acceptance as an active adoption or willingness to use the product, which can be distinguished from a reactive approval of the product (Dethloff, 2004). Examples for acceptance under this definition include an active proclamation as well as the purchase and use of a technology (Huijts et al., 2012). Regarding renewable energies, Wüstenhagen et al. propose a concept that divides acceptance into three categories: socio-political, community, and market acceptance of technologies and policies. *Socio-political acceptance* can be defined as the social acceptance by the public, key stakeholders and policy makers. *Community acceptance* refers to the acceptance of those locally affected by the (new) technologies. Lastly, *market acceptance* is the adoption of a technology by its roll-out on the market (Wüstenhagen et al., 2007). Between the three dimensions of technology acceptance interrelations may occur and as has been stressed Jones et al., they are of great importance in the case of CO₂ utilization technologies (Jones et al., 2017b). The current study surveys socio-political acceptance, as we assess public perceptions and the willingness to use CO₂-based fuels.

Different theoretical approaches conceptualize acceptance and define factors that promote or prevent positive attitudes toward and acceptance of a technology. Possible influences on acceptance are perceived benefits, costs and risks which have an impact on attitude and indirectly influence behavioural intention towards a new product (Huijts et al., 2012). A distinction between risks can be made depending on whether they are observable or not, whether they are rather new or old, their immediate effects, and dimensions like controllability, dreadfulness, and voluntariness (Slovic, 2000). A characteristic of conventional fuels which poses perceived risks for consumers is its toxicity and its health risk potential, e.g., due to air pollution (Brunekreef and Holgate, 2002). It is therefore advisable to examine how possible toxic effects of new transport technologies, like CO₂-derived fuels, are perceived by the public. For that reason, this study focuses on the perceived toxicity as one aspect of risk perceptions, as well as on possible relationships between perceived toxicity and the acceptance of CO₂-derived fuels as a carbon-reducing technology.

PUBLIC PERCEPTION AND RISK PERCEPTION OF CARBON DIOXIDE-DERIVED FUELS

The production of fuels is one option to reuse captured CO₂. Several ways exist to capture the CO₂ (e.g., as a by-product of power plants) for further processing, such as chemical absorption, capture by membrane separation or by hybrid processes (Al-Mamoori et al., 2017). Through different synthesis methods, e.g., Fischer-Tropsch or direct dimethyl ether synthesis, it is possible to upgrade hydrogen and carbon atoms to hydrocarbon fuels. Since these processes can be very energy-intensive, energy sources

with low or no emissions must be used to ensure that the CO₂-based fuels are (close to) emission neutral [International Council on Clean Transportation (ICCT), 2017]. The amount of energy the production requires is an example of an indicator for the environmental compatibility of CO₂-derived fuels. Additional parameters are emissions of soot, nitrogen monoxide and nitrogen dioxide (NO_x), as well as global warming as an environmental impact indicator (Deutz et al., 2018).

In recent years, the number of studies dealing with the perception of carbon capture technologies has increased. Initial qualitative results indicated that CCU technologies were viewed as delaying the actual release of CO₂, but also creating jobs and useful products at the same time and representing a step in the right direction to combat climate change (Jones et al., 2014). Although the general awareness of and knowledge about CCU is low, the public was still in favour of the technology, despite of doubts on the environmental benefits (Jones et al., 2017a). Since CO₂, depending on the end-product, is rereleased into the atmosphere after consumption or disposal, sustainability of CCU as a technology was questioned by laypeople (Arning et al., 2019). The actual products that can be carbonized with reused CO₂ themselves, e.g., fuels, mattresses or beverages, were evaluated positively. Fuels were the most favoured utilisation option from laypeople's point of view (Offermann-van Heek et al., 2018). Since the public particularly fears a (potentially harmful) impact on their own health and the environment, the acceptance of sustainable technologies like CO₂-derived fuels may depend on these factors. It is therefore important to focus on risk perceptions regarding CO₂-based fuels and their effect on acceptance.

"Risk perceptions" are evaluations of threats which are formed based on experience or knowledge of incidences and information about (possible) impacts (Rohrmann and Renn, 2000). Affect plays a major role in the development of risk perceptions. Affective patterns of thought and action, which—from an evolutionary point of view—serve survival, thus form the basis for the perception of various kinds of potential risks (Slovic and Peters, 2006). A central finding in this context is the divergence between (f)actual dangers that can be identified and measured and risk perceptions as a subjective assessment of risks by laypeople (Slovic, 1987). Especially for laypeople, these risk perceptions do not have a rational basis, but they strongly affect the evaluation of new or unknown technologies. To understand to what extent health-related risk perceptions exist, and how they influence acceptance of CO₂-based fuels, it is therefore important to study which risks of CO₂-based fuels people perceive.

Only a few studies have been carried out on the specific perceived risks of CO₂-based products such as fuels. Arning et al. (2017) identified four risk-categories for CCU technologies and products: perceived risks either referred to health, environment, sustainability or to the quality of the product. Referring to the process chain of CCU, people particularly expressed risk perceptions related to the disposal of a CO₂-based product, followed by risk perceptions directed on the production process itself and the use of a CO₂-derived product. Furthermore, higher risk perceptions regarding the

disposal and usage stage are linked to a lower acceptance of a CO₂-based product (Arning et al., 2019). Higher risk perceptions also coincide with a weaker relationship between purchase-determinants (e.g., performance expectancy, social influence) and the intention to buy a vehicle powered by alternative fuels (e.g., biogas, electricity) (Dk and Samarasinghe, 2019). Finally, a study found that higher ratings in acceptance of CCU was accompanied by lower ratings for risk perception towards the technology, i.e., the perception of CCU being rather risk-free and harmless (Linzenich et al., 2019). Hence, from a laypeople's perspective, CO₂-derived products such as fuels might pose risks, e.g., when handling the product. The focus of this study was therefore on the perceived risks regarding the toxicity of CO₂-based fuels, in order to determine whether toxicity is a relevant factor for laypeople's acceptance and willingness to use the product.

PERCEIVED TOXICITY OF CARBON DIOXIDE-DERIVED FUELS

The science of toxicology deals with the properties, identification and effects of toxic substances (e.g., on humans). The toxicity of a substance depends on the characteristics of the individual who encounters it, the properties of the substance (e.g., chemical composition) and external conditions (e.g., temperature). Toxic substances do not only have a noticeable effect on the affected individual, for example through the impairment of genetic material, they can also affect future generations (Gupta, 2016). For instance, the combustion of conventional petrol and diesel fuels causes toxic particulate matter which was found to cause potentially serious health risks (Wu et al., 2017). The actual toxicity naturally plays a major role in the production and consumption of goods. Nevertheless, it is apparent that subjective perception and objective factuality are not always congruent (Greven et al., 2018; Saleh et al., 2019). This is caused by gaps "between the rational analytic science of toxicology and the affective/emotional/instinctive way the human brain processes information and between the hard scientist's faith in reason and the social science evidence that reason can only take us so far" (Ropeik, 2011).

Several previous studies shed light on feared effects of toxicity of diverse goods and processes, some of them regarding human health, others the environment. The aversion to possibly harmful daily goods can be described as "chemophobia" when the cause for consumers negative feelings and concerns is the possibility of harmful substances and chemicals in products (Gribble, 2013). Such concerns have previously been expressed in the case of gene technology in biotechnology, where it was found that the acceptance of gene technology was directly influenced by perceived risks (and benefits) (Siegrist, 2000). An American study indicated that although participants knew little about gene modification in food technology, they still feared harmful effects on human health caused by consumption of genetically modified goods (Hallman et al., 2003). Furthermore, Kher et al. examined laypeople's opinions about possible contamination through chemical or microbiological impacts during

sustenance production in various food chains. Without further knowledge of the process people imagined critical production steps that pose risks of contamination and food chain traceability systems were discussed as a possibility to counteract these risk perceptions (Kher et al., 2013). Not regarding the digestion, but the inhalation of toxic substances, it was found that in the case of fires, inhaling smoke was considered to be toxic and that the risk of long-term effects caused by the proximity to a fire was overestimated (Greven et al., 2018). As aforementioned, next to risks on their own health, people also perceive toxicity risks for the environment. However, a study on the perceived environmental risks of discarded medicine showed that some people find it more difficult to assess the risk toxic substances pose to the environment than the risk it poses to their own health (Bound et al., 2006). Another recent study examined the relationship between risk perceptions and the evaluation of climate policy: people with a higher risk perception of negative impacts driving global warming are more likely to support climate policy (Mayer et al., 2017). Finally, a study found that there are connections between the public's knowledge about air pollution and physical health risk perception on the one hand and the willingness to reduce car use on the other hand (Shanyong et al., 2019), which raises the question of whether similar attitudes towards the environment and health are associated with other forms of emission reduction, such as the use of CO₂-based fuels. There are therefore already comprehensive insights into perception of toxic hazards from different origins. Nevertheless, further analyses on risk perceptions are needed, since an adaptation to new technologies and products like CO₂-derived fuels is not expedient.

Therefore, the present study aims for 1) the measurement of acceptance for CO₂-derived car and jet fuels, 2) the assessment of perceived toxicity of CO₂-derived fuels by an evaluation of risks and 3) the analysis of relationships between perceived toxicity and acceptance evaluations of CO₂-based fuels.

METHODS

Qualitative Pre-Study

In the following, the procedure, sample and results of the preliminary interview study are presented. Results were used to narrow down the selection of risk targets and contact situations with a fuel to be evaluated in the second part of the study.

Procedure

To collect first insights of risk perceptions (related to health and the environment) and on the toxicity of (alternative) fuels, semi-structured interviews were carried out. To ensure comparability of results and make sure that every participant answers the same set of questions, an interview protocol was prepared and used throughout the interviews (see **Supplementary Appendix A**).

In the beginning, interviewees received a short introduction on the focus and aim of the interview, informing them about modalities of data collection via audio recording and later-on usage of the data. After that they provided information about

demographic aspects (age, gender, educational and professional background, place of residency) as well as their mobility behavior and other attitudinal aspects like environmental awareness, and their knowledge of and associations with fuels (with recourse to six-point Likert scales, min = 1, max = 6). Once the participants were given a short definition of the term “alternative fuels,” which included the presentation of different types of alternative fuels such as bio- and synthetic fuels, they were asked about their personal experience with fuels and their opinion toward the possibility of fuel leakage and respective consequences.

The subsequent part of the interview focused on knowledge about and perceptions of emissions as result of fuel combustion in road traffic, followed by a briefer part on people’s personal attitude regarding the topics of sustainability and the environment. Towards the end of the interviews, the focus shifted more towards the issue of alternative fuels. This included a free association query as well as a benefit and risk evaluation. Finally, a broader set of questions referred to dangers perceived to be posed by alternative fuel usage and possible leakage incidents.

The interviews were audio-recorded and subsequently transcribed so that they can be evaluated by means of a qualitative content analysis by Mayring (2015) and Kuckartz (2018). The interview contents were analyzed by two coders using a developed category system to assure a high analyzing quality.

Participants

The pre-study’s sample consisted of 23 participants that participated voluntarily and without being incentivized. All participating individuals, of which 15 lived in Germany and eight in the United States, were selected based on personal contact. 30.4% of interviewees were female, 69.6% male, and the average age was 44.0 years (SD = 22.03, range: 19–83). The sample was highly educated: 52.2% held some form of university degree. The majority of interviewees reported to own a car themselves (73.9%) and within the sample, the participants had an average annual mileage of 7,208.7 km. Participants indicated to often use a car, as 56.5% stated to drive daily or several times a week. Owning a car was perceived as rather important (M = 4, SD = 1.86, min = 1, max = 6) for individual mobility. When asked to give information about the fuel type they were using primarily when fueling their cars, 69.6% reported to use mainly gasoline, followed by 30.4% of participants using diesel.

Results and Conclusions

The results for the data collected in two different countries are reported together, where there were no country-specific differences. In case of differences, which were rare, these will be discussed in more detail.

Regarding participants’ knowledge of and experience with conventional fuels it was found that the contact with fuels mainly consisted in refueling one’s own car at the filling station. Also, relatively little knowledge was prevailing about how and from which components fuels are produced. Regarding the risk perceptions of conventional fuels two major

aspects have been identified: On the one hand, risks were assessed for the fuel itself, on the other hand, emissions resulting from the combustion of fuels and their possible impacts were discussed. Possible impacts on the environment and on human health were two prominent areas perceived to be affected by risk for both fuel and combustion emissions. A special risk category, which was only specifically mentioned in the case of fuel, relates to risks arising from flammability, from which a perceived risk of explosion arose. However, what was more prominently feared than the possible impact of conventional fuels and emissions from their combustion were negative impacts on the environment, as to be exemplified by the following quotes:

“On the one hand, something like the death of plants or the alteration of plants or animals that are permanently exposed to such hazardous substances or the consequences of such contamination.” (male, 22 years) and “When fuel is shipped by ship, we naturally also have major risks for the seas and the animals that live there.” (male, 29 years)

Perceived risks to human health mentioned were related to people in the immediate vicinity of the fuel and emission source and to risk groups, as stated by an interviewee on the subject of emissions:

“I think it is much more harmful for people with allergies than for healthy people. And for children and pregnant women it is probably more harmful than for adult healthy people.” (male, 29 years)

When it comes to alternative fuels, which throughout the interviews were defined as being either bio-based (fuels obtained from renewable resources such as rapeseed, sunflower, sugar beet, wheat, maize or grasses) or synthetic (produced in the laboratory and consisting, e.g., of CO₂ or natural gas), as advantages participants mentioned that alternative fuels offer safer and cleaner combustion (than conventional fuels), lower levels of toxicity, lower emissions, easier planting/manufacturing, independence from the oil industry, re-use of waste products, lower costs, less damage to health, fulfillment of mobility needs and to be environmentally friendly.

Some of the points mentioned were perceived in the opposite way as barriers. Some participants feared rising prices or stressed that the combustion of alternative fuels would still produce emissions. Additional to these aspects, four barriers were expressed, that are linked to the uncertainties that the roll-out of a new product or technology might entail: a long establishment phase, reduced performance (feared only by German participants), low range of a car powered by alternative fuels and low infrastructure.

Concerning the perceived risks of using alternative fuels, the results differed only slightly from what participants had already commented on conventional fuels. At this point they emphasized the risk of explosions and threats for human health and the environment, e.g., during refueling processes and in case of fuel spill accidents, as they did before, whereby it is interesting to note

that the American part of the sample tended to assess the risks posed by alternative fuels in direct comparison with conventional alternatives as lower than the Germans did. An additional risk brought forward by German interview candidates was the risk of emerging monocultures for the production of biofuels.

When asked about tolerable toxic effects in the last part of the interview, the existence of a basic understanding of the consequences that toxicity can have on the human body was revealed as well as a broader tolerance:

“I would tolerate temporary phenomena, such as skin corrosion or irritation, if you come into contact with it. But I would not tolerate the long-term consequences of getting ill later on or really corroding the lungs, which, as with smokers, can no longer function. Or you get cancer. So, I would not tolerate such long-term damage.” (male, 22 years)

In other cases, it was shown that damage to the environment and their own health would not be tolerated:

“... it’s supposed to be better for the environment in the end and better for me too, you know? Otherwise it would be completely unnecessary to put it on the market.” (female, 20 years).

Another participant commented, that the toxic impact by fuel alternatives would be ruled out before they would enter the market, indicating that knowledge about toxicity by products already in daily use seemed to be either missing or not being associated with the alternatives discussed. Throughout the sample, the test persons tolerated toxicity levels in alternative fuels comparable to conventional fuels but at the same time expected them to be less toxic. Here, a cognitive-affective mismatch is obvious: on the one hand, conventional fuels do represent the benchmark (toxicity in alternative fuels should not be higher), on the other hand the claim for innovativeness is obvious, with the expectation that any alternative fuel should be less toxic than conventional fuels.

Questionnaire

The questionnaire was developed based on the qualitative pre-study and literature research (see **Supplementary Appendix B**). First, demographic characteristics (e.g., age, gender, education) and attitudinal characteristics (e.g., environmental awareness) were assessed. Second, a general evaluation of possible effects of the toxicity of fuels on health and the environment, driving and flight behaviour as well as attitudes towards vehicle and aircraft use were surveyed. Third, respondents received an explanation of the main focus of the survey and an introduction to the production of CO₂-based fuels. Fourth, we separately assessed knowledge about and perceptions of 1) conventional fuels and 2) CO₂-based fuels. The evaluation of fuels was carried out, among other things, using a semantic differential with a ten-point scale (e.g., 1 = toxic, 10 = non-toxic). The sequence of these “fuel assessment” blocks was randomized to avoid sequence effects. In the block on CO₂-based fuels, respondents also evaluated their use in automobile and air

traffic, and the possible positive and negative health effects for different risk targets compared to conventional fuels. Finally, trust in different stakeholders to minimize the environmental and health risks of CO₂-based fuels was surveyed. Unless otherwise noted below, all items contained in the questionnaire were evaluated using six-point Likert-scales.

Sample

In total 204 people volunteered to take part in the survey after it had been distributed through social networks and in forums on the web. After data cleaning and deleting incomplete cases, a data set of $n = 138$ complete responses was generated. 63% of the participants were female, 37% male, and the sample had an average age of 33.6 years ($SD = 13.93$, range: 18–70). With 57% of participants holding a university degree, the sample was highly educated. The largest proportion of the sample lived in the city center (42%), the smallest in a village or rural area (27%). More than half of the respondents drive a car more than once a week or on a daily basis (54%). Regarding flight behavior, during the past 12 months, the majority did not fly. Flights within the European Union were most frequent (34% “several times a year,” 27% “less frequently than annually”), followed by intercontinental flights (26% “several times a year,” 26% “less frequently than annually”) and domestic flights (16% “several times a year,” 13% “less frequently than annually”). People’s attitude was significantly more positive about driving ($M = 2.97$, $SD = 1.0$, $min = 1$, $max = 6$) than flying ($M = 2.52$, $SD = 0.93$, $min = 1$, $max = 6$; $F(1, 123) = 30.69$, $p < 0.001$). Finally, the sample’s environmental awareness was rather high ($M = 4.62$, $SD = 0.86$, $min = 1$, $max = 6$).

Statistical Analysis

Mean scores were calculated to assess the perception of fuel toxicity in general, regarding feared effects from fuels themselves, and regarding the emissions’ effect on human health, the environment, plants and animals. To analyze associations between the acceptance of CO₂-based fuels and their perceived toxicity, scores for the acceptance of fuels, divided into road and air traffic applications were calculated. Both constructs related to the evaluation of the use of CO₂-based fuels in the respective field and the willingness to use them. Cronbach’s α for the constructs was $\alpha > 0.7$, indicating a satisfactory internal consistency (see **Table 1**). The subsequent analysis of data was conducted by calculating bivariate correlations and univariate analyses of variance (ANOVA) with repeated measurement. The level of significance was set at 5%.

RESULTS

Toxicity Perception of Carbon Dioxide-Derived Fuels

Fuels in general were rather not perceived to be toxic for human health ($M = 3.32$, $SD = 0.96$; $t(137) = -2.2$, $p = 0.029$). The perceived impact of fuels on the environment was slightly higher ($M = 3.7$, $SD = 1.14$; $t(137) = 2.07$, $p = 0.04$). These findings were also reflected in the ratings of the semantic differential

TABLE 1 | Item analysis for scales used in the study.

construct	Item example	Number of items	Cronbach's alpha
Perceived fuel toxicity for health	I believe that toxic substances in fuels are the main cause of many health problems	6	0.86
Perceived fuel toxicity for environment	I believe that toxic substances in fuels are the main cause of many environmental problems	4	0.93
Acceptance of CO ₂ fuels for road traffic	I think it would be good if CO ₂ -based fuels were increasingly used in road transport	8	0.94
Acceptance of CO ₂ fuels for aviation	I would fly in a plane that uses CO ₂ -based fuels	8	0.93

(see **Figure 1**). The safety, danger, eco-friendliness, toxicity, cleanness, harmfulness of CO₂-based fuels was more positively evaluated compared to conventional fuels. The difference between the two types of fuel was particularly evident in the evaluation of the semantically opposing pair “polluting - eco-friendly.” Whereas the perceived toxicity of CO₂-based fuels was rather neutral ($M = 4.99$, $SD = 2.16$), it was more negative for conventional fuels ($M = 3.46$, $SD = 1.84$; $F(1, 137) = 48.34$, $p < 0.001$).

Perception of Toxicity Preconditions and Exposition Types

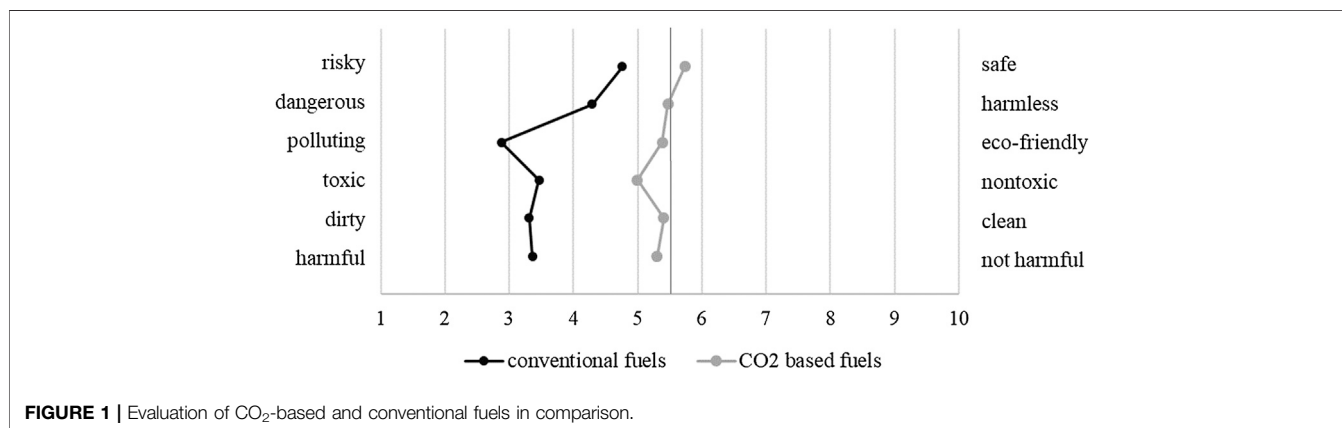
To gain deeper insights into the perception of toxicity and to discover what causes toxic substances to influence the human condition, we examined which characteristics of the fuel or of the affected person were perceived to influence toxic impacts. An ANOVA with the factor fuel (conventional vs. CO₂-based) revealed significant differences between the fuels for five of the six items dealing with the properties of the fuel or the individual which might influence toxic effects (see **Figure 2**). Although the difference was not particularly large, the physical condition of a person was slightly less decisive for the toxic effect of CO₂-based fuels ($M = 4.04$, $SD = 1.11$) than of conventional ones ($M = 4.23$, $SD = 1.04$; $F(1, 137) = 4.5$, $p = 0.036$). The differences regarding the perceived influence of material properties of and contact with the fuel were more apparent: The harmful effect of CO₂-based fuels was estimated to be significantly lower than that of conventional fuels for the factors composition and structure (CO₂-based: $M = 4.22$, $SD = 1.06$, conventional: $M = 4.47$, $SD = 0.95$; $F(1, 137) = 9.8$, $p = 0.002$), concentration

near the body (CO₂-based: $M = 4.27$, $SD = 1.02$, conventional: $M = 4.65$, $SD = 0.98$; $F(1, 136) = 23.91$, $p < 0.001$), frequency of direct body contact (CO₂-based: $M = 4.2$, $SD = 1.08$, conventional: $M = 4.65$, $SD = 0.99$; $F(1, 137) = 23.83$, $p < 0.001$), and inhalation of exhaust gases (CO₂-based: $M = 4.4$, $SD = 1.06$, conventional: $M = 4.78$, $SD = 0.93$; $F(1, 137) = 23.11$, $p < 0.001$).

As a further aspect of toxicity perception, the various types of exposition through which one can come into contact with fuel were assessed for their potential to cause health damage. The greatest difference was found for the exposure by inhalation of the exhaust fumes (see **Figure 2**). Whereas for CO₂-based fuels the fear of adverse health effects was moderate ($M = 3.09$, $SD = 1.23$), participants were much more concerned about the health risks of conventional fuels ($M = 4.48$, $SD = 1.07$; $F(1, 136) = 100.96$, $p < 0.001$). Similar results were found for the inhalation of fuel vapors (CO₂-based: $M = 3.07$, $SD = 1.24$, conventional: $M = 4.44$, $SD = 1.08$; $F(1, 136) = 95.86$, $p < 0.001$) and direct skin contact with the fuel (CO₂-based: $M = 3.03$, $SD = 1.15$, conventional: $M = 3.99$, $SD = 1.2$; $F(1, 136) = 51.97$, $p < 0.001$).

Risk Perceptions of Carbon Dioxide-Based Fuels

A further factor concerning risk and toxicity perception that was studied were risk targets. This was measured through the perceived negative influence that CO₂-based fuels, compared to conventional fuels, have on the respective object/area. There were no major differences between the various risk targets affected by the risk in terms of perceived disadvantages

**FIGURE 1** | Evaluation of CO₂-based and conventional fuels in comparison.

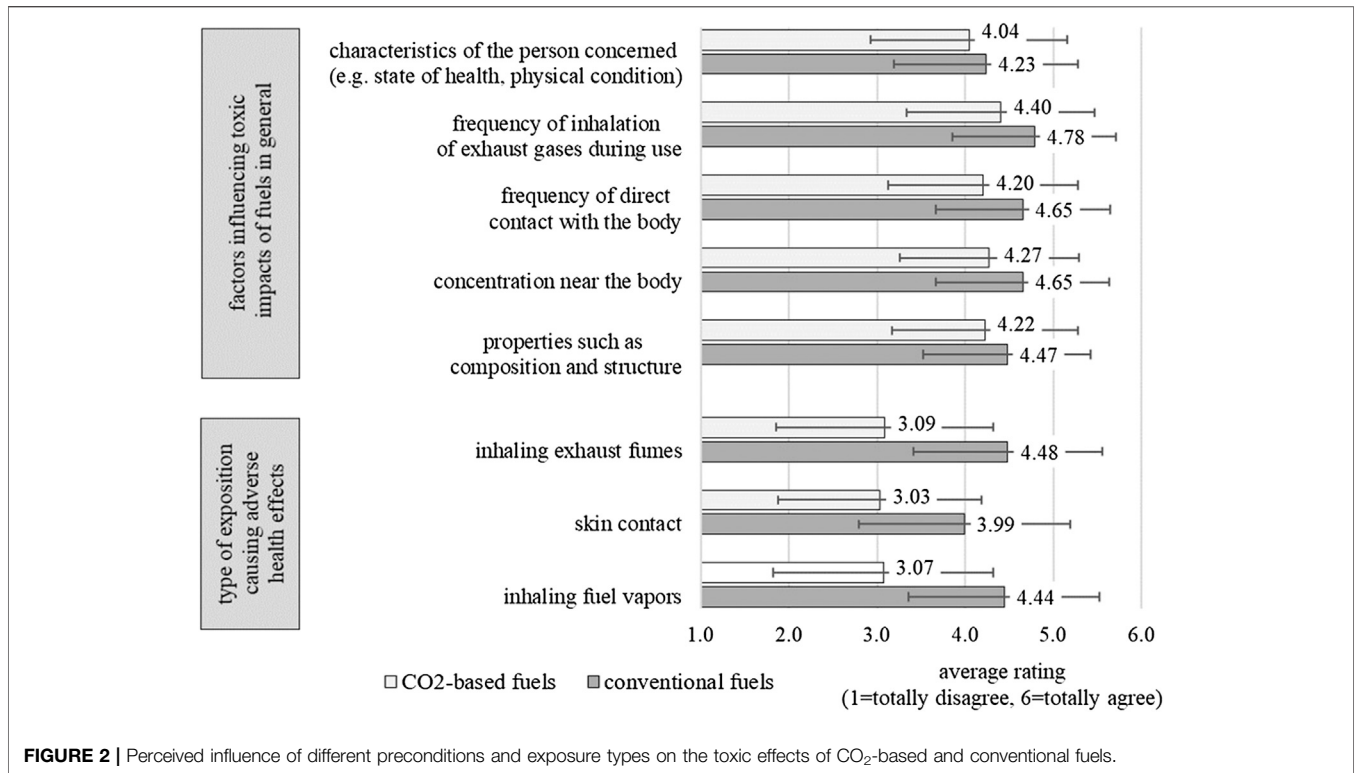


FIGURE 2 | Perceived influence of different preconditions and exposure types on the toxic effects of CO₂-based and conventional fuels.

compared to conventional fuels (see **Figure 3**), the mean values varied between M = 2.71 (“the climate,” SD = 1.18) and M = 2.86 (e.g., “(my) children’s health,” SD = 1.12).

The same applied to the assessment of potential health effects (see **Figure 4**). When asked to assess the expected frequency of specific health risks of CO₂-based fuels compared to conventional fuels, the participants rated the occurrence for all given (on a five-point Likert-scale, with 1 = much more scarcely, 5 = much more often) as rather equal. There was little difference between the

evaluation of the examined health consequences: the consequences that were estimated to be the rarest compared to conventional fuels were “cancer” (M = 2.72, SD = 0.75) and “fertility impairment” (M = 2.72, SD = 0.7). The item with the highest value was “respiratory irritation” (M = 2.84, SD = 0.79). No elevated greater perceived negative health effects for CO₂-based fuels compared to conventional fuels were found. At the same time, there were no significant differences between the health items.

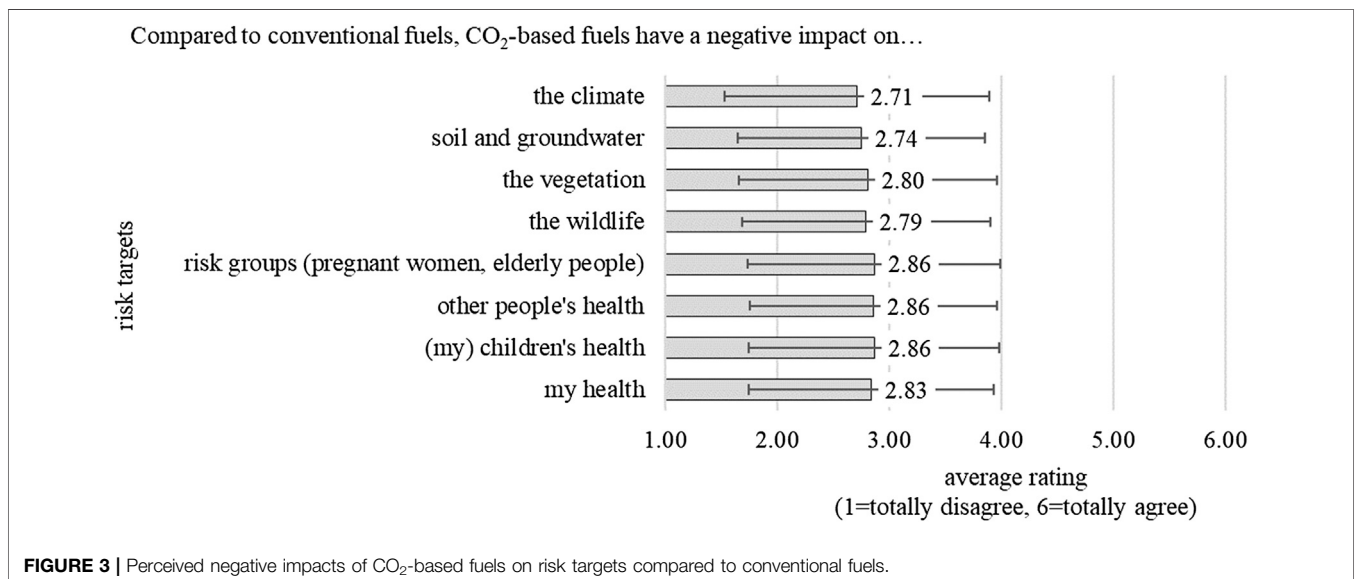
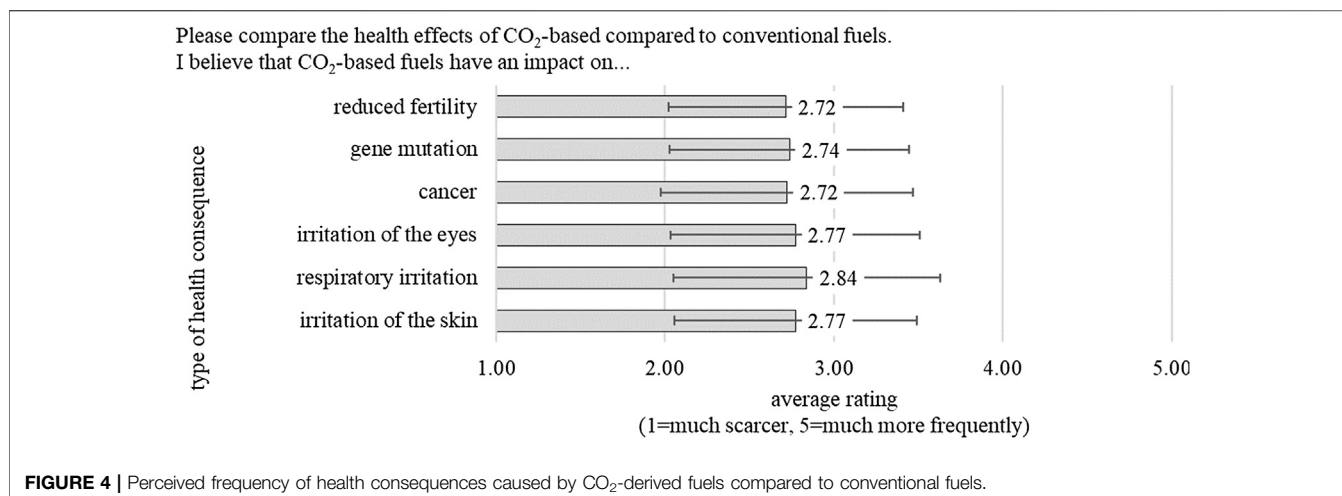


FIGURE 3 | Perceived negative impacts of CO₂-based fuels on risk targets compared to conventional fuels.



Acceptance of Carbon Dioxide-Derived Fuels and Their Perceived Toxicity

Bivariate correlations were calculated to investigate the association between different risk perceptions (e.g., toxicity) and the acceptance of CO₂-based fuels (see **Table 2**). Positive perceptions of CO₂-based fuels were generally highly significantly related to higher acceptance levels for CO₂-based fuels in both mobility contexts (road traffic and aviation). More specifically, when respondents evaluated CO₂-based fuels as nontoxic the acceptance ratings for using them in road traffic ($r = 0.48$, $p < 0.001$) and in aviation were also higher ($r = 0.41$, $p < 0.001$). The highest correlation was found for “risky–safe”: the more people perceive the use of CO₂-based fuels as being safe, the more they accept them for their use in cars ($r = 0.52$, $p < 0.001$) and airplanes ($r = 0.52$, $p < 0.001$).

Further bivariate correlations were carried out for the acceptance of CO₂-based fuels and risk perceptions of disadvantages for various *risk targets*. Statistically significant negative relationships with the acceptance of CO₂-derived fuels were found for all examined objects/areas (see **Table 3**), i.e., the higher the acceptance levels for CO₂-based fuels, the lower the perceived risks for one’s own health, other people’s health, risk groups, as well as the wildlife, vegetation, soil, ground water, and the climate. The highest, but still moderate association in both usage contexts (aviation and road traffic) was found between acceptance and the disadvantages for the vegetation (road traffic: $r = -0.53$, $p < 0.001$; aviation: $r = -0.54$, $p < 0.001$) and the climate (road traffic: $r = -0.52$, $p < 0.001$; aviation: $r = -0.58$, $p < 0.001$). In the case of risk groups, the correlation with acceptance of CO₂ fuels for road traffic ($r = -0.44$, $p < 0.001$) was significantly

weaker than with acceptance for the context of aviation ($r = -0.53$, $p < 0.001$) according to z-Test ($z = 1.67$, $p = 0.048$).

The analysis of relationships between acceptance evaluations of CO₂-derived fuels and evaluations of risks posed by different types of exposure to CO₂-based fuels aligns with the picture obtained so far: The more people value the use of CO₂-based fuels and the more they are willing to use them, the less they agree with the assumption that CO₂-derived fuels, compared to conventional fuels, cause major health hazards (see **Table 4**). The significant negative correlations differed depending on the acceptance context: While the correlations for the acceptance of CO₂-derived fuels in road traffic were rather weak (e.g., “skin contact”: $r = -0.45$, $p < 0.001$), there were medium strong negative correlations for the acceptance for use in air traffic (e.g., “skin contact”: $r = -0.59$, $p < 0.001$). According to conducted z-Tests, for all three items the correlation with acceptance of CO₂-based fuels was significantly weaker in the context of road traffic than for a usage in the field of aviation (e.g., “skin contact”: $z = 2.94$, $p = 0.002$).

Finally, bivariate correlations showed significant negative associations between the acceptance of CO₂-based fuels and perceived incidence of diseases caused by CO₂-based fuels, compared to conventional fuels (see **Table 5**).

With increasing acceptance of CO₂-based fuels specific physical symptoms such as the irritation of the skin, respiratory system, and eyes as well as more severe health effects such as cancer, gene mutation or a reduced fertility were perceived to be less frequent compared to these effects caused by conventional fuels. The more people believe that, e.g., fertility impairment occurs much more frequently when using CO₂-based fuels (compared to conventional ones) the less they

TABLE 2 | Bivariate correlations of acceptance of CO₂-based fuels and risk perception ratings (scale: e.g., 1 = toxic, 10 = nontoxic).

	harmful–not harmful	dirty–clean	toxic–nontoxic	polluting–eco-friendly	dangerous–harmless	risky–safe
Acceptance of CO ₂ fuels for road traffic	0.445*	0.438*	0.482*	0.507*	0.436*	0.521*
Acceptance of CO ₂ fuels for aviation	0.409*	0.353*	0.409*	0.424*	0.415*	0.518*

* $p < 0.000$.

TABLE 3 | Bivariate correlations of acceptance of CO₂-based fuels and risk perception of disadvantages of CO₂-based fuels for various risk targets.

	My health	(my) children's health	Other people's health	Risk groups (pregnant women, elderly people)	The wildlife	The vegetation	Soil and groundwater	The climate
Acceptance of CO ₂ fuels for road traffic	-0.477*	-0.477*	-0.492*	-0.440*	-0.480*	-0.534*	-0.487*	-0.524*
Acceptance of CO ₂ fuels for aviation	-0.526*	-0.532*	-0.541*	-0.525*	-0.538*	-0.540*	-0.492*	-0.582*

* $p < 0.000$.

accept CO₂-based fuels for aviation ($r = -0.37, p < 0.001$) or road traffic ($r = -0.42, p < 0.001$).

Finally, an ANOVA revealed no significant differences between the acceptance of CO₂-based fuels for road traffic ($M = 4.22, SD = 1.03$) and aviation ($M = 4.27, SD = 0.94$); $F(1, 137) = 0.93, p = 0.337$) as well as for the intention to use CO₂-based fuels for the propulsion of cars ($M = 4.37, SD = 1.09$) and airplanes ($M = 4.49, SD = 1.04$) (e.g., “I would fly in a plane that uses CO₂-based fuels.”), indicating no preferences for a specific usage context ($F(1, 135) = 1.76, p = 0.186$).

DISCUSSION

CO₂-based fuels represent a promising approach to reduce greenhouse gas emissions by reusing emitted CO₂ for fuel production instead of fossil resources. The perception of risks in terms of toxicity of CO₂-derived fuels (in comparison to conventional ones) has been identified as an important point and was therefore investigated for the first time in this study.

In general, we found CO₂-based fuels to be perceived by laypeople as a safe, rather harmless, eco-friendly, non-toxic and clean energy source. Compared to conventional fuels they were perceived more positively regarding their health- and environmental impacts. For factors influencing toxic effects and possibly health damaging types of exposition to a fuel, CO₂-derived fuels were perceived to pose less risks when getting in contact with consumers. The assessment of specific health risks and risk targets showed no major differences. In comparison to conventional fuels, health risks and negative impacts on vulnerable groups or the environment were perceived to occur less frequently.

Perceptions of Risk and Toxicity of Carbon Dioxide-Based vs. Conventional Fuels

The overall rather negative evaluation of conventional fuels in comparison to the proposed CO₂-derived alternative must be assessed against the background of experience, which can influence acceptance (Huijts et al., 2012). Since the public generally has practical experience with handling conventional fuels, it can be assumed they transferred their handling experience (e.g., at the gas station) with conventional fuels to CO₂-based fuels and evaluated the risk level accordingly. On the other hand, the highest discrepancy in risk perceptions between the fuel types for the feature “polluting - eco-friendly” might be explained by the increasing relevance of emissions and climate change as topics of public interest in media and public debate.¹ Further, factors influencing toxic impacts of fuels were feared more for conventional fuels, which also has to be put in reference to experience. Since CO₂-based fuels are in the process of development, there is no chance for the public to use them, which could be expressed in the form of ratings that rather reflect the wishful thinking of a “better” fuel.

¹<https://www.nationalgeographic.com/environment/2019/01/climate-change-awareness-polls-show-rising-concern-for-global-warming/>

TABLE 4 | Bivariate correlations of acceptance of CO₂-based fuels and evaluation of risks posed by different types of exposure to CO₂-based fuels.

	Inhaling fuel vapors	Skin contact	Inhaling exhaust fumes
Acceptance of CO ₂ fuels for road traffic	-0.433*	-0.449*	-0.389*
Acceptance of CO ₂ fuels for aviation	-0.587*	-0.594*	-0.534*

* $p < 0.000$.**TABLE 5 |** Bivariate correlations of acceptance of CO₂-based fuels and perceived frequency of health consequences of CO₂-based fuels compared to conventional fuels.

	Irritation of skin	Respiratory irritation	Irritation of the eyes	Cancer	Gene mutation	Reduced fertility
Acceptance of CO ₂ fuels for road traffic	-0.323*	-0.310*	-0.288*	-0.474*	-0.459*	-0.419*
Acceptance of CO ₂ fuels for aviation	-0.281*	-0.320*	-0.297*	-0.418*	-0.410*	-0.369*

* $p < 0.000$.

For exposure types it was observed that health effects for conventional fuels due to skin contact were perceived as less likely. In this context, it is important to consider the users' controllability of the situation: in contrast to skin contact, which is under one's own control, e.g., when refueling a car, the inhalation of fuel vapors or exhaust fumes is out of one's personal control. This finding indicates that perceived health risks perceptions are based on a probability assessment of exposure. Further, we assume that exposure types are categorized into internal and external body influences, since exposure to skin contact is perceived as less of a health hazard than the inhalation of gases.

Summing up so far, the public does not perceive or associate major environmental or health effect concerns with regard to CO₂-derived fuels. However, the actual risks to health and the environment should already be taken into account at early development stages of future CO₂-based products such as fuels. The fuel conversion and production process and the subsequent consumption and combustion of CO₂-based fuels must be checked for potentially harmful characteristics to human health or the environment and corresponding follow-up actions are necessary during implementation. Today, due to the early stage of development, potential toxicity-induced risks are not anchored in the awareness of potential users. Nevertheless, since health concerns are powerful barriers or breaking points to the adoption of innovations, ongoing and future developments should ensure that such risks are controlled and minimized.

Use of Carbon Dioxide-Based Fuels: Road Traffic and Aviation

Since CO₂-based fuels might not only be used in road traffic, but also in the aviation sector, the present study contrasted the perceptions and acceptance for both usage contexts. Even though previous studies showed that the application of alternative fuels in a personal mobility was preferred (Arning et al., 2020), the present study showed that the use of alternative fuels was equally accepted in both mobility contexts. Considering the increasing attention that flying with its large contribution to the human carbon footprint has received in the public debate, e.g., the term "flight shame" made it onto the Oxford's 2019 Word of the Year shortlist (Oxford Languages, 2020), the development of CO₂-based fuels for

aviation is a promising starting point. However, to obtain more in-depth insights into the relationship between willingness to use alternatives like CO₂-based fuels and motives and barriers to use, further studies would be carried out.

For both aviation and road traffic the acceptance of CO₂-based fuel in our sample increased the more people evaluated the fuel positively, the less they feared 1) consequences for human health and the environment and 2) impacts of direct contact with a fuel, emissions or vapors and the less frequently they estimated specific health consequences to occur due to CO₂-based fuels. It could not be found that the acceptance for an application is higher in either context.

Regarding the application of CO₂-derived fuels we can conclude that the more people tend to fear health effects by exposure to CO₂-based fuels via skin contact or inhalation of fuel vapors and exhaust fumes, the less they accept the use of CO₂-based fuel. For aviation fuels, an increase in concern about health impacts is linked to greater acceptance declines than for the use in road traffic.

Limitations and Future Research

When assessing the results, it must be taken into account that the sample was highly educated and that therefore the transferability of the results is limited. Further studies should therefore be conducted with more representative samples to verify and support our initial insights into risk perceptions and toxicity of CO₂-based fuels. Furthermore, the influence of user factors such as age, gender on acceptance, but also experience with and knowledge of alternative forms of energy were not examined in any greater depth. As discussed earlier, a more detailed study of these variables could provide further insights into the perception of CO₂-derived fuels.

Based on the correlational analyses, a first step was taken to investigate the relationship between acceptance and toxicity-related risk perceptions. However, further statistical analyses should be applied to investigate the explanatory power of perceived toxicity for fuel acceptance. Additionally, it should be considered that the survey focused on fuel as an end-product, but not the production process. Further research is needed to investigate perceived health- and environmental risks posed during the manufacturing of CO₂-derived fuels as well their effects on general and local acceptance.

One constraint of the conducted survey is its focus on toxicity as one facet of risk perception. Further work is needed to analyze possible interactions and trade-offs with other risk perceptions, but also with perceived benefits. Another important remark regarding the perceived influence of preconditions like characteristics of fuel or person affected, is the circumstance that participants were given the task of assessing not the influence of the product itself, but the influence of a constraint on the impact of the product. With a more direct type of risk assessment, the already high levels and significant differences could be even more evident. Finally, the perceived frequency and type of health consequences of CO₂-based fuel usage compared to conventional fuel usage has to be examined in more detail.

The occurrence of mild health effects such as irritations of skin, eyes and the respiratory tract had a lower relationship with acceptance, whereas the association with consequences like cancer, gene mutation and reduced fertility were stronger. This indicates that the relationship between perceived frequency of health effects and decreasing acceptance is greater when more severe, long-term health consequences are considered. This emphasizes the need for communication that informs about objective health risks and the toxicity of CO₂-based fuels in order to prevent a rejection of CO₂-based fuels based on unfounded fears.

CONCLUSION

To reduce greenhouse gas emissions and simultaneously maintain our mobility needs, alternatives to fossil-based energy carriers are required in the future. Since their market success depends on their acceptance, it is necessary to examine public perceptions and acceptance of fuel alternatives, such as CO₂-based fuels. The present study yielded first insights into health-related risk perceptions and the acceptance of CO₂-based fuels.

First, acceptance levels for use of CO₂-based fuels in road traffic and the aviation context are rather high but reveal no preferred context of use. In direct comparison to conventional fuels the CO₂-based alternative is perceived to be safer, rather harmless, eco-friendlier, and cleaner. Second, feared consequences and circumstances for human health and the environment have nevertheless negative impacts on acceptance, although CO₂-based fuels are also perceived to be less toxic than conventional fuels.

Finally, risk evaluation regarding toxic effects shows that frequency of health impacts (e.g. for risk groups) and the environment is estimated to be lower than it is perceived to be the case for conventional fuels. In addition to the investigation of actual health- and environmental risks due to the toxicity of

CO₂-based fuels, it is therefore of great importance to provide information tailored to the needs of laypeople, that informs about risks and thus enables an informed assessment of risks and benefits for users.

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. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2020.579814/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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