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# Factors influencing the willingness to use agrivoltaics: A quantitative study among German farmers

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## HIGHLIGHTS

- Perceived usefulness of the technology has the strongest influence.
- Important functions of agrivoltaics are additional income and development of the farm.
- Barriers to the purchase are bureaucratic effort and uncertain framework conditions.
- Lack of trust in the technology is not a relevant barrier.

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## ABSTRACT

As a combination of agricultural production and solar energy generation, agrivoltaics helps to mitigate land use conflicts. However, this requires the willingness of farmers to adopt the technology, as without them the dissemination of agrivoltaics is not possible. Therefore, the aim of this research was to investigate farmers' willingness to use agrivoltaics. An online survey among German farmers was conducted in February 2023. The dataset consists of 214 farmers. In order to answer the research aim, a factor analysis and a binary logistic regression were undertaken. The results show that 72.4% of the farmers would be willing to use agrivoltaics. The "perceived usefulness" of the technology has the strongest influence, followed by "subjective norm" and "innovativeness" of the farmer. For farmers, the most important function of agrivoltaics is the additional source of income and the future development of the farm. Furthermore, a lack of trust in the technology is not a barrier. The bureaucratic effort and the uncertain regulatory framework are a relevant hurdle, as is the more challenging agricultural processing of the land. Future efforts should focus on addressing these challenges to enable widespread adoption and realize the potential positive impact of agrivoltaics in the agriculture and energy sector.

## 1. Introduction

Germany has set the goal of becoming greenhouse gas neutral by 2045 [8]. Additionally, at least 80% of the electricity consumed in Germany is to be generated from renewable energies (RE) by 2030 [7]. To achieve this goal, the expansion of RE, and thus of photovoltaics (PV), is essential. Switching to RE is essential not only to meet the German government's targets, but also to fight climate change worldwide. However, the large-scale expansion of ground-mounted PV systems leads to a shortage of agricultural land and thus to land use conflicts between food production and energy production [48]. Agrivoltaics presents an innovative solution to the problem of land use conflicts by combining food and energy production on the same land [12].

Since farmers are the main adopters of the technology, they are particularly important for the uptake of the technology. Therefore, it is essential to learn more about their willingness to use agrivoltaics [26,33]. Previous literature already found that farmers have a keen interest in using agrivoltaics [26,33]. However, the perception of agrivoltaics depends on the perceived feasibility and usefulness of the

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technology. Currently, there is a high degree of uncertainty surrounding agrivoltaics as it is still perceived to be in the early stages of development [42]. The first aim of this study is to determine which factors influence the willingness to use agrivoltaics among German farmers. The second aim is to identify which functions of agrivoltaics are relevant to farmers and thus provide benefits, as well as which barriers stand in the way of the dissemination of the technology. For this purpose, an online survey among German farmers was conducted to identify the potential factors and use logistic regression to determine their influence on the willingness to use agrivoltaics. The findings of this study will provide a basis for the adoption of the technology in Germany.

## 2. Theoretical background

### 2.1. Definition of agrivoltaics and impact on farms

Various types of agrivoltaic systems can be distinguished, beginning with open and closed systems. However, the current paper does not include closed systems such as greenhouses. Overall, the use of agrivoltaics is very diverse and there are several farming methods that can be combined with various systems of agrivoltaics [37]. These applications include horticulture, orchards, viticulture as well as in arable farming and permanent grassland [17]. For applications on grassland (e.g., in combination with animal grazing), however, drawing the line between agrivoltaics – which permits agricultural harvests and performance like in agricultural mono use - and conventional ground-mounted PV systems seems important, especially when communicated to people with no background knowledge of the topic.

The use of agrivoltaics impact farming practices. Weselek et al. [48] and Schweiger et al. [38] found that crop yields can decrease due to reduced solar radiation. However, Schweiger et al. [38] noted that agrivoltaic systems have the potential to improve agricultural resilience to climate change. When precipitation decreases, yields can be stabilised in the long term due to the shade-providing function of the facilities. Moreover, yield losses due to extreme weather conditions such as hail, high winds or frost can be minimized [48]. It should be noted that due to the stabilizing effects on yields their resilience to climate change can be enhanced [38,48]. Furthermore, it gives farmers a perspective to become energy self-sufficient or even produce excess energy for an additional income and thus diversify their farm income [48,51]. Agrivoltaics also have the potential to conserve biodiversity on the strips of land that cannot be cultivated and restore ecosystem services, like the regulation of climate, water, soil and air quality [46].

Nevertheless, when applying agrivoltaics in practice, the technology faces challenges. Overall, the costs of agrivoltaics are higher compared to conventional ground-mounted PV systems, especially with regard to the investment costs [37]. However, lower costs are expected through economies of scale for higher mounting structures [43,51]. In addition, Trommsdorff et al. [43] found that agrivoltaics in apple farming can contribute to a 26% reduction in the investment cost of the farming system, primarily due to synergies with hail protection. Schindele et al. [37] find that agrivoltaics within perennial crops of berries, fruits, or wine grapes are the less expensive systems and take better advantage of synergies. They conclude that crop rotation systems in combination with agrivoltaics are not necessarily recommended because the high elevation of the system leads to higher costs. Weselek et al. [48] noted that technical management requirements, regarding farming, need to be considered, as well. For example, the design of the facility must be adapted to the existing farm machinery and its working widths and heights. Especially in arable farming, access by harvesters requires a system height of at least four to five metres. The elevation also results in land loss, which is assumed to be about 2% of the area [48]. Furthermore, drivers of the machines are required to be extra attentive and skilled [48]. The legal framework is an additional hurdle to the purchase of a facility, as the permitting process is complex and further complicated by the lack of expertise in agrivoltaics among local authorities [11].

### 2.2. Acceptance of renewable energies in agriculture with focus on agrivoltaics

As shown above, the integration of agrivoltaics into agricultural systems must be seen as large innovation as practices, yield, income structures and farmers energy consumption patterns are affected. To make research on the acceptance of agrivoltaics among farmers more robust and to integrate existing studies, it is important to get a more comprehensive picture on the acceptance of RE among farmers.

Granoszewski et al. [18] have investigated the determinants of decision-making behaviour for the application of RE using the example of biogas. According to this study, the financial situation of the company, the risk tolerance, the perceived negative external effects of biogas production as well as the competitive pressure play a role in the decision. Mbzibain et al. [28] found that solar panels are the most popular RE technology among British farmers. Farmers primarily use RE technologies to reduce costs and diversify farm incomes. The relevant constraints are not only economic, but also related to knowledge and driven by social acceptance. Furthermore, they noted that 65% of the current non-adopters may decide to invest in RE technologies in the next five years. Wang et al. [47] found that 25% of farmers in China use RE technologies. They concluded that the adoption of RE technologies is influenced by a number of factors, including education, farm size, government financial support, perceptions of RE and farmer entrepreneurial orientation.

Torma et al. [42] conducted a qualitative study in order to gain a better understanding of the innovation diffusion of agrivoltaics. The evidence presented was contrasting perspectives of the participants, for example on the high flexibility, the contribution to the energy transition as well as the complexity and the visual compromise [42]. It was found that the perception of agrivoltaics depended on the perceived feasibility and usefulness of agrivoltaics, which, however, is still associated with a high degree of uncertainty, as the technology is still perceived to be at an early stage of development [42]. Pascaris et al. [33] interviewed 11 agricultural experts on their perceptions of opportunities and barriers to agrivoltaics. Barriers identified in the interviews included ensuring the long-term productivity of farmland, market potential, fair compensation, and the flexibility needed for agrivoltaics systems to fit into different farming characteristics. In general, most participants expressed their willingness to use agrivoltaics. Li et al. [26] conducted a survey with over 600 farmers, to find out which key factors affect the willingness-behaviour consistency regarding agrivoltaics. The result shows that 37% of the participants, who want to use agrivoltaics, actually use the technology. The factors that have an impact on the three dimensions, which are “adoption willingness”, “adoption behaviour”, and “willingness-behaviour consistency”, are: “perceived usefulness”, “technical training” and “PV investment cost” [26].

Since no consistent model could be found and there is no empirical data on the acceptance of agrivoltaics by German farmers, this study fills the gap and proposes in the following chapter a model that examines the factors influencing the willingness of German farmers to use agrivoltaics.

### 2.3. Model development

In order to analyse the willingness to use agrivoltaics in Germany, a model-based empirical analysis is needed. To create such a model, potential factors influencing the adoption decision of farmers have to be conducted first based on existing literature. The term “acceptance” is used heterogeneously [35] and the term “adoption” lacks a clear definition in the field of agricultural innovation [32,47]. However, according to Montes de Oca Munguia et al. [32], “adoption” refers to a stepwise process driven by information in most models. To ensure clarity the term “willingness to use” serves as the dependent variable. This variable is supposed to reflect the intention of the farmers to take action, which refers to the application and integration of the technology. It was addressed by the question "In principle, would you be willing to use an agrivoltaic system on your farm?". The items for the factors listed below are presented in Table B-1 in the Appendix, along with the sources from which they were derived to fit agrivoltaics.

The model development was based on two existing models. Firstly, the Technology Acceptance Model by Davis [10] - widely common in acceptance research – was added. The constructs "perceived usefulness" and "perceived ease of use" used in the Technology Acceptance Model are applied to explain the acceptance of new technologies. "Perceived usefulness" describes the extent to which a person feels that their work performance is enhanced by the technology. Whereas the "perceived ease of use" describes the extent to which a person perceives that the use of a technology is effortless. The items for "perceived usefulness" and "perceived ease of use" used in the questionnaire were adjusted to the context of agrivoltaics following Mohr et al. [31] and Venkatesh et al. [44].

Since the Technology Acceptance Model ignores the social aspect in the explanation for acceptance [41], the construct of "subjective norm" is included in the model, which finds its origin in second model used - the Theory of Reasoned Action by Fishbein et al. [14]. It refers to the perceived social pressure from people considered to be relevant for the individual whether to perform or not perform a behaviour. As the "subjective norm" is a strong predictor of purchase intentions of PV systems [23], it is reasonable to examine this influence in the context of agrivoltaics as well. It is particularly relevant for farmers as they are part of a social structure consisting of family, village community and colleagues [45]. The items used were phrased following Voss et al. [45] and were adapted to agrivoltaics.

To address the complexity of the willingness to use agrivoltaics, other potentially relevant factors are added to test a range of possible factors and consider different aspects. There is evidence from research that the "risk tolerance" of decision makers influences their management behaviour [36] and has an essential influence on technology selection [18]. It can be assumed that risk averse farmers are less willing to bear the risks of a new technology like agrivoltaics. The corresponding items to measure "risk tolerance" were designed according to Kröger et al. [24].

Furthermore, an increased "innovativeness" suggests that the willingness to use an agrivoltaic system increases, as it provides the opportunity to farmers to further develop their business and remain competitive [15]. Various studies propose that technical innovations are more likely to be used by farmers with high "innovativeness" [1,24,45]. The items used were designed following Kröger et al. [24].

The "level of knowledge" regarding agrivoltaics is likely to vary among farmers as the technology is not yet widespread. Familiarity with the innovation serves as the foundation for investing in such a system. Several references suggest that a low "level of knowledge" about a technology acts as a barrier to the use of RE and that more knowledge leads to the reduction of perceived barriers ([53]; [28]; [54]). The items for the factor "level of knowledge" were created according to Voss et al. [45].

Agrivoltaic systems have the potential to improve biodiversity and other ecosystem services whilst providing RE [46]. Farmers with a greater "environmental awareness" may have a stronger interest in investing in agrivoltaics, as they can also contribute to sustainable energy production and environmental benefits. Trojecka [55] found that farmers with a special ecological awareness are more willing to invest in climate-friendly technologies out of conviction. The items on environmental awareness were arranged according to Geigler [16] and Granoszewski et al. [18].

In addition to the potential factors already outlined, the impact of "climate change impact" and "energy price impact" on the willingness to use agrivoltaics is investigated. Agrivoltaic systems may be used by farmers due to the impacts of climate change, as the systems have the potential to improve agricultural resilience to climate change by protecting against extreme weather events [48]. Furthermore, when precipitation decreases, crop yields can be stabilised in the long term due to the shade-providing function of the facilities [38]. Indeed, innovations are an important response to climate change and support for climate change mitigation and adaptation in agriculture [9,52]. Moreover, Wicker et al. [49] discovered that individuals who express concern about climate change are more likely to engage in actions to mitigate climate change and changes in energy consumption.

Due to current political developments, especially the Ukraine war, rising energy costs have become a focus of society and are also a serious problem for industry [5]. The self-consumption of self-generated PV energy can decrease the electricity costs [29]. In this context purchase of RE sources, in this case agrivoltaics, can be motivated by decreasing energy expenditures in the business [21]. In addition, the aspect of being able to operate energy self-sufficiently is also relevant to farmers [2]. The items used for the factors "climate change impact" and "energy price impact" were created by the author. Change impact" and "energy price impact" were created by the author.

Based on the considerations given, the following model (see Fig. 1) was derived to analyse the potential impact on the willingness to use agrivoltaics.

## 3. Methodology

### 3.1. Data collection and survey design

To investigate the willingness to use agrivoltaics among farmers, a standardised online survey was conducted among German farmers in February 2023. The survey was pre-tested among colleagues and experts in the field of agrivoltaics to validate the selected items for the factors. The target population of this survey are the 262,800 farms in Germany as of 2020 [34]. A representative survey was not possible due to restrictions in terms of time and finances. To ensure that all participants were suitable for the survey, only individuals who can make decisions about investments on the farm, can do so in the future or are close to people who decide about farm investments were chosen. This was done to ensure that participants have influence on the decision to use an agrivoltaics system on the farm. Farmers were recruited through various communication channels, resulting in a non-random sample. Among others, the support of the farmers' associations of the federal states and of other agricultural associations has been gained. In addition, the public relations department of the Faculty of Agriculture at the University of Göttingen and an agricultural influencer distributed the survey. Furthermore, the link was shared via Fraunhofer ISE in the agrivoltaics newsletter and website as well as at events. Finally, social media (WhatsApp, Instagram, Twitter, and Facebook) was used to share the survey to reach as many farmers as possible directly. To allow multivariate data analysis, the literature suggests a sample size of between 200 and 1200 respondents [39].

In order to check participants attention, an explicit instructed response item was included. Respondents who incorrectly answered these direct queries, were excluded from the online survey after data collection ($n = 27$). Additionally, respondents with an inconsistent response behaviour ($n = 10$) were eliminated from the dataset. There were 54 cases removed that had no influence on farm investments. After this procedure, 214 valid respondents remained in the dataset for analysis. The survey has a completion rate of 66.7%.

To measure farmers' knowledge of agrivoltaics, their sources of seeking information, their willingness to use agrivoltaics (as a dependent variable), factors potentially influencing this willingness (independent variables, presented in chapter 2.3), farmers' perceptions of the functions and barriers of agrivoltaics, a survey was developed and made available to the sample online. A short informative text on agrivoltaics was presented to the participants, as shown in Appendix C.

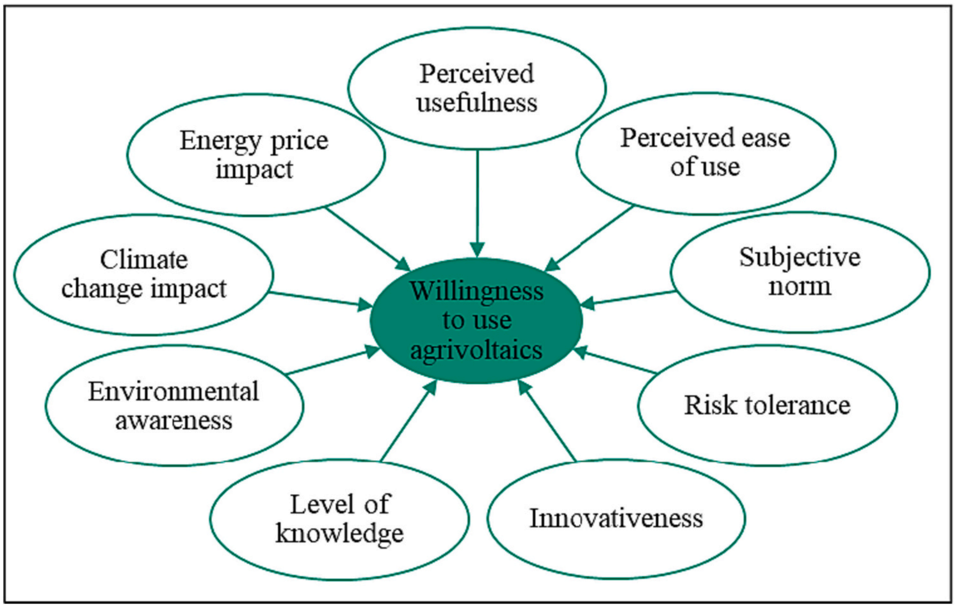


**Fig. 1.** Potential factors influencing farmers' willingness to use agrivoltaics. (Source: own presentation)

### 3.2. Statistical analysis

To identify the relevant factors and examine how they affect the dependent variable "willingness to use", an exploratory factor analysis is performed in the first step, followed by a binary logistic regression in the second step. In the following, these procedures are explained in detail. The statistical analysis was carried out using the IBM SPSS 28.

Exploratory factor analysis is conducted on the items for the independent variables mentioned earlier in Chapter 2.3 to ensure the validity of the scales [22]. In addition, several checks were conducted to validate the factor analysis and ensure reliable results. To determine that the data is appropriate for factor analysis Kaiser-Meyer-Olkin criterion and Bartlett's test of sphericity are calculated [4]. The number of extracted factors is determined according to the Kaiser criterion. Next, varimax rotation was applied to enhance interpretability. This results in eight factors, which are presented in detail in Chapter 4.3. Unsuitable items are removed after looking at correlations and communalities. Factors were interpreted to include all variables with factor loadings above 0.45. A variable's factor loading represents the correlation between the variable and the factor. The factors were generated using the Anderson-Rubin method, making them uncorrelated for use in logistic regression [13]. Cronbach's alpha should be at least 0.5 and is considered good if it is between 0.7 and 0.8 [13]. For the given factors, Cronbach's alpha is at least above 0.6.

To find out which factors influence the probability that farmers want to use agrivoltaics on their farms, binary logistic regression was applied. The binary dependent variable "willingness to use" was measured with the question: "In principle, would you be willing to use an agrivoltaic system on your farm?" (no = 0/yes = 1). The eight factors extracted from the factor analysis are included as independent variables to explain farmers decision behaviour.

Logistic regression requires a minimum sample size, which in the case of a binary dependent variable is 50 observations [3]. The number of observations is reduced from 214 to 206 due to missing values, but still exceeds the recommendations. The requirement for the data implies that the independent variables should be uncorrelated [3]. This is ensured by the application of the Anderson-Rubin method in factor calculation, which should prevent multicollinearity. Linearity was checked with the Box-Tidwell method and can be assumed [6]. Furthermore, the outliers were checked according to the recommendations of Field [13], but there was no further reason to remove observations. To consider Goodness-of-fit the Omnibus test of model coefficients and Hosmer-Lemeshow test was conducted. The explained variance of the model is presented by Nagelkerke's $R^2$, which equals the $R^2$ of linear regression. According to Backhaus et al. [3] values over 0.5 are very good. Another important indicator for the quality of the model is the classification table, which shows how many cases were correctly classified by the model.

### 3.3. Sample description

Descriptive statistics for the sample are presented in Table 1 and 2. The minority of respondents were female (19.6%) whilst the average age was 41.2. The farm structures differ from the average German farms. On average, farms in the sample cover 305.8 ha and are thus larger than farms nationwide. The proportion of horticultural, viticultural, and orchard farms is also higher in the sample. Furthermore, southern German

**Table 1**
Sociodemographics of the sample.

| | Sample | | German total population employed in agriculture (%) |
|---|---|---|---|
| | n | % | |
| **Sex** | | | |
| female | 42 | 19.6 | 36.0 |
| male | 169 | 79.0 | 64.0 |
| other | 3 | 1.4 | – |
| **Age** | | | |
| up to 25 | 28 | 13.1 | 8.6 |
| 26–35 | 57 | 26.6 | 15.7 |
| 36–45 | 53 | 24.8 | 14.7 |
| 46–55 | 36 | 16.8 | 24.5 |
| from 55 | 40 | 18.7 | 36.5 |
| **Education degree** | | | |
| Secondary school diploma | 6 | 2.8 | – |
| High school diploma | 12 | 5.6 | – |
| Agricultural vocational training | 18 | 8.4 | – |
| Technical college degree | 78 | 36.4 | – |
| University degree | 94 | 43.9 | – |
| Doctorate | 6 | 2.8 | – |

Source: own presentation according to Pascher et al. [34].

**Table 2**
Selected farm characteristics of the sample.

| | Sample | | German total population employed in agriculture (%) |
|---|---|---|---|
| | n | % | |
| **Operating orientation[1]** | | | |
| Arable farming | 157 | 73.4 | 33.4 |
| Forage production (grazing cattle, milk production) | 75 | 35.0 | 40.7 |
| Finishing (pigs, poultry) | 46 | 21.5 | 5.9 |
| Viticulture | 33 | 15.4 | 4.2 |
| Fruit growing | 37 | 17.3 | 1.6 |
| Vegetable Gardening | 28 | 13.1 | 0.3 |
| Other | 17 | 7.9 | 13.9 |
| **Farm size in categories** | | | |
| up to 20 ha | 30 | 14.0 | 45.2 |
| 21–50 ha | 37 | 17.3 | 23.2 |
| 51–100 ha | 48 | 22.4 | 17.0 |
| 101–200 ha | 50 | 23.4 | 9.5 |
| >200 ha | 49 | 22.9 | 5.0 |
| **Operating site** | | | |
| Northern Germany[2] | 66 | 30.8 | 19.9 |
| Southern Germany[3] | 66 | 30.8 | 46.8 |
| Eastern Germany[4] | 28 | 13.1 | 7.6 |
| Western Germany[5] | 54 | 25.2 | 25.1 |
| **Form of acquisition** | | | |
| Full-time farms | 174 | 81.3 | 43.0 |
| Part-time farms | 40 | 18.7 | 57.0 |
| **Form of cultivation** | | | |
| conventional | 159 | 74.3 | 86.5 |
| organic | 36 | 16.8 | 13.5 |
| both | 19 | 8.9 | – |

Source: own presentation according to Pascher et al. [34]; [1]Statistisches Bundesamt [40]; [2]Northern Germany = Mecklenburg-Vorpommern, Schleswig-Holstein, Lower Saxony; [3]Southern Germany = Bavaria, Baden-Württemberg; [4]Eastern Germany = Brandenburg, Saxony, Saxony-Anhalt, Berlin, Thuringia; [5]Western Germany = North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Hesse.

farms are underrepresented. There were more full-time farmers participating in the survey. Organic farms are reflected in the correct proportions. Conventional PV systems are used by 73.4% of the respondents. Wind energy is produced in 14.5% and biogas in 11.2% of the cases. There were three participants who already use agrivoltaics. It can be concluded that the sample is not representative.

## 4. Results

The following section presents the descriptive results, including the perceived functions and barriers, as well as the factor analysis and logistic regression results. The findings indicate that 72.4% of farmers are willing to use agrivoltaics. The most influential factor is the perceived usefulness of the technology, followed by subjective norm. Additionally, the innovativeness of the farmer also impact the willingness to use. For farmers, the primary benefit of agrivoltaics is the additional source of income and the potential for future farm development. The lack of trust in the technology is not a significant barrier. However, the bureaucratic effort and uncertain regulatory framework pose relevant hurdles, as does the more challenging agricultural processing of the land.

### *4.1. Descriptive statistics*

The results illustrate that in regard to Germany, 74.8% of the respondents consider it reasonable for agrivoltaics to contribute to energy production. In their own region, 61.7% of farmers feel it is desirable to install agrivoltaic systems. However, 72.4% are generally willing to use the technology on their own farm. Among the farmers who would be willing to use agrivoltaics, 18 people indicate that they are by now planning to install a system and two farmers already use agrivoltaics. Another 18 people are ready to purchase a system in the next twelve months, 32 people would purchase a system within three years, and 85 people would take this step in the next five years.

As a source of information to learn about agrivoltaics, trade newspapers are very important to the farmers (M = 4.17, SD = 0.80), followed by agricultural consultants (M = 3.93, SD = 1.00) and farmers' associations (M = 3.79, SD = 1.05). Other colleagues play an important role for many participants, too (M = 3.81, SD = 0.93). In contrast, radio (M = 1.82, SD = 0.95), television.

(M = 2.04, SD = 1.02), and social media (M = 2.75, SD = 1.07) are rather unimportant for obtaining information about agrivoltaics (see Appendix A).

The data illustrates the functions that respondents considered most important for their farm, if they were to purchase an agrivoltaic system (see Fig. 2). Generating additional income is clearly the most important function, followed by further development of the farm. Regarding energy production, the contribution to the development of renewable energies is particularly important. The functions for crop production, on the other hand, are less important than those already mentioned. Protection from sun and hail, as well as collecting rainwater for irrigation, are particularly important.

Furthermore, farmers were surveyed concerning the extent to which the barriers shown in Table 4 prevent them from purchasing an agrivoltaic system. The most important barrier mentioned is the bureaucratic effort and uncertainties in the policy framework. Additionally, the more challenging processing of agricultural land is a major barrier. However, limited trust in the technology is seen as a minor obstacle (see Fig. 3).

### *4.2. Evaluation of the factors used in the logistic regression*

The purpose of the factor analysis is to test the suitability of the factors for their use in the logistic regression. The factor analysis resulted in eight factors, namely: (1) level of knowledge, (2) perceived usefulness, (3) awareness of climate change and environmental protection, (4) impact of energy prices, (5) subjective norm, (6) innovativeness, (7) risk tolerance and (8) sense of responsibility towards the environment. They are slightly different from those described in Chapter 2.3. Some items loaded on a different factor than theoretically intended. In order to make the process transparent, the item names in Table 3 are based on the originally intended factors (see Appendix B).

The items PEU1 and PEU5 loaded on the factor "level of knowledge" instead of the intended factor "perceived ease of use". Similarly, the items PEU2 and PEU3 loaded on the factor "perceived usefulness", resulting in the removal of the "perceived ease of use" factor from the model.

Items EA2 and EA3 together with items CC1 - CC4 of the factor "climate change impact" loaded onto the new factor "awareness of climate change and environmental protection". The new factor "awareness of climate change and environmental protection" replaces the intended factor "climate change impact" described in Chapter 2.3. Furthermore, instead of loading on the factor "environmental awareness", the items EA1 and EA4 formed a new factor "sense of responsibility towards the environment". Internal consistency reliability is given as all Cronbach's alpha values are above 0.6 [19] indicating high reliability.

### *4.3. Logistic regression results*

The results of the logistic regression are listed in Table 4, the odds ratios (OR) and the corresponding standard errors are displayed, as well as the coefficients labelled as "B". In addition, the 95% - confidence intervals and p-levels are presented. OR values larger than 1 indicate that the factor positively contributes the willingness to use agrivoltaics while OR values below 1 indicate a negative impact.

The logistic regression model was statistically significant, $\chi^2$ (8) = 141.67, $p < 0.001$. The model explained 71.8% (Nagelkerke $R^2$) of the

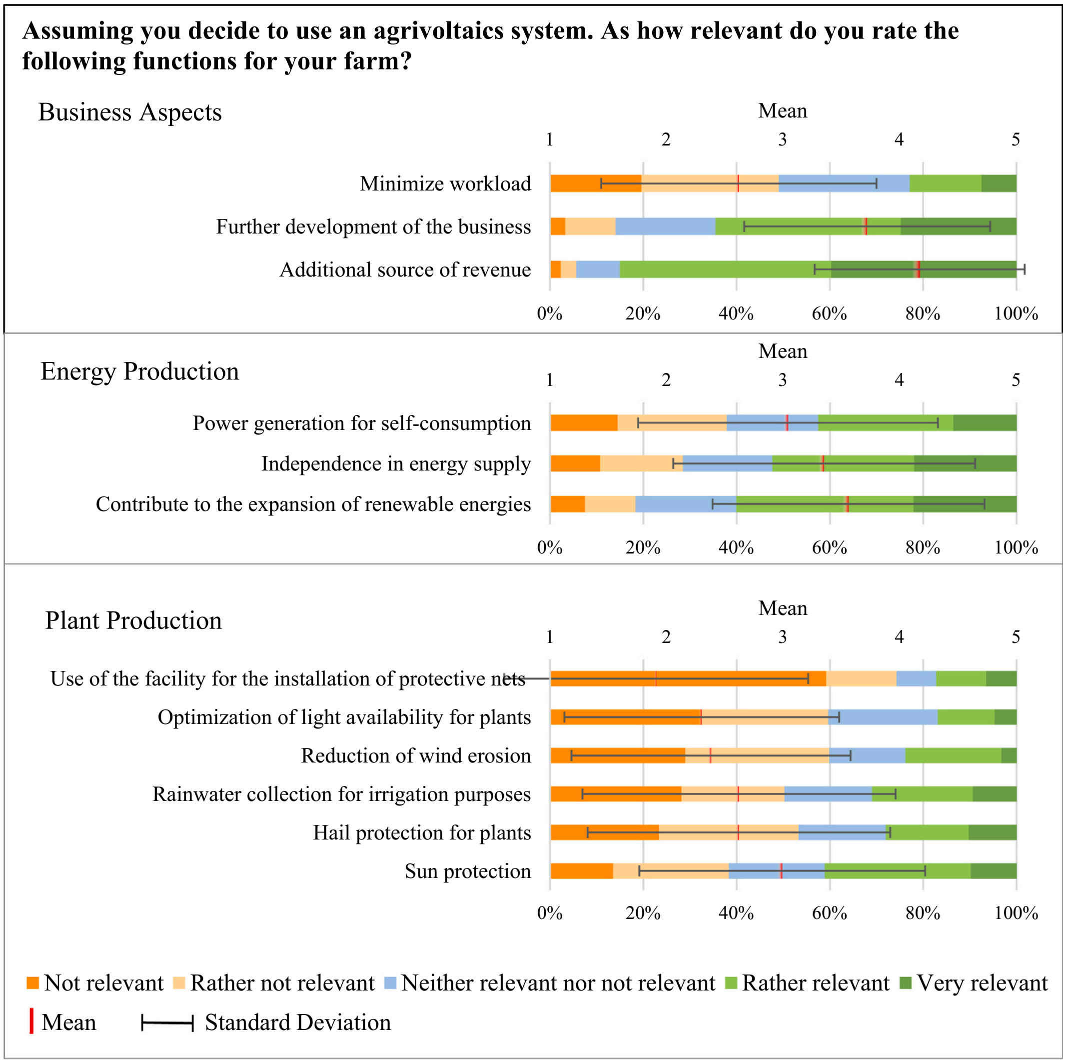


**Fig. 2.** Relevant functions of agrivoltaics for farmers.

variance and classified 90.8% of the cases correctly. Moreover, the Hosmer-Lemeshow test indicated a good model fit, $\chi^2(8) = 3.087$, $p > 0.05$.

Four of the eight factors recorded have an influence on the willingness to use agrivoltaics, of which three have a positive and one a negative influence. The logistic regression demonstrates that “perceived usefulness” has the strongest positive influence (OR = 16.306, $p < 0.001$) on the probability that a farmer wants to use agrivoltaics. Similarly, the factor “subjective norm” has a positive influence on the willing to use agrivoltaics (OR = 7.291, $p < 0.001$) e.g. if colleagues, family and the local community also have positive attitudes towards the technology. Minor positive influence shows the factor “innovativeness” (OR = 2.175, $p = 0.006$) e.g. if farmers who are more open-minded towards modern technologies are more willing to use agrivoltaics. In contrast, the factor “sense of responsibility towards the environment” has a negative effect on the willingness of farmers to use agrivoltaics (OR = 0.583, $p = 0.043$).

## 5. Discussion

### *5.1. Methodological discussion*

As described earlier, Germany’s energy policy has established promising conditions and now the market uptake is expected. Therefore, it is crucial to gather evaluations from farmers who demonstrate interest in the technology while taking their opinions into consideration for future improvements. The willingness to use agrivoltaics among farmers indicates a positive tendency and it can be assumed that the interest of farmers is high. The high number of participants and positive reactions of the respondents suggest this. Hence, it can be concluded that farmers with a keen interest in agrivoltaics participated in the survey and gave valuable feedback. However, this results in a sample that is biased and might distort the findings. In addition, since this is not a representative sample, the results do not allow for general assumptions to be made about all German farmers. This was promoted by the way in which the participants were recruited, particularly through social media and agrivoltaics networks. Future research should try to mirror the socio-demographic characteristics of farmers.

Another aspect to be discussed is the use of questionnaire items and scales which have been validated for other research topics but not agrivoltaics. Therefore, we have run factor analysis to test the measurement items for various reliability and validity criteria. For pragmatic reasons, in this study, the factor structure is tested, and logistic regression is calculated with the same sample. For a more robust test of external validity of the measurement, separate samples would have been more appropriate and have to be realized in future research. Still, this issue is not impacting on the concrete results of the analysis but would fully comply with good scientific practices.

In addition, some important aspects have received insufficient attention. These include the different ownership structures, which are

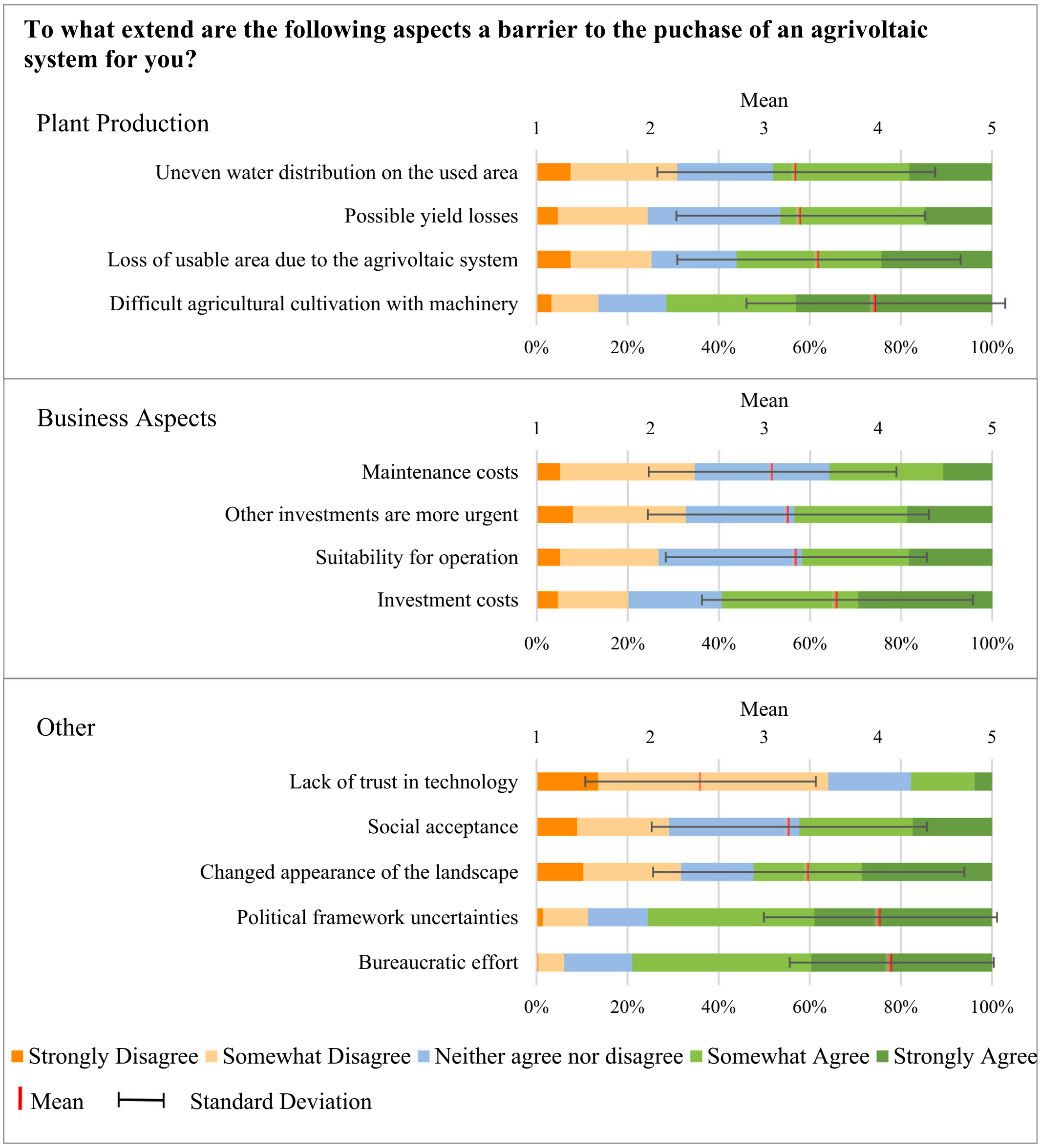


**Fig. 3.** Barriers in purchasing an agrivoltaic facility.

possible in the procurement of agrivoltaic systems, as well as economic issues. Different farming types, such as horticulture, orcharding and arable farming, need to be more deeply differentiated in future elaborations due to the wide range of possible applications of agrivoltaics. The attitudes of different types of farms towards agrivoltaics were examined. By using attitude-related items with Likert scales instead of the binary variable "willingness to use", we were able to perform an ANOVA. Still, no significant effects were observed. The limited number of respondents within distinct farming types could be a potential explanation for the lack of statistical significance. In addition, further research is needed regarding the differentiation between agrivoltaics on grassland with livestock, which was disregarded in this survey.

### 5.2. Discussion on the relevant factors to use agrivoltaics

The findings hold significant implications for the future of agrivoltaics in Germany. While there is a notable interest among farmers, underscored by a willingness to diversify agricultural operations and engage in renewable electricity generation, certain barriers, particularly bureaucratic complexities and uncertainties surrounding political frameworks, pose substantial challenges that should be recognized by policymakers. The barriers of bureaucracy and uncertainties regarding political frameworks play pivotal roles in shaping the marked conditions for the adoption of agrivoltaics and can significantly hinder or delay the implementation process. Similarly, uncertainties in the policy framework, such as evolving legislation or financial incentives, can undermine investment planning certainty and increase risk for potential adopters. Identifying and comprehending these barriers are essential for devising effective strategies to overcome these obstacles and foster the successful integration of agrivoltaics.

While the results for most of the factors appear plausible and are consistent with other findings in the literature, the interpretation of some results seem not entirely clear. Little surprising, the "perceived usefulness" has a very strong positive impact on the willingness to use agrivoltaics as already shown in existing literature [26]. The descriptive results indicate that the main benefit of agrivoltaics is seen in the diversification of the agricultural business and the securing of agricultural income through the production and sale of electricity.

Likewise, the factor "subjective norm" has a positive influence on the willing to use agrivoltaics which is in line with findings on other RE technologies [14,23,27]. One reason for this observation could be the impact of agrivoltaics on landscape aesthetics which frequently leads to

**Table 3**
Results of the factor analysis to validate the potential factors influencing farmers' willingness to use agrivoltaics for the regression analysis model.

| Item name | Item description | Factor loading | Mean | Standard deviation |
|---|---|---|---|---|
| **Factor 1: Level of knowledge** Cronbach's α: 0.889 | | | | |
| K2 | I am well informed about current developments in this industry. | 0.879 | 3.17 | 1.14 |
| K3 | I have already been able to get a comprehensive picture of agrivoltaics. | 0.838 | 3.41 | 1.10 |
| K4 | I know the different applications of agrivoltaics. | 0.821 | 3.18 | 1.16 |
| K5 | I know the legal framework for the acquisition of such a plant. | 0.762 | 2.57 | 1.21 |
| PEU1 | I know what to do to purchase an agrivoltaic system. | 0.708 | 2.78 | 1.18 |
| K1 | Can you imagine what is meant by agrivoltaics? | 0.683 | 4.12 | 0.88 |
| PEU5 | The way agrivoltaics work is clear and logical to me. | 0.617 | 3.87 | 0.91 |
| **Factor 2: Perceived usefulness** Cronbach's α: 0.859 | | | | |
| PU2 | I think that the use of agrivoltaics does not fit into my operation. | −0.810 | 2.76 | 1.31 |
| PU6 | I think that the use of agrivoltaics makes sense to further develop my business. | 0.790 | 3.27 | 1.20 |
| PEU3 | It is difficult to plan the system so that it benefits my business. | −0.765 | 3.34 | 1.07 |
| PEU2 | The use of agrivoltaics is possible on my farm without any problems. | 0.731 | 2.81 | 1.05 |
| PU1 | I think that the use of agrivoltaics would increase the productivity of my business. | 0.718 | 3.16 | 1.12 |
| PU4 | I think that the use of agrivoltaics protects my crops (or animals) from sunlight and weather conditions. | 0.516 | 3.12 | 1.16 |
| **Factor 3: Awareness of climate change and environmental protection** Cronbach's α: 0.722 | | | | |
| CC1 | I am concerned about the impact of climate change on my business. | 0.757 | 3.56 | 1.00 |
| CC2 | I have noticed that the weather in my region has changed in the last five years compared to the past. | 0.691 | 4.00 | 0.94 |
| CC3 | Due to the climatic changes, the yields of my farm suffer. | 0.656 | 3.35 | 1.14 |
| EA3 | More environmental protection also means more quality of life and health for all. | 0.626 | 3.59 | 1.11 |
| EA2 | The environmental protection in agriculture is exaggerated. | −0.543 | 2.99 | 1.23 |
| **Factor 4: Impact of energy prices** Cronbach's α: 0.736 | | | | |
| EP3 | I sometimes worry that I won't be able to continue my business because of high energy prices. | 0.838 | 2.38 | 1.10 |
| EP2 | Despite the high energy prices, I am confident about the future. | −0.824 | 3.48 | 0.98 |
| EP1 | Agriculture in Germany is undergoing fundamental changes due to high energy prices. | 0.707 | 3.57 | 0.95 |
| **Item name** | **Item description** | **Factor loading** | **Mean** | **Standard deviation** |
| **Factor 5: Subjective norm** Cronbach's α: 0.752 | | | | |
| SN2 | My village community would accept the adoption of agrivoltaics. | 0.779 | 2.92 | 1.03 |
| SN3 | The use of agrivoltaics would be accepted by my colleagues. | 0.748 | 3.12 | 1.02 |
| SN1 | The use of agrivoltaics would be accepted in my family. | 0.674 | 3.56 | 1.17 |
| **Factor 6: Innovativeness** Cronbach's α: 0.656 | | | | |
| IN2 | New production techniques and technologies interest me. | 0.744 | 4.30 | 0.79 |
| IN3 | It is important to me to be quick on the uptake of innovations. | 0.681 | 3.27 | 0.92 |
| IN1 | I am always looking for more development opportunities for my business. | 0.539 | 4.27 | 0.73 |
| **Factor 7: Risk tolerance** Cronbach's α: 0.804 | | | | |
| RT2 | Safety is important to me, so I avoid risks. | −0.815 | 2.79 | 0.93 |
| RT1 | I am prepared to take risks in order to position my business securely for the long term. | 0.816 | 3.71 | 0.85 |
| **Factor 8: Sense of responsibility towards the environment** Cronbach's α: 0.646 | | | | |
| EA1 | As a farmer, I have a special responsibility to the environment. | 0.801 | 4.37 | 0.75 |
| EA4 | Each and every one of us bears responsibility for leaving a liveable environment for future generations. | 0.784 | 4.59 | 0.60 |

Source: own calculation; K = Level of knowledge, PEU = Perceived ease of use, PU = Perceived usefulness, CC=Climate change impact, EA = Environmental awareness, EP = Energy price impact, SN = Subjective norm, IN = Innovativeness, RT = Risk tolerance; 5-point Likert scale from 1 = strongly disagree to 5 = strongly agree; Cumulative factor loading = 65%, KMO = 0.796. Bartlett test ($\chi2 = 2764$, df = 465, $p = 0.001$).

**Table 4**
Results of the logistic regression.

| Predictor | B | Standard Error | *p*-value | | Odds Ratio | 95% Confidence Interval |
|---|---|---|---|---|---|---|
| Level of knowledge | 0.200 | 0.277 | 0.470 | | 1.222 | [0.71; 2.103] |
| Perceived usefulness | 2.792 | 0.476 | <0.001 | *** | 16.306 | [6.416; 41.441] |
| Awareness of climate change and environmental protection | 0.461 | 0.268 | 0.086 | | 1.585 | [0.936; 2.682] |
| Impact of energy prices | 0.444 | 0.267 | 0.097 | | 1.558 | [0.923; 2.63] |
| Subjective norm | 1.987 | 0.360 | <0.001 | *** | 7.291 | [3.598; 14.774] |
| Innovativeness | 0.777 | 0.284 | 0.006 | *** | 2.175 | [1.247; 3.793] |
| Risk tolerance | −0.249 | 0.308 | 0.419 | | 0.780 | [0.426; 1.426] |
| Sense of responsibility towards the environment | −0.539 | 0.267 | 0.043 | ** | 0.583 | [0.346; 0.984] |
| Constant | 2.253 | 0.386 | <0.001 | *** | 9.516 | |

Source: own calculation; Level of significance **$p < 0.05$ and *** $p<0.01$.

reluctance of the local population towards RE projects [50]. Positive attitudes of the local community towards agrivoltaics might reduce the possibility of local resistance against agrivoltaic projects and, hence, encourage farmers to use agrivoltaics.

While also the results on farmers' affinity towards the uptake of innovations positively influences the willingness to use agrivoltaics as reported in other studies [30,47],the descriptive results indicate that bureaucratic efforts to get construction represent a major barrier for the farmers. In contrast, there are only minor doubts about the technology and its economic viability, which might also explain that, in turn, risk tolerance as a factor has a less important influence on the willingness to use agrivoltaics.

The negative influence of the factor "sense of responsibility towards the environment", in contrast, seems more difficult to interpret. Given the positive contributions of PV power generation to reducing CO2 emissions and protecting the climate, it would be intuitive to expect that farmers with a high sense of responsibility for the environment would be more willing to use agrivoltaics e.g., to improve their carbon footprint. On the other hand, possible negative impacts of agrivoltaics on the environment e.g. on biodiversity and soil quality might speak against the installation of agrivoltaic systems from the point of view of environmentally conscious farmers. Further research could aim at a more differentiated picture of environmentally responsibility splitting-up climate protection and local environment protection considerations. Another surprising result is that there are no significant differences in the "perceived usefulness" between the different farm types such as arable farming or horticulture operations. Results regarding the shade tolerances in arable farming and horticulture applications would suggest that the perceived usefulness farmers specialized on vegetable or fruit farming would be higher compared to arable farming operations [25]. Similarly, also the employment of large land machines in arable farming could reduce the perceived usefulness of farmers specialized on arable farming since pillars or PV module rows interfere with an easy and area-wide cultivation of the land. One explanation why we could not observe differences in farm types could be that, in the survey, we did not differentiate between different agrivoltaic systems designs. This seems particularly relevant due to the large variety of agrivoltaics approaches which might lead to a very different understanding of agrivoltaics among farmers. Accordingly, further research could investigate perceived usefulness with respect to different system designs, applications areas and the respective farming types.

## 6. Conclusion

While agrivoltaics is still emerging, the growing discourse and supportive regulations indicate increasing interest in the technology. The current research contributes to this discourse by providing empirical evidence of the factors influencing farmers' acceptance of agrivoltaics. It underscores the central role of "perceived usefulness", aligning with existing literature. Notably, the diversification of agricultural operations and the generation and sale of renewable electricity are seen as primary. Furthermore, the study highlights the influence of the "subjective norm" on agrivoltaic acceptance, emphasising farmers' awareness that the implementation of agrivoltaics extends beyond their operations, affecting their social environment. However, the study also notes that the social acceptance of agrivoltaics is not firmly established, possibly due to concerns about visual changes in the agricultural landscape. The analysis also confirms the influence of "innovativeness" on the willingness to use agrivoltaics. The role of the "sense of responsibility towards the environment" needs additional research.

While the research indicates relatively minor doubts about the technology and its economic benefits, the bureaucratic hurdles associated with construction represent a significant barrier. Importantly, the results reveal a nuanced perspective on the protective functions of agrivoltaics, which farmers only partly recognise. This may arise from the need for additional scientific and practical evidence showcasing the technology's potential to provide protection and synergies for agricultural practices.

Further research and practical initiatives are needed to remove bureaucratic barriers, increase social acceptance, and provide concrete evidence of the protective functions of agrivoltaics and potential synergies with agricultural practices. These efforts are essential to promote the adoption of agrivoltaics and its positive impact on both the agricultural and energy sectors.

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## CRediT authorship contribution statement

**Johanna Wagner:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Charlotte Bühner:** Writing – review & editing, Supervision, Methodology. **Sebastian Gölz:** Writing – review & editing, Supervision. **Max Trommsdorff:** Writing – review & editing, Funding acquisition. **Kristin Jürkenbeck:** Writing – review & editing, Validation, Supervision, Methodology.

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Information sources

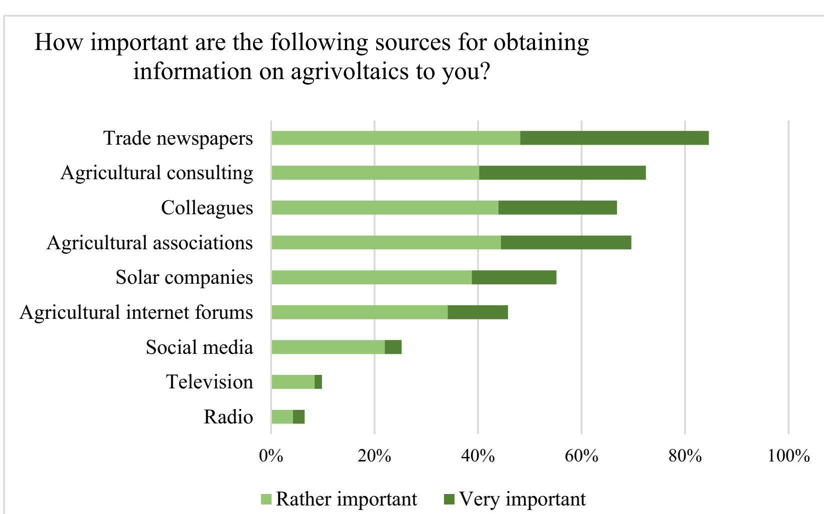


**Fig. A-1.** Information sources about agrivoltaics.

## Appendix B. Item description

**Table B-1**
Item description.

| Potential Factor | Item name | Item description | References |
|---|---|---|---|
| Level of Knowledge | K1 | Can you imagine what is meant by agrivoltaics? | Voss et al. [45] & Jürkenbeck et al. [20] |
| | K2 | I am well informed about current developments in this industry. | |
| | K3 | I have already been able to get a comprehensive picture of agrivoltaics. | |
| | K4 | I know the different applications of agrivoltaics. | |
| | K5 | I know the legal framework for the acquisition of such a plant. | |
| Climate change impact | CC1 | I am concerned about the impact of climate change on my business. | own creation |
| | CC2 | I have noticed that the weather in my region has changed in the last five years compared to the past. | |
| | CC3 | Due to the climatic changes, the yields of my farm suffer. | |
| | CC4 | I doubt that climate change will affect my life. | |
| Energy price impact | EP1 | Agriculture in Germany is undergoing fundamental changes due to high energy prices. | own creation |
| | EP2 | Despite the high energy prices, I am confident about the future. | |
| | EP3 | I sometimes worry that I won’t be able to continue my business because of high energy prices. | |
| Risk tolerance | RT1 | I am prepared to take risks in order to position my business securely for the long term. | Kröger et al. [24] |
| | RT2 | Safety is important to me, so I avoid risks. | |
| Innovativeness | IN1 | I am always looking for more development opportunities for my business. | Kröger et al. [24] |
| | IN2 | New production techniques and technologies interest me. | |
| | IN3 | It’s important to me to be quick on the uptake of innovations. | |
| | IN4 | The computer is an everyday companion for me. | |
| Environmental awareness | EA1 | As a farmer, I have a special responsibility to the environment. | Granoszewski et al. [18] & Geigler [16] |
| | EA2 | The environmental protection in agriculture is exaggerated. | |
| | EA3 | More environmental protection also means more quality of life and health for all. | |
| | EA4 | Each and every one of us bears responsibility for leaving a livable environment for future generations. | |
| Perceived usefulness | PU1 | I think that the use of agrivoltaics would increase the productivity of my business. | Venkatesh et al. [44] & Mohr et al. [31] |
| | PU2 | I think that the use of agrivoltaics does not fit into my operation. | |
| | PU3 | I think that the use of agrivoltaics would reduce my workload. | |
| | PU4 | I think that the use of agrivoltaics protects my crops (or animals) from sunlight and weather conditions. | |
| | PU5 | I think that the use of agrivoltaics improves the energy supply of my company. | |
| | PU6 | I think that the use of agrivoltaics makes sense to further develop my business. | |
| Perceived ease of use | PEU1 | I know what to do to purchase an agrivoltaic system. | Venkatesh et al. [44] & Mohr et al. [31] |
| | PEU2 | The use of agrivoltaics is possible on my farm without any problems. | |
| | PEU3 | It is difficult to plan the system so that it benefits my business. | |
| | PEU4 | The potential applications of agrivoltaics are difficult to overlook. | |
| | PEU5 | The way agrivoltaics works is clear and logical to me. | |
| Subjective norm | SN1 | The use of agrivoltaics would be accepted in my family. | Voss et al. [45] |
| | SN2 | My village community would accept the adoption of agrivoltaics. | |
| | SN3 | The use of agrivoltaics would be accepted by my colleagues. | |

Source: own presentation.

## Appendix C. Agrivoltaic Infotext

**English translation**
In the following, we would like to briefly introduce you to some of the basics of agrivoltaics. Please read the text carefully:

Agrivoltaics:
- Dual use of agricultural land (agriculture + photovoltaics)
- Agriculture remains in the foreground
- Entitlement to 85 % of direct payments
- Diverse applications possible (e.g.: Arable farming, viticulture, orcharding, vegetable growing or in combination with sheep or cattle grazing)

Advantages:
- Very large area potential
- Defuses land use conflicts
- Additional income for the farm
- Additional benefits for agriculture, including protection against hail, frost, and drought damage

Challenges:
- Reliable forecast of agricultural yields
- Optimization of the facility with regard to agricultural management
- Active management of grassland in conjunction with grazing animals can also be Agri-PV, but is difficult to distinguish from conventional ground-mounted systems (simple ground-mounted solar farms)

And this is what agrivoltaic can look like in practice:


**German original**
Nachfolgend wollen wir Ihnen kurz einige Grundlagen zur Agri-Photovoltaik näherbringen. Bitte lesen Sie dazu den Text aufmerksam durch:

Agri-Photovoltaik (Agri-PV):
- Doppelnutzung landwirtschaftlicher Nutzfläche (Landwirtschaft + Photovoltaik)
- Landwirtschaft steht weiter im Vordergrund
- Anspruch auf 85% der Direktzahlungen
- Vielfältige Anwendungen möglich (z.B.: Acker-, Wein-, Obst-, Gemüsebau oder in Kombination mit Beweidung von Schafen oder Rindern)

Vorteile:
- Sehr großes Flächenpotenzial
- Entschärft Flächennutzungskonflikte
- Zusätzliches Einkommen für den Betrieb
- Zusatznutzen für die Landwirtschaft u. a. durch Schutz vor Hagel-, Frost- und Dürreschäden

Herausforderungen:
- Zuverlässige Prognose der landwirtschaftlichen Erträge
- Optimierung der Anlage hinsichtlich der landwirtschaftlichen Bewirtschaftung
- Die aktive Bewirtschaftung von Grünland in Verbindung mit Weidetieren kann ebenfalls Agri-PV sein, ist jedoch schwer von herkömmlichen Freiflächen-Anlagen (einfache bodennahe Solarparks) abzugrenzen

Und so kann Agri-PV in der Praxis aussehen:

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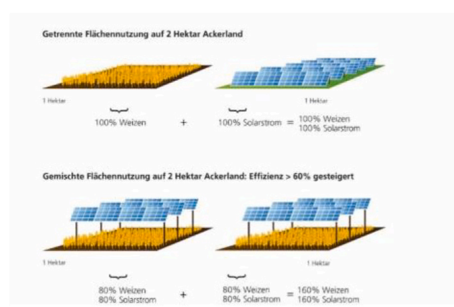


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