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SUSTAINABILITY EVALUATION OF MAIZE SILAGE CULTIVATION ACCORDING TO LEVELS OF NITROGEN FERTILIZATION USING THE ANALYTIC HIERARCHY PROCESS[1]

Key words: maize silage, multiple-criteria decision analysis, AHP, sustainability

ABSTRACT. This study aims at the sustainability assessment of maize silage cultivation according to levels of nitrogen fertilization. Based on data provided by a field experiment, economic, production and environmental criteria were evaluated for three levels of nitrogen fertilization: 80, 120 and 160 kg/ha. The environmental impact of maize cultivation was evaluated by the Life Cycle Assessment (LCA) methodology. In a multi-criteria assessment, the weights of sub-criteria were evaluated on the basis of scientists, agricultural advisers and farmers' responses through AHP methodology. Based on the mean opinion of the respondents, economic criteria have the greatest impact on overall sustainability evaluation (54%), while the impact of environmental criteria (30%) and production criteria (16%) is much smaller. Analysis of economic subcriteria proved to have the greatest impact of gross margin (61%) on sustainability assessment, followed by the economic efficiency index (31%), while the smallest impact (8%) was obtained for the economic independence index. Among the analysed production subcriteria, the level of production and complexity of agrotechnical operations (44% each) had the greatest impact on sustainability assessment, and the least – labour use (12%). The obtained results showed the best economic evaluation for 120 kg N/ha, while from a production and an environmental point of view the best alternative is the application of 80 kg N/ha. The overall evaluation, with estimated criteria weights, shows the best sustainability performance for an 80 kg/ha fertilization dose.

INTRODUCTION

It is anticipated that, in 2050, demand for food and other agricultural products will increase by 50% in comparison with 2012. Therefore, producing more, but with less chemical input causing negative side effects, is becoming an indicator of sustainable development. At the same time, it is pointed out that, in recent years, the yield growth process slowed down in spite of technological improvements because of climate change [FAO 2017]. It is forecasted that in Europe, under 2050 climate conditions, further climate change will lead to a 25% reduction in grain maize yield [Webber et al. 2018]. Adjustment of the fertilisation dose, taking N supply and crop demand into account, is key to optimising yield,

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profit, and environmental protection [Cassman et al. 2002]. The excessive fertilization rate of the nitrogen dose has an adverse impact on the environment through an increase of nitrate concentration in the soil, contamination of groundwater and eutrophication [Z. Mazur, T. Mazur 2006]. However, a nitrogen dose reduction may lead to a yield decrease [Księżak et al. 2012].

Sustainable agriculture aims at maintaining environmental health, economic profitability, and social and economic equity [Velten et al. 2015]. Nowadays, the concept of sustainable agriculture is increasingly gaining favour. The problem of maize sustainability is the theme of many research projects [Houshyar et al. 2018, Paulino-Flores et al. 2017, Vasileiadis et al. 2017]. Ehsan Houshyar et al. [2018] evaluated the impact of nitrogen and water use management on the sustainability of maize production through energy analysis to assess sustainability in terms of resource consumption. Miriam Paulino-Flores et al. [2017] presented the sustainability assessment of hybrid and native maize production systems by applying the IDEA method (Indicateur de durabilite des exploitations agricoles), which in overall assessment takes agroecological, socio-territorial and economic criteria into account. Vasileios Vasileiadis et al. [2017] used the DEXiPM model (DEXi Pest Management) for sustainability assessment in maize-based cropping systems considering the economic, environmental and social dimensions. Since sustainable agriculture evaluates production systems based on different aspects and criteria, it is increasingly considered a decision making problem that can be solved through MCDM (Multi-Criteria Decision Making) methods [Falcone et al. 2016, Sadok et al. 2008, Król et al. 2018]. AHP is one of the MCDM methods that is applied in agriculture [Chatzimouratidis, Pilavachi 2009, Chavez et al. 2012]. It is a multi-criteria decision support method developed by Thomas Saaty [1980], based on pairwise comparisons of decision alternatives, which enables the comparison of economic and environmental indicators. Similarly to Cesare Castellini et al. [2012], Giacomo Falcone et al. [2016] and Jingzheng Ren et al. [2015], LCA for environmental indicator evaluation in a multi-criteria approach was implemented. Although LCA methodology is becoming increasingly used in the environmental impact evaluation of agricultural products, the integration of LCA in MCDM studies is not widespread.

Maize is one of the major crops in Poland. Maize for silage has a 73% share in the total structure of field green fodder crop production in Poland. In 2017, maize for silage production, in Poland, was 29 million tons cultivated on 596 thousand hectares [GUS 2018]. The growing importance of maize cultivation in Poland induces its sustainability evaluation, according to which decision making in agriculture should consider economic, production and environmental goals. The aim of the study is the sustainability assessment of maize silage cultivation according to levels of nitrogen fertilization using the Analytic Hierarchy Process.

RESEARCH MATERIAL AND METHODS

On the basis of the literature review [Colomb et al. 2013, Falcone et al. 2016, Sadok et al. 2009], ten indicators were determined: three economic, three production and four environmental ones (Table 1). In relation to economic goals, it was assumed that sustainable agriculture should result in exceeding gross product over direct costs and ensure subsidy independence and economic efficiency [Colomb et al. 2013]. The economic dimension has been spread over the following components: gross margin (GM), economic independence (EI) and economic efficiency (EE). Economic indicators were calculated using the following equations [Colomb et al. 2013]:

$$GM = GP - OC \tag{1}$$

$$EI = \left(1 - \frac{DS}{GM}\right) \times 100\ (\%) \quad \text{and} \tag{2}$$

$$EE = \left(1 - \frac{OC}{GP}\right) \times 100\ (\%) \tag{3}$$

where *GP* is gross product, *OC* are operational costs and *DS* denotes direct subsidies. *GP* was calculated by adding the gross income to subsidies that include the single area payment and additional payment. The yield of green matter was multiplied by price (75 PLN/t) to calculate the gross income [Bojarszczuk, Księżak 2015]. *OC* considered costs of: seed material, fertilizers, herbicides, work of own machinery, outsourced services, human labour and fuel.

With regard to production goals, it was assumed that sustainable agriculture fulfils the objectives if it increases the productivity level (determined as dry matter yield – t/ha) and decreases the annual labour requirement (h/ha) as well as the complexity of cultivation (determined as complexity of agrotechnical operations related to the applied fertilization dose). The productivity level and annual labour requirement indicators were estimated based on field experiments and literature [Harasim 2002, W-MODR 2017]. The complexity of the cultivation indicator has been evaluated by an expert assessment using AHP methodology based on a questionnaire conducted among 10 scientists, 9 agricultural advisers and 8 farmers. The respondents were scientists from the Institute of Soil Science and Plant Cultivation – the State Research Institute (IUNG-PIB Puławy), agricultural advisers and farmers (including 4 workers of RZD IUNG-PIB leading long-term experiments), who participated in a workshop held by the Agricultural Advisory Centre in Radom. The questionnaire concerned the assessment of the complexity of the three levels of nitrogen fertilization 80 (A), 120 (B) and 160 kg N/ha (C), mainly in the context of the number of treatments and operations performed. Fertilization levels were compared in pairs (A with B, A with C and B with C) in order to assess the complexity of one fertilization level in relation to another according to the Saaty scale [Saaty 2008], from (1) equal complexity through (2) slightly more complex, (3) essentially more complex, (4) strongly more complex to (5) absolutely more complex (Figure 1).

Selected environmental criteria determine the potential impact of 1 kg of maize dry yield on the environment due to greenhouse gas (GHG) emissions (Global Warming Potential, GWP), acid emissions to the atmosphere and deposited in waters and surface soils (acidification potential, AP), nutrient over-enrichment in aquatic ecosystems (eutrophication potential, EP), and potential human toxic effects of chemicals entering the environment (human toxicity potential, HTP). The GWP, AP and EP criteria were established based on the EPD method while HTP was estimated based on ReCiPe 2016 Midpoint (H) methodol-

A

In your opinion, application of which fertilization level is more complex (e.q. requires more interventions) than the other and how much?

(please select only one answer)

A Nitrogen fertilization at a level of 80 kg N ha^{-1}	**B** Nitrogen fertilization at a level of 120 kg N ha^{-1}
☐ **A >>>> B**	(A is absolutely more complex than B)
☐ **A >>> B**	(A is strongly more complex than B)
☐ **A >> B**	(A is essentially more complex than B)
☐ **A > B**	(A is slightly more complex than B)
☐ **A = B**	(A and B are equally complex)
☐ **A < B**	(B is slightly more complex than A)
☐ **A << B**	(B is essentially more complex than A)
☐ **A <<< B**	(B is strongly more complex than A)
☐ **A <<<< B**	(B is absolutely more complex than A)

B

In your opinion, which criterion is more important and how much?

(please select only one answer)

B Share of subsidies in gross margin	**C** Ratio of operational costs to gross product
☐ **B >>>> C**	(B is extremely more important than C)
☐ **B >>> C**	(B is very strongly more important than C)
☐ **B >> C**	(B is strongly more important than C)
☐ **B > C**	(B is moderately more important than C)
☐ **B = C**	(B and C are equally important)
☐ **B < C**	(C is moderately more important than B)
☐ **B << C**	(C is strongly more important than B)
☐ **B <<< C**	(C is very strongly more important than B)
☐ **B <<<< C**	(C is extremely more important than B)

Figure 1. Sample of questions of the survey conducted for multi-criteria decision-making regarding the assessment of (A) the complexity of fertilization levels and (B) the weights of the analysed criteria

Source: own study

ogy using SimaPro software [IEC 2008]. A cradle-to-farm gate perspective was adopted, starting from soil cultivation one year before harvest and ending with the transport of maize silage. The foreground system includes soil cultivation, fertilization, sowing, plant protection application, harvest and transport. Whereas, raw material extraction and the production of input determines the background system. However, the distribution, processing and consumption of the product were not taken into account. Data on nitrous oxide emissions included: direct and indirect N_2O emissions to the air, and indirect emissions to the water that were estimated according to Cecile de Klein et al. [2006]. Background and foreground data as well as herbicide emissions come from Ecoinvent v3.4.

Data related to input consumption as well as yield level were collected in a long-term field experiment conducted in the Experimental Station of the Institute of Soil Science and Plant Cultivation, State Research Institute in Osiny (51°27'59.98'' N; 21°39'44.28''E) in the Lublin Voivodship, in the years 2008-2010 [Księżak et al. 2012]. The field experiment was planned in a split-plot design with four replications, on a very good rye complex (slightly acidic) and consisted of three treatments of nitrogen fertilization rates: 80, 120 and 160 kg/ha in green maize cultivation. At the set-up, each plot was 10.0 m in length by 3.0 m in width (30 m^2), while at harvest it was 9.0 m in length by 2.55 m in width (23 m^2). Besides nitrogen, all plots received 26.2 kg P/ha and 74.7 kg K/ha. Maize was planted from April 28th till May 6th, using air seeder, and the plant population was 130 thousand seeds/ha. Weeds were controlled with herbicides. The indicator evaluation was performed for each particular year (2008-2010). Fuel consumption, lifetime, weight and use of machinery were estimated based on tractor specifications, literature and data provided by centres for agricultural consultancy [Bacenetti, Fusi 2015, CDR, DODR, W-MODR 2017]. The labour was estimated based on data provided by the centre for agricultural consultancy in Olsztyn (W-MODR) regarding machinery use corrected by preparation time [Harasim 2002]. The prices of agricultural input and machinery use were estimated based on commercial offers, data provided by IERiGŻ-PIB and the centre for agricultural consultancy [Augustyńska-Grzymek et al. 2008, 2009, 2010, Abramczuk et al. 2011, Zalewski 2016, W-MODR 2017]. Price for human labour was set at 14.73 PLN/h [Skarżyńska 2017]. For highly cost-consuming operations such as sowing and harvesting, prices for services were set at 225 PLN/ha and 300 PLN/ha [MODR 2018].

From countless MCDM methods, in presence of multiple criteria, the Analytical Hierarchy Process (AHP) methodology was applied. The AHP method has the advantage of the weighting criteria evaluation based on a pairwise comparison of their importance, and the introduction of a consistency test of judgments [Król et al. 2018]. The method can be divided into six steps: (1) a definition of the decision problem; (2) preparation of the hierarchical structure of the problem; (3) a pairwise comparison of importance of each criteria; (4) a pairwise comparison of alternatives in relation to each criteria; (5) calculations of the vector of criteria weights and (6) calculations of the matrix of alternative scores for the evaluation of an alternatives ranking.

The weights of selected criteria were estimated by AHP methodology based on the questionnaire among the group of expert's discussed earlier. The respondents answered the series of pairwise questions to compare the importance of criteria (A with B, A with C and B with C, etc.) in order to assess the priority of importance of one criteria over another.

Responses were attributed to the Saaty scale [Saaty 2008] from (1) equally important, through (2) moderately more important, (3) strongly more important, (4) very strongly more important to (5) extremely more important (Figure 1). The criteria were compared within three groups, firstly, main criteria (economic with production and environmental criteria) and then economic and production subcriteria were compared. All environmental subcriteria were assumed to have equal importance [Falcone et al. 2016]. The individual opinions of respondents were aggregated into group judgments by the AIP method (Aggregation of Individual Priorities) using a geometric mean [Forman, Peniwati 1998]. In the AHP method, the consistency of judgments is assessed based on the consistency index (CI) and consistency ratio (CR). The CR should not exceed 0.1 [Saaty 2008] or 0.2 [Nardo et al. 2005], therefore answers with a CR more than 0.2 were not taken into account.

RESEARCH RESULTS

The best economic performance (the highest value of gross margin, economic independence and economic efficiency index) was obtained for a 120 kg N fertilisation dose, however the differences between fertilization levels were low (Table 1). For a 120 and 160 kg N fertilisation dose, the gross margin was higher by 4-5% than in an 80 kg N/ha dose, while in case of subsidy indepencency and economic efficiency the differences between fertilization doses were lower than 3%. The level of the gross margin was diversified by the nitrogen dose through gross product and fertilization costs. Jolanta Bojarszczuk et al. [2013], also reported an increase of direct and total costs due to a higher nitrogen dose in maize silage cultivation and, consequently, a reduction of the gross margin. Similarly to the study conducted by Bruno Basso et al. [2012], the possibility of reduction of N fertilization without affecting economic results was shown. By reducing the nitrogen dose from 160 kg/ha to 120 kg/ha a higher gross margin was obtained.

The best production results related to the lowest annual labour reqirement and the lowest complexity level were obtained for an 80 kg N fertilisation dose, while the highest productivity level was achieved for a 160 kg N/ha dose. The rise of the fertilisation dose from 80 kg N/ha to 120 kg N/ha and 160 kg N/ha increases the annual labour requirement by 6% and 13%, respectively. Higher labour needs associated with a fertilization level increase was also pointed out by Jolanta Bojarszczuk et al. [2013], due to growth in the number of operations applied. When 120 and 160 kg N/ha doses were applied, the productivity level was slightly higher (by 3% and 6%) compared to the fertilization dose of 80 kg N/ha. In the analyzed period, a significant statistical influence of the level of nitrogen dose was only observed in 2010 [Księżak et al. 2012]. Józef Sowiński and Agata Liszka-Podkowa [2008] also reported a slight improvement of matter yield due to a nitrogen level increase, however, likewise, in this study, the differences were not significant.

By applying the AHP method for the complexity of cultivation evaluation, it was shown that from all completed 27 surveys, 7 surveys did not comply with CR < 0.2 criterion, and hence could not be included in the final assessment of this criterion. Based on the average opinion of respondents, it was shown that the nitrogen level rise results in a complexity increase, and the biggest differences were found for a fertilization dose increased from 120 to 160 kg N/ha.

Table 1. Economic, production and environmental criteria evaluation regarding the level of nitrogen fertilization*

Application rate of nitrogen [kg N/ha]	80	120	160
Economic indicators			
Gross margin [PLN/ha]	2,419	2,528	2,511
Economic independence [%]	67	69	69
Economic efficiency [%]	46	46	44
Production indicators			
Annual labour requirement [h/ha]	10.9	11.6	12.3
Productivity level [t DM/ha]	21.0	21.7	22.2
Complexity [%]	18	28	54
Environmental indicators			
Acidification Potential [kg SO_2 eq/kg DM]	3.15×10^{-4}	3.49×10^{-4}	3.77×10^{-4}
Eutrophication Potential [kg PO_4 eq/kg DM]	1.44×10^{-4}	1.61×10^{-4}	1.76×10^{-4}
Global Warming Potential [kg CO_2 eq/kg DM]	6.67×10^{-2}	8.34×10^{-2}	9.77×10^{-2}
Human Toxicity Potential [kg 1.4-DCB/kg DM]	0.116	0.122	0.125

* Table shows values of economic, production and environmental indicators according to levels of nitrogen fertilization. The presented values are average values from the 2008-2010 timeframe

Source: own study

The obtained results showed that a reduction of fertilization has a positive effect on environmental aspects. The application of a 160 kg N/ha dose shows a higher environmental impact for AP by 8% and 20% than in fertilization doses reduced by 40 and 80 kg N/ha, respectively. Comparing EP, a reduction of the N-fertilisation dose from 160 kg N/ha to 120 kg N/ha and 80 kg N/ha reduces the environmental impact by 8 and 18%. The results show that a decrease of nitrogen level application by 40 and 80 kg N/ha reduces GWP by 15 and 32%. The LCIA showed that an increase in the fertilisation dose from 80 kg N/ha to 120 kg N/ha and 160 kg N/ha increases HTP by 5 and 8%, respectively. Jacopo Bacenetti et al. [2016], Frank Brentrup et al. [2004] and Alfredo Iriarte et al. [2011], have reported the high impact of fertilization on the environment. It has been showed that to meet the sustainability goal, higher fertilization rates have to be balanced by a yield improvement to compensate the additional impact on the environment [Brentrup et al. 2004, Iriarte et al. 2011].

For weights evaluation of the main criteria and production subcriteria, by applying the AHP method, it was shown that from all completed 27 surveys, 10 surveys did not comply with CR < 0.2 criterion and could not be included in the weight assessment of those criteria. However, in the assessment of economic subcriteria weights, 14 questionnaires did not meet this condition. The evaluated criteria weights in relation to the three groups of respondents (scientists, agricultural advisers and farmers) did not diversify the final ranking of the fertilization level, therefore the analysis was determined by the mean opinion of respondents (Figure 2).

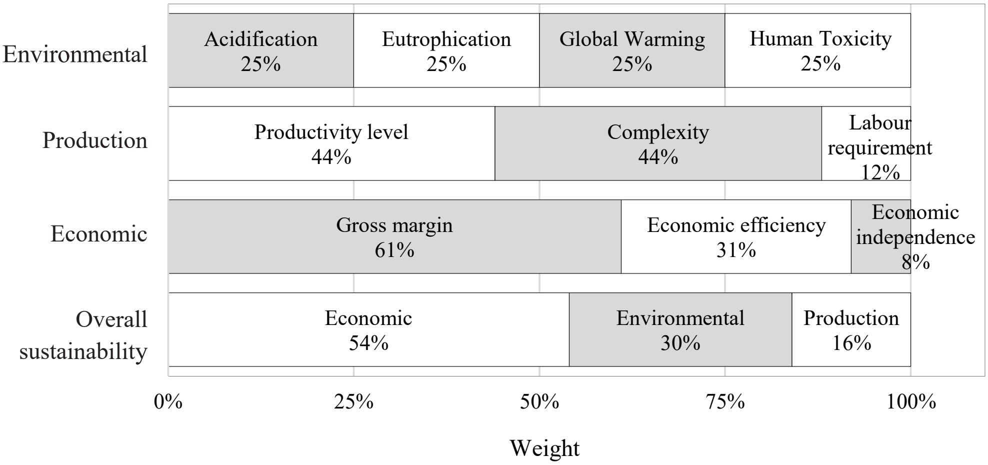

Figure 2. Priorities of criteria and sub-criteria evaluated based on the mean opinion of scientists, agricultural advisers and farmers' responses through AHP methods

Source: own study

According to respondents, economic criteria have the greatest priority (54%) in cultivation assessment, while the importance of environmental (30%) and production criteria (16%) is much lower. Among economic criteria, gross margin has the largest priority (61%), followed by economic efficiency (31%) and economic independence (8%). In production criteria, the productivity level with complexity has the largest priority (44% each), while the annual labour requirement has the lowest importance (12%). All environmental subcriteria were assumed to have an equal importance [Falcone et al. 2016].

The sustainability evaluation of maize cultivation according to different nitrogen level applications that consider the mean opinion of scientists, agricultural advisers and farmers (represented by criteria weights) shows that from an environmental and a production point of view the 80 kg N/ha fertilization dose is the most appropriate, while the best economic performance was assumed for a 120 kg N/ha dose (Figure 3). It should be underlined that there were no big differences between levels of fertilisation in terms of economic evaluation (less than 1%), whilst for the environmental and production evaluation, the difference was much bigger (up to 15%). In summary, the overall evaluation shows that the 80 kg N/ha fertilization dose, compared to higher doses, reached the best sustainability performance. Similarly, to our study, Guiliang Wang et al. [2014], also identified the nitrogen fertilization rate as a significant factor in maize cultivation with regard to the economic and environmental assessment. The value of the optimal nitrogen fertilization rate varied while agronomic, economic and ecologic issues were evaluated. Furthermore, Małgorzata Natywa et al. [2014], pointed out that the determination of optimum nitrogen doses, causing an environmental impact reduction, has a significant influence on economic performance.

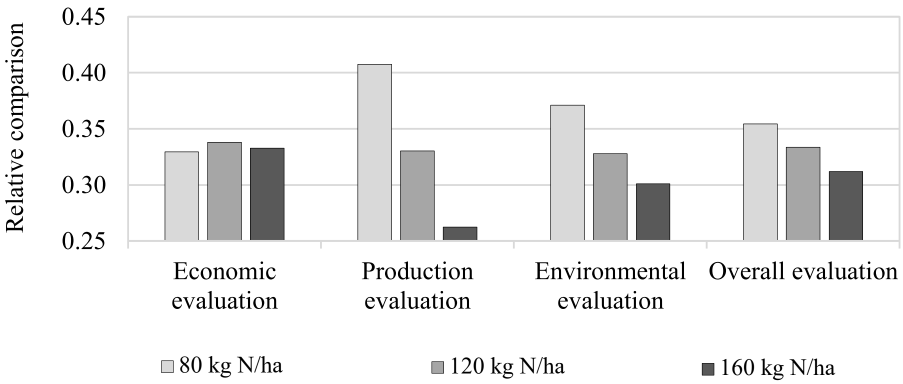

Figure 3. Final ranking based on the mean opinion of respondents according to levels of nitrogen fertilization

Source: own study

CONCLUSIONS

The proposed methodology enabled the consideration of a three dimensional approach in sustainability indicator evaluation based on economic, production and environmental issues. Based on data provided by a field experiment, the values of the following sustainable indicators were estimated: economic, production and environmental goals. The weights of selected criteria were estimated by applying AHP methodology based on a questionnaire conducted among scientists, agricultural advisers and farmers, allowing the considerations of their opinion in the final sustainability evaluation. According to the mean opinion of respondents, economic criteria have the greatest priority (54%) in the cultivation assessment, while the importance of environmental (30%) and production criteria (16%) is much lower. The best economic evaluation was obtained for a 120 kg N/ha dose, while the lowest environmental impact and the best production results were determined for an 80 kg/ha dose. According to estimated criteria weights, the overall evaluation shows the best sustainable performance for an 80 kg N/ha dose. It was obtained despite the fact that economic indicators have the highest priority for respondents (54%). However, the analysed doses of nitrogen fertilization caused greater differences in the obtained environmental and production indicators than economic indicators, which had an impact on the overall assessment of sustainability.

The presented results refer to selected sustainability indicators and conditions of the field experiment. However, the obtained results are encouraging and suggest further sustainability evaluation with reference to different sites and crops. Due to the variety of factors that may affect sustainability assessment (e.g. soil, climatic conditions and the type of fertilizer), a broader assessment may be useful in providing a full evaluation. In addition, expanding the expert group would make it possible to present sustainability assessments from different points of view (e.g. ecologists, economists, farmers).

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OCENA ZRÓWNOWAŻENIA UPRAWY KUKURYDZY NA KISZONKĘ W ZALEŻNOŚCI OD POZIOMU NAWOŻENIA Z WYKORZYSTANIEM ANALITYCZNEGO PROCESU HIERARCHICZNEGO

Słowa kluczowe: kukurydza na zielonkę, wielokryterialne wspomaganie decyzji, AHP, zrównoważenie

ABSTRAKT

Celem pracy jest ocena zrównoważenia uprawy kukurydzy na kiszonkę w zależności od poziomu nawożenia. Na podstawie doświadczenia polowego wyznaczono wartości wskaźników zrównoważenia (zgrupowanych według: kryteriów ekonomicznych, produkcyjnych i środowiskowych) dla trzech poziomów nawożenia azotem: 80, 120 i 160 kg/ha. Wpływ produkcji kukurydzy na środowisko oceniono wykorzystując metodę LCA (ocenę cyklu życia). W analizie wielokryterialnej wagi badanych kryteriów określono na podstawie przeprowadzanej ankiety, wykorzystując metodę analitycznego procesu hierarchicznego (AHP). Według średniej oceny ankietowanych, kryteria ekonomiczne mają największy wpływ na ogólną ocenę zrównoważenia (54%), podczas gdy wpływ kryteriów środowiskowych (30%) oraz kryteriów produkcyjnych (16%) jest zdecydowanie mniejszy. Największy wpływ na ocenę ogólną zrównoważenia wśród subkryteriów ekonomicznych miała nadwyżka bezpośrednia (61%), następnie indeks efektywności ekonomicznej (31%), a najmniejszy (8%) indeks niezależności ekonomicznej. Wśród analizowanych kryteriów produkcyjnych największy wpływ na ocenę uprawy ma poziom produkcji oraz złożoność uprawy (po 44%), a najmniejszy nakład pracy (12%). Przeprowadzone badania wykazały, że najlepsze wyniki ekonomiczne uzyskała uprawa kukurydzy z zastosowaniem 120 kg N/ha, natomiast z punktu widzenia oceny produkcyjnej i środowiskowej najlepsze wyniki otrzymano dla dawki 80 kg N/ha. Przy zastosowanych wagach kryteriów zrównoważenia analiza wielokryterialna wskazuje, że optymalną dawką nawożenia kukurydzy jest 80 kg N/ha.

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