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Categorisation of Biogas Plant Operators in Germany with Regards to Their Intention to Use Straw Pellets as Innovative and Sustainable Substrate Alternative

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Abstract: The cultivation of renewable raw materials on arable land is challenged by the ongoing fuel-versus-food debate resulting from increases in maize cultivation, shorter crop rotations and land competition. Accordingly, the current legal framework for biogas production in Germany focuses on limiting cultivation of traditional biogas substrates, such as silage maize, and promoting the use of various alternatives, such as waste materials and by-products. One new sustainable substrate alternative is the use of cereal straw compacted to pellets. Although straw pellets generally have good fermentation properties, they are still rarely used in German biogas production. Since earlier research on agricultural production practices in general has shown that farmers can be divided into groups regarding their acceptance behaviour and the speed to successfully adopt innovative practices and technologies on their farm, this study addresses the research question: How can biogas plant operators in Germany be categorised with regards to their intention to use straw pellets as innovative and sustainable substrate alternatives? In order to answer this question an exploratory factor analysis and subsequent hierarchical cluster analysis was conducted with survey data obtained from German biogas plant operators (n = 309) in early 2021. Based on variables indicating the *intention to use* and *use behaviour* regarding straw pellets in biogas plants, four clusters are identified. Plant operator's *innovativeness*, *perceived risk* and the influence of *social environment* show differences between the clusters. Additionally, the characteristics of the innovation "straw pellets", such as *economic performance* and *sustainability*, were assessed differently by the four clusters of German biogas plant operators. While the clusters do not show significant differences in the socio-demographic characteristics, they do so in the farm characteristics (*farm activities besides biogas production*, *size of the plant*, the *proportion of slurry/dung* and *silage maize*). According to the results two of the four clusters have a higher acceptance of straw pellets, which also means that they are earlier in considering the actual use. The initiation of regional working groups, information campaigns and financial incentives can support plant operators, especially in the two clusters of potential early adopters, in accepting straw pellets. This should ultimately result in a faster and wider use of straw pellets as substrates in the whole biogas sector.

Keywords: biogas; substrate alternatives; agricultural residues; straw pellets; sustainable innovations; acceptance

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1. Introduction

At the end of 2019, a total of 18,943 biogas plants and 725 biomethane plants existed across Europe [1]. Since the implementation of the German Renewable Energies Act (EEG) in the year 2000, Germany has developed towards a leading role in this sector, being home to 48.97% of the biogas plants in Europe in 2019 [2]. The EEG initially accelerated farm-scale biogas production due to its positive environmental benefits, including decentralized energy and heat production, improved manure management and on-farm use of manure nutrients, as well as the reduction of greenhouse gas (GHG) emissions from manure. However, the sharp increase in the number of German biogas plants in the first two decades of the millennium is also associated with negative side effects, such as land competition, augmented maize cultivation, shorter crop rotations and negative land-use changes overseas, causing a food-versus-fuel debate within society and politics, which is still ongoing [3–8]. Besides Germany, these discussions can also be observed in other European countries with a similar importance on cultivating renewable raw materials on arable land, such as Austria, Italy and Poland [5,9,10].

To mitigate those negative side effects, a transnational shift towards more sustainable material sources in energy and fuel production is politically desired in Europe, as can be seen in current developments, such as the Green Deal, CAP Reform 2023 or the new European Renewable-Energy-Directive (RED 2) [8,11–13]. The first political measures were already introduced in Germany a few years ago with the implementation of the "maize cap" (in dt. "Maisdeckel"), during the amendment of the Renewable Energies Act (EEG) 2012. This cap focuses on reducing the proportion of classic substrates, such as maize, in favour of residues, such as cereal straw or manure [7,14]. Limiting the share of crops that are intensively cultivated in some regions, such as maize, was also sought in the 2013 and 2023 CAP reforms to achieve crop diversification [13,15]. In addition, RED 2 established sustainability criteria for heat and electricity production, as well as biofuels and biomass fuels, potentially enabling new revenue streams through the marketing of CO_2 certificates, e.g., in the production of biomethane from more sustainable substrates and agricultural by-products, such as straw [16–18].

Following the changes in legal frameworks, biogas plant operators will sooner or later be forced to substitute cultivated biogas substrates with more sustainable and innovative substrate alternatives, such as agricultural by-products and residue [19]. Among these, cereal straw offers, with a quantity of about 8 to 13 Mio. tons of fresh mass per year that can be harvested under consideration of sustainability aspects, a great potential for energy production in Germany. In the case of biogas usage this potential could be raised up to 14 to 21.5 tons of fresh mass per year, as long as the digestate from the biogas plant is returned to the fields [20,21]. However, for technical or economic reasons, no significant energetic use of straw has yet been established in Germany or other EU countries, neither in biogas production nor other utilization options, such as combustion or fuel production [21–27]. Previous studies indicate that the use of untreated cereal straw for biogas comes with higher transportation costs, higher financial expenditure and a greater workload, as well as various process-related complications, such as floating layers or a too high dry matter contents in the digester [24,28,29]. Other promising approaches, such as co-digestion of chopped straw with sugar beet, have not yet led to a significant use of straw in biogas plants, in particular due to them being associated to great additional expenses [30,31]. A new, innovative approach that could help to utilise the existing straw potential in biogas production is the use of straw compacted into pellets [32]. Initial studies on the fermentation of straw pellets have demonstrated that the problems encountered in the fermentation of untreated straw can be greatly reduced by pelletisation [33,34]. Although straw pellets have great potential as a sustainable substrate alternative in terms of quantity and, according to initial findings, also from technological perspective, those have not yet become accepted in German biogas production either [26,27]. Scientific studies on farmers' investment behaviour in the biogas sector and on the acceptance of manure solids show that agricultural biogas plant operators often behave inconsistently and have different implementation thresholds for potential bioenergy investments [35–38]. This assumption also applies to farm managers in general who cannot be described as a homogeneous group regarding their innovation acceptance behaviour. Farmers differ in the speed of accepting and using an innovation, while one group of farmers is quicker to adopt new practices or technologies, another group of farmers acts more hesitantly [39–45]. This is also in accordance with Roger's diffusion of innovations theory, which segments customers into five categories, namely, innovators, early adopters, early majority, late majority and laggards, according to their innovation adoption behaviour [46]. Due to the fact that straw pellets are currently not used in principle, this study focuses on the acceptance of using straw pellets in biogas plants. Acceptance research focuses on the prediction of innovation adoption and the identification of explanatory causes for the success or failure of technological innovations [47,48]. The focus of those studies is on decision makers' readiness and the potential that this results in the actual use of an innovation. Acceptance as such is considered an early stage of a positive adoption process [48–51]. According to the current state of knowledge, no studies on the acceptance of innovative and sustainable substrate alternatives, such as straw pellets, in biogas production exist. This leaves politicians and technology providers with uncertainty about the general acceptance of straw pellets as an innovative and sustainable substrate alternative and the existence of potential adopter groups and their characteristics. Therefore, we raise the following research question: How can biogas plant operators in Germany be categorised with regards to their intention to use straw pellets as innovative and sustainable substrate alternative?

In order to answer this question, online survey data were collected from 309 biogas plant operators in Germany with regard to the characteristics presented in chapter 2. This data was analysed by means of both factor and cluster analyses to categorise the operators according to their innovation acceptance behaviour for the specific case of straw pellets as a biogas substrate. This study contributes to understanding agricultural decision makers' acceptance behaviour regarding the use of sustainable innovations in renewable energy production and identifies potential innovators and early adopters.

The results have important implications for biogas plant operators, pellet producers and policymakers at national and international levels and offer the possibility of tailoring technical procedures, as well as advisory and information services, to the needs and wishes of biogas plant operators willing to use straw pellets as a sustainable biogas substrate.

2. Factors Explaining Biogas Plant Operator's Acceptance Behaviour

Previous studies (e.g. [41,43–45,52]) on the adoption of innovations by farm managers have characterised innovators or rejectors in several decision situations. Rogers' diffusion of innovations theory is often employed in research which aims at categorising decision makers into different groups (innovators, early adopters, early majority, late majority and laggards) depending on how quickly they adopt an innovation [37,46]. In addition to the characteristics of the innovation itself, differences in the adoption of an innovation can be explained by personal, operational and external factors (e.g. social environment) [48,53]. Along with "characteristics of innovation" and "characteristics of innovator/rejector", similar factors were used by Voss et al. (2009) to explain the investment behaviour of farm managers in biogas plants. The "characteristics of innovator/rejector" include, for example, management behaviour (e.g. innovativeness or risk-aversion), sociodemographic characteristics and farm characteristics [37,38]. Based on the assumption that the influencing factors mentioned above are relevant for the acceptance behaviour in the early stage of the adoption and diffusion of innovations, the following findings are the current state of research on the agricultural sector [38,53].

Management behaviour: Personal innovativeness and risk-taking behaviour determine the basic willingness of farmers to use innovations [35,38,52,54–56]. Farmers can be distinguished by their risk-taking behaviour and are predominately described as risk-averse [57,58]. While Voss et al. (2009) have characterised farmers, who have invested in biogas production as typically less risk-averse farmers, Steinhorst et al. (2015) separated biogas plant operators into both categories of risk-taking and risk-averse operators, based on the planning and operation of their biogas plant [59]. The more pronounced a decision-maker's risk aversion, the more hesitant they are in deciding to use an innovation [54,60].

Social environment: Several studies have highlighted the relevance of social norms and social environment for the adoption of new technologies in the agricultural sector [61]. Especially family members and neighbouring farmers have a positive influence on farm managers' decision-making behaviour [62–67]. This similarly holds true for biogas plant operators. If neighbouring plant operators are known to use an innovative practice, this has a positive influence on the acceptance of other plant operators to use it as well [52]. The critical public opinion on growing maize for biogas production and political pressure is recognised by biogas plant operators and plays a role in their decision-making behaviour [52,68]. Furthermore, the availability and utilisation of consulting/advisory services can be named as an influencing factor in using innovations in agriculture [69–71].

Characteristics of the innovation: The benefits of an innovation and its perceptibility are drivers for the acceptance and implementation of an innovation. Additionally, the opportunity to test deployment and compatibility with previously used processes on the farm is relevant [38,46]. The attitude towards the innovation's characteristics is suitable to separate and describe different groups of farmers regarding their technology acceptance [41,44].

Sociodemographic characteristics: Age, professional experience and the educational level of the decision-maker have been identified in various studies as explaining the differences in behavioural intention regarding the usage of innovative farming practices [64,72–77]. Similar factors can also be cited for the introduction of sustainable innovations or environmentally friendly practices in agriculture [78–80]. Regarding the farm manager's age, it is often observed that the tendency to innovate decreases with increasing age [39,73,76]. The differences between the genders in decision-making behaviour are difficult to analyse because the majority of the farmers, e.g., in Germany, are men [81]. Independent of this fact, women farmers tend to be more willing to use environmentally friendly practices, such as organic farming [78]. Another important factor in farmers' adoption of new technologies and processes is their work experience [38,40,41,82] and the level of (job) education [74,82–86]. The better the farm manager's job education, the higher their willingness to use a new technology [39,87,88]. Similarly, more professional experience leads to a higher likelihood of implementing an innovation [38,74].

Knowledge about the innovation has an important influence, especially at the beginning of the adoption process when the decision to use or not to use an innovation has not yet been made [46,89]. A lack of knowledge was identified as a barrier to the implementation of technological or sustainable innovations in agriculture in previous research [90–92]. In direct relation to biogas production, limited knowledge of farmers about agricultural residues is identified as a barrier to the expansion of biogas production in Sweden [93].

Farm characteristics: In a company context, an increasing farm size is often accompanied by an increase in the intention to use sustainable practices and technologies [42,78,82,94]. This equally holds true for the introduction of energy crop cultivation [85,86,95,96]. The influence of biogas plant size has also been tested on the acceptance of separated slurry as a biogas substrate but with no statistically significant result [37]. The location of the farm has an influence on farmers' investments in buildings or new crop systems [97], in particular, due to differences in soil conditions and annual precipitation [53,98]. With regard to the use of straw pellets for biogas production, the degree of use could depend on various additional structural factors that are location-specific, such as the availability of straw or the density of livestock in a region [83,91].

3. Materials and Methods

3.1. Study Design and Data Collection

German biogas plant operators were surveyed during the period from February to April 2021 on the factors explaining the acceptance behaviour towards the use of straw pellets in biogas plants. The anonymous and standardised questionnaire was conducted online via the platform Unipark (Questback GmbH). Before the launch of the survey, a pretest was conducted to check functionality and comprehensibility. The weblink to the questionnaire was distributed via various associations and magazines with agricultural and bioenergy backgrounds, personal networks and social media platforms to achieve a wide distribution within the agriculture sector in Germany. A total of 316 respondents participated in the survey. Due to exceptional response times as well as a clear tendency towards placing responses in the middle of the scales, three observations were excluded. Four more observations from farmers operating biogas plants with a substrate share of commercial, industrial and municipal waste of over 90% were not considered in this study, resulting in 309 observations in the final dataset used for the analysis.

The questionnaire consisted of five parts. To avoid confusion with other processing forms of cereal straw or other raw materials, such as maize or rape straw, a definition of straw pellets as a substrate processed from cereal straw was provided at the beginning of the survey. Detailed information on the fermentation of straw pellets was not provided at this stage to avoid response bias. In the second part, biogas plant operators were asked about their farm characteristics, such as farm activities and farm size. In the third part, additional farm characteristics with specific questions on the biogas plant, including installed electricity capacity, other technical parameters and the current input substrates, were requested. The fourth part of the questionnaire contained eleven sections, including questions on the intention to use and use behaviour regarding straw pellets, management behaviour, social environment and characteristics of the innovation. Section-wise, six to eight statements were presented to the respondents in randomised order [35,38,52,64,99–104]. The items were measured on 5-point Likert scales (from 1 = strongly disagree to 5 = strongly agree). In the fifth and final part, the willingness to pay for straw pellets, and the socio-demographic characteristics of the biogas plant operators were queried.

3.2. Statistical Analysis

The statistical analysis was done using IBM SPSS Statistics Version 27. First, univariate analyses were conducted to generate descriptive statistics of the data [105]. Second, an exploratory factor analysis was performed with 13 acceptance variables to reduce dimension with regards to the intention to use straw pellets for biogas production [106]. The principal component approach with varimax rotation method and Kaiser normalization was chosen. The varimax rotation was applied because the variance of the squared loadings reached the maximum value with this rotation. This method allows for a clear separation of the factors, which simplified the assignment and interpretation of the single factors [107]. A measure of sampling adequacy (MSA), the Kaiser–Meyer–Olkin (KMO) value, Bartlett's test and subsequent reliability analysis were applied to control the quality of the analysis [108]. Regarding the MSA, only variables with values of $\geq$0.6 "medium" were used. This threshold was also valid for the KMO referring to all variables [109]. The Bartlett's test for sphericity tested the null hypothesis on whether the variables in the dataset show correlations. The Bartlett's significance was at a value of $p = 0.000$, which means that the null hypothesis was rejected and, thus, there was a correlation between the variables [106]. To assure reliability, the internal consistency was tested using Cronbach's Alpha (CA). A threshold of $\geq$0.6 is acceptable for exploratory research like this one [110]. The extraction of factors was only performed if the eigenvalue was greater than 1. Next, a hierarchical cluster analysis was performed to generate homogeneous groups based on the previously extracted factors [41,106]. Single-linkage-method was applied to remove outliers. The optimal number of clusters was analysed using the Ward method. The k-means method was used to optimise the previously generated start partition of Ward's method as recommended in the literature [111]. The discriminant analysis showed low significant values for the Wilks–Lambda and high eigenvalues greater than 1, meaning that the groups have a clear demarcation [106,112]. For a detailed characterisation of the generated clusters, a one-way ANOVA was performed. In the case of variance heterogeneity (Levene test: $p \leq 0.001$), the Welch–ANOVA was conducted, which has a higher robustness against variance heterogeneity in comparison with the one-way approach. To determine significant differences between the individual clusters, the Tamhane T2 post-hoc multiple comparison test, which assumes that groups may differ in variance, was conducted. In the case of categorical variables, cross-tabulation with a Chi-square test according to Pearson was performed. This approach was extended by a pairwise comparison using Bonferroni correction ($\alpha = 0.05$).

4. Results

4.1. Sample Description

Comparing the sample of 309 observations to the statistics of the German Farmers' Association for 2020, the age structure of the survey participants roughly corresponds to the overall age structure of farm managers in Germany, although the sample is comparatively younger, with the age groups "55–65 years" and "over 65 years" being a little underrepresented [81]. The educational level of the sample can be described as comparatively high in comparison to the data of the German Farmers' Association from 2020 [81]. Regarding job-related degrees, 39.2% of the respondents stated that they had completed an agricultural university degree (bachelor, master, Ph.D. or habilitation), compared to only 9.38% of the farm managers in the general statistics. A total of 44.3% of the participants had a two-year vocational diploma in agriculture (24.12% of farm managers). 7.8% of the participants completed an agricultural training or a one-year vocational diploma (33.5% of farm managers), while 8.7% stated only practical experience or various vocational qualifications that cannot be classified as directly related to agriculture (33% of farm managers) [81]. A high level of education can also be ascertained for the general school-leaving qualifications compared to the overall German population in 2019 [113]. A total of 59.9% of the respondents have an entrance qualification for a university of applied sciences or a general university entrance qualification (A-level) (33.5% of the German population). A total of 27.51% have a secondary school diploma or equivalent (23.5% of the German population). Approx. 12% have a lower secondary school leaving or polytechnical certificate (35.1% of the German population). No participants of the survey are still in school or do not have a general school leaving certificate (7.5% of the German population) [113]. A total of 0.65% of the participants did not provide any information. In terms of gender, men clearly dominate the sample, with 96.8% (in German Farmers' Association statistics from 2020, 89% of farm managers are men) [81]. Only 2.6% and 0.6% of the respondents indicated their gender as women and diverse, respectively. One participant (0.3%) did not state the gender. When comparing the regional distribution of biogas plants in the sample to the statistics of the German Biogas Association for the year 2020, it becomes evident that it corresponds to the structural proportions for most federal states, except for Bavaria (underrepresented) and Lower Saxony (overrepresented). Minor deviations are also observed for Mecklenburg-Western Pomerania, Saxony-Anhalt and Schleswig-Holstein [2].

The plant operator's experience with biogas production from the date of the first operation of a biogas plant to the date of participation in the survey amounts to an average of 12.8 years. A total of 56.6% of the biogas plants are funded by the EEG 2009, 22.98% by the EEG 2004 and 6.1% by the EEG 2012. At the time of the survey, three plants (0.9%) were still being operated according to the EEG 2000. Remuneration according to the EEG 2014 applies to 1.62% and to the EEG 2017/tender to 0.65% of the plants. A total of 11% of the participants indicated funding by several different EEGs.

In terms of power generation capacity, the survey comprises mainly larger biogas plants with an installed power capacity of more than 1000° kW (see Table 1). Statistically, larger plants ferment higher proportions of classic crop biogas substrates, such as maize, than smaller biogas plants that typically use higher proportions of manure and slurry. This provides great informative value with regard to the investigation of the acceptance of straw pellets as an alternative substrate option to replace current crop substrates [26]. A total of 96.1% of the participants use maize silage in their biogas plant. The average substrate share of maize silage is 42.6%. Cereal straw was indicated as a substrate by ten biogas plant operators (3.2%). Two of them currently use straw compacted into pellets (0.01%). A total of 25.6% (n = 80) of the operators have already tested straw in general in their biogas plant in the past, of which seven participants (2.2%) stated that they had done so temporarily in the form of cereal straw pellets. The question of whether the operators had ever dealt with the use of straw pellets in biogas plants before participating in the survey for this study was answered in the affirmative by 59 operators (19.2%).

Table 1. Size distribution according to the power generation capacity.

	Installed Power Capacity		Rated Power Capacity
Size-Class	**Sample (2021) [1]**	**Biogas Plants (2015) [2]**	**Sample (2021) [1]**
≤70 kW	0.6%	0.4%	1.3%
71–150 kWel	3.6%	2.4%	4.9%
151–300 kWel	9.7%	40.8%	15.5%
301–500 kWel	12.9%		25.2%
501–750 kWel	17.5%	41.3%	24.3%
751–1000 kWel	13.3%		12.9%
>1000 kWel	42.4%	15.1%	15.9%

Source: Own illustration based on [1] own data collection; [2] [114].

4.2. Results of the Factor and Cluster Analyses

From the exploratory factor analysis, two factors were extracted based on statements regarding the acceptance of straw pellets by the biogas plant operators. Factor 1, "Intention to use straw pellets" (CA = 0.862), describes the current intention to try out straw pellets as a substrate in biogas plants. Factor 2, "Use behaviour" (CA = 0.807), is characterised by statements on concrete plans to use straw pellets (see Table 2). These two factors explain 66.4% of the total variance of the nine variables. The KMO value of 0.87 is relatively high and can be rated as "meritorious" according to the literature [109]. Thereby these factors are well-suited for the cluster analysis. Using Ward's method followed by k-means optimisation, a four-cluster solution was found and confirmed by the dendrogram, scree plot and elbow criterion. Detailed results of the two clustering factors with their single statements and the four extracted clusters are explained below. In Tables 3–5 (for additional descriptive statistics see Appendix A, Tables A1–A3), the clusters are characterised by cluster-describing variables divided into management behaviour, characteristics of the innovation and socio-demographic characteristics.

Table 2. Results of the factor and cluster analysis.

Variables	**Cluster A (n = 78)**	**Cluster B (n = 117)**	**Cluster C (n = 73)**	**Cluster D (n = 37)**
Factor 1: Intention to use straw pellets * (CA = 0.862)**	**−1.22 [bcd] (0.384)**	**−0.06 [acd] (0.338)**	**1.26 [abd] (0.553)**	**0.320 [abc] (0.786)**
Straw pellets are a real substrate alternative for me. *** FL = 0.822	1.51 [bcd] (0.597)	2.52 [acd] (0.761)	3.55 [acd] (0.578)	2.95 [abc] (0.705)
I think about testing smaller quantities of straw pellets in my biogas plant. *** FL = 0.821	1.47 [bcd] (0.618)	2.70 [acd] (0.864)	3.85 [abd] (0.681)	3.22 [abc] (0.886)
I intend to buy straw pellets as an input substrate for my biogas plant in the near future. *** FL = 0.818	1.14 [bcd] (0.386)	1.81 [acd] (0.472)	2.88 [ab] (0.832)	2.54 [ab] (0.803)
I expect to use straw pellets as an input substrate in my biogas plant very soon. *** FL = 0.791	1.29 [bcd] (0.486)	2.06 [acd] (0.577)	3.07 [ab] (0.694)	2.81 [ab] (0.877)
The use of straw pellets in my biogas plant is not an option for the time being. *** FL = 0.744	4.32 [bcd] (0.987)	3.27 [acd] (0.916)	2.15 [ab] (0.758)	2.59 [ab] (0.927)

Table 2. *Cont.*

Variables	Cluster A (n = 78)	Cluster B (n = 117)	Cluster C (n = 73)	Cluster D (n = 37)
Factor 2: Use behaviour * (CA = 0.807)**	**−0.22 ^{bcd} (0.217)**	**−0.39 ^{ad} (0.238)**	**−0.42 ^{ad} (0.451)**	**2.00 ^{abc} (0.485)**
I am currently applying for planning permission for an own stationary pelleting plant for my biogas plant. *** FL = 0.864	1.00 ^{d} (0.000)	1.01 ^{acd} (0.092)	1.00 ^{d} (0.000)	1.73 ^{abc} (0.450)
I am growing less maize in the current harvest year as I have firmly planned straw pellets as an input substrate from the summer onwards. *** FL = 0.848	1.04 ^{d} (0.194)	1.03 ^{d} (0.182)	1.15 ^{d} (0.360)	2.08 ^{abc} (0.682)
I have grown more grain for the 2021 harvest so that the straw can be pelleted for the biogas plant. *** FL = 0.757	1.03 ^{cd} (0.159)	1.07 ^{d} (0.285)	1.18 ^{ad} (0.420)	2.05 ^{abc} (0.780)
I have already bought or stored straw pellets for biogas production to feed them in the near future. *** FL = 0.732	1.03 ^{d} (0.226)	1.02 ^{d} (0.130)	1.10 ^{d} (0.531)	1.18 ^{abc} (0.559)

Significance level at * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$; letters (a, b, c, d) signify a significant difference to the corresponding cluster (Tamhane post-hoc multiple comparison test at significance level 0.05). Numbers without brackets show mean values, and numbers in brackets illustrate the items' standard derivations. All statements were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". n = 305. Source: Own illustration based on [1] own data collection.

Table 3. Cluster description: Management behaviour and social environment.

Variables	Cluster A (n = 78)	Cluster B (n = 117)	Cluster C (n = 73)	Cluster D (n = 37)
Willingness to pay and voluntariness of use				
Willingness to pay for straw pellets as biogas substrate (freely queried) (€/t) **	28.43 ^{bcd}	43.51 ^{a}	43.70 ^{a}	49.94 ^{a}
Willingness to pay for straw pellets as biogas substrate (with upfront information) (€/t) ***	40.43 ^{bcd}	56.19 ^{a}	56.68 ^{a}	56.67 ^{a}
I will only use residual materials, such as straw pellets, when I am obliged to do so. ***	3.10 ^{bcd} (1.420)	2.54 ^{a} (1.055)	2.15 ^{a} (1.050)	2.49 ^{a} (0.932)
Innovativeness				
I attach great importance to being innovative quickly, knowing that this can lead to disappointment. *	2.86 ^{cd} (1.003)	3.03 (0.982)	3.33 ^{a} (0.898)	3.43 ^{a} (0.835)
I am interested in new production processes and technologies. **	4.13 (0.727)	4.04 (0.700)	4.19 (0.518)	3.95 (0.705)
In my circle of biogas plant operators/colleagues, I am usually the first to try out new things on my farm.	2.91 (0.983)	2.93 (0.980)	3.19 (0.844)	3.14 (0.887)
When I hear about new substrate alternatives, I immediately think about how I could use them in my biogas plant. ***	2.86 ^{cd} (1.192)	3.21 (0.933)	3.52 ^{a} (0.884)	3.46 ^{a} (0.960)
Perceived Risk				
The risk of using straw pellets is too high for me. ***	2.96 ^{bcd} (1.133)	2.43 ^{ac} (0.780)	1.97 ^{abd} (0.707)	2.46 ^{ac} (0.803)
Safety is important to me, so I avoid risks.	3.09 (0.956)	3.02 (0.799)	2.78 (0.870)	3.16 (0.834)
I avoid risky decisions, especially in the biogas operating branch. *	3.05 ^{c} (1.005)	2.98 ^{c} (0.919)	2.59 ^{ab} (0.955)	2.97 (0.928)

Table 3. *Cont.*

Variables	Cluster A (*n* = 78)	Cluster B (*n* = 117)	Cluster C (*n* = 73)	Cluster D (*n* = 37)
Social environment				
My family environment would support trying alternative substrates, such as straw pellets, in my biogas plant. **	2.97 [c] (1.069)	3.31 (0.987)	3.58 [a] (0.942)	3.24 (0.895)
Friendly biogas plant operators advocate the use of alternative substrates, such as straw pellets. **	2.62 [ab] (1.047)	3.05 [a] (0.808)	3.08 [a] (0.954)	2.81 (0.845)
By using straw pellets, I can improve the image of biogas production in the region. ***	2.69 [a] (1.097)	3.09 (1.030)	3.38 [c] (0.981)	2.97 (0.928)
The agricultural advice in my region is very helpful in the introduction of new input substrates in biogas production. *	2.08 [d] (1.054)	2.42 (0.976)	2.27 (1.071)	2.65 [a] (1.086)
Local advice will support me in the use of straw pellets. *	2.50 [b] (1.148)	2.97 [a] (0.960)	2.82 (0.918)	2.78 (0.947)
Societal pressure				
As a biogas plant operator, I am increasingly exposed to public criticism.	2.86 (1.170)	3.04 (1.125)	3.04 (1.148)	2.97 (1.067)
Acceptance of biogas production by society has declined sharply in the last ten years.	3.41 (1.062)	3.32 (1.088)	3.44 (1.041)	3.37 (0.982)
Conflicts with neighbours and village residents because of the biogas plant (transport volume, noise, maize cultivation) are part of my daily business.	2.04 [d] (0.889)	2.19 (0.999)	2.22 (1.003)	2.68 [a] (1.056)
Prior knowledge and involvement				
Prior involvement with straw pellet usage for biogas plants (yes/no in %) [1,*]	15.38/84.62	12.82/87.18 [c]	30.14/69.86 [b]	27.03/72.97
Self-evaluated knowledge of straw pellet usage in biogas plants [2]	2.13 (0.945)	2.09 (0.788)	2.14 (1.058)	2.43 (0.867)
I have the necessary knowledge to use straw pellets in my biogas plant.	2.64 (1.289)	2.62 (1.181)	2.92 (1.341)	2.84 (1.093)

Significance level at * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; letters (a, b, c, d) signify a significant difference to the corresponding cluster (Tamhane post-hoc multiple comparison test at significance level 0.05). Numbers without brackets show mean values, and numbers in brackets illustrate the items' standard derivations. All statements except the willingness to pay and marked variables ([1,2]) were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". *n* = 305. [1] "Prior to this survey, have you ever specifically looked into the use of cereal straw, in the form of straw pellets, for biogas production?"; [2] "How would you rate your level of knowledge about the fermentation of straw pellets in biogas plants?" (scale from 1 = "very low" to 5 = "very high").

Table 4. Cluster description: Characteristics of the innovation.

Variables	Cluster A (*n* = 78)	Cluster B (*n* = 117)	Cluster C (*n* = 73)	Cluster D (*n* = 37)
(Economic) Performance				
I am convinced that the use of straw pellets in biogas plants is worthwhile. ***	2.24 [bcd] (0.840)	2.82 [ac] (0.715)	3.22 [abd] (0.672)	3.08 [ac] (0.682)
I am convinced that the use of straw pellets in the biogas plant brings more benefits than (additional) costs. **	2.32 [bcd] (0.947)	2.81 [ac] (0.730)	3.33 [abd] (0.765)	3.14 [ac] (0.673)
The use of straw pellets offers my biogas plant economic advantages.	2.12 [bcd] (0.806)	2.72 [ac] (0.753)	3.16 [abd] (0.782)	2.86 [ac] (0.787)
Straw pellets are far too expensive compared with other substrates. *	3.53 [c] (0.817)	3.37 (0.714)	3.14 [a] (0.787)	3.27 (0.693)

Table 4. *Cont.*

Variables	**Cluster A (*n* = 78)**	**Cluster B (*n* = 117)**	**Cluster C (*n* = 73)**	**Cluster D (*n* = 37)**
With straw pellets, the electricity production costs per kwh are more favourable than with other substrates. *	2.36 [c] (0.772)	2.58 (0.722)	2.84 [a] (0.727)	2.73 (0.732)
The financial cost of transporting and producing straw pellets is higher than the fermentation benefit. *	3.51 [c] (1.041)	3.26 (0.835)	2.96 [a] (0.815)	3.08 (0.722)
The use of straw pellets increases the sustainability of biogas production. ***	2.79[c] (1.121)	3.16[c] (0.909)	3.53[ab] (0.867)	3.11 (0.843)
Advantages in substrate and digestate management				
The biogas yield per ton of fresh mass is higher than from silage maize. *	2.77 [c] (1.309)	3.00 (1.189)	3.36 [a] (1.171)	2.89 (1.100)
Due to the low amount of digestate produced when using straw pellets, the cost of transporting digestate is reduced. ***	2.72 [bcd] (1.005)	3.30 [a] (0.843)	3.18 [a] (1.005)	3.22 [a] (0.821)
Expected Effort				
The biogas plant's own power consumption will increase due to the use of straw pellets. *	3.62 [d] (0.983)	3.31 (0.942)	3.30 (1.032)	3.11 [a] (0.875)
The amount of work required to rectify faults will increase considerably with the fermentation of straw pellets.	2.82 (1.029)	2.74 (0.930)	2.60 (0.924)	2.62 (0.828)
The agitator running times and intervals must be increased for straw pellet use.	3.76 (1.022)	3.50 (0.943)	3.30 (0.982)	3.51 (0.804)
To be able to use straw pellets in my biogas plant, I need additional equipment for substrate processing (e.g., mechanical crushing).	2.92 (1.277)	2.58 (1.116)	2.51 (1.056)	2.62 (1.010)
The use of straw pellets increases the amount of work required for daily control work.	2.88 (1.044)	2.79 (0.952)	2.78 (0.946)	2.86 (0.787)

Significance level at * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; letters (a, b, c, d) signify a significant difference to the corresponding cluster (Tamhane post-hoc multiple comparison test at significance level 0.05). Numbers without brackets show mean values, and numbers in brackets illustrate the items' standard derivations. All statements except categorical variables were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". *n* = 305.

Table 5. Cluster description: Sociodemographic and farm characteristics.

Trait/Statement	**Cluster A (*n* = 78)**	**Cluster B (*n* = 117)**	**Cluster C (*n* = 73)**	**Cluster D (*n* = 37)**
Sociodemographic characteristics				
Age in years [1]	46.12	45.29	47.49	48.35
Work experience in biogas production (Ø in years)	12.62	12.87	12.88	12.76
Farm characteristics				
Arable farming (yes/no) [1]	57/21	92/25	54/19	29/8
Agricultural contracting (yes/no) [1]	11/67	26/91	13/60	11/26
Other renewable energies (yes/no) [1]	46/32	75/42	46/27	26/11
Dairy cattle (yes/no) [*,1]	26/52 [c]	25/92	10/63 [a]	9/28
Beef cattle (yes/no) [1]	10/68	20/97	7/66	8/29
Sows (yes/no) [1]	3/75	10/107	6/67	3/34
Fattening pigs (yes/no) [1]	20/58	34/83	19/54	10/27
Chicken (yes/no) [1]	4/74	11/106	7/66	4/33
Other livestock (yes/no) [1]	5/73	10/107	5/68	6/31

Table 5. *Cont.*

Trait/Statement	Cluster A (*n* = 78)	Cluster B (*n* = 117)	Cluster C (*n* = 73)	Cluster D (*n* = 37)
Rated electricity production capacity in kW (%) *,[1]				
<150 KW	12.82 [bd]	2.56 [a]	8.22	0.00 [a]
151–500 kW	41.03	45.30	38.36	32.43
501–1000	28.21	40.17	39.73	40.54
>1000 kW	17.95	11.97	13.70	27.03
Ø Rated electricity production capacity in kW	603.63	823.22	838.15	821.91
Proportion of manure and slurry (%) *	47.00 [c]	37.78	35.25 [a]	38.60
Ø Share of maize silage in % **	35.65 [bc]	45.94 [a]	47.55 [a]	41.68

Significance level at * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; letters (a, b, c, d) signify a significant difference to the corresponding cluster (Tamhane post-hoc multiple comparison test at significance level 0.05). Numbers without brackets show mean values, and numbers in brackets illustrate the items' standard derivations. All statements except categorical variables were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". [1] Chi-square test according to Pearson. Pairwise comparison using Bonferroni correction. $n = 305$.

Cluster A, "risk-averse rejectors", includes 78 participants and is characterised by a low intention to use straw pellets (factor 1). Currently, straw pellets are "not an option for the time being" for operators in this cluster (μ = 4.32, σ = 0.987). This is confirmed by the strong disagreement with the statements about concrete plans for straw pellet usage (factor 2). The variables describing the management behaviour of the plant operators in this cluster show a low level of interest in the use of straw pellets in biogas plants (see Table 2). Biogas plant operators in cluster A indicate a comparatively low willingness to pay 28.43 €/t (openly queried) or 40.43 €/t (with information provided on the fermentation of straw pellets) for straw pellets (see Table 3). Compared with the other clusters, there seems to be less interest in the voluntary use of straw pellets in cluster A (μ = 3.1, σ = 1.420). Plant operators in this group do not appreciate being quick in innovating (μ = 2.86, σ = 0.1003) or using new biogas substrates (μ = 2.86, σ = 1.192), although a general interest in new products or practices exists (μ = 4.13, σ = 0.727). In addition, a tendency to be risk-averse can be observed in comparison to the other clusters. Regarding the "social environment", cluster A operators assume that befriended biogas operators are rather sceptical and unsupportive regarding the use of straw pellets for biogas production (μ = 2.62, σ = 1.192). Biogas plant operators in cluster A have the greatest doubts about the availability of advisory services that could support the introduction of new biogas substrates (μ = 2.08, σ = 1.054). Similar concerns exist regarding support from local advisory services for the adoption of straw pellets (μ = 2.50, σ = 1.148). No statistically significant differences regarding "societal pressure" are determined. Cluster A has the second lowest share of plant operators who have already dealt with the fermentation of straw pellets in biogas plants, at 15.4% (μ = 2.13, σ = 0.945). Currently, no biogas plant operators in this cluster use pellets, but two participants have already tested straw pellets in the past.

When characterising the innovation "straw pellets" for biogas production (see Table 4), it is noticeable that plant operators in cluster A rate the six statements related to economic performance comparatively lower on a statistically significant level. Cluster A operators are not convinced that the use of straw pellets is worthwhile (μ = 2.24, σ = 0.840) and do not assume that it brings more benefits than (additional) costs (μ = 2.32, σ = 0.947). They disagree with the statement "The use of straw pellets offers my biogas plant economic advantages" (μ = 2.12, σ = 0.806). This cluster is also less convinced of the sustainable value of biogas production (μ = 2.79, σ = 1.121). Operators in cluster A rather disagree with the statements on the benefits of feeding straw pellets to the substrate and digestate management. They are not convinced that the lower amount of digestate produced when using straw pellets will reduce the cost of transporting digestate (μ = 2.72, σ = 1.005).

Cluster A biogas plant operators expect a tendentially higher effort, in particular regarding technical parameters, such as a higher own power consumption (μ = 3.62, σ = 0.983) and increasing agitator running times and intervals (μ = 3.76, σ = 1.022).

Cluster B, "reluctant majority", represents the largest group with 117 plant operators. The intention to use straw pellets is restrained but somewhat more positive than among the members of cluster A (factor 1). Those operators are rather hesitant when asked whether straw pellets can be considered as a real substrate alternative in general (μ = 2.52, σ = 0.761) or they would test straw pellets on a trial basis (μ = 2.70, σ = 0.864). A use of straw pellets in the near future is currently not considered, but also not strictly denied (μ = 2.06, σ = 0.577). Just like cluster A, cluster B does not have any concrete plans for the use of straw pellets (factor 2). The willingness to pay for straw pellets of cluster B operators is 43.51 €/t (56.19 €/t with the given information), the third highest level compared to the other clusters. In contrast to cluster A, plant operators in cluster B show a tendency to be willing to use straw pellets voluntarily and not only if obliged to do so (μ = 2.54, σ = 1.055). However, also cluster B operators tend, similar to cluster A operators, to be less innovative, with only slightly more emphasis on innovating quicker (μ = 3.03, σ = 0.982) and a slightly greater interest in using new substrate alternatives (μ = 3.21, σ = 0.933). Cluster B is tendentially risk-averse, but the members of this group are less afraid of using straw pellets in their biogas plant than cluster A (μ = 2.43, σ = 0.780). The social influence of professional colleagues and the influence on the image of biogas production are seen rather neutrally, whereas family members would tend to welcome the use of straw pellets (μ = 3.31, σ = 0.987). The availability of advisory services to support in the use of straw pellets receives more agreement by cluster B than by cluster A, with mean values between two (disagree) and three (neither agree nor disagree). About 87% of the plant operators in this cluster B had not yet dealt with the fermentation of straw pellets before participating in this study. This value is the highest in comparison to the other clusters and shows a statistically significant difference from cluster C. The self-assessed knowledge of the plant operators in this group is at a similarly low level as in cluster A.

The assessment of the profitability of straw pellet usage shows a certain indecisiveness by cluster B operators. The statements on this innovation being worthwhile and bringing more benefits than costs are slightly disagreed upon (μ = 2.82, σ = 0.715; μ = 2.81, σ = 0.730). The respective mean values are higher than those of cluster A and much lower than those of cluster C, both on a statistically significant level. Besides economic aspects, there is little conviction among cluster B members that straw pellets improve the sustainability of biogas production (μ = 3.16, σ = 0.909). Regarding advantages in substrate and digestate management, the lower amount of digestate and the associated lower transport costs are perceived as relatively advantageous (μ = 3.30, σ = 0.843). Cluster B cannot be differentiated on a statistically significant level from the other clusters regarding the items reflecting the expected effort. However, compared to cluster A the expected technical effort (increasing own power consumption and agitator running times) is tendentially lower.

Cluster C, "risk-taking acceptors", shows the strongest expression of "Intention to use straw pellets" (factor 1). It tends to affirm that straw pellets are a real alternative (μ = 3.55, σ = 0.578). The strongest willingness to test straw pellets is also observable in this cluster (μ = 3.85, σ = 0.681). In addition, the statement, "The use of straw pellets in my biogas plant is not an option for the time being", was denied (μ = 2.15, σ = 0.758). While a high level of agreement can be observed with factor 1, this is not the case with factor 2. There are no concrete plans for the use of straw pellets, even if the mean values of the single statements are slightly higher than in clusters A and B. The willingness to pay of cluster C members is on average 43.70 €/t (56.68 €/t with the given information) and thus on a similar level as cluster B, but with a higher willingness to pay than cluster A. The statement, "I will only use residual materials, such as straw pellets when I am obliged to do so", is denied most strongly by this group (μ = 2.15, σ = 1.050). The willingness to innovate is the greatest of all clusters and differs statistically significant from clusters A and C. For cluster C operators, it is important to be involved in innovations in a timely manner (μ = 3.33, σ = 0.898). This also applies to the use of new input substrates in biogas production (μ = 3.52, σ = 0.884). The risk propensity of operators in cluster C is statistically significant lower compared to the other clusters. The statement "The risk of using straw pellets is too high for me" is rated the lowest with a mean value of μ = 1.97 (σ = 0.707). The statement "I avoid risky decisions, especially in the biogas operating branch" also has a comparatively low mean value (μ = 2.59, σ = 0.955). Compared to the other clusters, the social environment plays a greater role for cluster C, with a statistically significant difference to cluster A. While the assessment of the professional colleagues' opinion on the use of straw pellets is rather inconclusive, it is assumed that family members would rather support the use of straw pellets (μ = 3.58, σ = 0.942) and that this could be an opportunity to improve the image of biogas production (μ = 3.38, σ = 0.981). The operators in cluster C are comparatively less convinced of the availability of advisory services that could be helpful in the use of straw pellets but less critical than in cluster A. When it comes to "societal pressure", the clusters differ little overall; cluster C tends to agree slightly more with the statement that the image of biogas production has declined significantly in the last ten years. The proportion of operators in cluster C who were already involved in the use of straw pellets before this study is with 30.14% the highest among all the clusters and differs on a statistically significant level from cluster B. Nevertheless, the self-assessed knowledge of straw pellet use in biogas plants in general is similarly as low as in clusters A and B with a mean value of 2.14 (σ = 1.058), while the assessment is comparatively higher with regard to the use of straw pellets in relation to their own plant (μ = 2.92, σ = 1.341). Cluster C operators rate the economic performance best in all six statements in the cluster comparison. Particularly the three statements reflecting worthwhileness, cost-benefit ratio and economic advantages show that this cluster is more convinced of straw pellet use in a biogas plants than the others. Despite a generally positive perception of the economic performance, members of cluster C are rather undecided whether straw pellets are too expensive compared to other substrates. Besides economic factors, the biogas plant operators of cluster C, in contrast to the other clusters, expect a positive effect of the use of straw pellets on the sustainability of biogas production (μ = 3.53, σ = 0.867). With regard to substrates and digestate management, the biogas yield of straw pellets compared to silage maize, is assessed more positively by cluster C than by the other clusters, at a statistically significant level (μ = 3.36, σ = 1.171). A slightly positive rating is also observed for the expected reduced digestate production and the resulting lower transport costs (μ = 3.18, σ = 1.005). The effort required to use straw pellets in biogas plants tends to increase according to operators in cluster C but less than expected by operators in the other clusters (see Table 4).

Cluster D, "forward-looking hesitators", also has a rather positive intention towards the use of straw pellets in biogas production but less pronounced than cluster D. They are willing to test straw pellets (μ = 3.22, σ = 0.866) and do not generally refuse their use (μ = 2.59, σ = 0.927) (factor 1). The mean value of factor 2 "use behaviour" for cluster D shows the highest expression among all clusters. Statistically significant differences are observed for each of the four single statements mentioned in this factor. Nevertheless, also in cluster D, a low level of approval can be determined with mean values between μ = 1.18 and μ = 2.08. The willingness to pay for straw pellets is comparably high at 49.97 €/t, while the willingness to pay with information on the fermentation properties of straw pellets is 56.67 €/t. Both values are at a similar level to clusters B and C. The innovativeness is at a comparable level to cluster C, with a statistically significant higher innovativeness compared to cluster A as well. A slightly higher mean value can be observed for the statement "I attach great importance to being innovative quickly, knowing that this can lead to disappointment" (μ = 3.43, σ = 0.835). Biogas plant operators of cluster D have a higher risk aversion than those in cluster C, but lower than those in cluster A. This observation stems from the statistically significant difference in the mean values between cluster A and clusters C and D for the statement, "The risk of using straw pellets is too high for me" (μ = 2.46, σ = 0.803). Regarding the social environment mean values around the value of three are observed for cluster D. For the same cluster, the mean value for the statement "The agricultural advice in my region is very helpful in the introduction of new input substrates in biogas production" (μ = 2.65, σ = 1.086) is rather high compared to the other clusters. Similar observations are made for the statements on societal pressure. For example the statement "Conflicts with neighbours and village residents because of the biogas plant are part of my daily business" (μ = 2.65, σ = 1.056) shows a slightly higher value for cluster D than for the other clusters. Cluster D contains with 8.3% the greatest share of plant operators who gathered prior experiences with using straw pellets for biogas production. This is consistent with 27% of the cluster D members signalling previous involvement with this topic. The self-assessed knowledge shows, with an average mean value of 2.43 the highest value in comparison to the other three clusters. Cluster D operators rate the economic characteristics more positively than operators in cluster A, but more negatively than operators in cluster C. Compared to them, operators in cluster D are less convinced that the use of pellets brings more benefits than costs (μ = 3.14, σ = 0.673) and that this offers economic advantages their biogas plants in general (μ = 2.86, σ = 0.787). Regarding the substrate management, cluster D operators expect less fermentation residue when using straw pellets as biogas substrate, which could lead to lower transport costs (μ = 3.22, σ = 0.821). The biogas yield from straw pellets is expected to be relatively lower by cluster D than by clusters B and C. No clear tendencies are discernible in the case of expected effort for the use of straw pellets, although it is remarkable that an increase in own power consumption is assumed by all four clusters (see Table 4).

The comparison of the four clusters with regard to the sociodemographic and farm characteristics show only a few statistically significant differences. In terms of age and gender, no statistically significant differences between the four clusters are observed. While the average age is very similar across all clusters, the share of women plant operators is extremely low and therefore not statistically assessable. In terms of the general educational level, captured by the highest general school-leaving qualification, only in cluster D no operator indicated a lower secondary school-leaving qualification, while the proportion of operators with higher secondary school-leaving or more advanced qualification is with approx. 95% (approx. 5% indicated "others") the highest of all clusters. In terms of vocational training, the share of cluster B operators with practice-oriented qualifications, such as a two-year vocational diploma, is greater than 50%. Cluster A contains a comparatively great share of operators with agricultural training (7.69%). The share of operators with university degrees in the agricultural domain is above 30% in all clusters, while cluster D shows with 48.65% the greatest share. Plant operators' overall experience in biogas production is very similar across all four clusters and varies between 12.62 and 12.88 years (see Table 5). A total of 76% of the sample runs arable farming activities in parallel to the biogas production, with only minor variations across clusters. Many biogas plant operators are also active in other renewable energy sectors besides biogas production without significant differences between the clusters. The share of agricultural contracting varies between 14% and 30%, with no statistically significant differences between the four clusters. Regarding the livestock production, a statistically significant difference in dairy farming can be observed between cluster A (high share of dairy cattle) and cluster C (low share of dairy cattle).

The regional distribution of biogas plants in the individual clusters is similar. Most of the biogas plants in the sample are mainly allocated in the north-west region of Germany. A share of one-quarter to one-third of the plants are assigned to the southern region of Germany. The share of plants located in eastern Germany varies between 10.26% and 21.62% across clusters. Statistically significant differences between the clusters are not observed in the EEG funding, but in the size of the biogas plant. While the operators of cluster A represent a statistically significant higher number of biogas plants with a rated electricity production capacity of less than 150 kW compared to clusters B and D, cluster D contains an above-average share of operators running plants with a nominal output of over 1000 kW. The higher proportion of biogas plants with a low production capacity in cluster A is also reflected by the comparatively lower average of the rated electricity production capacity. The storage capacity for digestate varies only slightly between 7.75 and 8.18 months across the clusters. The mass-related substrate shares of slurry and farm manure amounts to 47.00% in cluster A, which differs on a statistically significant level from cluster C with a share of 35.25%. The share lies around 38% for both cluster B and D.

5. Discussion

Separated by "management behaviour", "social environment", "sociodemographic characteristics" and "farm characteristics", the clusters are discussed as follows.

Management behaviour: Differences between the clusters can be observed in particular for the plant operator's management behaviour. Above all, perceived risk and innovativeness demarcate the clusters. Both, plant operators with higher risk aversion (cluster A) and operators with a lower risk aversion (cluster C) are found in this study. This confirms the observation of Steinhorst et al. (2015) that biogas plant operators can be classified into different risk types. It can be interpreted that more risk-taking operators (cluster C) use higher proportions of plant substrates, with approx. 47.6% maize (35.3% manure and slurry), than risk-averse operators in cluster A, with approx. 35.7% maize (47% manure and slurry) [59]. Among biogas plant operators a greater risk-taking tendency is accompanied with early adoption of innovations, as shown in past studies with farm managers by Schaper et al. (2010) and Emmann et al. (2013) [54,60]. Straw processed to pellets, as a rather new form of biogas substrate, is being used on farm currently by only two plant operators (one operator each belonging to cluster B and C). Seven respondents had already used straw pellets in the past, of which three are assigned to cluster D. These results indicate plant operators overall lower interest in the use of straw pellets in biogas production. Cluster B and also cluster A operators have almost not dealt with the topic of the fermentation of straw pellets at all before participating in the survey. In contrast, almost twice as many operators in clusters C and D have already dealt with this topic, signalling a greater intention to use straw pellets in biogas plants.

The comparison of the willingness to pay with and without information on the fermentation of straw pellets in biogas plants indicates that the additional information leads to an increase of 42.2% by cluster A, 39.2% by cluster B and 29.7% by cluster C. For cluster D (the group with highest involvement), the increase rate lies only at 13.5%. Similar disproportionately high effects are observed when giving additional information to people who have less involvement in the willingness to pay in consumer context [115]. The greater level of self-assessed knowledge about straw pellet fermentation goes hand-in-hand with the involvement cluster D operators show. Cluster C, which has an even greater involvement than cluster D, has a lower knowledge rate and is on the same level as cluster A. This could be related to the rather negative assessment of the advisory service availability by cluster C. Cluster B has the lowest involvement rate and lowest knowledge rate, which confirms the low interest of these operators in straw pellet fermentation. That business decision maker's lack of knowledge goes along with a higher risk perception, as assumed by Padel (2002), is not indicated by this study [116]. The differences in dealing with the topic of straw pellets, as well as the generation of knowledge about it, may also be related to the respective characteristics of the biogas plants and the changing legal frameworks respectively. In particular, the maize cap shows that this is less of a problem for operators in clusters A and B than for cluster C. In addition, more innovative plant operators manage imponderability of e.g. innovation complexity or lack of performance because they are focused on the long-term benefits of the innovation [117,118].

Social environment: The social environment serves to distinguish the clusters. Plant operators with a higher intention to use straw pellets (factor 1) are more convinced that this substrate alternative would improve the image of biogas production and are supported by their family members (clusters C and D). Likewise, the disagreement of cluster A operators towards the statements that the use of straw pellets improves the overall image of biogas production and that other biogas plant operators would favour the use of straw pellets for biogas production, go along with a low intention to use (factor 1) and less use behaviour (factor 2). Based on that observation, a strong effect of family members and neighbouring farmers on the decision-making is evident also for biogas plant operators [38]. Societal pressure plays an equally subordinate role for biogas plant operators in this study. Overall, it is agreed that the societal acceptance of biogas production has decreased over the last ten years, but no statistically significant differences are found with regard to the intention to use straw pellets. The availability of biogas advice, which can support new substrates such as straw pellets, is rated as rather low overall. Especially cluster A, having the lowest intention and use behaviour with regard to straw pellets, shows also the lowest mean values for the perceived availability of corresponding advisory services. This is in line with the existing literature, which indicates that the acceptance of straw pellets decreases with a low availability and confidence in advisory services [69–71].

Characteristics of the innovation: A clear distinction between the clusters can be made based on how plant operators estimate the economic performance of straw pellets for biogas production. This observation is not surprising, as economic aspects are often among the most important criteria in innovation adoption. Especially in the field of substrates for biogas production, the profitability of a new substrate, such as straw pellets, can have a great influence on the profitability of the entire biogas plant, since the substrate costs account for about 50% of the total costs of biogas production [26,119]. The (additional) effort that could result from the use of straw pellets in biogas production is estimated similarly by all groups, with cluster A indicating the highest and cluster C the lowest effort. The mean values of the six considered statements for "expected effort" are all close to the value of three ("neither agree nor disagree"), which signals uncertainty or a lack of knowledge. It is remarkable that across all the clusters, a higher own power consumption and increasing agitator running times are expected, while no major changes are expected in the labour input due to the use of straw pellets. Especially an increase in own power consumption can result in less overall profitability of the biogas plant [120,121].

Sociodemographic characteristics: The differences between the clusters in intention to use and use behaviour cannot be associated to the sociodemographic differences. Cluster C, which is characterised by a greater willingness to innovate and take risks, is not younger in average age, contrary to what has often been stated in the literature [39,73,76]. Similarly, cluster A, which has been characterised as less innovative and risk-averse, is on average not older than the other groups. The differences in gender cannot be adequately assessed due to the dominant proportion of men participants being around 97% of the total sample. Distinctions in the degree of general education and vocational qualification among the clusters are not clearly confirmed in this study. While the proportion of operators with an agricultural training is greater in cluster A, the proportion of operators with an agricultural university degree is greater in cluster D. The work experience in biogas production is almost the same in all groups. In addition to biogas production, the operators run other renewable energy production, arable farming and agricultural animal husbandry. While a comparatively high proportion of farmers in cluster A are engaged in dairy farming, this is statistically significantly lower in cluster C. Smaller biogas plants below 150 kW, which are fed with higher shares of manure and slurry and are predominant in cluster A, are less affected by the legal framework (e.g. EEG or RED 2) mentioned in the introduction due to the lower share of cultivated biogas substrates. Accordingly, for those plants there is less need to replace renewable raw materials such as silage corn, which is reflected in a low intention to use straw pellets as a sustainable future substrate.

Farm characteristics: Clusters B, C and D are very similar to each other in the average of the rated power of the biogas plants, but cluster D has a significantly higher proportion of plants with more than 1000 kW of electrical power at around 27%. This observation indicates that larger biogas plants are more willing to innovate and thus the intention and planning behaviour to use straw pellets in the biogas plant increases [42,78,82,94]. The digestate storage capacity varies only little and can therefore not contribute to the differentiation of clusters in this study. The expectation to reduce the amount of fermentation residue, seems unrelated to the intention to use straw pellet use against the background of the new fertiliser regulation, which requires a storage volume of at least nine months for landless farms (which also includes biogas plants) at present [27,122]. This is additionally confirmed by the fact that the statement, "Due to the low amount of digestate produced when using straw pellets, the cost of transporting digestate is reduced", only shows a slight agreement by clusters C and D. The geographical distribution, examined on the basis of the three regions, north-west, south and east of Germany, shows little differences between the clusters. The proportion of plants from the southern region is slightly higher in cluster A. This may indicate that those are smaller biogas plants or plants with lower average rated output [2]. A closer look at the electricity remuneration of the plants does not show any statistically significant differences in the corresponding EEG. Still the majority of the plants are operated according to the EEG 2009 and EEG 2004, which means that the first funding period for most of the biogas plants in the sample of this study ends between 2024 and 2031, as also predicted by the DBFZ for the development of biogas production in Germany [123]. Therefore, plant operators may not (yet) feel urgency to think about changing the input substrates as there is still some time left until e.g. the maize cap applies to their plants.

Finally, the results show that the knowledge about fermentation of straw pellets is independent of the level of education and quite low. To close this knowledge gap on the use and fermentation of straw pellets, more information and advisory services need to be provided. Thus, a barrier to use straw pellets is a rapidly developing but unsatisfied need for knowledge and information on straw pellet fermentation by plant operators [90,116,124]. This goes along with knowledge gaps of other stakeholders, such as local advisory institutions [90,91].

Cluster C, which contains a higher share of larger biogas plants fermenting a moderate share of slurry, show similarities to both "innovators" and "early adopters" according to Rogers' innovation diffusion theory [46]. Operators in this cluster are highly innovative and less risk-averse and show a higher acceptance based on the intention to use straw pellets. In addition, they mentioned a relatively high willingness to test straw pellets in their biogas plant. If it succeeds that a first group, such as cluster C, operators use straw pellets as a substrate in their biogas plant, they can help disseminate the new technology to other plant operators [46]. If more cluster C plant operators are able to adopt the new technology themselves with the help of additional information and advice and apply it in their local environment, the potential for successful and lasting adoption increases [125]. Those operators are important for convincing other professional colleagues and sharing similarities with the "early majority" according to Rogers' innovation diffusion theory, via face-to-face communication about their experiences with using straw pellets [46]. Clusters C and D should also be the preferred target groups for advisors and researchers regarding pilot projects and field tests on biogas plants [126].

Besides that, providing subsidies or financial incentives in the context of policy measures can help to reduce the risk of first-time use of straw pellets. This can lead to a higher intention to use, especially for groups that have a slight tendency towards risk aversion and are still hesitant, such as the potential "early majority" in cluster D [127,128]. Finally, plant operators in cluster B and potentially also some from cluster A will join the community of straw pellet users later as they might be "late majority" or "laggards" respectively, in line with Rogers' innovation diffusion theory [46].

Similar to most of the non-experimental studies, this study has some limitations that should be considered while interpreting the results. Compared to the population of biogas plant operators/biogas plants, this study is with a sample of 309 plant operators not fully representative. While biogas plants from Bavaria are underrepresented, operators from Lower Saxony are overrepresented [2]. Furthermore, more operators of larger biogas plants participated than of smaller ones in the survey. The format of the online survey also comes with certain limitations. On the one hand, it is easy to implement and realise, on the other hand, representativeness can be limited due to differences in internet use habits among certain segments of the population. Women, elderly persons, and persons with low education use the internet less frequently than men, younger persons, and persons with higher education [129,130]. Since biogas plants are usually monitored online, this study assumes a smaller effect in this respect. Another disadvantage of online surveys is that the response rate cannot be determined because there is no information available on how many people received the link via the various distribution channels. Furthermore, the occurrence of high standard deviations within the results indicates that the answers of plant operators also differ within clusters. Finally, the nomenclature of the clusters was created by the authors and cannot be considered as generally binding.

6. Conclusions and Implications

Biogas producers in Germany are facing sustainability challenges since the end of the first funding period of the EEG. Due to changes in the legal framework, pressure increases to replace previously used renewable raw materials with more sustainable alternative substrates. A new innovative substrate alternative is cereal straw in the form of pellets. Although initial studies have shown that straw pellets generally have good fermentation properties, they are currently hardly used in biogas production. Previous studies in agricultural research have shown that farm managers behave non-homogeneously in their decision behaviour and can be divided into groups regarding their acceptance and the time they need to successfully adopt innovative practices and technologies. Therefore, the research question of this study was how biogas plant operators in Germany can be categorised according to their intention to use straw pellets as innovative and sustainable substrate alternative. To answer this question, we analysed a dataset from 309 biogas plant operators with regard to their intention to use straw pellets as an innovative and sustainable substrate alternative in their biogas plant. Based on the factor and subsequently conducted cluster analysis, four clusters are identified: **Cluster A "risk-averse rejectors", cluster B "reluctant majority", cluster C "risk-taking acceptors"** and **cluster D "forward-looking hesitators"**. Cluster A, "risk-averse rejectors", is characterised by a very low intention to use straw pellets in biogas production combined with a relatively high risk-aversion. Cluster B, "reluctant majority", do not have a clear position regarding the utilisation of straw pellets in their biogas plant. Also, no clear tendencies are discernible in the characterisation of personal traits either. Cluster C, "risk-taking acceptors", shows a strong intention to use straw pellets. In particular, a low propensity to take risks and a high willingness to innovate stand out. Cluster D, "forward-looking hesitators", demonstrates concreter ideas on future straw pellet usage with a less pronounced inclination to risk and innovation.

The characterisation of the clusters was completed by focusing on *management behaviour, social environment, characteristics of the innovation, sociodemographic* and *farm characteristics*. The management behaviour differs regarding willingness to innovate, perceived risk and social environment. In addition, straw pellets as a biogas substrate are assessed very differently by the clusters with regard to economic performance and sustainability. No significant differences were found between the clusters in the socio-demographic characteristics while significant differences could be found in the farm activities besides biogas production, size of the plant (according to rated power output), the proportion of manure/slurry and silage maize. The level of knowledge on the fermentation characteristics of straw pellets is similar across clusters at a low level.

In order to expand the use of straw pellets in biogas plants, the following implications are drawn:

- Improve biogas plant operators' knowledge of straw pellet fermentation by providing information and (official) advisory services.
- Support plant operators in developing a higher intention to use straw pellets (cluster C and cluster D) to test them on their biogas plant. Pilot projects supervised by research institutes or practical trials on biogas plants could be successful to increase the knowledge about straw pellet use for biogas production among potential early adopters and early majority.

- Build regional working groups with biogas plant operators who intend to use straw pellets and other innovative and sustainable substrate alternatives. Official and private advisory service, as well as applied research institutions, could support as initiators [80].
- Provide financial incentives via the electricity tariff or special support programmes to reduce plant operators' economic risks of using innovative and sustainable substrate alternatives such as straw pellets [127]. Policymakers should act here and be supported by biogas associations as advisors in development of public funding programs.

Further research should be conducted regarding the behavioural intention to use straw pellets and employing structural equation modelling to investigate complex relations between acceptance variables. In addition, the profitability and fermentation characteristics should be further researched for generating the integral knowledge on the fermentation of straw pellets.

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Appendix A

Table A1. Descriptive statistics corresponding to Table 2.

Variables	Mean Values (σ)	Strongly Disagree	Tend to Disagree	Neither Agree nor Disagree	Tend to Agree	Strongly Agree
Intention to use straw pellets						
Straw pellets are a real substrate alternative for me	2.56 (0.992)	48 (15.7%)	98 (32.1%)	103 (33.8%)	52 (17.0%)	4 (1.3%)
I think about testing smaller quantities of straw pellets in my biogas plant.	2.72 1.148	52 (17.0%)	87 (28.5%)	70 (23.3%)	85 (27.9%)	11 (3.6%)
I intend to buy straw pellets as input substrate for my biogas plant in the near future.	1.98 0.887	99 (32.5%)	134 (43.9%)	51 (16.7%)	20 (6.6%)	1 (0.3%)
I expect to use straw pellets as an input substrate in my biogas plant very soon.	2.2 0.914	68 (22.3%)	141 (46.2%)	67 (22%)	26 (8.5%)	3 (1.0%)
The use of straw pellets in my biogas plant is not an option for the time being.	3.19 1.199	27 (8.9%)	68 (22.3%)	76 (24.9%)	88 (28.9%)	46 (15.1%)
Use behaviour						
I am currently applying for planning permission for my own stationary pelleting plant for my biogas plant.	1.09 0.289	277 (90.8%)	28 (9.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
I am growing less maize in the current marketing year, as I have firmly planned straw pellets as an input substrate from the summer onwards.	1.19 0.469	255 (83.6%)	44 (14.4%)	4 (1.3%)	2 (0.7%)	0 (0.0%)
I have grown more grain for the harvest 2021 so that the straw can be pelleted for the biogas plant.	1.2 0.505	253 (83.0%)	45 (14.8%)	5 (1.6%)	1 (0.3%)	1 (0.3%)
I have already bought or stored straw pellets for biogas production to feed them in the near future.	1.18 0.559	265 (86.9%)	32 (10.5%)	4 (1.3%)	1 (0.3%)	3 (1.0%)

All statements were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". *n* = 305.

Table A2. Descriptive statistics corresponding to Table 3.

Variables	Mean Values (σ)	Strongly Disagree	Tend to Disagree	Neither Agree nor Disagree	Tend to Agree	Strongly Agree
Willingness to pay and voluntariness of use						
Willingness to pay for straw pellets as biogas substrate (freely queried) (€/t)	40.52 (36.6)	No Likert-scale used.				
Willingness to pay for straw pellets as biogas substrate (with information) (€/t)	52.29 (30.04)					
I will only use residual materials, such as straw pellets, when I am obliged to do so.	2.58 (1.189)	55 (18.0%)	116 (38.0%)	59 (19.3%)	51 (16.7%)	24 (7.9%)
Innovativeness						
I attach great importance to being innovative quickly, knowing that this can lead to disappointment.	3.11 (0.969)	11 (3.6%)	75 (24.6%)	109 (35.7%)	90 (29.5%)	20 (6.6%)
I am interested in new production processes and technologies.	4.09 (0.670)	2 (0.7%)	3 (1.0%)	35 (11.5%)	191 (62.6%)	74 (24.3%)
In my circle of biogas plant operators/colleagues, I am usually the first to try out new things on my farm.	3.01 (0.942)	10 (3.3%)	88 (28.9%)	110 (36.1%)	82 (26.9%)	15 (4.9%)
When I hear about new substrate alternatives, I immediately think about how I could use them out on my biogas plant.	3.22 (1.024)	14 (4.6%)	64 (21.0%)	94 (30.8%)	106 (34.8%)	27 (8.9%)
Perceived Risk						
The risk of using straw pellets is too high for me.	2.46 (0.935)	34 (11.1%)	149 (48.9%)	79 (25.9%)	34 (11.1%)	9 (3.0%
Safety is important to me, so I avoid risks.	3 (0.868)	8 (2.6%)	83 (27.2%)	124 (40.7%)	82 (26.9%)	8 (2.6%)
I avoid risky decisions, especially in the biogas operating branch.	2.9 (0.964)	11 (3.6%)	114 (37.4%)	83 (27.2%)	87 (28.5%)	10 (3.3%)
Social environment						
My family environment would support trying alternative substrates, such as straw pellets, in my biogas plant.	3.28 (1.005)	15 (4.9%)	53 (17.4%)	94 (3.8%)	118 (38.7%)	25 (8.2%)
Friendly biogas plant operators advocate the use of alternative substrates, such as straw pellets.	2.92 (0.930)	19 (6.2%)	80 (26.2%)	121 (39.7%)	77 (25.2%)	8 (2.6%)
By using straw pellets, I can improve the image of biogas production in the region.	3.04 (1.049)	26 (8.5%)	68 (22.3%)	93 (30.5%)	103 (33.8%)	15 (4.9%)
The agricultural advice in my region is very helpful in the introduction of new input substrates in biogas production.	2.32 (1.043)	75 (24.6%)	108 (35.4%)	75 (24.6%)	42 13.8	5 (1.6%)
Local advice will support me in the use of straw pellets.	2.79 (1.013)	30 (9.8%)	93 (30.5%)	103 (33.8%)	68 (22.3%)	11 (3.6%)
Societal pressure						
As a biogas plant operator, I am increasingly exposed to public criticism.	2.99 (1.133)	30 (9.8%)	86 (28.2%)	68 (22.3%)	100 (32.8%)	21 (6.9%)
Acceptance of biogas production by the society has declined sharply in the last ten years.	3.38 (1.054)	8 (2.6%)	64 (21.0%)	83 (27.2%)	105 (34.4%)	45 (14.8%)
Conflicts with neighbours and village residents because of the biogas plant (transport volume, noise, maize cultivation) are part of my daily business.	2.22 (0.993)	71 (23.3%)	142 (46.6%)	55 (18.0%)	29 (9.5%)	8 (2.6%)
Prior knowledge and involvement						
Self-evaluated knowledge on pellet usage in biogas plants [1]	2.15 (0.910)	80 (26.2%)	122 (40.0%)	81 (26.6%)	20 (6.6%)	2 (0.7%)
I have the necessary knowledge to use straw pellets in my biogas plant.	2.72 (1.240)	55 (18.0%)	96 (31.5%)	60 (19.7%)	67 (22.0%)	27 (8.9%)

All statements were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree" except [1] measured as very low/low/medium/high/very high. n = 305.

Table A3. Descriptive statistics corresponding to Table 4.

Variables	Mean Values (σ)	Strongly Disagree	Tend to Disagree	Neither Agree Nor Disagree	Tend to Agree	Strongly Agree
(Economic) Performance						
I am convinced that the use of straw pellets in biogas plants is worthwhile.	2.8 (0.817)	16 (5.2%)	90 (29.5%)	138 (45.2%)	61 (20.0%)	0 (0.0%)
I am convinced that the use of straw pellets in the biogas plant brings more benefits than (additional) costs.	2.85 (0.872)	21 (6.9%)	77 (25.2%)	136 (44.6%)	69 (22.6%)	2 (0.7%)
The use of straw pellets offers my biogas plant economic advantages.	2.69 (0.861)	25 (8.2%)	99 (32.5%)	128 (42.0%)	52 (17.0%)	1 (0.3%)
Straw pellets are far too expensive compared with other substrates.	3.34 (0.766)	0 (0.0%)	36 (11.8%)	148 (48.5%)	102 (33.4%)	19 (6.2%)
With straw pellets, the electricity production costs per kwh are more favourable than with other substrates.	2.6 (0.754)	16 (5.2%)	123 (40.3%)	132 43.3	34 (11.1%)	0 (0.0%)
The financial cost of transporting and producing straw pellets is higher than the fermentation benefit.	3.23 (0.896)	6 (2.0%)	57 (18.7%)	123 40.3	99 (32.5%)	20 (6.6%)
The use of straw pellets increases the sustainability of biogas production.	3.15 (0.982)	15 (4.9%)	67 (22.0%)	95 31.1	113 (37.0%)	15 (4.9%)
Advantages in substrate and digestate management						
The biogas yield per ton of fresh mass is higher than from silage maize.	3.01 1.219	26 (8.5%)	102 (33.4%)	63 (20.7%)	70 (23.0%)	44 (14.4%)
Due to the low amount of digestate produced when using straw pellets, the cost of transporting digestate is reduced.	3.18 (0.909)	14 (4.6%)	55 (18.0%)	104 (34.1%)	126 (41.3%)	6 (2.0%)
Expected Effort						
The biogas plant's own power consumption will increase due to the use of straw pellets.	3.36 (0.974)	8 (2.6%)	63 (20.7%)	67 (22.0%)	145 (47.5%)	22 (7.2%)
The amount of work required to rectify faults will increase considerably with the fermentation of straw pellets.	2.71 (0.943)	20 (6.6%)	123 (40.3%)	94 (30.8%)	60 (19.7%)	8 (2.6%)
The agitator running times and intervals must be increased for straw pellet use.	3.52 (0.967)	8 (2.6%)	42 (13.8%)	77 (25.2%)	140 (45.9%)	38 (12.5%)
To be able to use straw pellets in my biogas plant, I need additional equipment for the substrate processing.	2.66 (1.14)	37 (12.1%)	136 (44.6%)	48 (15.7%)	63 (20.7%)	21 (6.9%)
The use of straw pellets increases the amount of work required for daily control work.	2.82 (0.954)	16 (5.2%)	115 (37.7%)	88 (28.9%)	79 (25.9%)	7 (2.3%)

All statements were measured on a scale from 1 = "strongly disagree" to 5 = "strongly agree". *n* = 305.

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