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Perception of EU citizens on engineered biocatalytic solar fuels

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A B S T R A C T

Genetic modification of microorganisms for enhanced metabolic activity shows excellent promise for biotechnological exploitation. The production of solar fuels can be facilitated by novel advances in the metabolic engineering of microalgae and cyanobacteria. Contaminant-free biocatalytic production with high cell densities at a large scale and low costs need to be achieved for commercial application of this innovation from the technical perspective. From a market perspective, possible citizens' concerns towards genetically modified organism and products need to be investigated and addressed before product development and sale. Across EU countries, this paper shows citizens' views on solar fuel produced by genetically engineered microorganism. For the first time, this study investigates the EU citizens' attitudes towards this novel technology and possible relationship to gender, age and education. The results indicate that EU citizens consider engineered biocatalytic solar fuels as environmentally superior to established biofuels. The majority of the respondents (84%) would be their final consumers, and 70% of them are willing to pay a surcharge for them, provided that they have environmental advantages in general and in particular for climate protection. However, compared to electric cars fueled with renewable power, citizens perceive biocatalytic solar fuels as less environmentally friendly.

1. Introduction

Microalgae and cyanobacteria are considered promising organisms for the production of third-generation biofuels. They can support climate protection policy as they are cultivated in biotechnical systems using sunlight, CO_2, water, and nutrients. They do not compete for land use with food production, such as the first-generation biofuels bioethanol and biodiesel [1–4]. Despite these advantages and ongoing research at a global scale, algal biofuel is not commercially available due to its high-energy demand, costs and contamination of microalgae cultivation in photobioreactors, as well as complex harvesting and downstream processes in algal biofuel production [3,5–7]. It is of high interest to alter algae species to achieve high yields of compounds that are converted into biofuels, such as carbohydrates and lipids or other fuel precursors [2,8]. Since it is difficult to achieve this goal with natural algae strains, there is ongoing research in the genetic modification of microalgae and cyanobacteria to develop innovative fuel production pathways [9–13]. Genome editing techniques can increase processes and carbon fixing efficiency and biological transformation to specific high-value solar fuels. Following the "milking cows" narrative, the

engineered biocatalytic microorganisms are considered green synthetic living factories that release their products to the culture media to be harvested without destroying them [14]. This steady-state production process allows for a continuous harvest of biocatalytic solar fuels. In addition, genetic engineering facilitates the design of desired fuel characteristics of biocatalytic solar fuels. Thereby it is possible that no further fuel processing, neither changes in the existing infrastructure for fuel storage and distribution, nor their utilisation in current combustion vehicles are required [15,16]. Cradle-to-grave life cycle assessments (LCA) underline the necessity of metabolic engineering to enhance carbon partitioning to fuel products and improve light utilisation. With the supply of renewable process power, this technology can reduce the carbon footprint of algal fuel [6,17,18]. Given the critical citizens' attitude towards genetically engineered plants in Europe, this promising innovation can be contested with reservations, criticism or even rejection by the citizens once the technology is ready for the market [17]. Social investigations on public perception of biocatalytic solar fuels produced with engineered microorganisms are required to understand the attitudes and views of future consumers at an early stage. Although lack of, or incorrect knowledge about the conditions of public

acceptance can emerge as a powerful barrier for genetically engineered microorganisms, this issue is not addressed in technology development. An analysis of expert opinion on engineered biocatalytic solar fuels revealed that experts believe that citizens view on solar fuels produced with engineered microorganisms would be critical or even negative regardless of the specific cultural settings [19]. This paper addresses this hypothesis of experts and stakeholders since this is a crucial issue to close the socio-technical knowledge gap. This work provides the first insights into EU citizens' views on solar fuels produced with engineered microorganisms, as part of the inter- and transdisciplinary research project PHOTOFUEL funded by the European Union (EU) [7].

2. Methods

An elaborated questionnaire was designed to conduct a quantitative survey via social media platforms. This approach is well suited to investigate public opinion across EU countries relatively easily, quickly and at low expenses. A draft questionnaire was developed in the English language and discussed with experts in biocatalytic solar fuel production and laypersons unfamiliar with this topic. Two revision loops improved the questionnaire further and made it easily accessible, appealing and quick to carry out for the participants. Native speakers translated the final questionnaire from the English language into five common European languages: French, German, Italian, Portuguese and Spanish to overcome language barriers and reach people from non-academic population groups.

For the online survey, the open-source and free platform Sosci Survey (www.soscisurvey.de) was applied. The questionnaire was distributed online via different social network platforms, e.g. Facebook, Instagram, Twitter, Whatsapp, Xing, LinkedIn, ResearchGate. Native project partners spread the survey link in their home countries to different social communities. With this procedure, a broad and diverse range of people regarding gender, profession, education, and knowledge can be reached. Participants were asked to forward the questionnaire to other colleagues, family and friends to benefit from the snowballing effect and expand the sample and its variety even further [20]. The web-based questionnaire facilitated to reach many persons at different and distant places and enabled fast response and low overall personnel and material expenses.

2.1. Structure of the questionnaire

A structured questionnaire comprising 16 questions, addressing the following six main issues, which have possible impacts on public acceptability, was developed with interdisciplinary experts and pre-tested with laypersons.

(1) Sociodemographic profile (e.g. gender, age, educational level, family and employment status)
(2) Knowledge on the topics of microalgae and genetically modified organisms
(3) Environmental comparison of biocatalytic solar fuels with other fuels
(4) Feelings towards a biocatalytic solar fuel production plant in the neighbourhood
(5) Risk perception of biocatalytic solar fuels produced with genetically modified microorganism
(6) Willingness to support and consume biocatalytic solar fuels and to pay more money for them

2.2. Data analysis of the completed questionnaires

The Sosci Survey platform automatically saved the responses. To avoid more than one response per person, the link of the questionnaire was valid only one time per electronic device. Data analysis was performed in two steps: first, a descriptive statistic was completed and

presented by using Microsoft Excel® [21], and second, an inductive statistic was conducted by using IBM-SPSS.25 [22]. The databases provided by Sosci Survey were exported in MS Excel and SPSS files for statistical analysis. An overview of the variables and the statistical tests performed to find relationships between them is summarised in Fig. 1. The ordinal opinion variables were ranked on a 5-Point Likert scale [23].

A Kruskal-Wallis test [24] was performed to analyse the answers between the EU countries for significant variation. This test indicates whether at least one of the multiple samples is significantly different but does not reveal which sample or group is diverse. Although clear and comprehensive reference sources on posthoc tests after Kruskal-Wallis are hard to find, in the cases where Kruskal-Wallis test was significant, the posthoc test Tukey Kramer used for unequal sample sizes was chosen. Correlations between sociodemographic ordinal variables and opinion ordinal variables were completed by using Spearman's rank correlation coefficient with SPSS software. This correlation coefficient ranges from -1 to $+1$. The larger the absolute value of the coefficient, the stronger is the relationship between the variables. Correlations between sociodemographic ordinal variables and opinion nominal variables and correlations between sociodemographic nominal variables and opinion ordinal and nominal variables were performed using the Chi-Square (χ^2) test of independence with SPSS software. Chi-square test shows if there is a significant relationship between variables (p-values < 0.05), but it does not indicate the degree of significance. Cramer's V is a test that measures the relationship between the variables indicating their strength. The interpretation of Cramer's V values are as follows: values < 0.10 indicate weak, values between 0.10 and 0.30 indicate moderate, and values > 0.30 indicate strong relationships. Fisher's test was done in cases of having two dichotomous categorical variables.

3. Results

The survey scored 417 completed and valid responses across EU countries.

3.1. Descriptive statistical analysis

3.1.1. Sociodemographic profile

The sociodemographic profile of the respondents (Fig. 2) shows an almost equal distribution of male and female respondents, with a share of 54% and 46%, respectively. An almost even distribution was observed between the respondents' ages, with the highest percentage in the age group 30–39 years (32%) followed by the group 20–29 years and 40–49 years, with 27% and 23%. The share of people older than 60 years was reöatively small (7%) as expected due to the online format of the survey. There was a balance between respondents with and without children, with a share of 50% each. The respondents had a relatively high educational level; 79%of them had a university degree, and 12% had technical training. Most respondents (67%) were employees living in big cities with more than 100,000 inhabitants (60%). Thus, the survey did not succeed in reaching the desired number of non-academic population groups. The low proportion of non-academic participants was probably due to the research topic. The questions were rather academic and too far away from the living environment of non-academic groups. Besides, EU citizens living in rural areas could not be reached as good as citizens living in cities. Again that might be the impact and drawback of the online format chosen.

Citizens from 21 EU countries and the United Kingdom participated, and thus a large cultural diversity is represented in the survey. At the same time, the number of participants per country is relatively small (Fig. 3). 74% of the total respondents were currently living in Italy, Finland, France, Germany, Portugal, Sweden, and the United Kingdom. The numbers of respondents correspond with the size of the countries' population: Germany and France's responses were significantly more prominent than in the Scandinavian countries (Fig. 3). For further statistical analysis, responses from Eastern EU countries (Greece, Hungary,
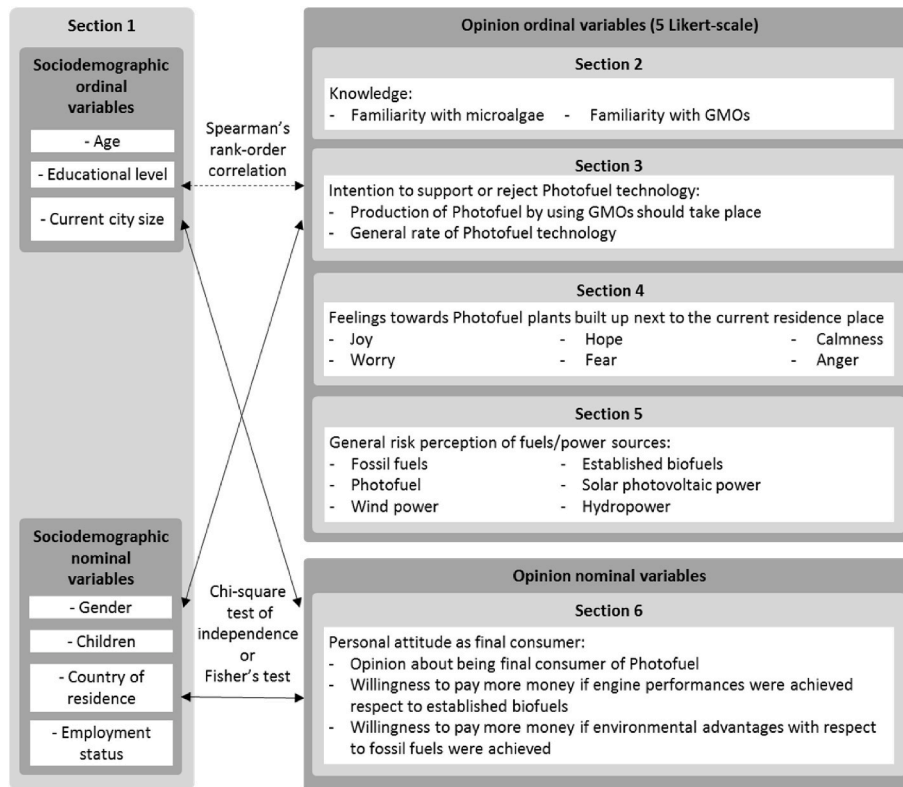
Fig. 1. Overview of the analysis with variables and statistic tests applied.
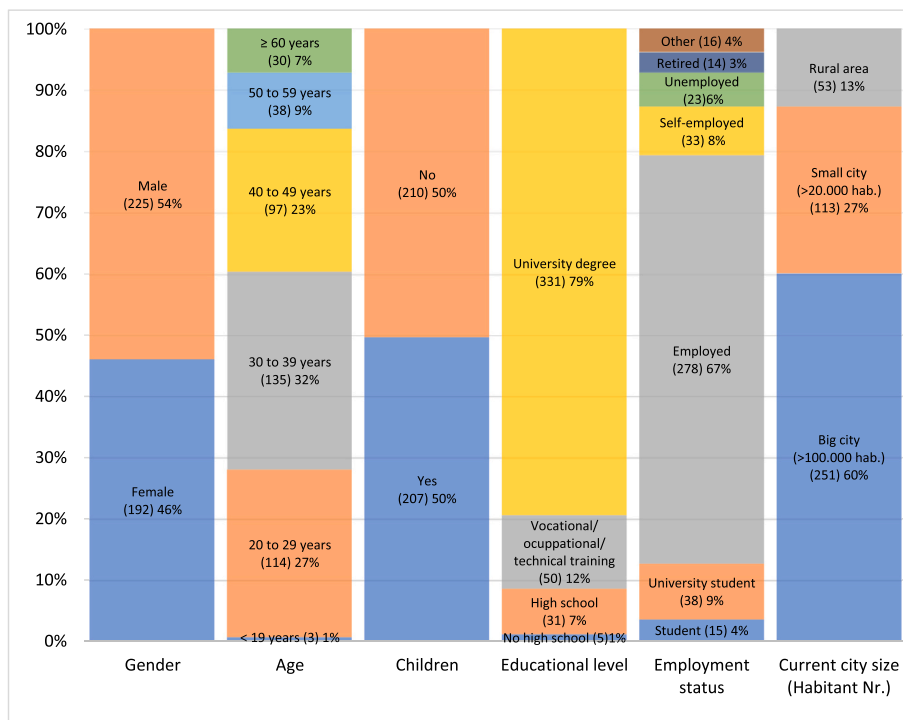

Fig. 2. Sociodemographic profile of survey respondents (absolute numbers in brackets), n = 417.

Latvia, Poland, Romania, Slovakia, Bulgaria, Croatia, Cyprus and the Czech Republic) were clustered because of their low response quote (Fig. 3). No response was obtained from the countries Estonia, Ireland, Lithuania, Luxembourg, Malta and Slovenia.

3.1.2. Level of knowledge and familiarity with the topic

One surprising result was that the familiarity with microalgae was relatively high: most respondents (72%) were somehow familiar with them, and only 28% never heard about them. It can be assumed that distributing the survey across the project partners has led to this bias.
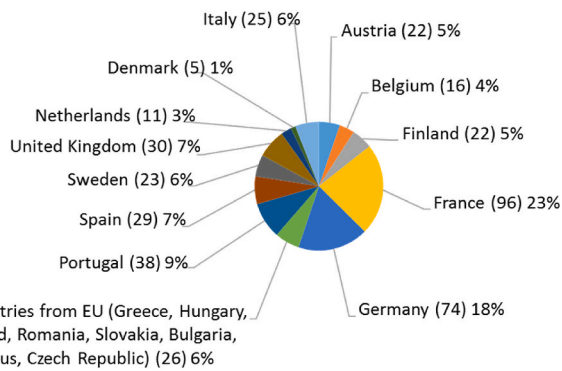
Fig. 3. Residence country of respondents (absolute numbers in brackets), n = 417.

However, answers in the different countries (Fig. 4a) were significantly varying (Kruskal-Wallis H = 68.3, df = 12, p < 0.001). Pairwise comparisons made with Tukey-Kramer test indicated significant differences between the countries (p < 0.05). According to this test, respondents from Sweden (M = 2.78) and Portugal (M = 2.89) were more familiar with microalgae than the other countries' respondents.

In the case of familiarity with the genetically modified organism (GMOs), 91% of the respondents were familiar with GMOs, and only 9% never heard about them. The answers analysed by country (Kruskal-Wallis H = 43.6, df = 12, p < 0.001) show a significant difference (Fig. 4b). According to the pairwise comparisons made with Tukey-Kramer test, respondents from Sweden (M = 2.61) and Portugal (M = 2.84) were more familiar with GMOs than the respondents from the other countries (p < 0.05).

3.1.3. Intention to support or reject engineered biocatalytic solar fuels

The intention to support or reject engineered biocatalytic solar fuels was reflected in the responses to whether or not these fuels should be produced by using GMOs (Fig. 5a) and their general rate of the
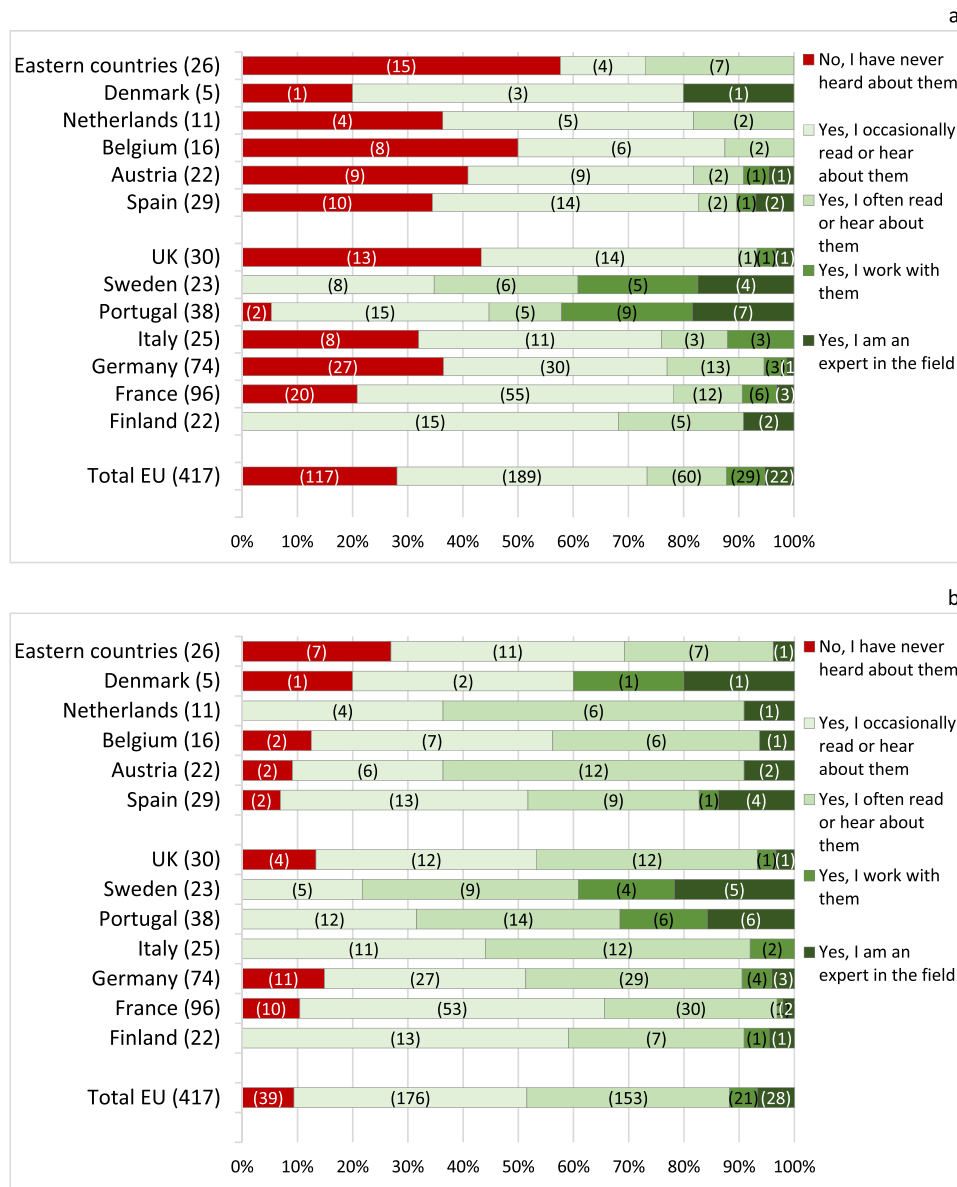

Fig. 4. a. Familiarity with microalgae (absolute numbers in brackets, n = 417). b. Familiarity with genetically modified microorganisms (absolute numbers in brackets, n = 417).
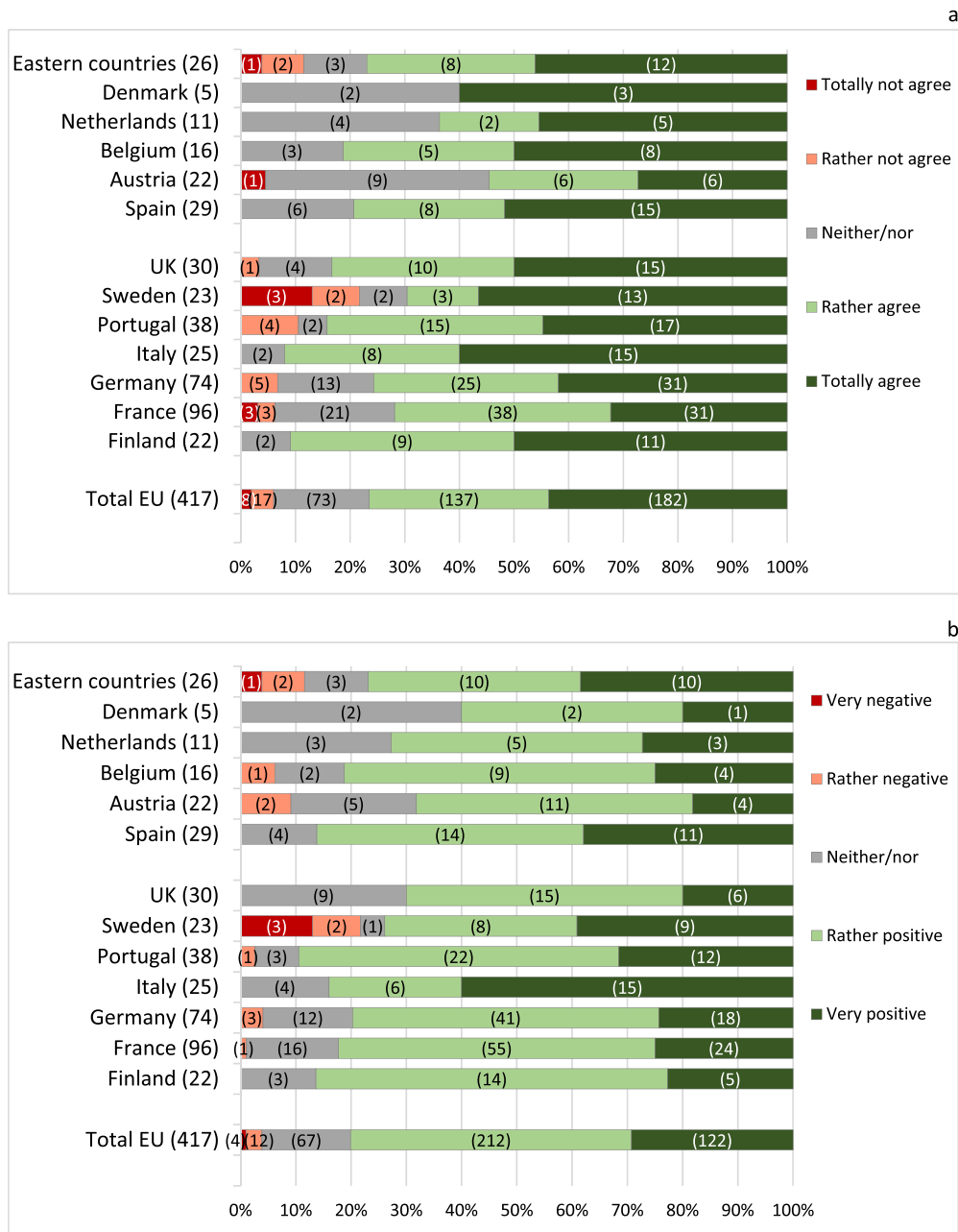
Fig. 5. a. Approval or disapproval of engineered biocatalytic solar fuels (absolute numbers in brackets, n = 417). b. Opinion on the technology for biocatalytic solar fuel production (absolute numbers in brackets, n = 417).

technology (Fig. 5b). In both questions, a high share of respondents, 77% and 80%, respectively, revealed an intention to support the technology, while only 2% and 1% were opponents. Although some differences were observed between the answers per country, these were not statistically significant.

3.1.4. Feelings towards a neighbouring biocatalytic solar fuel production plant

Most respondents had positive or neutral feelings when asked about having a biocatalytic solar fuel production plant built near their current residences (Fig. 6a). Kruskal-Wallis test showed some significant differences (Kruskal-Wallis $H_{(joy)}$ = 27.0, $H_{(worry)}$ = 48.9 and $H_{(anger)}$ = 36.3; df = 12; p < 0.05) between the answers of different countries. Tukey-Kramer test showed no significant differences between the countries. Still, the mean plots (show that respondents living in Spain, Italy, Belgium and Germany have positive feelings. In contrast,

respondents from France, Portugal, and the Netherlands have rather negative feelings about having such a plant built near their residences (Fig. 6b).

3.1.5. Risk perception of engineered biocatalytic solar fuels

The perception of the general risk, i.e. health, environment and accidents, of different fuels and power sources for future mobility is shown in Fig. 7a. Most respondents indicated fossil fuels as rather harmful or entirely harmful, with 42% and 45% shares, respectively, followed by established biofuels. 35% of the respondents believe that biofuels are somewhat dangerous, and only 4% think they're entirely harmful. Most respondents considered wind power, photovoltaic, and hydropower as the most harmless options, followed by 56% of the respondents who believe that engineered biocatalytic solar fuels would also be innocuous or relatively benign. This result is displayed in mean plots (Fig. 7b).

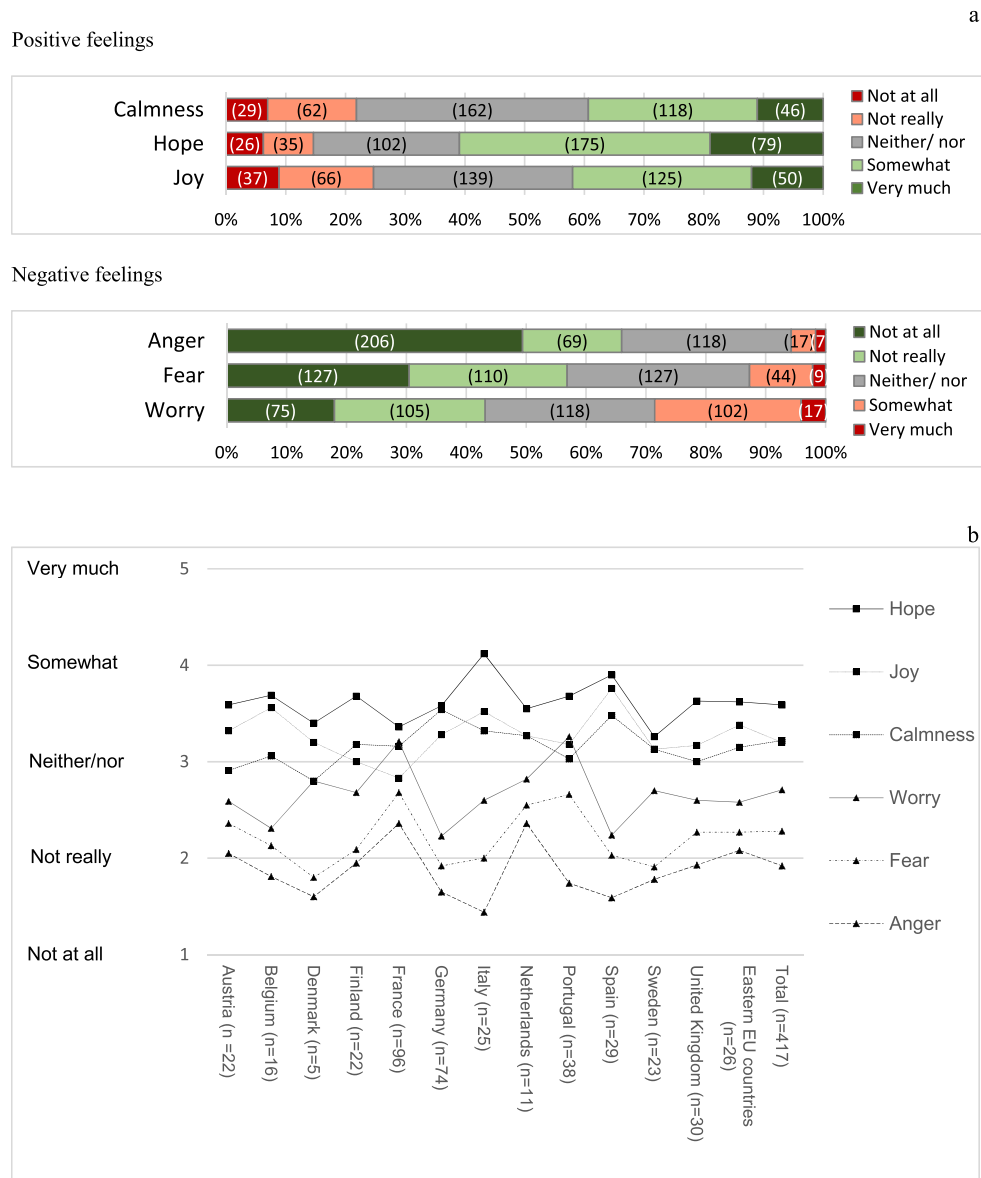Kruskal-Wallis test showed some significant differences (Kruskal-

Fig. 6. a. Overall feelings about a biocatalytic solar fuel plant in the residential neighbourhood (absolute numbers in brackets, n = 417). b. Country-specific feelings about a biocatalytic solar fuel plant in the residential neighbourhood (absolute numbers in brackets, n = 417).

Wallis $H_{(fossil\ fuels)} = 21.1$, $H_{(established\ biofuels)} = 54.3$, $H_{(Photofuel)} = 43.3$, $H_{(solar)} = 46.3$, $H_{(wind)} = 24.2$ and $H_{(hydroelectric)} = 24.4$; df = 12; p < 0.05) between the answers of participants from different countries. The Tukey-Kramer test showed significant differences (p < 0.05) in the following cases:

(1) Established biofuels: respondents from France (M = 3.49) and Sweden (M = 3.35) believe that traditional biofuels are rather harmful, whereas respondents from Italy (M = 2.24) and Finland (M = 2.41) perceive them relatively harmless;

(2) Engineered biocatalytic solar fuels (Photofuel) are rated as harmless by respondents from Italy (M = 1.68), whereas respondents from Denmark (M = 3.00) and France (M = 2.79) rate them as not so harmless;

(3) Electric mobility powered with photovoltaic is perceived as less harmless by respondents from France (M = 2.38) than from Belgium (M = 1.44)

3.1.6. Possible consumer behaviour concerning engineered biocatalytic solar fuels

The majority of the respondents (84%) would be final consumers of engineered biocatalytic solar fuels (Photofuel) (Fig. 8). The willingness to spend more money on biocatalytic solar fuels for higher engine performances compared to established biofuels and more environmental advantages than fossil fuels is shown in Fig. 9 and Fig. 10, respectively. If biocatalytic solar fuels could achieve higher engine performances, 70% of respondents would spend more money on them than on established biofuels. 24% of the respondents will only buy these solar fuels if they have the same or a lower price than biofuels. Only 6% of the respondents would not be final consumers of these fuels. If biocatalytic solar fuels have environmental advantages over fossil fuels, many respondents answered they would spend more money on Photofuel (79%). In general, with the higher ranges of willingness to pay, respondents seem to be more interested in increasing environmental protection than in improved engine performance.
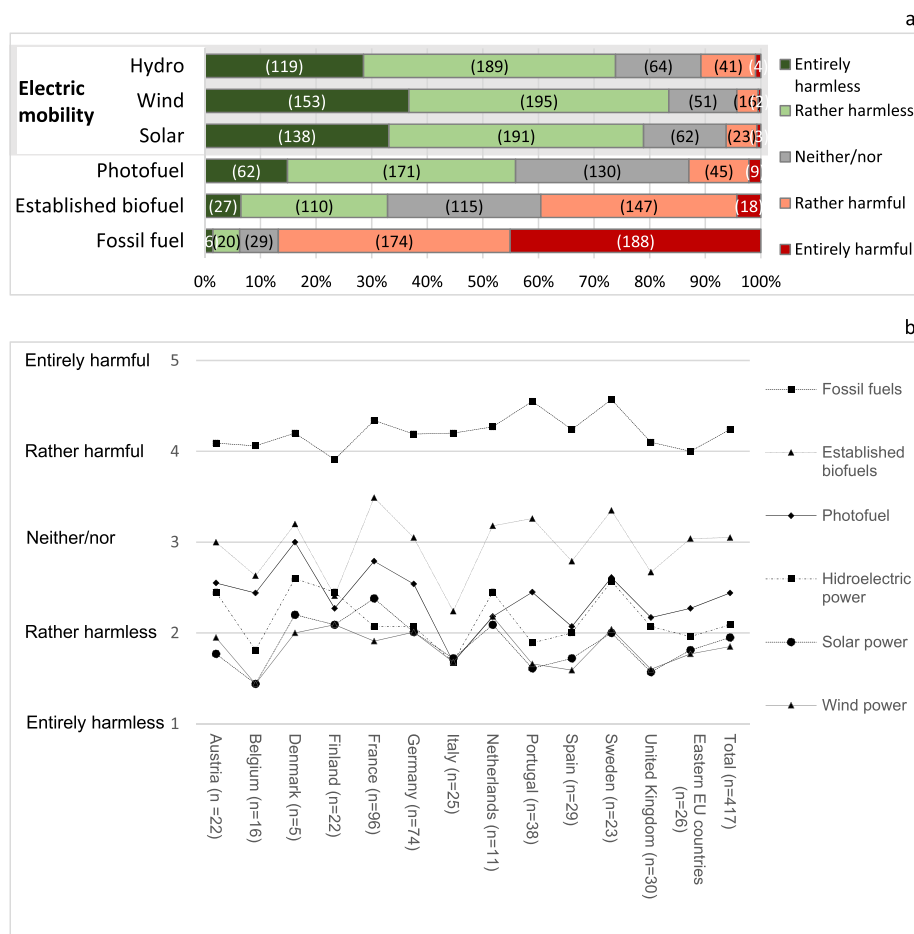
Fig. 7. a. Overall perceptions of the environmental friendliness of different fuels and electric mobility (absolute numbers in brackets, n = 417). b. Country-specific perception of the environmental friendliness of different fuels and electric mobility (n = 417).
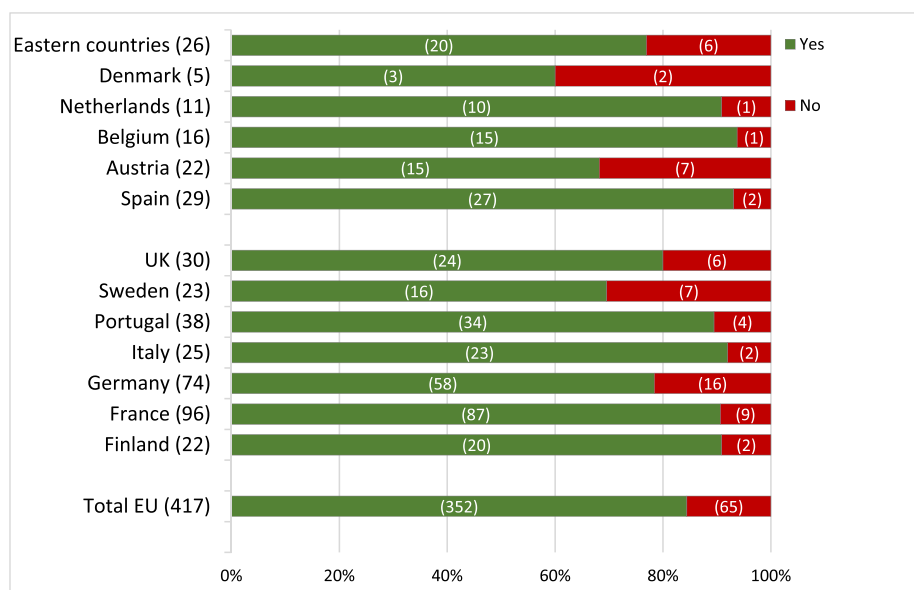
Fig. 8. Willingness to be a consumer of biocatalytic solar fuels (absolute numbers in brackets, n = 417).

3.2. Inductive statistical analysis

Inductive statistical tests were performed to seek possible relationships between the variables, as shown in Fig. 1. Spearman's rank correlation coefficients (Table 1) between sociodemographic ordinal variables and opinion ordinal variables indicated weak relationships between the variables due to their low values. Nevertheless, some p-values lower than 0.05 were found, showing statistically significant
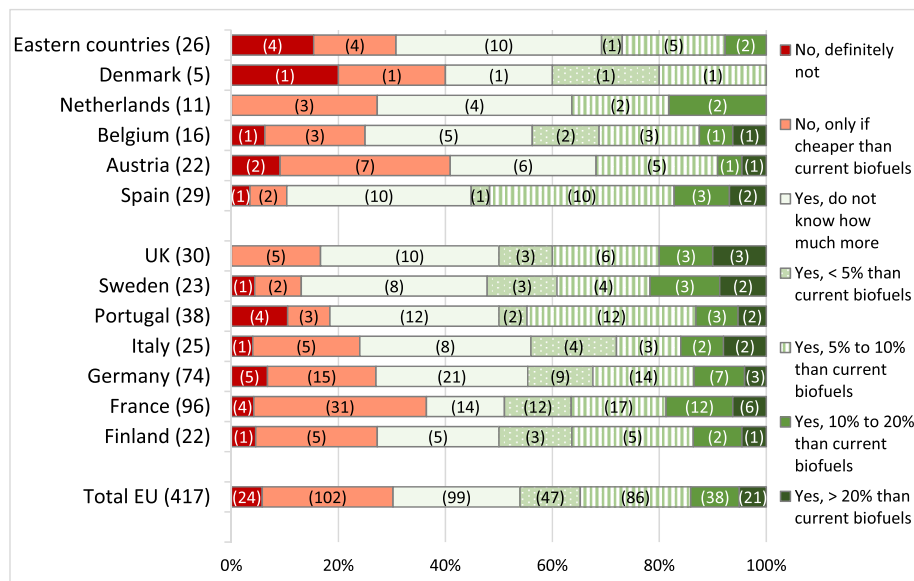
Fig. 9. Willingness to spend more money on biocatalytic solar fuels if they provide higher engine performances than established biofuels (absolute numbers in brackets, n = 417).
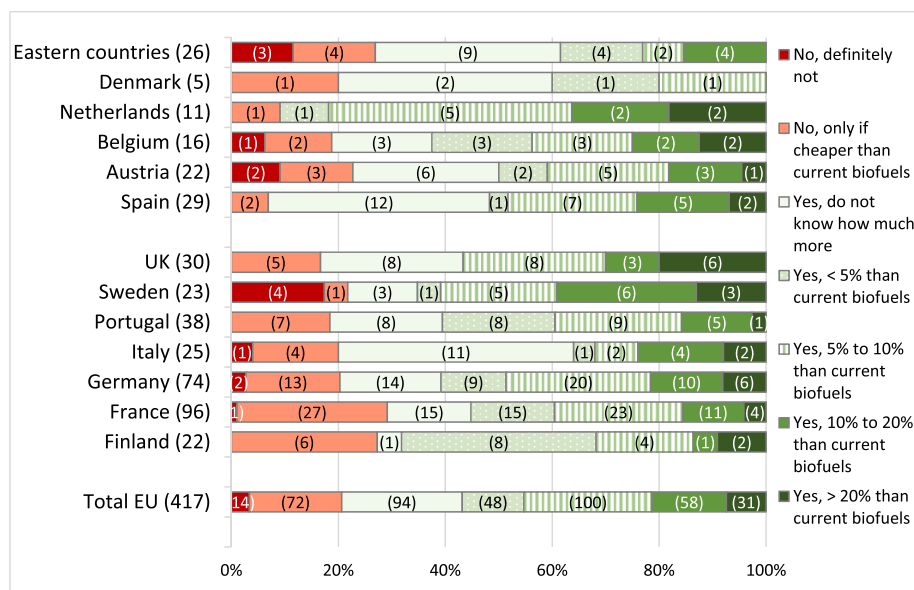
Fig. 10. Willingness to spend more money on biocatalytic solar fuels if they have higher environmental advantages than fossil fuels (absolute numbers in brackets, n = 417).

correlations.

The background of the weak correlation displayed in the table is explained below.

(1) Respondents with higher age tended to support the idea of producing engineered biocatalytic solar fuels and rated the Photofuel technology more positive. These respondents had more positive feelings (i.e. joy and hope) and less negative emotions (i.e. worry, fear and anger) about having a Photofuel next to their residence places

(2) Respondents with higher educational level were more familiar with microalgae and GMOs. These were also more fearful about having a Photofuel plant next to their residence places and believed that fossil fuels, established biofuels, and Photofuel in

general present more risks than solar photovoltaic, wind and hydroelectric power for the mobility of the future.

(3) Respondents living in big cities were more familiar with GMOs. They presented more negative feelings (i.e. worry, fear and anger) about constructing a Photofuel plant next to their residence. These respondents believed that fossil fuels are the power source of future mobility with more risks (i.e. health, environmental and accidents).

Statistically significant relationships were found between some sociodemographic ordinal variables and opinion nominal variables, and between sociodemographic nominal variables and opinion ordinal and nominal variables after Chi square test of independence (Tab le1.) Cramer's V test showed moderate associations between the variables. Excluding the already described significant variations of the answers

Table 1

Statistic relevant values for correlations between variables (only significant values (p < 0.05 are shown).

Socio-demographic	Opinion	Statistic values	
Ordinal variables	Ordinal variables	Spearman's rank order coefficient	p-value
Age	**Intention to support or reject Photofuel technology**		
	Production of Photofuel by using GMOs should take place	**−0.108**	**0.028**
	The general rate of Photofuel technology	**−0.105**	**0.033**
	Feelings towards Photofuel plants next to the residence place		
	Joy	**−0.102**	**0.037**
	Hope	**−0.117**	**0.017**
	Worry	**0.123**	**0.012**
	Fear	**0.110**	**0.025**
	Anger	**0.127**	**0.009**
Educational level	**Knowledge**		
	Familiarity with microalgae	**−0.220**	**0.000**
	Familiarity with GMOs	**−0.273**	**0.000**
	Feelings towards Photofuel plants next to the residence place		
	Fear	**−0.121**	**0.013**
	General risk perception of fuels/power sources		
	Fossil fuels	**0.201**	**0.000**
	Established biofuels	**0.106**	**0.030**
	Photofuel	**0.163**	**0.001**
Current city size	**Knowledge**		
	Familiarity with GMOs	**0.142**	**0.004**
	Feelings towards Photofuel plants next to the residence place		
	Worry	**0.157**	**0.001**
	Fear	**0.163**	**0.001**
	Anger	**0.133**	**0.006**
	General risk perception of fuels/power sources		
	Fossil fuels	**−0.165**	**0.001**

Ordinal variables	Nominal variables	χ² test (p-value)	Cramer's V
Age	**Individual consumer behaviour concerning Photofuel**		
	Willingness to spend more money for possible higher engine performances compared o established biofuels	**0.047**	**0.145**
	Willingness to spend more money for possible environmental advantages compared to fossil fuels	**0.017**	**0.153**

Nominal variables	Ordinal variables	χ² test (p-value)	Cramer's V
Gender	**Knowledge**		
	Familiarity with microalgae	**0.001**	**0.215**
	Intention to support or reject Photofuel technology		
	The general rate of the Photofuel technology	**0.031**	**0.159**
	General risk perception of fuels/power sources		
	Fossil fuels	**0.050**	**0.151**
	Established biofuels	**0.007**	**0.184**
	Solar photovoltaic power	**0.022**	**0.166**
	Wind power	**0.022**	**0.166**
Children	**Knowledge**		
	Familiarity with microalgae	**0.048**	**0.152**
	Familiarity with GMOs	**0.006**	**0.186**
	Feelings towards Photofuel plants bu next to the residence place		
	Worry	**0.037**	**0.156**
	Knowledge		

Table 1 (*continued*)

Socio-demographic	Opinion	Statistic values		
Country of residence	Familiarity with microalgae	**0.000**	**0.272**	
	Familiarity with GMOs	**0.000**	**0.232**	
	Intention to support or reject the Photofuel technology			
	Production of Photofuel by using GMOs should take place	**0.023**	**0.204**	
	The general rate of the Photofuel technology	**0.000**	**0.229**	
	Feelings towards Photofuel plants next to the residence place			
	Joy	**0.006**	**0.214**	
	Worry	**0.000**	**0.232**	
	Anger	**0.012**	**0.209**	
	General risk perception of fuels/power sources			
	Fossil fuels	**0.028**	**0.202**	
	Established biofuels	**0.000**	**0.254**	
	Photofuel	**0.000**	**0.243**	
	Solar photovoltaic power	**0.001**	**0.225**	
	Wind power	**0.041**	**0.199**	
	Hydropower	**0.040**	**0.200**	
Employment status	**Intention to support or reject the Photofuel technology**			
	Production of Photofuel by using GMOs should take place	**0.025**	**0.154**	
	General risk perception of fuels/power sources			
	Photofuel	**0.042**	**0.149**	

Nominal variables	Nominal variables	χ2 test (p-value)	Cramer's V	Fisher's test (p-value)
Country of residence	**Individual consumer behaviour concerning Photofuel**			
	Opinion about being a final consumer of Photofuel	**0.032**	**0.233**	
	Willingness to spend more money for possible higher engine performances compared o established biofuels	**0.042**	**0.194**	
	Willingness to spend more money for possible environmental advantages compared to fossil fuels	**0.008**	**0.204**	
Gender	**Individual consumer behaviour concerning Photofuele**			
	Opinion about being final consumer of Photofuel	**0.000**	**0.187**	**0.000**
	Willingness to spend more money for possible higher engine performances compared o established biofuels	**0.014**	**0.195**	
	Willingness to spend more money for possible environmental advantages compared to fossil fuels	**0.019**	**0.191**	

between the different EU countries determined by Kruskal Wallis test and Tukey Kramer posthoc test, the type of associations between variables were not investigated in this study. The only significant correlation found between two dichotomous variables after Fisher's test was the support of Photofuel by being a potential final consumer three times more by male than by female respondents.

4. Discussion

The discussion refers to the applied method and the possible impact of selecting an online survey on the results. For a long time, face-to-face and telephone interviews were in quantitative empirical social research considered the best options to generate good quality data through surveys, giving adequate information about the population's opinions, attitudes, and behaviour [25]. Due to increasing digitisation, empirical social research has various new methods at its disposal, including online surveys [26]. The growing number of internet users and the advantages that online surveys offered increased the application of web-based surveys. At the same time, research interest in data collection via the internet using online survey methods multiplied [27]. Compared to the classic survey types, web-based surveys can be implemented quickly and cost-effectively. Modern technology makes faster and easy access to data possible and research results available to communities in a shorter time [28,29]. Therefore, online surveys are becoming more and more popular in the social sciences, and many researchers consider web-based surveys to be an inexpensive alternative to conventional survey methods.

Despite these advantages, however, online surveys are often criticised based on concerns about the quality of web-based surveys and methodological problems in inadequate information about the composition of internet users and the difficulties of sample recruitment. In particular, the drawing of a random sample from a defined population is considered problematic [29,30]. The application of online methods in social research is thus assessed differently and is the subject of controversial discussion.

Other studies based on online surveys showed that participants in online surveys differ significantly from those of face-to-face or telephone surveys regarding their sociodemographic background and political attitudes [31]. There are concerns about the quality (representativeness) of online surveys and doubts about their validity due to differences in access to electronic devices. Besides, the quality of the internet and the connectivity is unequal among regions and sociodemographic profiles. Even more relevant than the format of the survey is the topic. In principle, people are more likely to participate in a study if the subject matter interests them [32]. Despite the disadvantages, the online survey is considered an appropriate tool to reach persons at different and distant places with timely and financially constrained research budget since this study aims to give first insights into the citizens' perception of engineered biocatalytic solar fuels across EU countries, Concerning the results, respondents show a high tendency of having positive or neutral feelings about having a biocatalytic solar fuel production plant next to their residences. Since the share of respondents worried about having a neighbouring biocatalytic solar fuel production plant is higher than the share of opponents of the technology, some supporters of the technology would also be worried about having a production plant next to their homes. Based on that, a difference between the acceptability of the technology and the citizens' feelings regarding the production plant was found. Regarding a previous study addressed to EU experts and stakeholders [33] and this study, the majority of the experts and citizens would be final consumers of engineered biocatalytic solar fuel. However, even though the general risk perception is lower than for fossil fuels and established biofuels, they are considered less superior to electric mobility. Additionally, a relatively low amount of experts (11%) thought that citizens would have a high acceptance and 50% thought that citizens would have medium acceptance of the Photofuel technology. However, the results found in this study revealed a high approval from EU citizens. Since this research topic at the socio-technical interface is relatively new, we found only one similar study investigating stakeholder perceptions of risks and opportunities associated with algal biofuel from Oltra [34]. This research is based on semi-structured interviews with key actors in the Spanish innovation network to identify technological and economic obstacles. One finding of Oltra [34] was that the production of lipid enriched microalgae at low costs is considered to be a crucial bio-technical bottleneck. However, perceptions of the chances and challenges of algal biofuels in a broader and comparative societal context were not the study's objective.

One common argument between the studies on EU citizens and experts is their willingness to spend more money on algae biofuels if they provide improved engine performances. However, the more important argument is that engineered algal biofuels must fulfil their expectations regarding climate change and environmental protection. Positive feedback was recovered from the open comments section of the surveys due to the high percentage of supporters of the Photofuel technology. Nevertheless, some concerns from supporters, as trustful communication to the population in spill risks or olfactory nuisances, were described. In the opponents' case, the significant concerns expressed were high water consumption and doubts about truthful research and communication of risks due to economic interests. Concerns were revealed about spills and uncontrolled spread. of modified algae in the environment. Fear was expressed of enhanced competition between microorganism in the ecosystems and unknown spreading strategies of these modified organisms. These additional comments of EU citizens indicate the need for more qualitative research with interviews to get a deeper insight into the risk perception of engineered biocatalytic solar fuel production.

The results confirm the positive perception of citizens across EU countries regarding the engineered biocatalytic solar fuels on a general level. However, the somewhat positive or neutral perception and the high level of acceptance can decrease when constructing a plant in the neighbourhood. Since most of the survey respondents were not familiar with microalgae, information about the changes and challenges of biocatalytic solar fuels provided by scientists or influencers in media can influence the normative mind setting and how environmental friendliness is defined for solar fuels. There is evidence that protecting the environment is of great importance regardless of the country-specific cultural identities and values and linked with a willingness to spend more money for exceptionally environmentally friendly fuel. However, it has to be noted that the population perceives algae fuels to be much less environmentally friendly than electrically powered vehicles. Even though solar fuels are considered more environmentally friendly than first and second-generation biofuels, their use in internal combustion engines increases emissions making them less attractive than the emission- and noise-free electric cars. This shows that people's opinions are strongly influenced by the media and the marketing of car manufacturers and that they are suspicious of any kind of fuel for operating a combustion engine. The general acceptability of technology does not mean that citizens cannot be worried about it. Therefore, the necessity to have a close and open interaction with the population to know their perceptions and expectations before new innovative technologies as engineered biocatalytic solar fuels are implemented is essential.

5. Conclusions

On the way to commercialisation engineered biocatalytic solar fuels produced by genetically modified microorganism face technical and social challenges, Contaminant-free production with high cell densities at a large scale and low cost remain a significant challenge to overcome for scaleup and commercial production. Further improvement of the biocatalytic solar fuel production should consider the co-design and co-development with citizens who are the potential future consumer of the product. By integrating their perception and views and improved human-product interaction., the attractiveness and benefits of biocatalytic solar fuels can be enhanced, regardless of the age, gender, or social and cultural background of possible consumers. There is evidence that it will be challenging to market engineered biocatalytic fuels for short distance individual mobility in cities because of the perceived superioress and availability of electric cars in cities. However, there is a market for long-distance transport and travelling via car, truck, ship and aeroplane, esüpecially if the environmental benefits are significantly more significant than the concerns of possible alteration of ecosystems

by the unintended release of genetically modified algae. More research and development are required to improve EU citizens' involvement in research projects in a more systematic and compressive way to integrate their knowledge, expectations, and needs. By establishing a citizens' advisory board as a complement to the established scientific advisory council, the researcher can mirror and reflect their research objectives and results based on public opinion.

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Authors' contributions

CR designed and coordinated the study and the data analysis, and made valuable inputs in preparing and revising the manuscript. JVV designed the questionnaire, analysed the data, and wrote the manuscript. Both authors drafted the original manuscript and read and approved the final manuscript.

Ethics approval and consent to participate

This study is based on a survey answered by people in anonymous

way, this declaration is not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declaration of competing interest

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

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Appendix

Table. A.1
Sociodemographic Ordinal Variables

Variable Name	Answers
Age	<19 years
	20–29 years
	30–39 years
	40–49 years
	50–59 years
	>60 years
Educational level	Did not complete high school
	High school
	Vocational/occupational/technical training
	University degree
Current city size	Big city (>100.000 habitants)
	Small city (>20.000 habitants)
	Rural area

Table. A.2
Opinion Ordinal Variables (5 Likert-scale)

Variable Name	Answers
Knowledge	
Familiarity with microalgae	(1) Yes, I am an expert
Familiarity with GMOs	(2) Yes, I work with them
	(3) Yes, I often read or heard about them
	(4) Yes, I occasionally read or heard about them
	(5) No, I have never heard about them
Intention to support or reject Photofuel technology	
Production of Photofuel by using GM algae should take place	(1) Totally not agree
	(2) Rather not agree
	(3) Neither/nor
	(4) Rather agree
	(5) Totally agree
General rate of Photofuel technology	(1) Very negative
	(2) Rather negative
	(3) Neither/nor
	(4) Rather positive
	(5) Very positive
Feelings towards Photofuel plants being built up next to current residence place	
Joy	

Table. A.2 (*continued*)

Variable Name	Answers
Hope	(1) Not at all
Calmness	(2) Not really
Worry	(3) Neither/nor
Fear	(4) Somewhat
Anger	(5) Very much
General risk perception of fuels/power sources	
Fossil fuels	(1) Entirely harmless
Established biofuels	(2) Rather harmless
Photofuel	(3) Neither/nor
Solar photovoltaic power	(4) Rather harmful
Wind power	(5) Entirely harmful
Hydropower	

Table. A.3

Sociodemographic Nominal Variables

Variable Name	Answers
Gender	Female
	Male
Children	Yes
	No
Country of residence	Austria; Belgium; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Other (which one?)
Employment status	Student
	University student
	Employed
	Self-employed
	Unemployed/seeking employment
	Retired
	Other

Table. A.4

Opinion Nominal Variables

Variable Name	Answers
Personal attitude as final consumer	
Opinion about being final consumer of Photofuel	Yes
	No
Willingness to pay more money if higher engine performances were achieved respect to established biofuels	Yes, less than 5%
Willingness to pay more money if environmental advantages were achieved respect to fossil fuels	Yes, 5–10% more
	Yes, 10–20% more
	Yes, more than 20%
	Yes, do not know how much more
	No, only if cheaper than current biofuels
	No, definitely not

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