Supplementary materials

Determinants of sustainability and cross-dimensional synergies: A comparison of Polish farms participating and not participating in short food supply chain

Supplementary S1 – detailed description of the study sample

Compared to average results for Polish farms, the surveyed farms had a larger agricultural area (by approximately 6 hectares) and a higher value of annual production (by over EUR 14,000). The share of crop production and the level of annual work units were also higher. Farm managers were younger (by over 3 years), and the proportion of male managers was higher (76% vs. 66%). The level of education was also slightly higher. In turn, when comparing SFSC and non-SFSC farms, the sample selection process sought to identify farms with similar characteristics, allowing for comparison of results between the two groups. For example, SFSC and non-SFSC farms did not differ significantly in terms of average area and production volume, the share of crop production in total production, labour input, and manager age. However, statistically significant differences were observed in the gender structure of farm managers, with SFSC farms having a higher proportion of women. Differences were also observed in crop structure: SFSC farms had a higher share of fruit and vegetables (24% of arable land) and a lower share of cereals and corn (42.5%), whereas in non-SFSC farms these values were 10.7% and 55.0%, respectively. At the same time, non-SFSC farms had a higher livestock density per unit area – 1.2 LU/ha UAA, while in SFSC farms it was 0.9 LU. These differences in crop structure and livestock density result from the fact that sales in short channels primarily concern fruit and vegetables. Therefore, the results of the specified sustainability dimensions may, to some extent, result from differences in crop production structure and animal density.

Supplementary S2 – construction of sustainability indicators

The selection of a set of variables for each group was based on substantive premises, a discussion among experts (a total of 16 scientists from 6 academic centers in Poland, Romania and Serbia), taking into account the literature on the subject and the availability of data collected during the interviews. The economic component included three classic variables describing productivity, i.e. production per ha of agricultural land, production per unit of family work (i.e. Family Work Unit), production per unit of productive assets, and also a subjective assessment of the financial situation, level of saving and debt. A similar approach was used by, among others, Bartkowiak-Bakun (2025), Bossel (1999), FAO (2017), Farouq and Sulong (2025), Latruffe (2010), Yu et al. (2025). The economic sustainability of a farm refers to its ability to efficiently utilize production resources, generate stable income, and maintain financial stability over the long term. Efficient use of basic production factors is particularly important for short supply chains, as they often rely on a greater amount of labour, operate on relatively smaller areas, and require capital investment (processing, logistics, certification, etc.). Using measures of basic production factor productivity allows us to assess whether farms participating in short supply chains are able to effectively convert their resources into income, which is the foundation of their economic sustainability. A subjective assessment of a farm's financial situation complements objective measures of efficiency, reflecting the perceived economic stability and the farm's ability to function under the risk conditions typical of short supply chains. Considering savings and debt levels allows us to assess the farm's financial sustainability and its ability to sustain operations in the long term. It also allows us to assess investment capacity, which in the case of SFSCs involves, for example, adapting premises for sales or processing and purchasing necessary infrastructure (machinery and equipment, refrigerators).

To determine the social component, housing conditions, health and physical condition, and the level of socialisation of the farm (the so-called socialisation index) were used, the latter measured by: 1) participation of the farmer in continuing education (training, courses, workshops, postgraduate schools, etc.) – yes/no answer; 2) participation of the farmer in cultural and social events (cinema, theatre, concerts, fairs, etc.) – yes/no answer; 3) membership of the farmer in an organisation, association, producer group, cooperative, etc. – yes/no answer. The above-mentioned elements determine the quality of life. For example, housing conditions and educational needs are identified as some of the key human needs by authors such as Awan et al. (2025), Beckerman and Bacon (1966), Lebacq et al. (2013) and Stępień et al. (2017). Last mentioned, as well as van Cauwenbergh et al. (2007) draw attention to cultural elements, traditions and ethical values as significant for this assessment. Housing conditions are a fundamental indicator of the quality of life especially for farms involved in short supply chains, if only because customer contact often takes place within the household. The health and physical condition of the farm owner reflects the state of human capital, which plays a key role in farms participating in short supply chains due to the high level of individual labour and direct involvement in production and distribution processes. The farmer's involvement in the functioning of the local community, the so-called socialization, is considered an important factor of social dimension in rural areas. Data on this subject are not common, which increases the value of this factor in determining social sustainability (Roobavannan et al, 2025; Vrolijk et al., 2016). The degree of socialization of the farm is crucial for the functioning of SFSCs, which are based on relationships, trust, and interpersonal contacts. Social integration and local embeddedness increase the farm's adaptability and are one of the factors contributing to the sustainability of short selling.

The environmental component, in turn, consists of the following elements: crops monoculture index, share of cereals in the total crop area, share of arable land coverage outside the season, share of permanent grasslands in the total area, share of forested land in the total area, livestock units index , expenditure on energy, fertilisers and pesticides. The justification for the selection of these variables can be found in the works of Awan et al. (2025), Bathaei & Baum (2011), Castillo-Díaz et al. (2025), Duer et al. (2002), Harasim (2012), Vereijken (1997).

In that case, three complementary dimensions of a farm's environmental impact were considered: (1) land use structure and biodiversity, (2) production pressure and degradation risk, and (3) the intensity of environmentally burdensome inputs. The level of crop diversity and the share of cereals in the crops reflect the degree of diversification of crop production and the stability of the agroecosystem. In this context, it is assumed that short food supply chains promote diverse production, local varieties, and greater product flexibility. The share of arable land covered with vegetation in winter, the share of permanent grassland, and the degree of forestation indicate the use of conservation practices, attention to long-term soil fertility, and promote water retention and carbon sequestration. Since one of the success factors of SFSCs is offering environmentally friendly products, such a set of variables seems justified. The share of permanent grassland, along with the animal density, allows for an assessment of the efficiency of animal husbandry systems, which is important for potential customers involved in short selling (high-quality meat from extensive farming is preferred over meat from industrial, intensive production). Energy expenditures are a significant indicator of the environmental sustainability of farms participating in short supply chains, as they reflect the energy intensity of both production processes and the local forms of processing, logistics, and distribution characteristic of this model. Assessing the level of expenditure on fertilizers and pesticides is important for building trust and reputation among potential customers by improving food quality and reducing chemical use.

Supplementary S3 – SEM specification

Structural Equation Modeling (SEM) can be understood as an extension of path analysis that incorporates latent variables – also referred to as unobserved or theoretical variables – which underlie observable indicators in the dataset (Hoyle, 2012). These latent variables are not directly measurable; instead, they are approximated through indicators that represent components of a given construct (Rabe-Hesketh et al., 2007). Their values can only be inferred from observable indicators, even though they originate from an unobserved, latent construct. Path analysis provides a graphical way to represent theoretical models, using standard notations to replace complex sets of equations. This visualization highlights the relationships among measured variables, capturing direct, indirect, and overall effects. In such diagrams, ellipses denote latent variables, while rectangles indicate observed ones. Parameters (ε) represent the measurement error associated with observed variables. Covariance, or non-directional relationships, is shown as a curved double-headed arrow, whereas straight single-headed arrows indicate directional paths or regression effects.

Supplementary Table 1. Hypotheses verified in the SEM model

No	Var_num	Relationship	Expected Sign	Literature references
H1	e1	Land productivity has a positive impact on economical dimension/construct	+	Kirmikil & Arici (2013), Senanayake et al. (2021)
H2	e2	Labour productivity has a positive impact on economical dimension/construct	+	Kirmikil & Arici (2013), Saad et al. (2025), Veipane et al. (2025)
H3	s1	Good housing conditions have a positive impact on social dimension/construct	+	Fan et al. (2025), Wu et al. (2025)
H4	s2	Good health condition has a positive impact on social dimension/construct	+	Kang et al. (2025)
H5	s3	High level of socialisation has a positive impact on social dimension/construct	+	Schäfer & Morillas (2025)
H6	v1	Crop monoculture has a negative impact on environmental dimension/construct	-	Olsson et al., (2024), Bouvier, Lavigne, Sentenac, & Boivin, (2024)
H7	v2	High share of cereals has a negative impact on environmental dimension/construct	-	Gharaei et al. (2025), Istudor et al. (2025)
H8	v3	High animal density per unit area has a negative impact on environmental dimension/construct	-	Nacimento et al. (2022), Yildirim (2025)
H9	v4	High usage of pesticides has a negative impact on environmental dimension/construct	-	Geballa-Koukoula et al. (2026)
H10	cor_ECO-SOC	economic and social dimensions/constructs are positively correlated	+	Ninh & Tam (2026), Ishaq et al. (2026)
H11	cor_ECO-ENV	economic and environmental dimensions/constructs are positively correlated	+	Acevedo-Arenas, Guerrero-Macias, Muñoz-Maldonado, Amado-Alvarado, & Petit-Suárez (2026)
H12	cor_ENV-SOC	environmental and social dimensions/constructs are positively correlated	+	Ishaq et al., (2026)

Supplementary references

Acevedo-Arenas, C.Y., Guerrero-Macias, J.E., Muñoz-Maldonado, Y.A., Amado-Alvarado, J.S., and Petit-Suárez, J.F. (2026). Grid extension vs. off-grid systems in rural Areas: Methodologies, tools, and criteria for decision-making. Utilities Policy, 99, 102028. https://doi.org/10.1016/j.jup.2025.102028

Awan, A., Hossain, M., Ngoc, B., Yusoff, N., and Tiwari, A. (2025). Investigating the time-invariant impact of agriculture on environmental degradation: focusing on pesticide use, human capital, and green energy. Journal of Environmental Planning and Management. https://doi.org/10.1080/09640568.2025.2504522

Bartkowiak-Bakun, N. (2025). Diversification of Rural Development in Poland: Considerations in the Context of Sustainable Development. Sustainability, 17(2). https://doi:10.3390/su17020519

Bathaei, A., & Streimikiene, D. (2025). Assessing Sustainable Agriculture in the EU/Baltic Countries Using Multi-Criteria Decision Making (MCDM) and EUROSTAT Data Using Stakeholder's View. Sustainable Development, 33(5), 7429-7440. https://doi.org/10.1002/sd.3529

Beckerman, W., and Bacon, R. (1966). International comparisons of income levels – suggested new measure. The Economic Journal, 76(303): 519-536. https://doi.org/10.2307/2229519

Bossel, H. (1999). Indicators For Sustainable Development: Theory, Method, Applications. Winnipeg. International Institute of Sustainable Development.

Bouvier, J.Ch., Lavigne, C., Sentenac, G., and Boivin, T. (2024). Environmental filtering and landscape composition drive multifaceted diversity of bird assemblages in vineyards. Journal of Applied Ecology, 61(4), 746-758. https://doi.org/10.1111/1365-2664.14587

Castillo-Díaz, F., Belmonte-Ureña, L., Gálvez-Sánchez, F., & Camacho-Ferre, F. (2025). Sustainable technological innovations in agriculture: Financial challenges and investment priorities under the European Green Deal. Journal of Environmental Management, 389. https://doi.org/10.1016/j.jenvman.2025.126150

Duer, I., Fotyma, M., and Madej, A. (2002). Kodeks dobrej praktyki rolniczej. Warsaw. MRiRW– FAPA.

Fan, N., Chen, X., and Yang, Z. (2025). Does affordable housing provide a better life for vulnerable groups? Measuring social equity through public transit accessibility. Journal of Transport Geography, 128. https://doi.org/10.1016/j.jtrangeo.2025.104340

Farouq, I., and Sulong, Z. (2025). The resource-rich countries' blue economy: prospects for sustainable economic development. Romanian Journal of Economic Forecasting, 29(2), 120-146.

Geballa-Koukoula, A., Pijper, M., Senou, O., Zomer, P., and Peters, J. (2026). Effective rapid screening for sulfoxaflor insecticide in ornamental flowers by paper-based biosensing formats implementing sustainable extraction and packaging approaches. Talanta, 300. https://doi.org/10.1016/j.talanta.2025.129168

Gharaei, M., Gliesmi, B., and Roig, J. (2025). From metrics to insights: Evaluating cereal farming sustainability in Catalonia using composite index approach. Agricultural Economics-Zemedelska Ekonomika, 71(11), 592-603. https://doi.org/10.17221/462/2024-AGRICECON

Harasim, A. (2012). Ocena produkcji roślinnej na gruntach ornych w gospodarstwie rolniczym w ujęciu długookresowym. Monografie i Rozprawy Naukowe IUNG, 34(63).

Hoyle, R. H. (2012). Handbook of Structural Equation Modeling. New York. The Guilford Press.

Ishaq, H., Siddiqui, O., and Tseng, C. (2026). Replacing conventional energy resources with wind: An integrated economic, environmental, and social assessment. Utilities Policy, 99. https://doi.org/10.1016/j.jup.2025.102085

Istudor, N., Constantin, M., Privitera, D., Ignat, R., Petrescu, I., and Teodor, C. (2025). Systemic Competitiveness in the EU Cereal Value Chain: A Network Perspective for Policy Alignment. Land, 14(4). https://doi.org/10.3390/land14040731

Kang, Q., Li, X., and Li, L. (2025). Implications for the Global South: China's Integrated Health Care Delivery System as a Public Good With Institutional Strengths. Chinese Public Administration Review. https://doi.org/10.1177/15396754251385345

Kirmikil, M., and Arici, I. (2013). The use of landscape metrics to assess parcel conditions pre- and post-land consolidation. Journal of Food Agriculture & Environment, 11(2), 985-989.

Latruffe, L. (2010). Competitiveness, Productivity and Efficiency in the Agricultural and Agri-Food Sectors. OECD Food, Agriculture and Fisheries Papers, 30: 12-30. https://doi.org/10.1787/5km91nkdt6d6-en

Lebacq, T., Baret, P.V., and Stilmant, D. (2013). Sustainability Indicators For Livestock Farming. A Review. Agronomy For Sustainable Development, 33: 317-327.

Nacimento, R., Luiz, V., Mendes, C., Giannetti, B., & Gameiro, A. (2022). Sustainability comparison of commercial Brazilian organic and conventional broiler production systems under a 5SENSU model perspective. Journal of Cleaner Production, 377. https://doi.org/10.1016/j.jclepro.2022.134297

Ninh, N., and Tam, T. (2026). The role of social capital in enhancing community participation for sustainable agricultural tourism. Sustainable Futures, 11. https://doi.org/10.1016/j.sftr.2025.101612

Olsson, L., Andersson, E., Ardoe, J., Crews, T., David, C., Dehaan, L., . . . Vestin, P. (2024). What is the prospect of a perennial grain revolution of agriculture? Global Sustainability, 7. https://doi.org/10.1017/sus.2024.27

Rabe-Hesketh, S., Skrondal, A., and Zheng, X. (2007). Multilevel Structural Equation Modeling. Sik-Yum, L. (ed.), Handbook of Latent Variable and Related Models. Hongkong. Elsevier.

Roobavannan, M., Kandasamy, J., and Vigneswaran, S. (2025). Policy Measures to Lead Sustainable Development of Agriculture Catchment: Socio-Hydrology Modeling Insights. Hydrology, 12(2). https://doi.org/10.3390/hydrology12020029

Saad, S., Ramli, Z., and Lyndon, N. (2025). The relationship between work environment and labour productivity. Geografia-Malaysian Journal Of Society & Space, 21(3), 190-208. https://doi.org/10.17576/geo-2025-2103-12

Schäfer, G., and Morillas, M. (2025). Strangers in paradise? The wellbeing of migrant professionals across professional and personal environments. Comparative Migration Studies, 13(1). https://doi.org/10.1186/s40878-025-00447-x

Senanayake, S., Pradhan, B., Huete, A., and Brennan, J. (2021). Proposing an ecologically viable and economically sound farming system using a matrix-based geo-informatics approach. Science of The Total Environment, 794. https://doi.org/10.1016/j.scitotenv.2021.148788

Stępień, S., Smędzik-Ambroży, K., and Guth, M. (2017). Oddziaływanie Wspólnej Polityki Rolnej na zrównoważenie ekonomiczno-społeczne gospodarstw rolnych na przykładzie polski. Wieś i Rolnictwo, 4(177): 39-58. https://doi.org/10.53098/wir042017/03

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Cidad, V. G., Hermy, M., Mathijs, E., Muys, B., Reijnders, J., Sauvenier, X., Valckx, J., Vanclooster, M., Van Der Veken, B., Wauters, E., and Peeters, A. (2007). Safe – A Hierarchical Framework For Assessing The Sustainability Of Agricultural Systems. Agriculture Ecosystems & Environment, 120: 229-242.

Veipane, U., Pilvere, I., Lillemets, J., Bilande, K., and Nipers, A. (2025). Land Use and Production Practices Shape Unequal Labour Demand in Agriculture and Forestry. Land, 14(10). https://doi.org/10.3390/land14102097

Vereijken, P. (1997). A metodical way of prototyping integrated end ecological arable farming systems (I/EAFS) in interaction with pilots farms. Perspectives of Agronomy, Developments in Crop Science, 25: 293-308.

Vrolijk, H., Poppe, K., and Szilard, K. (2016). Collecting Sustainability Data In Different Organisational Settings Of The European Farm Accountancy Data Network. Studies in Agricultural Economics, 118(3): 138-144. https://doi.org/10.7896/j.1626

Wu, R., Pomeroy, M., Prichett, L., Duchen, J., Runge, K., Andes, L., and Cudjoe, T. (2025). Prevalence and Correlates of Social Isolation Among Older Adults in Subsidized Housing. Gerontologist, 65(5). https://doi.org/10.1093/geront/gnaf017

Yildirim, R. (2025). From livestock manure to renewable energy: multicriteria assessment of carbon footprint and environmental impacts. Integrated Environmental Assessment and Management. https://doi.org/10.1093/inteam/vjaf157

Yu, N., Xiong, K., Zhao, R., and Feng, F. (2025). Quantification and attribution of agriculture eco-efficiency in the desertification control of South China Karst core area. Environment Development and Sustainability. https://doi.org/10.1007/s10668-025-06286-1