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PREDICTION OF DYNAMICS CHANGE IN BIOWASTE QUANTITY COLLECTED IN FUNCTIONALLY DIFFERENT REGIONS. A CASE STUDY OF POLAND

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ABSTRACT: The aim of the paper is to determine the dynamics of change in biowaste quantity as well as to forecast the amount of biowaste generated in 4 functionally different regions of Poland. The analysis was made for a period of 16 years (2007-2022), and a prognosis was made for the next 4 years (2023-2026). Based on the obtained data, the following calculations were made: share of biowaste from households in the quantity of total municipal biowaste, accumulation rate of biowaste from households, medium-term change rate in the amount of biowaste from households, and prediction of changes in the biowaste accumulation index until 2026. In all the analysed regions, an increasing trend in the collected biowaste mass index has been observed. The agricultural and recreational regions were characterised by the highest dynamics of changes in collected biowaste quantity (T=0.21 and 0.25, respectively) and by the lowest values of their accumulation indicator (48.9 and 44.7 kg/ca per year, respectively). The highest quantity of biowaste is predicted to be generated in urbanised and industrialised regions (62.1 and 53.2 kg/ca per year, respectively).

KEYWORDS: biodegradable, dynamics of change, prediction, biowaste quantity

Introduction

Waste generation in developing countries has been increasing along with the growing population and economic growth (Tun et al., 2018). According to the World Bank Group 2018 Report, by 2050, municipal waste generation is expected to reach 3.40 billion Mg/year across the world and 490 million Mg per year in Europe (Kaza et al., 2018). Biodegradable waste is the most dominant fraction in municipal waste, and it is assessed, that approximately 30-50 million Mg of this waste is produced in the EU every year. Recently, there has been a growing interest in the utilisation of biomass, which can be considered a renewable product or energy source. (Ahrens et al., 2017; Boschin et al., 2014; Tot et al., 2017; Generowicz, 2020; Babalola, 2020; Szyba & Muweis, 2022; Tesfamariam et al., 2022). It can be used as an energy resource for the production of biogas and as high-nutritive compost for rehabilitation of degraded lands or improving crop yield (Ahrens et al., 2017; Tot et al., 2017; Generowicz, 2020; Tesfamariam et al., 2022). Transition of biowaste to energy is also part of European Union's main priorities of a low-carbon energy system. In this context, it is particularly important to know what biowaste resources are available for processing and how they are likely to develop over the next few years.

An overview of the literature

The high share of biodegradable waste in municipal waste generated in Poland indicates the possibility of developing both energy and material recycling (Boschin et al., 2014; Babalola, 2020; Szyba & Muweis, 2022). In order to properly design a biowaste recovery facility and to ensure its proper operation, it is necessary to have the data on the quantity of biowaste that will be fed into the facility as well as the data on the dynamics of its changes in the future. This information is also important for estimating the amount of energy that can be generated from the bio-waste. That is why forecasting the quantitative changes of waste is a crucial decision-making tool, which can assist in the implementation of the circular economy (Ayeleru et al., 2021).

Since the prognosis of solid waste quantity represents an increasingly challenging problem for policy makers, various predictive methods were proposed in order to ensure sustainable waste management (Ghinea et al., 2016). In literature, the frequently described prognostic models are: multiple linear regression (Araiza-Aguilar et al., 2020; Ceylan, 2020), artificial neural networks (Azarmi et al., 2018; Jalili & Noori, 2008; Kurtulus et al., 2006), and decision analysis methods (Ahuja & Bahukhandi, 2012; Nassereldeen et al., 2011). Multiple linear regression technique was applied by Kumar and Samadder (2017) to develop models for the prediction of biodegradable MSW generation rate and for non-biodegradable MSW generation rate for individual households of the city of Dhanbad, India. Multiply linear regression was also used for seasonal municipal solid waste generation prediction for 20 cities from Iran (Azadi & Karimi-Jashni, 2016; Ghinea et al., 2016). Karnasuta and Laoanantana (2022) used statistical numerical modelling for the prediction of biodegradable waste quantity. The analysis included employing the Pearson's correlation, moving average and exponential smoothing for the biodegradable waste quantity forecast in Bangkok city. Artificial neural networks and supported vector machine were employed to forecast the quantity of municipal waste that would be generated in the Johannesburg (South Africa). The Obtained results showed that the machine learning algorithm was effective for the development of models for waste forecasting (Ayeleru et al., 2021). The artificial neural network was also used by Kulisz and Kujawska (2020) and Batinic et al. (2011) for prediction future waste generation.

The literature review shows that research on forecasting the amount of waste was conducted by various authors and focused primarily on municipal waste. However, there are much less studies on the prediction of biodegradable waste quantity. There is also a gap in broader research determining the differences in the dynamics of changes of biodegradable waste in functionally different regions. Conducted analysis by Baquero et al. (2022), Karnasuta and Laoanantana (2022), Szyba and Muweis (2022), Tesfamariam et al. (2022), Generowicz (2020), and Tun et al. (2018) pointed out that a sustainable approach to biowaste management could become a future method of creating a clean energy source from this waste in many countries. In this context, the aim of the paper is to determine the

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dynamics of change of biowaste as well as to forecast the amount of biowaste generated in functionally different regions of Poland.

Research methods

Material

When starting to analyse the problem, it is worth clarifying the nomenclature. According to the regulations of the Waste Act of 14 December 2012 as amended (Act, 2012), biodegradable waste is defined as any waste that undergoes aerobic or anaerobic decomposition with the participation of microorganisms. A specific group, among biodegradable waste, which has received a separate definition in the European Parliament and Council Waste Framework Directive 2008/98/EC (Directive, 2008), is biowaste. Biowaste is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. It also excludes those by-products of food production that never become waste.

The presented study analyses the dynamics of changes in collected biowaste from households. The analysis therefore excludes park waste (from greenery maintenance) and food and kitchen waste from restaurants, caterers and retailers.

Analysis of the dynamics of changes and prediction of biowaste generated was made for Poland, located in the central-east of Europe. Poland covers an area of 322 719 square kilometers and has a population of 37 766.3·103 inhabitants (GUS, 2023). Almost 60% of the population resides in urban areas and the remaining part in rural ones. 13% of the population works in agriculture, 30% – in industry and 57% in the service sector. Poland is characterised by a high percentage of areas of special nature values under legal protection, which is 32%. Major mineral resources is hard and brown coal, and its deposits are mainly located in southern Poland. The agricultural areas are located within the range of medium and high quality soils. Poland is composed of 16 voivodeships, which include areas of different economic function and importance. According to territorial division, they can be divided into: agricultural land, industrial areas, urbanised areas and recreational and leisure areas (GUS, 2023).

Table 1. Analysed regions with their basic characterisation

	POLAND average	Agricultural	Industrial	Recreational and leisure	Urbanised
persons using water supply system (%)	92.4	89.3	95.6	95.7	86.5
persons using sewage system (%)	71.9	59.8	78.1	78.2	68.1
persons using gas (%)	55.6	39.0	64.1	53.0	61.4
Average monthly available income per capita [PLN]	2 062	1 956	2 197	2 049	2 245
Urbanisation (%)	59.68	53.6	71.9	63.7	56.3
Population density (person/ km2)	121.2	69.0	250.1	64.5	190.5
Population at working age (%)	59.1	59.0	58.9	59.2	59.5
Population at post-working age (%)	22.5	22.9	23.7	22.9	21.15
Biowaste from household collection rate (kg/capita·y)	45.8	39.7	52.8	38.0	43.0

Amount of municipal waste collected in 2022 in Poland was 13 420·10^3 Mg (355 kg/ca year), in which almost 87% (11 584·10^3 Mg, 307 kg/ca year) came from households. Biowaste makes up the dominant share of household waste. In 2022 the quantity of collected biowaste waste from households was 1 809.8·10^3 Mg (48 kg/ca year) (GUS, 2023). Due to the high proportion of biowaste and the possibility of using it as an energy or material source, it is important to know theirs quantities in

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the following years and the dynamics of the quantitative changes. Calculations of the dynamics of changes and forecasts of biodegradable waste were made for four functionally different regions of Poland: a) agricultural lands, b) industrial areas, c) urbanised areas and d) recreational and leisure areas. The voivodeship's affiliation to the above-mentioned regions has been adopted in accordance with the Atlas of Regions presented in the GUS data (GUS, 2023). For the further analyses, voivodeships assigned to several regions at the same time as well as those without a dominant share of a specific function were excluded. In accordance with this principle, the analysis covered 4 regions with the 8 voivodeships: agricultural (with lubelskie and podlaskie voivodeships), industrial (śląskie and dolnośląskie voivodeships), recreational and leisure (warmińsko-mazurskie and zachodnio-pomorskie voivodeships) and urbanised (małopolskie and mazowieckie voivodeships). Table 1 presents the analysed regions with their basic characterisation.

Methods

The data adopted for the analyses came from the data of Statistics Poland (2023) and covered the period of 16 years (2007-2022). Forecasts of the amount of biowaste generated were made for the next four years, until 2026.

For each of the region adopted for analysis following analyses were made:

a) share of collected biowaste from households in quantity of total collected municipal biowaste (including garden and park, restaurants, caterers, etc. biowaste),
b) calculation of the accumulation rate of collected biowaste from households (kg/ca year), defined as an yearly collected biowaste amount per capita, according to the equation:

$$b_t = \frac{M(b)_t}{I_t} \ , \tag{1}$$

where:
$M(b)_t$ – mass of collected biowaste from households in year t,
I_t – number of inhabitants in year t.

c) calculation of medium-term change rate in the amount of biowaste from households, which gives information how the level of the biowaste collection changes on average in the time period covered by the observation. Medium-term change rate in the amount of biowaste from households T, was calculate according to the formula (Tatarczak, 2021):

$$T = \sqrt[n-1]{\frac{x_n}{x_1}} - 1 \ . \tag{2}$$

where:
n – number of periods,
x_1 – value from the first period,
x_n – value from the last period.

d) prediction of changes in the collected biowaste accumulation rate until 2026. The prediction was made using a regression approach. Due to the nature of the phenomenon, a logarithmic approximation was used. As a result, an equation of the trend function and a determination coefficient indicating the degree of its adjustment to real data were obtained for each voivodeship. It was assumed that the values of the coefficient of determination above 0.75 well describe the development tendency of the analysed variable.

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Results of the research

Share of biowaste from households in municipal biowaste

In Poland in 2022, a total of $1914 \cdot 10^3$ Mg of municipal biowaste was generated, with $1809.8 \cdot 10^3$ Mg (94%) originating from households (GUS, 2023). The proportion of biowaste from households in the total amount of municipal biowaste varied across different functional regions and changed over the analysed years from 2007 to 2022 (Figure 1).

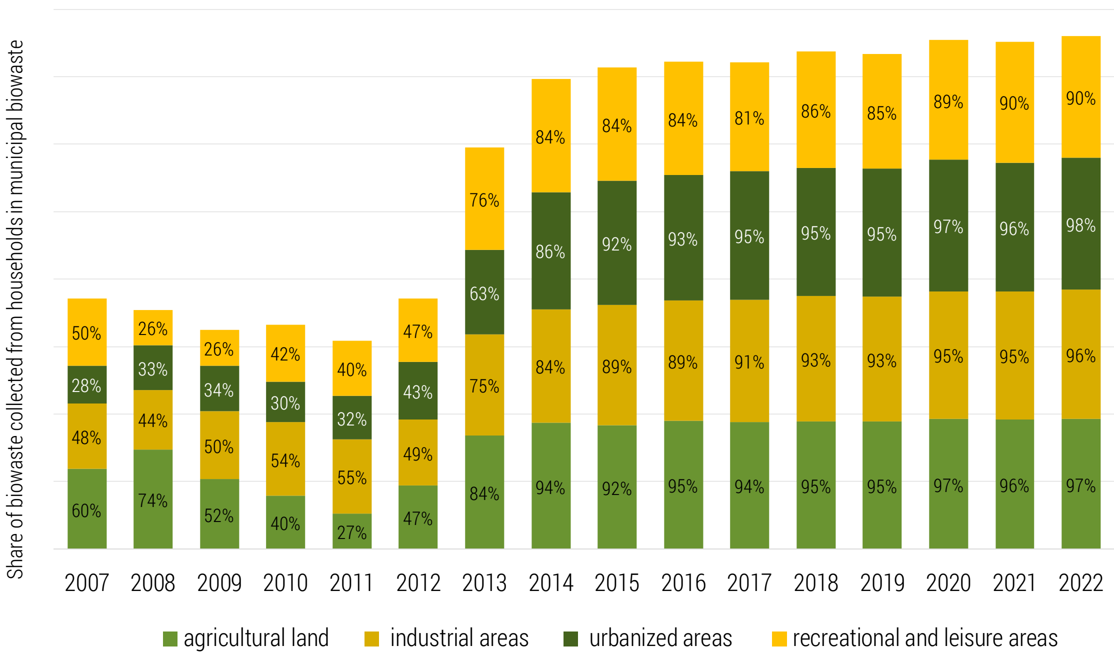

Figure 1. Share (%) of biowaste collected from households in municipal biowaste for the analysed regions

Table 2 presents basic statistical data regarding the share of biodegradable waste in waste across four analysed regions over the 15-year period.

Table 2. Share of biodegradable waste in municipal waste over the years 2007-2022 in the analysed regions

	Agricultural	Industrial	Urbanised	Recreational and leisure	POLAND average
Min	0.27	0.44	0.28	0.26	0.35
Max	0.97	0.96	0.98	0.90	0.94
Average	0.77	0.75	0.69	0.67	0.72
St. Dev	0.233	0.198	0.290	0.234	0.224

The average share of biowaste from households in municipal biowaste from 2007 to 2021 in Poland was 72%. Two of the analysed regions, urbanised areas and recreational and leisure areas, had averages below this level, at 69% and 67%, respectively. The other two regions, agricultural lands and industrial areas, achieved higher averages of 77% and 75%, respectively (Table 1).

Until 2014, the share of biowaste from households in total municipal biowaste in specific regions varied significantly, ranging from 28% to 86% in urbanised areas, from 27% to 94% in agricultural land, from 44% to 84% in industrial areas, and from 26% to approximately 84% in recreational and leisure areas. From 2015 onwards, these fluctuations stabilised, with an amplitude not exceeding 7% in the analysed regions (Figure 1). The observed variability in the first 8 years (2007-2014) of the analysed period resulted from the unregulated management of biodegradable waste (also biowaste)

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in the country and the absence of regulations mandating selective collection. The Ministry of Environment introduced regulations requiring selective waste collection, including biodegradable waste, only in 2016. Since then, the amount of separated biowaste from households has significantly increased, reflecting a higher proportion in municipal waste (Figure 1). In 2022, the share of biowaste from households in total municipal biowaste in all functional regions was no less than 90%. The high share of this waste was already visible since 2014, when it exceeded 84% in all regions. This indicates that biowaste from households can be a significant source of raw material for facilities for biowaste energy recovery or high-nutrient compost production.

Rate of household biowaste generation

The average accumulation rate of collected biowaste from households in Poland in 2022 was 48 kg/ca per year, with a total municipal biowaste accumulation rate of 51 kg/ca per year. Figure 2 illustrates changes in the accumulation rate of collected biowaste from households from 2007 to 2022, and Table 3 provides basic statistical data concerning the accumulation rate of collected biowaste, including minimum, maximum, average and standard error.

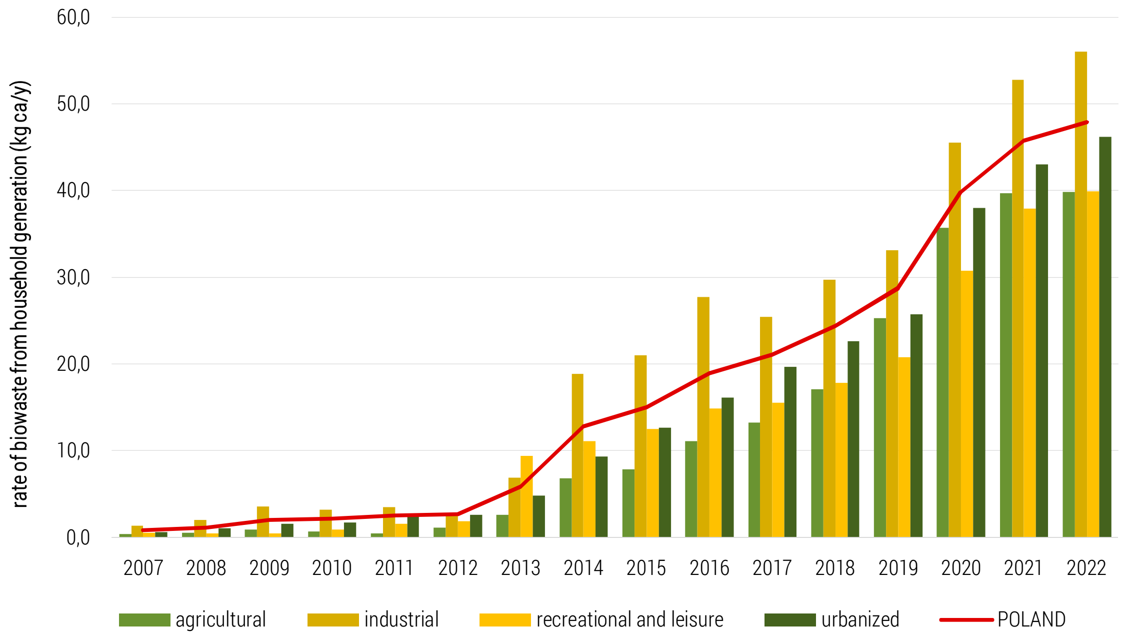

Figure 2. Changes in the accumulation rate of collected biowaste from households in 2007-2022

Table 3. Basic stastistical data for the accumulation rate of collected biowaste from households (kg/ca year) in the analysed regions

	Agricultural	Industrial	Recreational and leisure	Urbanised	POLAND average
Minimum	0.41	1.37	0.46	0.62	0.89
Maximum	39.87	56.07	39.93	46.23	47.92
Mean	12.75	20.87	13.56	15.54	17.01
Standard error	12.82	16.33	11.22	13.43	14.18

The lowest accumulation rate of collected biowaste from households was observed in agricultural and recreational and leisure areas, at 0.41 and 0.46 kg/ca per year, respectively. Both regions also exhibited the lowest share of biowaste from households in total municipal biowaste. The highest rate of biowaste from households was recorded in industrial areas, reaching 56.07 kg/ca per year.

Analysing the variability of the accumulation rate over the years, it is evident that the lowest values are in the agricultural and recreational and leisure areas, with averages of 12.75 and 13.56 kg/

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ca per year, respectively. Lower values in agricultural land can be explained by the possibility of managing or utilising biowaste within households, such as using it as animal feed or in home gardens. However, the low value of this indicator in recreational and leisure areas is interesting. Examining the characteristics of each region presented in Table 1, it can be observed that recreation and rest areas have the highest percentage of individuals using sewage systems (78.2%). This may influence the way biowaste from households is disposed of. The potential impact of the standard of living on the amount of generated waste is also highlighted in the studies of Namlis and Komilis (2019).

A higher average value of the biowaste accumulation rate was observed in urbanised areas (15.54 kg/ca per year), and the highest was in industrial areas (20.97 kg/ca per year). Both regions have the highest average monthly available income per capita [PLN] and the highest population density, exceeding the national average. These factors may contribute to the higher biowaste accumulation rate. The significant influence of socio-economic variables on biowaste generation was also noted in the studies of Baquero et al. (2022), Nguyen et al. (2020), and Trang et al. (2017).

Medium-term rate of change in the amount of biowaste from households

To assess the dynamics of changes in biowaste quantity, the medium-term rate of change in their amount was calculated over successive time periods. The results of the calculations are presented in Figure 3.

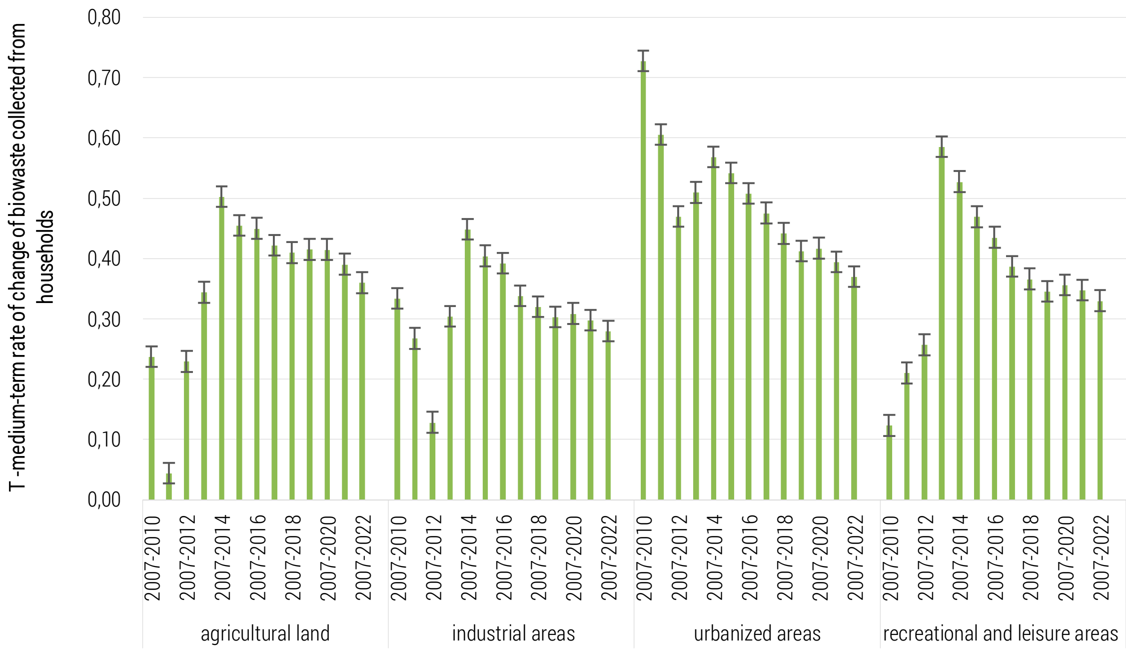

Figure 3. Medium-term change rate of biowaste collected from households (with standard error bars)

The positive values of the rate of change indicator (T) in all analysed regions indicate a continuous increase in the amount of selectively collected biowaste from households. The greatest variability in the rate of change from 2007 to 2022 was observed in recreational and leisure areas, ranging from 0.12 to 0.59 (Δ=0.47), and urbanised areas, from 0.12 to 0.59 (Δ=0.47). Until 2017, the values of the medium-term change rate were highly diverse, with the highest amplitude reaching 0.46 for agricultural land, 0.37 for recreational and leisure areas, 0.32 for industrial areas, and 0.26 for urbanisation areas. From 2017 onwards, the rate of change stabilised, resulting in a decrease in amplitude to 0.06 for agricultural, industrial, and recreational and leisure areas, with urbanised areas being the only exception, maintaining a higher amplitude of 0.11. This is mainly due to the impossibility of managing this waste on its own and the fact that an increasing number of residents are participating in separate collection of biowaste. Additionally, according to Janmaimool and Denpaiboon (2016), most urban populations with a good economic condition, enhance their efforts to purchase things and food, which results in higher amounts of biowaste collected.

Prediction of changes in the biowaste accumulation index

To predict changes in the household biowaste accumulation index, a logarithmic regression function was used. Due to the unstable nature of the data in the initial years of the study period, the forecast was based on data from 2017 to 2022, with a forecast period extending from 2023 to 2026. The forecast was conducted separately for each region and is presented in Figure 4. The equations of the obtained trend functions, their determination coefficients, and the medium-term rate of change are included in Table 4. High determination coefficient values (≥ 0.92) obtained for all analysed regions indicate a good fit of the predictive functions. The data suggest that the highest percentage increase in the amount of biowaste, reaching 23%, is expected in agricultural land. This area also projects the highest medium-term biowaste amount change rate for the years 2022-2026, reaching 0.05. The predicted amount of waste at the end of the forecasted period is 48.9 kg/ca·year. Despite the highest growth rate, the collected household biowaste accumulation index in the agricultural region is lower than in industrial and urbanised regions.

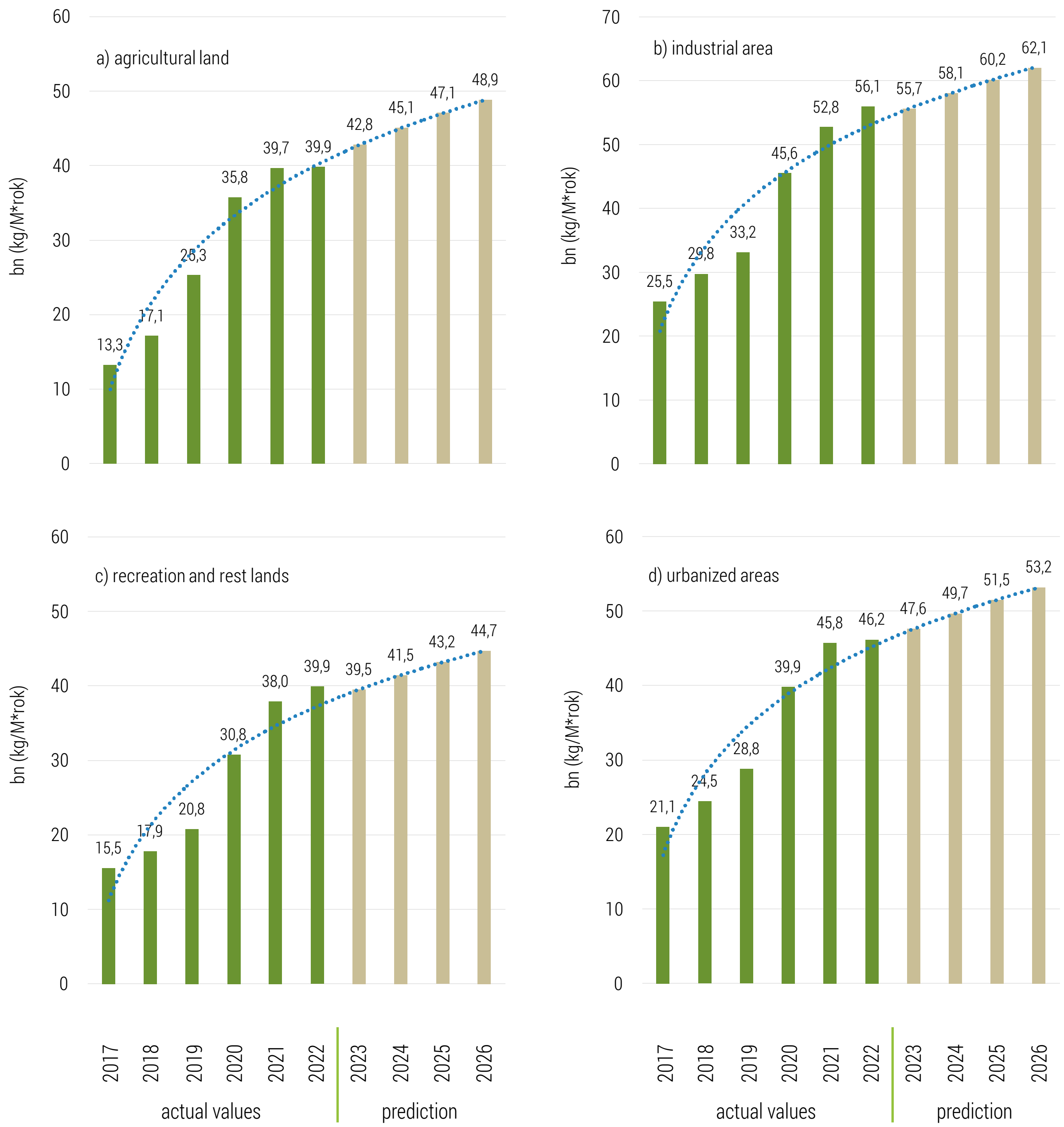

Figure 4. Prediction of accumulation rates of collected biowaste from households (kg/ca·year) in a) agricultural land, b) industrial areas, c) recreational and leisure areas and d) urbanised areas

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Studies by Kamran et al. (2015) suggest that socio-economic status has a significant impact on the amount of waste generated. The obtained results confirm this rule; in the analysed agricultural land, the average monthly available income per capita is 1 956 PLN, the lowest among the regions. Furthermore, this region has the lowest percentage of people using water supply and sewage systems, indicating lower wealth of residents. According to Namlis and Komilis (2019), a lower standard of living can affect the generation of smaller amounts of waste, including biowaste. A similar situation is observed in recreational and leisure areas, with the second-lowest income among the analysed regions (2 049 PLN), resulting in a lower biowaste accumulation rate in both the years 2017-2022 and the predicted years up to 2026.

Table 4. Regression line function, determination coefficient, actual and predicted mid-term for collected biowaste rate change and their increase for analysed

Type of region	Regression line	Determination coefficient R^2	T for region actual (2017-2022) / predicted (2022-2026)	Increase (%) actual (2017-2022) / predicted (2022-2026)
Agricultural	y = 16.866*ln(x) + 10.021	0.96	0.25 / 0.05	200/23
Industial	y = 17.937*ln(x) + 20.81	0.94	0.17 / 0.03	120/11
Recreational and leisure	y =14.564*ln(x) + 11.196	0.92	0.21 / 0.03	157/12
Urbanised	y=15.594*ln(x) + 17.281	0.94	0.17/0.04	119/15

A completely different situation is observed in the remaining two regions: urbanised and industrial. In both regions, an increase in waste is projected for 2026, reaching 53.2 kg/ca·year and 62.1 kg/ca·year, respectively. Both regions have the highest average monthly income per capita and the highest population density. In the case of industrial regions, the high accumulation rate may also be influenced by a high percentage of the population residing in urban areas, which is almost 72% (GUS, 2023). According to studies by Baquero et al. (2022), urban populations have a positive influence on biowaste generation and collection. This aligns with the findings of Ghinea et al. (2016), concluding that the population living in urban areas has a positive influence on municipal solid waste (MSW) and biowaste collection. The predicted mid-term rates of biowaste quantity changes for both regions are 0.03 in industrial areas and 0.4 in urbanised areas. This implies a 15% increase in waste amounts in urbanised areas and an 11% increase in industrial areas from 2021 to 2026. A similar dynamic change for the industrial region is also reported by Seruga (2021).

The obtained results may be significant in the context of constructing or expanding facilities for biowaste processing. The currently planned capacity of energy recovery installations from biowaste in agricultural areas may not be sufficient for the next few years. The analyses indicate that the planned increase in the capacity of installations should be adopted at least at a level of 23% in these areas.

In the other analysed regions, the increase in the capacity of biowaste treatment installations should not exceed 15%. This growth will mainly be driven by urbanisation, economic expansion, and higher living standards. These factors were mentioned in studies by Voukkali et al. (2023) and Chioatto et al. (2023) as determinants of biowaste generation.

The analyses and forecasts conducted suggest the need to increase the current capacity of installations for biowaste treatment. The most environmentally beneficial solution for biowaste treatment could be methane fermentation, allowing for the recovery and use of energy from organic waste (Generowicz, 2020). According to Saravanan et al. (2023), in terms of energy security and climate change, bioenergy is a crucial component in promoting the sustainable development of nations.

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Conclusions

In the paper, the quantity and dynamic changes of biowaste collected from households was analysed. The biowaste was defined as a as biodegradable food and kitchen waste from households.

The analyses showed that the accumulation rate of biowaste quantity from households changed dynamically over the last 15 years, with the highest growth rate observed in the years 2007-2017 (T > 0.3), followed by a stabilisation period. The forecast for 2026 suggests that the predicted medium-term rate of change in biowaste amount from households in the analysed regions will not exceed the value of T = 0.05.

Obtained results indicated that the projected quantity of biowaste in in agricultural areas will increase by 23%. In the other analysed regions, the increase in the biowaste quantity should not exceed 15%.

It is predicted that the accumulation index of biowaste will reach its highest value in 2026 in industrial and urbanised areas, at 62.1 and 53.2 kg/ca·year, respectively. However, as it was depicted, the percentage increase will be highest in agricultural land, characterised by a lower income level.

The obtained results may be significant in the context of design or exploitation facilities for biowaste processing. The conducted analyses and forecasts indicate the potential need to expand the biowaste processing capacity.

The presented data also indicate that urbanised and industrial regions should consider investing in advanced biowaste management systems to handle the growing waste volumes associated with higher population densities and urbanisation. It is also worth launching educational campaigns to raise public awareness about promoting biowaste segregation practices. Focus efforts on urbanised regions where biowaste accumulation rates are highest. It is important to regularly review and update biowaste accumulation forecasts to align with economic, demographic, and technological developments. This will ensure that stakeholders can better manage the forecasted growth in biowaste and address regional disparities in waste generation.

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The contribution of the authors

Conceptualization, I.A.T.; methodology, I.A.T..; validation, I.A.T., S.H. and A.W.; formal analysis, I.A.T.; investigation, I.A.T.; resources, I.A.T., S.H. and A.W.; funding acquisition, I.A.T. and S.H.; data curation, I.A.T., S.H. and A.W.; supervision, I.A.T.; project administration, I.A.T.; writing, I.A.T., S.H. and A.W.; writing – review & editing, I.A.T.

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Izabela Anna TAŁAŁAJ • Sławomira HAJDUK • Anna WISZNIEWSKA

PROGNOZA DYNAMIKI ZMIAN ODPADÓW BIODEGRADOWALNYCH W FUNKCJONALNIE ZRÓŻNICOWANYCH REGIONACH. STUDIUM PRZYPADKU POLSKI

STRESZCZENIE: Celem artykułu jest określenie dynamiki zmian ilości bioodpadów oraz prognoza ilości generowanych bioodpadów w czterech funkcjonalnie różnych regionach Polski. Analizy zostały przeprowadzone dla okresu 16 lat (2007–2022), a prognozy obejmują kolejne 4 lata (2023–2026). Na podstawie uzyskanych danych obliczono: udział bioodpadów pochodzących z gospodarstw domowych w całkowitej ilości odpadów komunalnych, wskaźnik akumulacji bioodpadów z gospodarstw domowych, średniookresową dynamikę zmian ilości bioodpadów zebranych z gospodarstw domowych oraz prognozę zmian wskaźnika akumulacji bioodpadów do 2026 roku. We wszystkich analizowanych regionach zaobserwowano rosnący trend wskaźnika nagromadzenia zebranych bioodpadów. Obszary rolnicze i rekreacyjne charakteryzowały się najwyższą dynamiką zmian ilości bioodpadów (T = 0,21 i 0,25, odpowiednio) oraz najniższymi wartościami wskaźnika ich nagromadzenia (odpowiednio 48,9 i 44,7 kg/os. rocznie). Największe ilości zbieranych bioodpadów prognozuje się dla regionów zurbanizowanych i uprzemysłowionych (odpowiednio 62,1 i 53,2 kg/os. rocznie).

SŁOWA KLUCZOWE: odpady biodegradowalne, dynamika zmian, prognoza, bioodpady

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