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CONCEPTUAL MODEL OF A COMMUNITY-DRIVEN CIRCULAR SUPPLY CHAIN FOR BIOGAS PRODUCTION

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Abstract:
This research aimed to develop a specific replicating conceptual model for the establishment and maintenance of a circular supply chain for biogas production at the community level. The village Ilandža (Serbia) was selected to pilot the model, with four main goals: risks and benefits identification, spatial analysis, crops and by-products evaluation, and capacity building and sustainability. The research showed that a balanced application of *energy crops cultivation* and *by-product utilization* can result in biogas supply chain sustainability. Biogas production actions should be planned according to areas, energy crops, and by-products priority lists developed participatory. Entrepreneurs' capacities should be strengthened enough to implement such a comprehensive model. A monitoring system should be defined as participatory and should be applied during the implementation of each community-driven biogas project. Also, evaluation of strategies should be conducted after each project. All stakeholders must be informed of the importance of sustainable community-based entrepreneurship and actions.

Keywords:
energy crops, marginal lands, by-products, risk identification, community awareness.

1. INTRODUCTION

A conceptual model is a tool for visually depicting the context within which a community project is operating and the major impacts on society and the environment. A well-developed model should link community goals to the main direct and indirect threats and benefits that can be turned into opportunities and provide the basis for defining strategy and specific actions (Margoluis et al., 2009; Amidžić, Veličković & Trkulja Vujičić, 2019; Chioatto & Sospiro, 2023). Circular supply chains are a very efficient model to address the problem of waste at the community level (Mukherjee, 2020). In the process of anaerobic digestion (AD), it is possible to convert energy from a wide range of biomass, including biodegradable waste, manure, sludge, biodegradable polymers, and biomass originating from agro-energy crops (De Meester et al., 2012). As a way out of the process, biogas, and the rest (digestate) appear. The digestate can be used as a biological fertilizer or as a top dressing, depending on the composition (which reflects the starting material and the design of the microbiological process and the reactor) (Nkoa, 2014). A large number of studies relate to improving the quality of marginal lands to enable acceptable yields of different crops and manage nutrient cycles in AD plants and their surroundings (Duan et al., 2018). The results vary, because of lands of different structures, climatic conditions, and crops, among which agro-energy crops should be considered. For example, *Sida hermaphrodita* on marginal soils has a significantly higher yield when digestate is applied (Nabel et al., 2017), and sorghum with adequate nitrogen supplementation on marginal soils achieves yields that are sustainable in the use of silage for biogas production (Ameen et al., 2017).

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This research aimed to develop a specific replicating conceptual model for establishing and maintaining a circular supply chain for biogas production at the community level and to test it in a local community. The village of Ilandža in the municipality of Alibunar in Serbia was selected to pilot the developed conceptual model.

2. MATERIALS AND METHODS

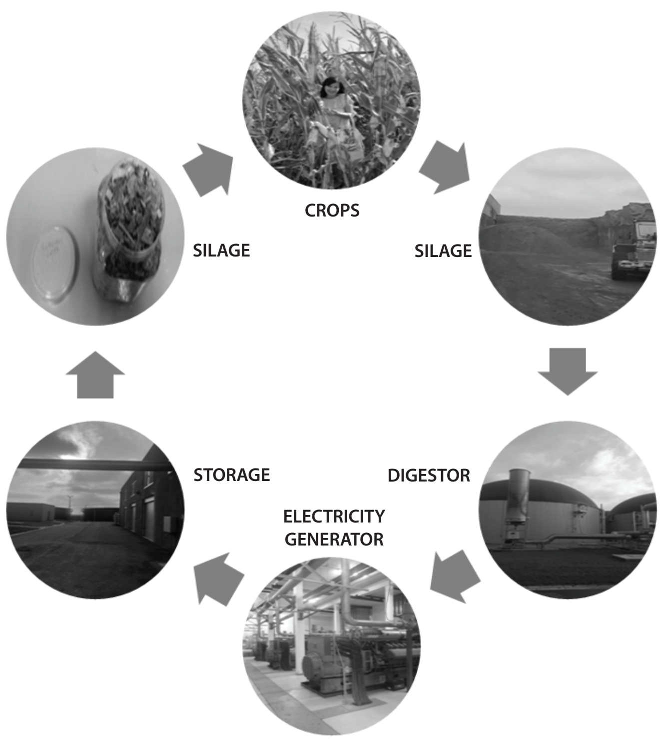
2.1. DEVELOPMENT OF A CONCEPTUAL MODEL

We used universal building components of a conceptual model, proposed by Margoluis et al. (1998, 2009) and adapted them for the needs of a specific community-based biogas project and the pilot locality. The first step was to determine the *scope* of the project which is related to the selected pilot area as well as conceptual targets. Brainstorming was done with the managers of the selected biogas power plant to define *direct threats* to their supply chain and the main *indirect threats/contributing factors* related to policy, social, and/or economic context. The parameters of the current situation defined the *opportunities* for improving the status by implementing the activities of the circular supply chain project.

2.2. DESCRIPTION OF THE PILOT AREA

Village Ilandža in the municipality of Alibunar (Serbia), was selected as an example of a local community exposed to environmental, social, and economic pressures. Here, the company Biogas Energy Alibunar owns 11.4 ha of construction land, including the power plant with ancillary facilities on 4.5 ha, and the land that they receive by right of first refusal based on infrastructure, with a total area of 204 ha. The total planned capacity of the power plant is 3 MW of electricity per year. Electricity is produced in three special GE Jenbacher plants, each with a total power of 999kW, as well as 3.6 MW of thermal energy per year, which can be converted into water vapor in a cogeneration plant, with a total capacity of 2100 kg/h. In the AD process, 80,000 tons of raw materials are used. For the planned production of biogas, it is necessary to provide a maximum of 40% of raw material from silage. In the AD process, digestate is formed as a by-product, about 16,000 tons per year. The digestate from the digester goes to the separator, where the liquid and solid are separated. Liquid digestate is stored in special tanks until the export to agricultural plots. Solids can be dumped on agricultural land, spread using manure spreading trailers, and liquid using trailers or watering systems on sown crops on the plot (Figure 1). An additional 480 ha of agricultural land, as well as the part of the irrigation system covering 400 ha of land, are used for their own production of substrates used in the biogas power plant. Also, the company receives raw materials from subcontractors from an area of 1 100 ha.

Figure 1. The production process in the biogas power plant in Ilandža.



2.3. DESK RESEARCH AND FIELDWORK

Desk research included the collection of all data on the pilot locality and biogas facility. Fieldwork included identification and spatial definition of marginal lands suitable for energy crops cultivation in Serbia, experiments to assess productivity and potentials for biogas production of different energy crops, and experiments to assess the effects of by-products on the cultivation of different crops.

3. RESULTS AND DISCUSSION

3.1. CONCEPTUAL MODEL OF A CIRCULAR SUPPLY CHAIN FOR BIOGAS PRODUCTION

The community-driven circular supply chain for biogas production, developed on the example of village Ilandža, is shown in Figure 2. Here, we opted to place *a circular supply chain* as the scope of the conceptual model.

The conceptual model emphasizes four main *goals*:

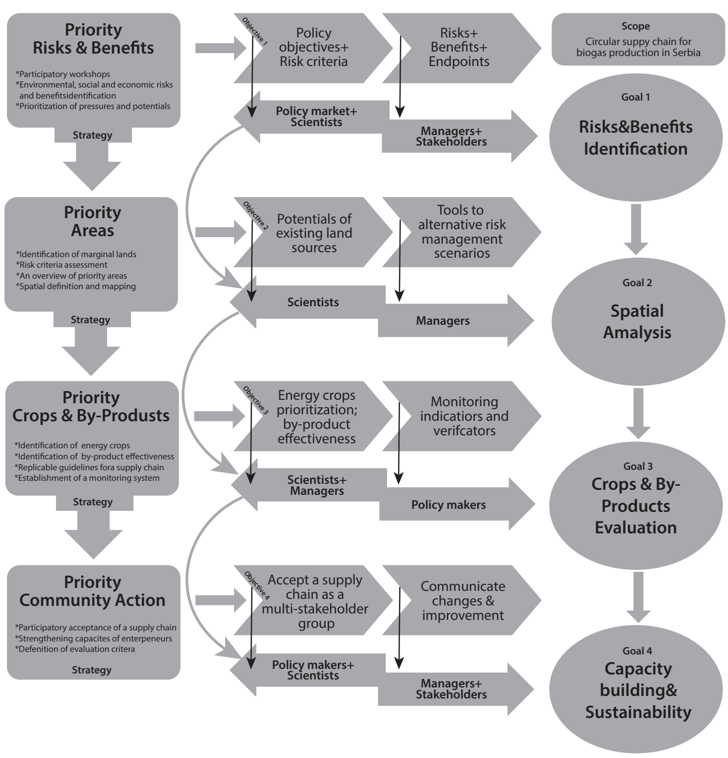
Goal 1 (*Risks* & *Benefits Identification*): Participatory identification and prioritization of all risks and benefits related to biogas production in the village. The indispensable contributors to this goal are policymakers, scientists, managers/entrepreneurs, and all other stakeholders. A set of actions, within the strategy titled *Priority Risks* & *Benefits*, included several participatory workshops, reporting on threats and opportunities identified by stakeholders, and priority lists of pressures/risks and opportunities/benefits.

Goal 2 (*Spatial Analysis*): Scientific approach to availability and productivity of existing land sources and identification of possible tools to alternative risk management scenarios. The main strategy to fulfill this goal was to define *Priority Areas* for energy crops cultivation. The main output was an overview and a map of marginal lands prioritized according to the risk criteria. This step was implemented by scientists with the support of managers/landowners or users during the field survey.

Goal 3 (*Crops and By-Products Evaluation*): Prioritization of energy crops suitable for cultivation on spatially defined marginal lands, assessment of by-product effects on energy crops production to be able to achieve higher yields, and establishment of a consistent monitoring system based on measurable indicators and verifiers. A strategy titled *Priority Crops* & *By-Products* included: a priority list of energy crops; identification of by-products and their effects on crops cultivation; development of replicable guidelines for a biogas circular supply chain to be maintained; and establishment of a monitoring system.

Goal 4 (*Capacity Building* & *Sustainability*): The final goal within the model should ensure the sustainability of the whole scope and all previously implemented actions. For community-driven projects to take root, they need to be embraced by stakeholders, through participatory workshops and discussions. This step involves all participants, from community decision makers, through scientists, managers/entrepreneurs, to all stakeholders. Strengthening the capacities of managers/entrepreneurs for the implementation of the conceptual model is necessary as well as the definition of evaluation criteria for proposed actions.

Figure 2. Conceptual model of a community-driven circular supply chain for biogas production piloted in Ilandža.



The following project activities that contribute to the strategies defined within the model have been identified:

Priority Risks & Benefits

1. Participatory workshops for risks and benefits identification and prioritization.
2. A report on risks and benefits identification.
3. A list of priority risks to be addressed and benefits to be exploited.

Priority Areas

4. Field survey and identification of marginal lands.
5. Assessment of the degree of endangerment of identified areas/risk criteria assessment.
6. An overview of priority areas for energy crops cultivation.
7. Spatial definition and mapping of the priority localities.

Priority Crops & By-Products

8. Prioritization of energy crops suitable for cultivation on spatially defined marginal lands.
9. An assessment of by-products effects on energy crops production.
10. Development of replicable guidelines for a biogas circular supply chain based on the model.
11. Establishment of a monitoring system.

Priority Community Actions

12. Participatory elaboration and acceptance of the proposed conceptual model.
13. Strengthening the capacities of managers/entrepreneurs.
14. A well-structured public awareness campaign.
15. Definition of evaluation criteria.

3.2. APPLICATION OF THE CONCEPTUAL MODEL IN SERBIA

The application of the conceptual model in the village of Ilandža enabled the establishment of a sustainable project.

Goal 1 (*Risks & Benefits Identification*)

The participatory approach mapped a significant number of pressures and threats to the sustainability of community development as well as to biogas production. Risk prioritization (7 priorities) was performed as follows:

1. depopulation (village-town migration)
2. lack of rural economy diversification
3. no completed value chain for biogas production
4. declining soil quality for agriculture
5. unsustainable biomass yields
6. natural disasters
7. climate change

Depopulation was recognized as the risk of the first priority. It is most rational to produce biomass on marginal lands, which are located near biogas power plants, where it is necessary to apply additional measures to achieve sustainable yields. In this way, the value chain at the community level is completed, the lack of which is recognized as the third priority risk. Soil shows poorer production capacities, which is a consequence of the long-term inadequate management that has led to the deterioration of physical, chemical, and biological characteristics, recognized as the fourth priority risk. A power plant must have a constant inflow of biomass to function sustainably. It is necessary to provide sufficient quantities of energy crops, produced on marginal lands, which is often not feasible. Unsustainable biomass yields are identified as the fifth priority risk. The danger of natural disasters is a consequence of climate change, both of which have been identified as the sixth and seventh priority risks.

Also, a significant number of benefits have been identified. Environmental benefits include reduced greenhouse gas emissions, as the methane is used as biogas in the power plant, and improvement of the production capabilities of degraded lands. Social benefits are mitigation of climate change using renewable energy sources. Economic benefits are related to the fact that mineral fertilizer necessary for biomass production is substituted by a by-product from their own production, the possibility of placing digestate to subcontractors while avoiding long-term storage, and a production chain is established on the nearest land.

Goal 2 (*Spatial Analysis*)

Degraded land suitable for biofuel production is formed through very intensive agricultural activities or chemical pollution. Crop production is not possible on this land and there is an opportunity for energy crops cultivation. An added value is soil remediation. Additional potential localities for biofuel production are wastelands (Milovanović et al., 2012) and surface exploitation areas which should be re-naturalized.

Identification of marginal land for energy crops cultivation is a challenge due to insufficient data and unclear definitions of land categories. Within this goal, we identified and quantified marginal lands in Serbia and prioritized them according to the risk criteria. The most important areas for growing energy crops are categorized as unused agricultural land which covers over 420 000 ha. This land is most often not used due to decreased soil fertility or contamination. The categorization included three degrees of fertility degradation: optimal fertility (no reduction of fertility parameters), reduced fertility (one fertility parameter reduced), and degraded (more than one fertility parameter reduced). Three classes of soil have also been established depending on the degree of contamination:

none, one, or more than one parameter above the permitted limit. In addition to unused agricultural land, energy crops can be grown on about 11,000 ha of degraded land due to surface exploitation and on about 1,500 ha of ash dumps. The total area of marginal land, suitable for growing energy crops, is about 436 500 ha in the whole of Serbia (Radojević et al., 2015).

In the case of the province Vojvodina, where the village of Ilandža is located, marginal land belongs to the category of unused agricultural land. Prioritization of areas available for energy crops cultivation (7 priorities) was performed as follows:

1. Contaminated agricultural land (more than one parameter above the permitted limit).
2. Contaminated agricultural land (one parameter above the permitted limit).
3. Surface exploitation land located in Vojvodina (e.g., Kovin which is closest to the village).
4. Abandoned and degraded agricultural land (more than one fertility parameter reduced).
5. Abandoned agricultural land with reduced soil fertility (one fertility parameter reduced).
6. Ash dumps closest to the village (e.g., Obrenovac, Kostolac, and Kolubara).
7. Abandoned agricultural land of optimal fertility (in case there are no other options).

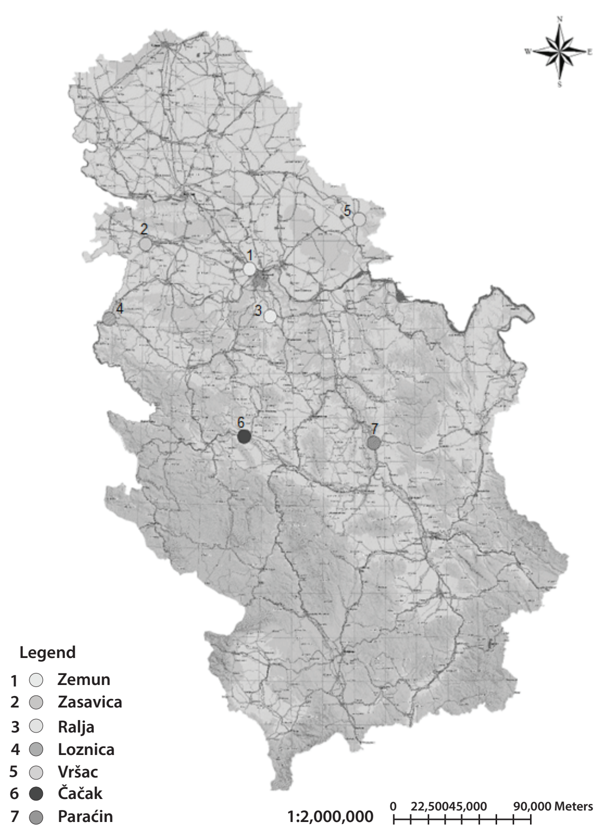
Goal 3 (*Crops and By-Products Evaluation*)

In accordance with the list of priorities of marginal lands, experimental research was conducted to assess the productivity of different energy crops and their ability to remediate degraded and contaminated soils. Productivity and adaptability of the energy crop *Miscanthus* × *giganteus* Greef et Deu has been researched in Serbia for more than 14 years (Dražić et al., 2010; Jureková & Dražić, 2011; Milovanović et al., 2012; Aranđelović et al., 2014; Dražić, Milovanović & Aranđelović. 2014; Marišová, Milovanović & Djordjević, 2016; Dražić et al., 2018; Milovanović, Radojević & Šijačić-Nikolić, 2017) (Figure 3), showing that the production of this energy crop is possible.

In field conditions, the expected quality of biomass was obtained in terms of the content of relevant elements, moisture, and energy values. It has been shown that in the conditions of the field experiments during the development of miscanthus, significant recycling of the relevant elements occurred, and yields showed the expected values, while in some extreme conditions, the production of miscanthus biomass was not possible.

The energy efficiency of miscanthus biomass production is strongly influenced by the method of cultivation on the energy consumption side and the achieved yields on the energy production side. In Serbia, optimal values of the energy balance can be easily achieved in seasons without extreme droughts.

Figure 3. Locations of Miscanthus × giganteus Greef et Deu experimental plots in Serbia.



The harvest should be done as late as possible, just before the beginning of the new vegetation cycle. Delaying the harvest accelerates the translocation of nutrients from aboveground parts into rhizomes, while fertilization provides a sufficient amount of nitrogen necessary for the next vegetation cycle. The cycle is repeated on the same plot for up to 20 years. The advantage of miscanthus compared to other raw materials is that it can be grown on contaminated or degraded land, with the potential for bioremediation of contaminated soil and water.

The second energy crop, researched in Serbia for many years, is *Sorghum bicolor* L. The most important segment of the research, from the aspect of the development of the circular supply chain for the production of biogas, is the examination of the effects of by-products on the production of energy crops. The effects of digestate from the AD process application were investigated for the production of sorghum and corn. The results of the experimental research were presented to the local community and the prioritization of energy crops and by-products for the needs of the functioning of the circular supply chain (5 priorities) in the village of Ilandža was performed as follows:

1. Cultivation of miscanthus and sorghum on contaminated agricultural land by applying digestate.
2. Cultivation of miscanthus and sorghum on surface exploitation land by applying digestate.
3. Cultivation of miscanthus and sorghum on ash dumps by applying digestate.
4. Cultivation of miscanthus and sorghum on degraded agricultural land by applying digestate.
5. Cultivation of miscanthus and sorghum on land with reduced soil fertility by applying digestate.

Defining replicable guidelines for a community-driven circular supply chain for biogas production was a very important action within the conceptual model. The guidelines contain a comprehensive monitoring system.

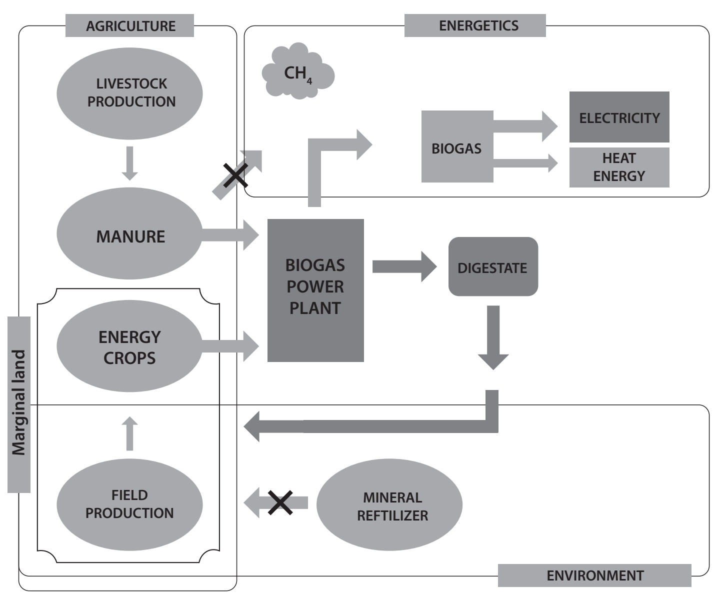
Goal 4 (*Capacity Building* & *Sustainability*)

Based on the participatory prioritization of marginal areas, energy crops, and by-products, a circular supply chain for the power plant in the village of Ilandža was developed and accepted by the local community (Figure 4).

Biomass from energy crops is a necessary raw material for the AD process because manure does not have satisfactory energy characteristics (Scarlat et al., 2018). It is most rational to produce this biomass on marginal lands (Cervelli, Scotto di Perta & Pindozzi, 2020), which are located near biogas power plants. As such lands have poorer production capabilities, it is necessary to apply additional measures to achieve sustainable yields. As a by-product of the AD process, digestate is formed, which can be used to improve the characteristics of marginal soils and the production of energy crops. In this way, a circular supply chain is created, which engages the entire local community and creates the preconditions for sustainable rural development.

The acceptance of the proposed supply chain and changes in the community management by stakeholders was the priority. A series of participatory workshops for presenting the conceptual model and the supply chain have been organized and the impact of the proposed actions on the daily activities of the local community and other stakeholders were estimated. The conceptual model envisages an awareness-raising strategy to disseminate information on the circular supply chain, as well as to prevent inadequate decisions by policymakers. A well-structured media campaign was established, followed by the printing and distribution of information packages.

Figure 4. Community-driven circular supply chain for biogas production in the village of Ilandža.



To prevent untimely and unprofessional reactions to pressures, it was necessary to develop a comprehensive system of monitoring and evaluation of the community-driven biogas project. The presented conceptual model was a basic tool for defining indicators for monitoring and evaluation. The conceptual model envisages the development of a program for strengthening the capacities of managers/entrepreneurs for the implementation of the model and manages the process by sustainability principles.

4. CONCLUSION

The main messages of the conceptual model were as follows:

- Only a balanced application of two approaches, 1) energy crops cultivation and 2) by-products utilization, can result in biogas supply chain sustainability on a community level.
- Biogas production actions should be planned according to areas, energy crops, and by-products priority lists developed participatory, combining desk research, field surveys, and stakeholders' attitudes.
- Managers'/entrepreneurs' capacities should be strengthened to be able to implement such a comprehensive conceptual model.
- A monitoring system should be defined as participatory and applied during the implementation of each community-based biogas project.
- An evaluation of strategies and actions should be conducted after each project with the aim of proposing their redefinition.
- All stakeholders must be informed on the importance of sustainable community-based entrepreneurship, and the planned and applied actions, providing indispensable inputs to the process.

5. ACKNOWLEDGMENTS

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