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Where Are Poland's Agricultural Biogas Plants? Livestock Density and Municipal Context

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Abstract

Are agricultural biogas plants in Poland more common in municipalities with high livestock densities? We linked the October 2026 register of the National Support Centre for Agriculture with livestock data from the 2020 Agricultural Census and municipal characteristics from 2025. We mapped registered presence across 2479 municipalities and fitted logistic regression models to 2004 municipalities with complete data. Registered plants were more common at higher pig stocking densities: 18.4% of municipalities in the highest decile had a registry entry, compared with 7.6% in the estimation sample. For cattle, the upper-quartile share (7.8%) was close to the overall share, and cattle density was not statistically significant after adjustment for other municipal characteristics. Registered presence was also associated with larger municipal area and lower population density. Both quadratic and spline models indicated increasing predicted probabilities at higher pig densities, while the pattern at very low densities depended on model specification. Livestock maps can help identify areas for further assessment, but project decisions require evidence on collectible feedstock, supply across municipal boundaries, and site feasibility.

Keywords: agricultural biogas; renewable energy infrastructure; livestock stocking density; spatial distribution; municipalities; logistic regression; Poland

1. Introduction

Agricultural biogas production connects renewable energy generation with the management of agricultural organic materials. By converting livestock manure and other suitable substrates into biogas, anaerobic digestion can support local energy supply and the recovery of resources from agricultural production. Understanding where agricultural biogas plants are established is therefore relevant to the development of energy infrastructure and its relationship with the agricultural economy [1].

The spatial distribution of agricultural biogas plants raises questions about the relationship between feedstock availability and infrastructure deployment. Livestock production provides a potential source of substrates, but livestock abundance alone does not determine whether a municipality contains a biogas plant. Plant establishment may also depend on substrate collection and transport, investment conditions, access to infrastruc-

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ture, planning procedures, and local acceptance. Consequently, areas with substantial agricultural resources may differ in the extent to which these resources are associated with registered biogas infrastructure [1,2].

Scarlat et al. [1] estimated European manure-based biogas potential using livestock distribution, manure production, and collection possibilities. Their distinction between theoretical and collectible resources provides a basis for cautious use of livestock density as a resource indicator.

Ginda and Szyba [2] used DEMATEL to examine interrelated development factors for Polish agricultural biogas plants, including substrate availability, technology, energy prices, waste-management costs, population density, and spatial planning. These studies motivate considering resource indicators alongside institutional and settlement conditions.

Previous research has examined the spatial distribution of biogas infrastructure in Poland. Szymańska and Lewandowska [3] analysed plant types, installed capacity, and territorial differences, drawing on data covering agricultural, landfill and wastewater biogas plants. Their study combined mapping with correlation analysis and selected regression analyses, primarily at the municipal level. It provides a foundation for examining the relationship between biogas infrastructure and territorial socioeconomic characteristics.

Martinát et al. [4] examined the distribution and development of agricultural biogas plants in the Czech Republic using spatial and regression methods, including municipal plant presence. The present study extends this approach to Poland by considering cattle, pigs, and selected municipal characteristics together and comparing high livestock density with registered deployment.

Bartoli et al. [5] used a spatial partial-equilibrium framework for the Lubelskie region to examine plant number, size, and location under alternative incentive schemes. Their analysis explicitly links feedstock availability and transport to profitability, but estimates modelled development scenarios rather than the observed probability of municipal plant presence.

Plinke et al. [6] developed a GIS-based register of biogas plant sites in Lower Saxony, Germany, demonstrating how precise infrastructure records can support subsequent energy planning.

Sefeedpari et al. [7] estimated manure production, nutrient content, and bioenergy potential in Lubelskie using farm information aggregated to municipalities. Höhn et al. [8] used GIS to identify potential plant locations and capacities in southern Finland, considering biomass distribution and transport distances.

A complementary research stream examines the feasibility of particular locations. Bojesen et al. [9] combined spatial multicriteria evaluation with economic, environmental, and social considerations in four Danish municipalities. Metson et al. [10] incorporated transport costs, road capacity, housing distances, and land-use constraints in Swedish biogas siting analysis. The binding constraints differed between national and local assessments. Sahoo et al. [11] developed a GIS-based assessment of sustainable crop residues for optimal biogas siting, connecting spatially explicit resource assessment with location analysis. These approaches evaluate potential resources and candidate sites rather than explain the distribution of existing registered plants.

Investment and social research further qualifies the relationship between agricultural resources and deployment. Kochanek et al. [12] investigated Polish farmers' perceptions of benefits and risks of investing in biogas and their willingness to invest, with GIS supporting the spatial component of the research. Kusz et al. [13] analysed the economic efficiency of a dairy-farm biogas investment under alternative cash-flow assumptions. Chodkowska-Miszczuk et al. [14] examined public support, local relationships, and rural development in Central European peripheral regions. Together, these studies motivate an interpretation of municipal correlates within a wider investment and institutional context, rather than as sufficient conditions for plant establishment.

Feedstock composition also changes over time. Chodkowska-Miszczuk et al. [15] documented a shift in Polish anaerobic digestion towards a greater role for food-industry and municipal biowaste, associated with legal, financial, and market conditions. This evidence motivates including a food-processing indicator alongside livestock variables, while acknowledging that the number of registered processing businesses does not directly measure substrate flows. It also supports caution when combining census characteristics with a later snapshot of registered infrastructure.

The development of the Polish sector has been discussed over several stages. Igliński et al. [16] reviewed investment procedures, economic and environmental aspects, and biogas resources, while Chodkowska-Miszczuk and Szymańska [17] situated agricultural biogas within agricultural diversification. The later review by Igliński et al. [18] combined sector history and resource assessment with owner surveys concerning barriers and investment risk. These publications provide a temporal context for the present registry snapshot. Historical plant counts reported in them describe their respective observation periods and should not be treated as current totals or compared directly without checking registry coverage.

Oniszk-Popławska et al. [19] assessed long-term agricultural biogas development in Lubelskie, while Sliz-Szkliniarz and Vogt [20] evaluated manure and crop resources in Kujawsko-Pomorskie. Koryś et al. [21] reviewed biomass residues from the agri-food sector. These studies describe different feedstock sources and spatial conditions for their use.

The distinction remains relevant outside Poland. Ferrari et al. [22] analysed Italian livestock production in relation to nitrogen loading and biogas potential at several spatial levels. Feiz et al. [23] developed a framework for biogas site selection in Sweden that brings together resource, infrastructure, and stakeholder considerations. Siegrist et al. [24] assessed how techno-spatial restrictions affect energy generation potential from agricultural residues in Switzerland. These approaches connect agricultural geography to environmental management and energy use, but their dependent outcomes and decision settings differ from municipal infrastructure presence. They inform the interpretation of the municipal indicators without providing directly transferable coefficient estimates. Connecting these assessments to actual energy production also requires information on plant technology and energy users.

Institutional and financial evidence helps explain why favourable resource conditions may not be sufficient. A subsequent DEMATEL assessment by Ginda and Szyba [25] also addresses the development conditions of the Polish sector. Bednarek et al. [26] examined development barriers using an employee questionnaire in one enterprise; their findings provide organisational evidence rather than a representative national survey. Kusz et al. [27] investigated return on equity in operating Polish biogas plants, whereas Eder and Mahlberg [28] examined technical efficiency and subsidies in Austrian plants. These studies concern different stages of investment and operation and identify conditions that cannot be adequately represented by municipal revenue or a count of processing businesses.

Previous studies address resources, site selection, and investment conditions. A further task is to connect these perspectives to national patterns of existing agricultural biogas plants at the municipal level. This study combines presence regression with a descriptive comparison of deployment in high-livestock-density groups and the complete-case sample. Municipalities with high density and no KOWR entry are treated as candidates for subsequent resource and feasibility assessment, rather than as evidence of a measured investment deficit [1,7,19,20].

The aim is to examine associations between agricultural, spatial, and socioeconomic characteristics and registered agricultural biogas presence. Five questions guide the study: (1) Is presence associated with cattle and pig stocking density? (2) Is the pig density relationship nonlinear? (3) How are area, population density, food processing, own-source

revenue, and municipality type related to presence? (4) Do the main findings remain after including voivodeships? (5) How does registered presence in high-livestock-density groups compare with the overall sample, and does this depend on the density threshold?

2. Materials and Methods

2.1. Data Sources and Municipal Coverage

The study uses municipalities (gminas) as the units of analysis. The statistical base contains 2479 unique seven-digit TERYT identifiers: 302 urban, 718 urban–rural, and 1459 rural municipalities, consistent with the administrative division of 1 January 2025 [29]. Warsaw is represented once as a municipality; its districts are not separate observations. Agricultural biogas registry records were linked to municipal statistical data using these identifiers, which distinguish municipalities with identical names and different administrative types. The 2025 municipal base was used for linking source-year statistics; this should not be interpreted as a reconstruction of all historical boundaries.

Information on agricultural biogas plants was obtained from the register maintained by the National Support Centre for Agriculture (KOWR), dated 1 October 2026. Registry addresses were assigned to municipalities. The dependent variable takes the value of 1 when a municipality contains at least one assigned registry record and 0 otherwise. This variable indicates registered agricultural biogas plant presence; it does not represent the number of distinct physical installations or include all types of biogas facilities. In particular, the absence of a registry entry should not be interpreted as proof that no biogas microinstallation exists in a municipality.

Municipal explanatory variables were obtained from Statistics Poland's Local Data Bank and the Agricultural Census 2020. Census data were used to describe cattle and pig numbers and agricultural land area. These statistics are assigned according to the location of the agricultural holding's headquarters; therefore, they do not exclusively describe livestock and land physically located within municipal boundaries. Population, municipal area, food-processing business counts, and municipal own-source revenue refer to the 2025 annual statistics recorded in the compiled dataset.

The 2020 census provides an earlier structural baseline, not a measurement of livestock availability in 2026. Municipal livestock numbers, farming systems, and substrate supply may have changed during the intervening years. The 2025 covariates describe a more recent municipal context but may postdate construction of some registered plants. The analysis therefore concerns cross-sectional associations between observations from different years. It neither identifies conditions at the time of investment nor establishes temporal or causal effects. Harmonising administrative identifiers does not remove this temporal mismatch.

The national database contains 2479 municipalities, including 167 with registered agricultural biogas presence. An audit identified 76 urban–rural municipalities whose 2025 TERYT codes differed from their rural predecessor codes in the 2020 census. Correspondence was checked against official Statistics Poland administrative-change documents for 2021–2025, municipal names, and code prefixes. Census values were transferred only for verified predecessor–successor pairs; unavailable source values remained missing. This recovered 67 complete cases, including two municipalities with registered presence (Piekoszów and Mieścisko). The revised complete-case sample contains 2004 municipalities: 152 with presence and 1852 without it. The remaining 475 municipalities include 15 with registered presence. No missing values were replaced with zero or statistically imputed. This procedure corrects verified code mismatches, rather than reconstructing all historical boundaries; split or otherwise unresolved units were not assigned predecessor

values automatically. Documentation: official Statistics Poland administrative-change records for 2021–2025 (consulted 5 November 2026); verified pairs are listed in the TERYT audit workbook.

Each municipality is one observation, regardless of the number of assigned KOWR entries.

The revised sample retains 80.8% of municipalities and 91.0% of registered presence municipalities. Registered presence occurs in 15 of 475 excluded municipalities (3.2%) and 152 of 2004 included municipalities (7.6%). To assess sensitivity to missing cattle data, the same model excluding cattle was fitted to 2004 complete cases and to 2098 municipalities with the other required variables available (157 events). This comparison addresses exclusion associated with cattle data availability; it does not establish that all missing-data selection is harmless. Compared with municipalities in the estimation sample, excluded municipalities were more often urban (30.5% versus 7.8%), had a smaller median area (85 versus 116 km^2), and had a higher median population density (93.9 versus 59.0 inhabitants per km^2). These differences limit the generalisation of the regression findings to all Polish municipalities. The spatial coverage of the 2004 municipalities included in Model M3 is shown in Figure S1.

2.2. Definition of Variables

Cattle and pig stocking densities were calculated separately as the number of animals per 100 hectares of agricultural land. Food-processing business density was measured as the number of REGON entities classified under PKD Division 10 per 10,000 inhabitants. This measure describes registered business locations and serves as an indirect indicator of local food-processing activity; it does not measure processing capacity or the volume of substrates available for biogas production.

Population density was calculated as inhabitants per square kilometre. Municipal own-source revenue per capita was calculated by dividing annual own-source revenue by the population at the end of the year. Municipal area was expressed in square kilometres. Municipality type was represented by urban and urban–rural indicators, with rural municipalities as the reference category.

Cattle and pig stocking densities, food-processing business density, and population density were transformed using ln(1 + x), and municipal area using ln(x). Adding 1 retains observed zeros. Revenue per capita was expressed in thousands of PLN. Squared terms were calculated as squared deviations from the transformed-variable means in the original 1937 case sample. These fixed centring constants were retained after TERYT correction and in the sensitivity analyses to keep the coefficient parameterisation comparable. With both the linear term and intercept included, changing the centring constant would reparameterise the same quadratic curve. Table 1 defines the variables.

Table 1. Definition and measurement of model variables.

Variable	Measurement	Year	Model Form
Plant presence	At least one assigned KOWR record: 1; otherwise: 0	2026	Binary outcome
Cattle stocking density	Cattle per 100 ha agricultural land	2020	ln(1 + x)
Pig stocking density	Pigs per 100 ha agricultural land	2020	ln(1 + x)
Food-processing business density	REGON PKD 10 per 10,000 inhabitants	2025	ln(1 + x)
Own-source revenue per capita	PLN per inhabitant; year-end population	2025	x/1000
Population density	Inhabitants/km^2	2025	ln(1 + x)
Municipal area	km^2	2025	ln(x)
Municipality type	Urban, rural, urban–rural	2025 municipal base	Rural reference
Pig quadratic term	Squared centred ln(1 + pig density)	2020	M3 and M4

Voivodeship	Regional affiliation	2025 municipal base	Indicators in M4

Sources: KOWR and Statistics Poland. M2 additionally contains centred squared terms for all six continuous predictors.

Stocking density describes livestock intensity, while area and population density describe spatial and settlement conditions. Own-source revenue concerns local-government finances rather than funds available to an individual investor.

Coefficients for logged variables should not be read as the effect of adding one animal or resident. In the model containing squared pig density, the linear and squared terms must be interpreted together. The linear coefficient alone does not describe the full relationship.

2.3. Statistical Analysis

Binary logistic regression [30] was performed in JASP 0.19.3 [31], coding registered agricultural biogas presence as 1 and no entry as 0. The revised main model used 2004 municipalities and a rural municipality-type reference. All basic explanatory variables were retained, together with the centred quadratic pig density term. This analysis estimates conditional associations with registered presence, not the probability that a future investment will occur.

For municipality i, the modelled probability of a registered agricultural biogas plant is:

$$p_i = P(Y_i = 1 \mid X_i) = exp(\eta_i) / [1 + exp(\eta_i)] \quad (1)$$

Here, $Y_i = 1$ indicates at least one agricultural biogas plant recorded in the KOWR registry and $Y_i = 0$ indicates no entry. X_i denotes the included municipal characteristics, and η_i is the linear predictor. Thus, the model estimates the probability of registered presence conditional on these characteristics; it does not estimate the probability of a future investment.

Equations (2)–(5) define four specifications. M1 includes six continuous predictors and municipality type; M2 adds six centred squared terms; M3 retains only the additional pig quadratic term; and M4 adds voivodeship indicators to M3. The quadratic pig specification was identified during the exploratory analysis. All four models were estimated on the same revised sample after TERYT correction and compared using AIC and BIC.

$$M1: \eta_i = \alpha + \sum_{j=1}^{6} \beta_j x_{ij} + \delta_1 R_i + \delta_2 U_i \quad (2)$$

$$M2: \eta_i = \alpha + \sum_{j=1}^{6} \beta_j x_{ij} + \delta_1 R_i + \delta_2 U_i + \sum_{j=1}^{6} \gamma_j (x_{ij} - \mu_j)^2 \quad (3)$$

$$M3: \eta_i = \alpha + \sum_{j=1}^{6} \beta_j x_{ij} + \delta_1 R_i + \delta_2 U_i + \gamma_p (x_{ip} - \mu_p)^2 \quad (4)$$

$$M4: \eta_i = \alpha + \sum_{j=1}^{6} \beta_j x_{ij} + \delta_1 R_i + \delta_2 U_i + \gamma_p (x_{ip} - \mu_p)^2 + \sum_{r=1}^{15} \theta_r V_{ir} \quad (5)$$

The six predictors x_{ij} are cattle density, pig density, food-processing business density, own-source revenue per capita, population density, and area, transformed as in Table 1. The constants μ_j are the transformed-variable means from the original 1937 case sample; x_{ip} is transformed pig density. In the revised parameterisation, R_i denotes the urban indicator and U_i the urban–rural indicator; rural municipalities form the reference. V_{ir} denotes 15 voivodeship indicators with one reference region omitted. Intercepts and coefficients are estimated separately for each specification.

Models were compared using deviance, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) reported by JASP. Lower AIC and BIC favour a better balance between fit and model complexity; BIC imposes a stronger penalty for additional parameters at this sample size. The area under the receiver operating characteristic curve (AUC) measures discrimination between municipalities with and without registry entries. An AUC of 0.5 indicates chance-level discrimination and 1 indicates perfect discrimination. These measures describe performance in the estimation sample, rather

than independently validated predictive performance. Statistical significance was set at $p < 0.05$. The coefficient table reports estimates, standard errors, p-values, odds ratios, and their 95% confidence intervals as reported by JASP. For the quadratic pig density specification, exponentiated term coefficients must not be interpreted as a constant odds ratio for an increase in pig density. JASP variance inflation factors (VIFs) were used to assess overlap among explanatory variables.

Three sensitivity checks were performed in JASP. First, identical models without cattle were estimated on 2004 and 2098 municipalities. Second, the main model with cattle was refitted after excluding municipalities with zero pig density ($N = 1868$). Third, it was refitted after separately excluding urban municipalities ($N = 1847$), omitting the now-constant urban indicator. The last two exclusions were applied separately, not jointly. Fixed transformations and centring constants were retained. Coefficient patterns were compared across samples; AIC and BIC were not used to rank models fitted to different observations. Descriptive statistics and high-density tabulations were recalculated from the revised data separately from the regression estimates; no additional group-difference tests were performed. The quadratic minimum was calculated algebraically from rounded JASP coefficients, and is therefore approximate. To assess sensitivity to functional form, a natural cubic spline with three degrees of freedom replaced the linear and quadratic pig density terms in a separate logistic regression fitted in JASP. The sample (2004 municipalities) and the remaining covariates were unchanged. Knots were placed at the 5th, 35th, 65th, and 95th percentiles of log-transformed pig stocking density.

Residual spatial autocorrelation was assessed in GeoDa version 1.22.0.10 using global Moran's I [32] on the deviance residuals of M3. First-order queen contiguity weights were constructed for the estimation sample, and the reference distribution was generated using 9999 permutations. This is a global diagnostic, rather than a local indicator of spatial association [33].

2.4. Screening the Mismatch Between Livestock Density and Plant Presence

Supplementary tabulation used the 2004 complete cases. Cattle and pigs were considered separately. High density was defined at or above the third quartile (Q3) and, alternatively, the 90th percentile (P90). Quantiles were calculated on untransformed densities using linear interpolation. Equal-to-threshold observations were included. Species groups may overlap and were not combined into an energy indicator. Presence shares were compared descriptively with 152/2004 (7.6%). No group-difference significance tests were performed, and excluded municipalities were not classified.

2.5. Cartographic Presentation

The stocking density maps show stocking densities across the 2479 municipalities in the mapping dataset. Available values, including zeros, were grouped into five classes using Jenks natural breaks, calculated separately for pigs and cattle. Municipalities without stocking density data are shown in grey (381 for pigs and 128 for cattle). The maps combine 2020 Agricultural Census data with the KOWR registry snapshot of 1 October 2026.

3. Results

3.1. Spatial Distribution of Agricultural Biogas Plants

Registered agricultural biogas plants were present in 167 of the 2479 municipalities included in the mapping dataset (6.7%). Figure 1 shows their distribution across Poland. Figures 2 and 3 compare plant presence with pig and cattle stocking densities. Visual inspection indicates that registered plants occur across different stocking density classes. Areas with high cattle stocking densities do not consistently coincide with municipalities containing registered plants. These maps provide descriptive context and do not establish statistically significant associations.

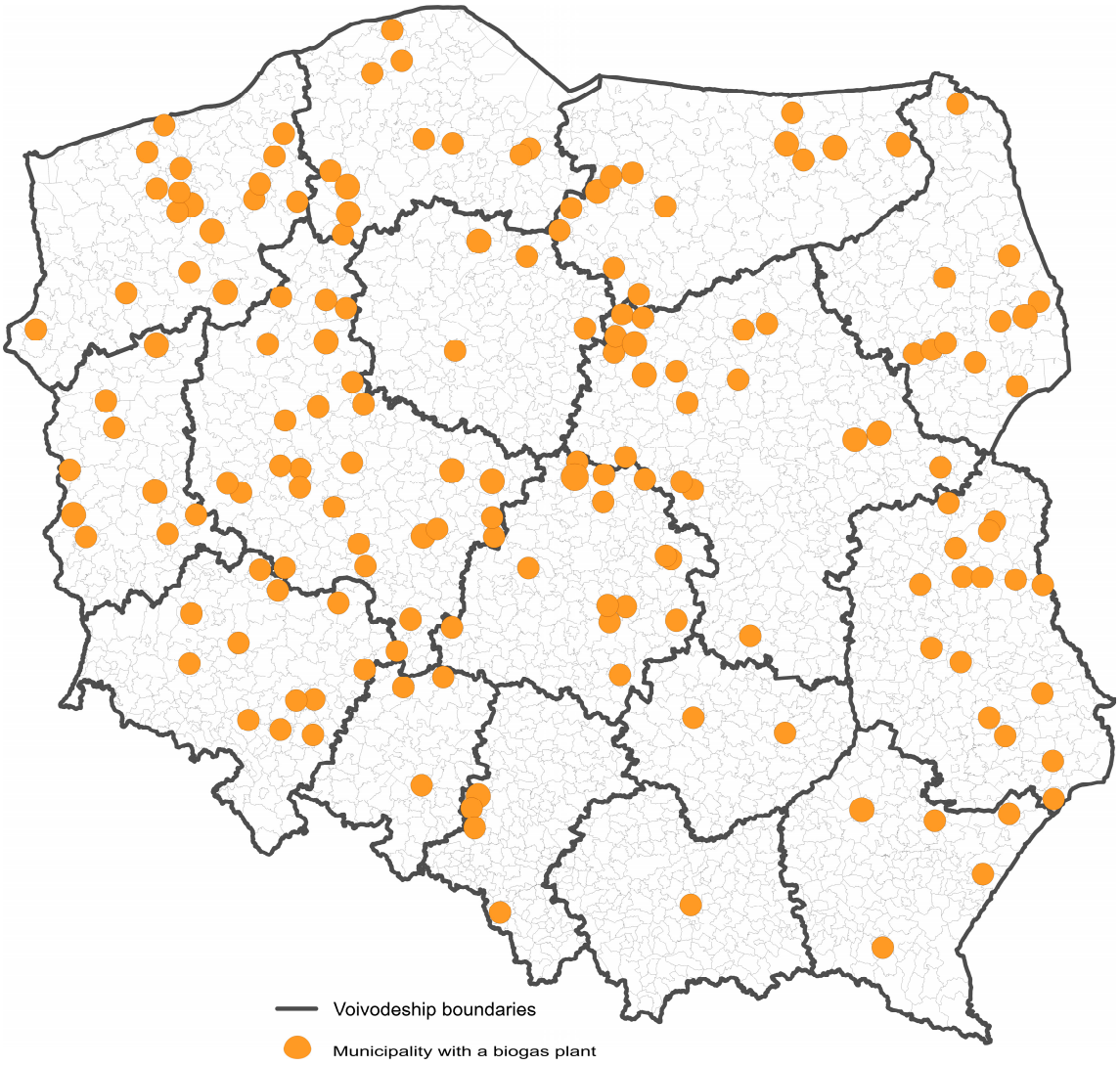


Figure 1. Municipalities with registered agricultural biogas plants in Poland. Orange symbols indicate municipalities with an agricultural biogas plant in the KOWR register, not exact installation locations. Source: KOWR register, 1 October 2026.

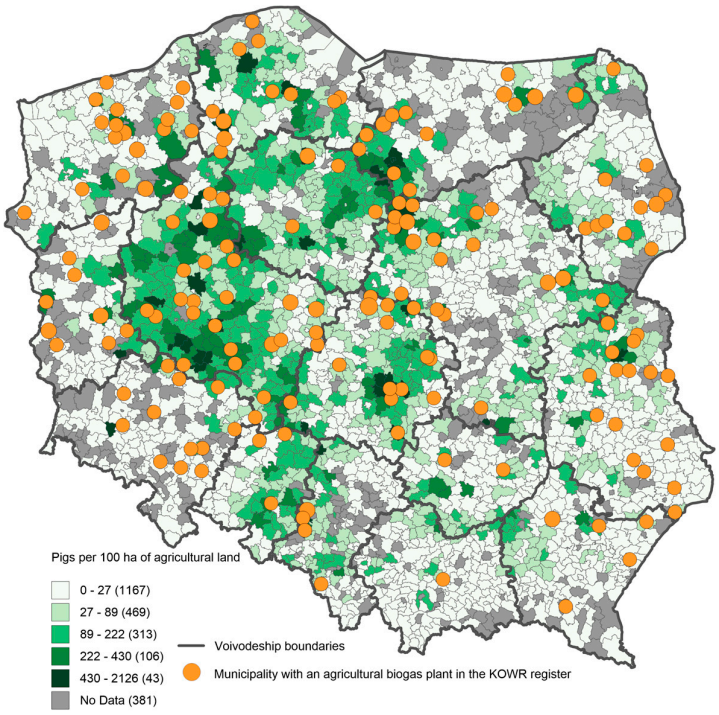


Figure 2. Pig stocking density and registered agricultural biogas plant presence in Polish municipalities. Grey shading indicates 381 municipalities without stocking density data. Orange symbols indicate municipalities with an agricultural biogas plant in the KOWR register. Sources: Statistics Poland, Agricultural Census 2020; KOWR register, 1 October 2026; GUGiK, State Register of Boundaries (PRG), 2025.

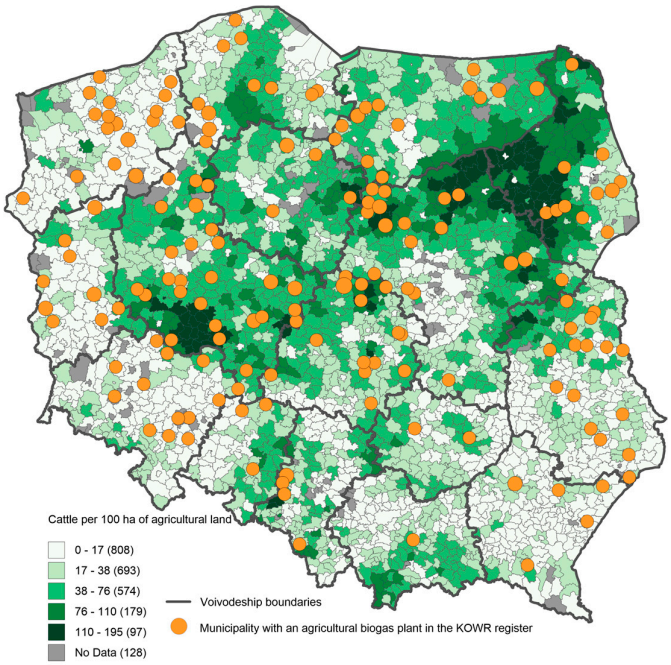


Figure 3. Cattle stocking density and registered agricultural biogas plant presence in Polish municipalities. Grey shading indicates 128 municipalities without stocking density data. Orange symbols indicate municipalities with an agricultural biogas plant in the KOWR register. Sources: Statistics Poland, Agricultural Census 2020; KOWR register, 1 October 2026; GUGiK, State Register of Boundaries (PRG), 2025.

Plant supply may involve neighbouring municipalities and other feedstock sources. Points on the maps therefore do not represent actual supply areas.

3.2. Descriptive Characteristics of the Regression Sample

Registered presence occurred in 152 of 2004 municipalities (7.6%). Table 2 summarises the revised sample before transformation. Means, sample standard deviations, medians, and quartiles describe the variation in municipal characteristics; they do not measure collectible feedstock quantities.

Table 2. Descriptive statistics for continuous explanatory variables.

Variable	Mean	SD	Median	Q1–Q3
Cattle per 100 ha	38.23	33.58	28.97	13.18–54.05
Pigs per 100 ha	69.17	139.89	21.36	3.81–80.59
Food-processing businesses per 10,000	9.47	6.70	8.30	5.25–12.21
Own-source revenue per capita, PLN	5154.41	1787.71	4862.39	4071.32–5816.46
Population density, inhabitants/km^2	158.71	338.19	59.00	38.96–109.10
Municipal area, km^2	130.92	75.29	116.00	84.00–161.00

N = 2004. Variables before transformation. SD: sample standard deviation; Q1 and Q3: first and third quartiles.

3.3. Model Comparison

Table 3 compares the four models fitted to the revised sample. M3 had the lowest AIC and BIC and was retained as the main specification. M4 had the lowest deviance and the highest in-sample AUC, but its 15 additional voivodeship parameters increased both information criteria relative to M3.

Table 3. Comparison of logistic regression models.

Model	Specification	Deviance	AIC	BIC	AUC
M1	Baseline	983.266	1001.266	1051.692	0.722
M2	Six quadratic terms	965.222	995.222	1079.265	0.736
M3	Pig quadratic term	972.901	992.901	1048.930	0.727
M4	M3 + voivodeships	946.071	996.071	1136.143	0.754

AIC: Akaike information criterion; BIC: Bayesian information criterion; AUC: area under the receiver operating characteristic curve. All models used 2004 municipalities with 152 events. AUC describes discrimination in the estimation sample and does not establish out-of-sample performance. Model labels refer to Equations (2)–(5).

3.4. Municipal Characteristics Associated with Plant Presence

Global Moran's I indicated weak positive spatial autocorrelation in the deviance residuals of M3 (I = 0.0289; GeoDa permutation pseudo-p = 0.0244). The diagnostic covered 1997 municipalities because GeoDa omitted seven municipalities without neighbours under the specified weights. All 2004 municipalities were retained in the estimation of M3.

The linear pig density coefficient was 0.219 (SE 0.054; $p < 0.001$), and its centred quadratic coefficient was 0.084 (SE 0.025; $p < 0.001$). The quadratic is convex on the log-odds scale, which does not make the entire probability curve convex. Larger area and lower population density were associated with higher odds of registered presence. Cattle density, food-processing business density, and own-source revenue were not significant at the 0.05 level. These results concern revised M3; the comparison with the regional specification is reported in Section 3.3.

With the fixed pig centring constant $\mu_p = 2.992519$, the minimum implied by rounded coefficients is $\exp(\mu_p - 0.219/(2 \times 0.084)) - 1$, approximately 4.41 pigs per 100 ha. There are 541 municipalities (27.0%) below this value: 82 urban, 142 urban–rural, and 317 rural. The fitted form permits a declining segment below the minimum and an increasing segment above it. This turning point is neither a technical requirement nor evidence that increasing livestock numbers reduces investment. Its uncertainty and the low-density segment require cautious interpretation.

Relative to rural municipalities, urban–rural municipalities had OR 1.541 (95% CI 1.045–2.272; $p = 0.029$). The urban contrast was imprecise (OR 3.353, 95% CI 0.921–12.204; $p = 0.066$). Choosing a rural reference changes the contrasts and their interpretation; it does not add urban events or by itself change fitted probabilities for an otherwise identical model.

Non-significant results for cattle, processing, and revenue do not demonstrate that these characteristics never matter. They mean that the fitted models did not provide sufficient evidence of an association with presence. Coefficient sizes should not be compared directly because the variables use different units and transformations.

3.5. Sensitivity Analyses

The pig quadratic coefficient was 0.086 ($p < 0.001$) in both cattle-omitting models, fitted to 2098 and 2004 municipalities. With cattle included, it was 0.096 ($p < 0.001$) after excluding zero-pig municipalities and 0.078 ($p = 0.003$) after excluding urban municipalities (Table 4). Corresponding AUC values were 0.733 and 0.732. These checks show that the quadratic association is not confined to zero-pig observations or urban municipalities. They do not establish causality, validate an investment threshold, or independently confirm the declining segment. Changing samples also altered some municipality-type contrasts. The spline specification had slightly lower deviance than M3 (971.890 versus 972.901), but higher AIC (993.890 versus 992.901) and BIC (1055.522 versus 1048.930). Both fitted curves increased at higher stocking densities. The spline did not reproduce the initial decline at very low densities implied by M3.

Table 4. Main model M3 and sensitivity refits with cattle included.

Variable	M3 B (SE)	M3 OR (95% CI)	*p*	Without Zero Pigs B (SE)	Without Urban B (SE)	*p* Without Urban
Intercept	−6.124 (1.408)	0.002 (<0.001–0.035)	<0.001	−5.999 (1.518)	−6.221 (1.610)	<0.001
Cattle ln(1 + x)	−0.118 (0.099)	0.889 (0.732–1.080)	0.235	−0.070 (0.104)	−0.118 (0.103)	0.253
Pigs ln(1 + x)	0.219 (0.054)	1.245 (1.119–1.384)	<0.001	0.189 (0.063)	0.243 (0.056)	<0.001
Food processing ln(1 + x)	0.098 (0.136)	1.103 (0.845–1.440)	0.471	0.077 (0.139)	0.106 (0.138)	0.440
Revenue PLN 1000	0.035 (0.051)	1.036 (0.937–1.145)	0.489	0.067 (0.052)	0.059 (0.051)	0.249
Population density ln(1 + x)	−0.487 (0.157)	0.615 (0.452–0.837)	0.002	−0.630 (0.178)	−0.597 (0.181)	<0.001
Area ln(x)	0.905 (0.198)	2.471 (1.678–3.640)	<0.001	0.947 (0.212)	0.967 (0.225)	<0.001
Urban	1.210 (0.659)	3.353 (0.921–12.204)	0.066	1.391 (0.800)	Omitted	—
Urban–rural	0.433 (0.198)	1.541 (1.045–2.272)	0.029	0.489 (0.205)	0.452 (0.205)	0.027
Pig centred square	0.084 (0.025)	1.087 (1.035–1.142)	<0.001	0.096 (0.029)	0.078 (0.026)	0.003
Voivodeship indicators	No	—	—	No	—	—

$N = 2004$; 152 events. B: coefficient; SE: standard error; OR: odds ratio; CI: confidence interval. Estimates and intervals are transcribed from JASP. Rural municipalities are the type reference. ORs for transformed predictors refer to one unit on the transformed scale. The two pig terms must be interpreted jointly; their separate ORs are not constant effects of an additional pig per 100 ha. The intercept lower CI bound is below 0.001, displayed as 0.000 by JASP. Sensitivity samples: $N = 1868$ without zero-pig municipalities; $N = 1847$ without urban municipalities. The pig quadratic *p*-value is <0.001 in the zero-pig exclusion model. Other sensitivity *p*-values and intervals are retained in the accompanying JASP reports.

3.6. Relationships Among Explanatory Variables

In revised M3, VIF values range from 1.104 to 2.063. Values for the urban and urban–rural indicators are 1.889 and 1.252. Rural reference coding therefore provides more directly interpretable contrasts for this study. VIF is a property of the predictor matrix and depends on coding; lower dummy-specific VIF values after reparameterisation should not be described as proof that the underlying information has increased. The sparse urban-event group still warrants caution.

3.7. High Livestock Stocking Density and Registered Biogas Presence

At Q3, the thresholds are 54.05 cattle and 80.59 pigs per 100 ha. Registered presence occurs in 39 of 501 high-cattle-density municipalities (7.8%) and 63 of 501 high-pig-density municipalities (12.6%), compared with 7.6% overall (Table 5). Species groups may overlap and must not be added.

Table 5. Registered presence in high-livestock-density groups within the revised 2004 municipality sample.

Species	Group	Density≥	Municipalities	With KOWR	Without KOWR (%)
Cattle	Q3	54.05	501	39	462 (92.2%)
Cattle	P90	84.20	201	20	181 (90.0%)
Pigs	Q3	80.59	501	63	438 (87.4%)
Pigs	P90	184.00	201	37	164 (81.6%)

Density in animals per 100 ha of agricultural land. Q3: third quartile; P90: 90th percentile. Sources: Agricultural Census 2020 and KOWR register dated 1 October 2026. Own calculations using complete cases.

At P90, presence occurs in 20 of 201 cattle-group municipalities (10.0%) and 37 of 201 pig-group municipalities (18.4%). These are descriptive comparisons. Large absence shares partly reflect the low overall prevalence of registered presence and do not establish disproportionate underinvestment.

4. Discussion

4.1. Agricultural Characteristics and Biogas Infrastructure

The geography of registered agricultural biogas plants does not simply mirror the geography of livestock production. High pig stocking density was associated with more frequent registry presence, whereas cattle density showed no equally clear pattern. Larger area and lower population density were also associated with presence, pointing to the relevance of the municipal setting. These patterns support using livestock density to identify areas for closer study and assessing actual feedstock supply over the wider area from which a plant can draw resources.

The pig density finding links infrastructure distribution with livestock production structure, but its quadratic form requires caution. It permits a decline at the lower end and an increase above the fitted minimum. A turning point inferred from an exploratory model is neither a technological threshold nor evidence that changes in livestock production cause changes in deployment. The spline sensitivity analysis indicates that the shape at low stocking densities depends on the functional form. The minimum implied by M3 should therefore not be interpreted as a robust threshold.

The non-significant cattle result does not question the suitability of cattle manure for biogas. Stocking density does not measure collectible manure, which Scarlat et al. [1] and Sefeedpari et al. [7] assessed. The dairy-farm investment study [13] demonstrates the importance of project assumptions. Municipal findings and individual investment assessments therefore address different stages of investigation.

The processing indicator counts REGON businesses without measuring their scale or residue volumes. Its non-significance does not imply that processing residues are unimportant. Koryś et al. [21] assessed residue resources and Chodkowska-Miszczuk et al. [15] examined actual feedstock changes. Such data would improve assessment of the relationship between processing and plant distribution. In the Polish context, a small number of large, specialised agro-industrial facilities may generate substantial, concentrated residue streams, while numerous small registered businesses may generate much smaller volumes. Such facility-level differences and deliveries across municipal boundaries are not captured by a count of PKD Division 10 entities per inhabitant; this measurement mismatch offers a possible explanation for the non-significant coefficient, rather than evidence that food-processing residues lack value for anaerobic co-digestion.

Differences between cattle and pig findings suggest a need to examine production organisation more closely. Similar density may occur with large concentrated herds or dispersed farms. Storage and collection arrangements may also differ. Polish regional assessments [7,19,20] and the Italian study [22] cover some of these resource conditions. The database lacks that information, so these remain possible explanations rather than established causes.

The nonlinear pig density relationship does not identify a minimum density for profitable investment. Such a threshold requires feedstock volumes and collection costs together with plant technology and size.

High-density groups without registry presence provide a screening perspective rather than a measured investment deficit. The cattle Q3 presence share is 7.8%, compared with 7.6% overall. Pig groups show presence shares of 12.6% at Q3 and 18.4% at P90. High density does not quantify collectible manure, and no entry does not show that feedstock is unused in neighbouring municipalities. Resource availability and actual investment barriers require further investigation [1,7,19,20].

4.2. Spatial Characteristics and Previous Research

Larger area and lower population density are associated with presence in the revised main model. Settlement and land-use conditions provide possible explanations, but plot availability, transport costs and planning restrictions were not directly measured. Larger municipalities also provide more space in which a plant can occur. The association cannot be attributed solely to favourable investment conditions.

The revised analysis compares urban and urban–rural municipalities with rural municipalities. The urban–rural contrast remains positive after separately excluding zero-pig and urban municipalities, whereas the urban contrast in the full model is imprecise. Szymańska and Lewandowska [3] studied county characteristics, while Martinát et al. [4] examined municipal presence. The present results add a species-specific and municipal comparison without establishing causal suitability.

Swedish research [10] shows that distances to housing and road conditions constrain siting, while crop-residue analysis [11] addresses resource availability. Only part of the land was suitable in the Danish assessment [9]. Larger municipal area therefore need not mean proportionately more feasible sites. The German register [6] illustrates how plant-level data can support more detailed assessment.

Social acceptance remains outside the municipal regression. Farmers' investment perceptions [12] and the relationships between biogas projects and rural communities [14] offer complementary evidence, but municipal population density cannot substitute for these attitudes. Future research should combine administrative indicators with investor and community information rather than infer opposition or support from settlement patterns alone.

The planning factors identified by Ginda and Szyba [25] support adding local-plan coverage, plot availability, and road access to future analyses.

Municipal revenue describes local-government finances, not investor resources. Polish plant research [27] and Austrian evidence [28] concern company finances and efficiency. Owner surveys [18] and employee evidence [26] also identify project-level barriers. Non-significant municipal revenue therefore does not mean that finance is unimportant to plant construction.

Local consequences also depend on facility scale and context. Zemo et al. [34] analysed rural housing transactions in Denmark and found different property-value associations for large and farm-scale biogas plants. Their study provides evidence on local economic consequences relevant to siting and acceptance, rather than a direct measure of community attitudes. It reinforces the need to examine facility characteristics and nearby settlements before drawing conclusions from municipal population density. The current binary outcome cannot distinguish these differences in scale or estimate effects on neighbouring property markets.

4.3. Implications for Agricultural Biogas Development

The practical use of the findings is to select areas for further assessment. Collectible resources should be examined first, followed by supply organisation, siting and connection conditions, and ultimately project profitability. This sequence connects resource assessment [7], GIS and transport [8–11,35,36], economic appraisal [5,13], and stakeholder evidence [12,14].

High-density municipalities with existing plants offer opportunities to examine supply organisation and investment history. Those without entries require verification of animal numbers, housing systems, available manure, contracts, and neighbouring plants' supply areas. Comparing the groups may help identify development barriers. The classification should not serve as a stand-alone ranking for grant allocation.

Energy use determines further infrastructure requirements. Combined heat and power requires heat offtake and delivery, whereas biomethane requires gas-grid access or other offtake arrangements [24]. Registers containing precise plant locations and characteristics [6] can support this assessment.

4.4. Limitations and Future Research

First, the KOWR outcome does not cover every biogas category or prove the absence of microinstallations. A binary presence indicator assigns the same value to municipalities with different numbers and sizes of registered plants. It therefore cannot measure installed capacity, energy output, investment expenditure, or missing investment volume. Second, the 2020 livestock baseline may differ from 2026 substrate conditions; 2025 covariates may also postdate plant construction. Headquarters-based census assignment can differ from physical livestock locations. Third, despite verified TERYT corrections, 475 municipalities remain excluded, including 15 with registered presence. The 2098-case check addresses missing cattle data only; missing pig data and other systematic selection mechanisms remain unresolved.

The pig quadratic term was selected by exploratory comparison and evaluated on the estimation data. This creates a risk of overfitting and overly optimistic performance or significance estimates. Sensitivity refits preserve the quadratic association after separate exclusions of zero-pig municipalities and urban municipalities, but are not external validation and do not prove the declining low-density segment is economically meaningful. Main M3 has 152 events for nine explanatory coefficients (about 16.9 events per coeffi-

cient). The regional model M4 has 24 explanatory coefficients (about 6.3 events per coefficient), plus an intercept, so its greater complexity warrants caution. Network constraints, investor support, and acceptance remain unmeasured.

The weak positive spatial autocorrelation in the M3 residuals indicates that some spatial structure remains after adjustment for the included covariates. The regression's conventional standard errors and *p*-values should therefore be interpreted with caution. In practical terms, neighbouring municipalities may share unmeasured feedstock catchments, transport links or other local conditions, so substrate supplies and logistical networks extending across their borders could contribute to similar residual patterns. These are plausible mechanisms, but Moran's I alone cannot identify them or establish that the presence of a plant causes a spillover effect in adjacent municipalities.

Municipal averages may hide differences between farms, while feedstock deliveries can cross administrative boundaries. Exact plant locations, road data, and supply areas would help account for these connections. Adding voivodeships does not establish independence between neighbouring municipalities; unresolved spatial dependence may affect uncertainty estimates and should be examined using an explicitly defined spatial weights matrix.

Data from successive years would allow for closer examination of the investment process. Conditions before construction could be linked to plant opening dates, and changes in plant numbers, capacity, and output could be analysed. The present study describes registry status at one point in time rather than investment decisions over time.

High-density tabulation covers only the 2004 complete cases. Q3 and P90 are distributional thresholds, not technological requirements. Neither the tabulation nor the logistic model measures unused manure, a shortage of energy capacity or the profitability of new plants.

5. Conclusions

Registered agricultural biogas plants in Poland were more common in municipalities with high pig stocking densities, whereas cattle density showed no clear association after adjustment for other municipal characteristics. Registered presence was also associated with larger municipal area and lower population density. The rise in predicted probability at higher pig densities was visible in both the quadratic and spline models, but the pattern at very low densities depended on the specification.

Livestock density maps can help identify areas for further assessment. A project appraisal should examine how much feedstock can actually be collected, where it comes from, and whether transport, planning, and grid conditions support a viable site. The relevant supply area can extend beyond the municipality hosting the plant. The municipal associations therefore inform where to investigate further without establishing causal effects, technical energy potential or project viability.

Registered presence reached 18.4% in the highest decile of pig density and 12.6% in its upper quartile, compared with 7.6% across the estimation sample. The corresponding upper-quartile share for cattle was 7.8%. These descriptive comparisons do not quantify missing capacity, investment expenditure, or the number of profitable projects. Registry presence also does not distinguish between plants of different sizes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19235767/s1. Figure S1: Spatial coverage of the municipal sample used to estimate Model M3 (2004 municipalities). Green indicates municipalities included in the model; grey indicates municipalities outside the sample. Thick lines indicate voivodeship boundaries.

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