Eco-innovation assessment of biodigesters technology: an application in cassava processing industries in the south of Brazil, Parana state

Marco Antonio Sampaio de Jesus¹ · Ana Regina de Aguiar Dutra¹ · Claudia Brito Silva Cirani² ·
Katia Regina Evaristo Jesus³ · Ruy Castro Sobrosa Neto¹ · José Baltazar Andrade Guerra¹

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Abstract

Eco-innovations are innovations capable of helping to reduce the environmental impacts of production processes. In this sense, the adoption of models that assess comprehensively, in an integrated manner and in different perspectives, the general performance of these innovations allows managers to guide their decisions. The object of this research is the use of an eco-innovation in the production processes of cassava, where the waste generated is treated by biodigesters. These cassava processing industries are located in southern Brazil, Paraná State, comprising a multiple case study. A literature review was also carried out to propose a set of indicators capable of assessing the overall impact of this eco-innovation in eight lines of action: (1) environmental, (2) social, (3) economic, (4) human resource training, (5) institutional development, (6) introduction of innovation, (7) unwanted occurrences, and (8) characteristics of environmental management. To compile and process the data, the computerized model INOVA-tec System was used. The objective was to employ the INOVA-tec System model as an instrument for evaluating eco-innovative processes in leading companies in its segment, looking for evidence to expand its usability to other realities in the agro-industry. The results show that the technology scenario is favorable to its dissemination; however, the low performance of the indicators together makes it underutilized.

Graphical Abstract

Keywords Eco-innovation · Sustainability · Environmental performance assessment · Biogas or biodigester · Cassava processing industry

Introduction

The world has been facing problems related to sustainability, be they economic, environmental, and/or social. Part of these problems was exacerbated by the COVID-19

✉ José Baltazar Andrade Guerra
jose.baltazarguerra@animaeducacao.com.br

Extended author information available on the last page of the article

pandemic, while another part in the view of some researchers was minimized. Social and economic problems associated with social isolation have amplified existing problems, while researchers have pointed out the fact that fewer people used means of transport and this minimized the environmental impact during the period of isolation imposed by the presence of COVID-19 (Tisdell 2020; Saladié et al. 2020).

Socioeconomic development and a clean and healthy environment are basic conditions for maintaining sustainable economic well-being and the good standard of living of a population (Auzina and Zvirbulė 2016), which together with energy consumption are elements capable of assessing the HDI, as well as employment, capital, and R&D (Menegaki and Tugcu 2017). To deal, mainly, with environmental problems, there is a worldwide pressure for models that prioritize the sustainable development of nations. For Jesus Pacheco et al. (2017), the ideas of reducing the environmental impact, maintaining life, and existing natural resources are associated with classic innovations in products, processes, and innovation management practices.

The concept of sustainable development is not yet unanimous in scientific publications, and its origins as well as the contributions coming from different sciences and schools are still confused (Barbieri et al. 2010). For some years, this concept has been present in the discourse of companies with a minimum of market perception. Many companies are still limited to defensive initiatives, for example, introducing quality actions only at the end of the production process (Porter and Kramer 2006), instead of incorporating the ideals of sustainable development as catalysts for innovations. One such possibility to be explored in this sense is eco-innovation.

In general, studies on eco-innovations characterize them as new or improved products, processes, or services, which can meet human needs and provide quality of life, while significantly reducing environmental impacts, as well as enhancing development sustainable production, and consumption in organizations of all sizes (Isa et al. 2019; Barbieri and Santos 2020), aiming at the sustainable business performance (García-Granero et al. 2020). It should also be noted that eco-innovations provide a dynamic of knowledge generation and diffusion that determines the direction and selection of paradigms and technological trajectories, to be adopted, sometimes causing the discontinuity of a technology that was hitherto dominant.

The implementation of an eco-innovation can be a strategy to combine economic benefits and reduce the negative environmental impact (Kuntosch et al. 2020), that is, the environment may not have been the main motivation for its development and implantation, since there are technologies that produce environmental gains as an adjunct to its main function. For example, innovations in processes that aim to reduce production costs and that also bring environmental

gains and also to improve business competitiveness (Isa et al. 2019). This reinforces the need for full engagement on the part of organizations, in view of the urgency for sustainable development (Jänicke 2008), to which Arranz et al. (2020) point out that eco-innovations arise from the capacity of companies to innovate.

In the context of eco-innovations, science and technology policies play a major role in pointing out how these can be developed and appropriated by the market, highlighting strengths and weaknesses, as opportunities and threats, in order to achieve a sustainable society, where it is necessary to expand knowledge about impacts generated by innovations, both to support the elaboration of public policies and to sensitize the market and motivate the business community to adopt them (Viederyte 2016).

Following the example of these movements, the INOVATEC System model, a method created by the Brazilian Agricultural Research Corporation (EMBRAPA), aims to assess the impacts of technological innovations in the different lines of action that these may cover: (1) environmental, (2) social, (3) economic, (4) human resource training, (5) institutional development, (6) introduction of innovation, (7) unwanted occurrences, and (8) characteristics of environmental management. This model also aims to analyze the scope of the innovation and its performance based on indices of significance and magnitude, since the inclusive nature of the method allows it to be used appropriately for the evaluation of agricultural biotechnologies (Jesus-Hitzschky et al. 2008).

In the global context, each year the demand for agricultural products increases. Furthermore, it is expected that by 2050, there will be three billion more people to be fed. According to the predictions of the World Resource Institute, for food production it will be necessary to close a column of 56% in food between the calories of the crops produced in 2010 and those needed in 2050, considering the usual growth of agribusiness to meet the demand from the growing world population, which points to the need for innovative strategies to fight hunger (World Resource Institute 2018).

The application of concepts aimed at the circular economy makes it possible to meet most of the SDGs since renewable flows are integrated into the green economy and functionality through a more efficient management of resources and thus contribute to reducing inequalities. The current socio-environmental pressures that are presented to organizations and the expectations of meeting the UN Sustainable Development Goals combined with the feeling that corporate discourses are not aligned with their business practices, sometimes resulting in competitive market dynamics that can lead managers to make wrong decisions on projects, especially in times of crisis or slowdown in economic activity. In attempt to make these managers aware that other aspects should also be considered, science has

Fig. 1 Residues from cassava processing in Nigeria. *Source* Achi et al. (2018)

developed studies and presented models that incorporate different dimensions, which is the case of the Triple Bottom Line (Elkington 2001) which argues for the need to evaluate the three dimensions, environmental, social, and economic.

Previous studies have analyzed the biodigester technology studied here, however, limited to a single dimension of sustainability (Guimarães et al. 2014), respectively, its environmental performance and economic viability, with positive results that the technology is sustainable. Even so, there was a gap in the proposal of new models that add other aspects or dimensions, contemplate different realities, and allow a joint evaluation between performances.

In Brazil, in recent years, the agribusiness sector has contributed significantly to the growth of the country's economy, especially the trade balance, offering good opportunities for the introduction of innovations. For Santos and Araújo, in 2017, despite all the growth, the sector still had some deficiencies and limitations, such as raising financial resources to invest in technology and innovation, to improve production performance (Xu and Chen 2020). The Confederation of Agriculture and Livestock of Brazil (CNA) pointed out that the sector was responsible for approximately 23.5% of the Brazilian Gross Domestic Product in 2017, equivalent to R\$ 1.551 trillion, demonstrating the importance of the sector, and it is in this context that the cassava processing industry, called starch plants, is inserted (CNA 2021).

Cassava is a tuber of the species *Manihot esculenta*, being one of the most important food crops in many parts of the world, emerging as a rich source of energy for millions of people and playing a crucial role in resolving global food insecurity (Sukara et al. 2020). Coelho and Ximenes (2020) point to a panorama of the global production of cassava root, emphasizing that there was an increase of 0.5% between 2014 and 2018. Nigeria, Ghana,

Congo, Mozambique, and Angola produce 45% of the planet's cassava. Brazil, on the other hand, had successive annual reductions in production, due to alternating droughts in most of the producing regions.

Agri-food industries, including cassava production and processing, are the largest contributors to waste in most developing countries, which reinforces the importance of measures to encourage eco-innovations. Babbitt (2020) corroborates by saying that food production, in general, leads to significant demands for energy, water, and nutrients, emitting pollutants to ecosystems, making them vulnerable and thus promoting local climate change (Singh et al. 2018). In Nigeria, which is the world's leading country, as an example, cassava production has been given little attention regarding sustainable solutions, thus contributing to the problem of the emission of solid waste, as shown in Fig. 1, contaminating the environment. However, these residues are rich in organic matter and suspended solids, providing great potential for conversion into value-added products (Li et al. 2017).

In addition to solid waste, the starch plants, when using water in the processes of washing cassava and producing starch (or tapioca flour), generate effluents with large quantities of nutrients. However, if they are disposed of indiscriminately in rivers and lagoons, these effluents will be responsible for eutrophication of the waters, developing an overpopulation of decomposing microorganisms that consume oxygen from the water, resulting in the asphyxiation of aerobic species. The result produces adverse effects, such as odor problems, fish death, the formation of toxins, and harmful effects on human health. Omotosho and Sangodoyin (2013) and Sánchez et al. (2017) reinforce that these effluents are very polluting and that they need to be treated before disposal, representing a serious threat to the environment and the quality of life in rural areas.

Due to the cost of electricity consumed in aerobic treatment systems, the great majority of starch plants use anaerobic lagoons to treat their effluents, and it is during this process that biogas is formed, a gas mixture that is composed of a large amount of methane, classified as a more aggressive greenhouse gas than carbon dioxide, and pointed out by researchers like Santamouris (2016), as having a direct relationship to climate change and local pollution problems. However, this biogas can be recovered and used in the production process to heat boilers, in addition to its potential as a fuel to drive electric power generators. Okudoh et al. (2014) recommend considering cassava and its biomass as the next energy crop for biogas production in Africa, especially in South Africa. Andrade et al. (2020) reinforce that the treatment of effluents from starch plants can produce biogas, thus enhancing the socio-environmental and economic benefits.

The need for rigor in the disposal of wastewater, which is water already used in production processes and which returns to the environment with added materials, has driven research to reduce the environmental impact of effluents. In the case of the present study, in addition to seeking to reduce environmental impacts, they envisage increasing the value of the cassava food chain (Achi et al. 2018), and it is important to highlight that environmental liabilities increasingly impact the value chain of production processes. Water is a valuable resource that is doubly affected in starch plants: first, because of its direct and abundant use in the production process, and later, in the discharge of effluents in rivers or in the soil without proper treatment, causing negative impacts on the environment.

In turn, integrated eco-innovations are technologically cleaner processes and products than their competitors, which contribute to the solution or mitigation of environmental problems in companies or other organizations (Jesus Pacheco et al. 2017). In this way, develop eco-innovative technologies and methodologies for evaluating them are important, useful, and scientifically justified, because the implications of eco-innovation span a wide spectrum of elements related to business, from those that are essentially economic, passing through those determinants of social relations with the market, to those linked to the environmental responsibility of companies. In this sense, the present research starts from the assumption that the impact of an eco-innovation can be methodologically evaluated with objectivity and comprehensiveness, offering greater security to the decision-making process by Brazilian agribusiness companies.

The objective was to employ the INOVA-tec System model as an instrument for evaluating eco-innovative processes in leading companies in its segment, looking for evidence to expand its usability to other realities in the agro-industry, processes that are based on sustainability. So, this

Fig. 2 Theoretical framework

research sought to answer the following question: Is the INOVA-tec System model, as an instrument for evaluating eco-innovative processes in leading companies in its segment, capable of showing processes based on sustainability, and thus expanding its usability to other realities of the agribusiness?

Theoretical framework

The theoretical framework of this article will touch on eco-innovation content, biodigesters as eco-innovative technologies, and, finally, discuss sustainability and its indicators, as shown in Fig. 2.

Understanding the concepts of eco-innovation, biodigesters, and sustainability indicators is essential to understand the methodological procedures adopted in the assessment of environmental performance designed to meet the cassava agribusiness based on the INOVA-tec system. In this sense, a bibliographic review of themes central to this research is carried out, aiming to build a theoretical framework that supports the presented ideas.

Eco-innovation

The idea of eco-innovation is just over two decades old. In the literature, one of the first appearances of the concept is in the book by Fussler and James (1996). In the following year, James (1997) defined eco-innovation as new products and processes that offer value to the customer and the business, significantly reducing environmental impacts. Extrapolating the environmental dimension of sustainability, eco-innovation can also be understood as the production, application, or use of a new product, process, organizational structure, or management methods for the company or for the user, whose life cycle results in the reduction of environmental risk, as pollution and the negative impacts of resource use (Kemp and Pearson 2007), also demonstrating its potential as a source of competitive advantage.

For Rennings (2000), eco-innovation concerns the decisions and actions of relevant actors that lead to the development and application of new ideas, behaviors, products, and processes, contributing to the reduction of environmental degradation and to achieving specific ecological goals. This included product and process innovations, changes in organizational management, and, concerning the sociopolitical level, changes in environmental regulation, consumer behavior, or way of living in general. This definition resembles Kemp's (1997), who understood eco-innovation as new or improved processes, products, techniques, and management systems that prevent or reduce negative environmental impacts.

The Organization for Economic Cooperation and Development (OECD 2021) states that the concept of eco-innovation refers to one of the types of innovations arising from demands for a new context of socio-environmental challenges, explored by academics and entrepreneurs. It reinforces that it is the capacity with which companies modify, redesign, and create products, processes, and operational and organizational procedures in order to reduce environmental impact (Arranz et al. 2020). However, in Brazil, public policies to support technological innovation have not always converged to scientific policy. Only with the opening of the market, since 1990, the private sector started to invest in research and development, persisting, cooperation, and convergence between the different actors involved in the innovation process (Sbragia et al. 2006).

Subsequently, Arundel and Kemp (2009) stated that this understanding is in line with the definition of environmental technology adopted by the European Commission's Environmental Technologies Action Plan (ETAP), referring to processes that manage pollution, such as air pollution control and management of water, products, and processes less intensive in material and/or energy resources and other mechanisms aimed at more efficient management of resources. The authors analyzed several concepts presented in the literature and proposed a typology applied to eco-innovations: (a) environmental technologies, that is, pollution control, including waste and water treatment, cleaner processes, waste management equipment, instrumentation and environmental monitoring, green energy technologies, water supply for consumption and noise and vibration control; (b) organizational innovations, which are organizational methods and management systems to deal with environmental problems, substitution of inputs, changes in production plants, formal environmental management and audit system, and management of the production chain; (c) innovations in products and services with environmental benefits, such as ecological constructions, less resource-intensive products and services, waste management, water management, environmental consultancy, analysis and testing, and engineering services; and (d) changes in green systems, which concern

environmentally friendly production and consumption systems, organic farming, and systems based on renewable energies.

Other authors added that eco-innovations provide new business opportunities, contributing to the transformation towards a sustainable society according to the interaction and engagement of interested actors (Carrillo-Hermosilla et al. 2010), in addition to offering technical support for different technologies to increase the capacity for product innovation and environmental commitment (Yang and Chen 2011). Corrêa et al. (2011) analyzed the negative environmental impacts generated by innovations implemented by Brazilian companies, using raw material, electricity, and water consumption as a parameter for evaluation, concluding that there is a positive relationship between innovation and reduction in environmental impacts, suggesting that technological innovations are potential actions to minimize or even avoid environmental impacts.

Over the years, interests in eco-innovations have taken over in business. Barbieri and Santos (2020) argue that eco-innovative businesses are fundamental for the development of sustainable production and consumption in organizations of all sizes. Transforming an industry into eco-innovative businesses requires new forms of production, one of which is the implementation of "green" or "environmental" technologies, which aim to reduce or prevent pollution, optimize the use of natural resources, in addition to seeking new materials, processes, and products that generate less impact on the environment, and meet human needs and provide quality of life (García-Granero et al. 2018).

Eco-innovation is considered one of the European Union's strategic pillars in response to the global environmental and economic challenges to be faced in the coming years. For this reason, the Eco-Innovation Observatory (EIO) was created, financed by the European Commission's Environment and Competitiveness and Innovation Program, which aims to provide an integrated source of information on eco-innovation for companies and innovation service providers, providing a solid database to support policy design and decision making. The entity offers a series of analyses on trends in eco-innovation, market, and business segmentation, for innovation service providers, policymakers, analysts, and researchers, and its studies are used by the European Commission in its program aimed at eco-innovations as an instrument of environmental policies to collect and analyze a wide range of information on eco-innovation, including indicators, collected from member countries of the European Union and other key economic regions (EC 2021).

The present research chose as a field of study the starch plants in the State of Paraná, where an eco-innovation based on biogas technology was implemented. Nigeria, the world's largest producer of cassava, has used biogas to generate biogas from waste from its processing (Mama

Fig. 3 **a** Longitudinal section of the pilot reactor and **b** pilot reactor installed in the cassava starch industry. Source Adapted from Kuczman et al (2017)

and Agunwamba 2018; Aisien and Aisien 2020). Paraná is the second largest producer of cassava in Brazil. The first is the State of Pará, located in the North of Brazil. Therefore, Paraná is the main producer of cassava in the south and southeast regions of the country, accounting for 16.6% of national production, which is equivalent to 3.65 million tons/year, and 67% of the volume of starch produced in-country, about 506 thousand tons/year, according to data from the State Secretariat of Agriculture and Supply/Department of Rural Economy (SEAB 2021).

In Brazil, following the example of Silva et al. (2020), other researchers also discuss the benefits of biodigester technologies, like a way to mitigate the emission of greenhouse gases and environmental degradation with possible financial return (Sánchez et al. 2017). Kuczman et al. (2017) developed, according to Fig. 3a and b, a pilot reactor, in the horizontal, single-phase anaerobic format in a cassava starch industry in Toledo, PR, Brazil.

Biodigesters as an eco-innovation

Biodigesters are structures capable of transforming organic matter, rich in carbon, and which are generally used in production processes associated with negative environmental impacts, in environmental, economic, and social advantages for producers and entrepreneurs who choose this solution (Rashama et al. 2019). Anaerobic biodigesters have a process with the presence of microorganisms that live without air or oxygen. They are closed structures, with inlet and outlet tubes, which can have different shapes, the best known being the Indian, the Chinese and the Canadian models.

Biogas can be used directly in the generation of thermal energy, or in the conversion into electrical energy, in which in both cases it is possible to rely on biodigesters to assist in distributed generation (Freitas et al. 2019). With the energy supply, the HDI tends to raise the HDI of the regions where agribusiness stands out, being an important element to minimize the rural exodus (Sánchez et al. 2015).

Biodigesters have a special vocation to assist projects centered on concepts such as the circular economy (Secco et al. 2020) and the water, energy, and food nexus (Sanchez-Zarco et al. 2020), since it is capable of converting waste and other polluting elements, such as gray water, into energy and revenue sources, minimizing the environmental impact and expanding the generation of jobs (Hyman and Bailis 2018), its full compliance with the dimensions of sustainability is well noted (Javaheri et al. 2020). To corroborate with the central idea of the research, which is the use of biodigesters as an eco-innovation for the treatment of polluting materials with a high organic load, and with this generating biogas, in addition to producing biofertilizers, eco-innovative initiatives carried out around the world and in Brazil.

Okudoh et al. (2014), when investigating the potential of cassava biomass and the technologies applied to the sustainable production of biogas in South Africa, observed that cassava contains large amounts of fermentable sugars inferior only to sugarcane and beetroot, in addition, to present one of the best water footprints, especially in low-fertility soils. Because it is resistant to diseases and has a good yield, food and non-food applications have been developed. To exemplify this, China has been adopting this culture to fulfill its goal of biofuel.

When pointing out the importance of encouraging eco-innovation initiatives, Sivamani et al. (2018) highlight that cassava is the third significant source of calories after rice and corn in tropical countries and that, including the husk, bagasse, stem, rhizome, and leaves, the annual production of solid cassava waste is 350 million metric tons (MMT), and that in general, with the exception of leaves, all this raw material can be exploited for the production of solid, liquid, and gaseous biofuels. With that, it is observed in this input and with the proposal of this research, that it is a raw material with a low water footprint, capable of producing more than one type of biofuel, through the treatment of the residue of its food production, in a way that the authors of this article reiterate positions such as those of Okudoh et al. (2014) and Sivamani et al. (2018). These authors suggest a paradigm shift and a more holistic and complementary view of food production and biomass energy, aiming to overcome the existing technical and economic challenges, which can be achieved through research incentives (Sikdar 2020).

Adewuyi (2020) discusses the production of clean energy at affordable prices in Nigeria, considered the world's largest producer of cassava, and a major exporter of fossil fuel,

in addition to generating clean energy from residues from cassava production. It also points to the use of waste materials and underutilized inedible seed oil, such as *Jatropha curcas*, to minimize controversies associated with the use of food materials as raw material for production of biofuels in Nigeria and other African countries. The author also points out that this strategy would boost the creation of jobs and income, so the focus should be on developing Nigeria's waste management strategy, which has the potential to generate enough energy to boost the economy and serve as a means of employment, and thus, while promoting the generation of clean energy, and the economic and environmental developments.

Shah et al. (2015) point out that co-digestion, pre-treatment, and the design of the biodigester are the main techniques to optimize the production of biogas, which confirms the understanding that eco-innovations, including those aimed at the conceptions of new models and constructive methods of biodigesters, prove to be excellent sustainability strategies. In Cambodia, Hyman and Bailis (2018) evaluated the National Biodigester Program, established in 2006, to build and maintain domestic biodigesters through a program that, in just its first six years, installed almost 20,000 biodigesters and established a network in the country of financiers, construction companies, qualified masons, specialists, and after-treatment technicians to rural users in more than half of Cambodia's provinces. In this same direction, Livia et al. (2020) in their research, on the evaluation of the potential for reusing wastewater for irrigation in semiarid rural areas in Chile, highlighted the relevance of integrating social and environmental criteria, in addition to technical and economic ones, to support decision-making processes related to the reuse of effluents.

Clemens et al. (2018) analyzed the Partnership Program for Biogas in Africa in three countries, Kenya, Tanzania, and Uganda, created in 2009, to promote the adoption of biodigesters by rural families in Sub-Saharan Africa. They noted that between 2009 and 2017, more than 27,000 families installed a biodigester, half of them in Kenya. In Zimbabwe found the profile of fostering a distributed generation that eco-innovation aimed at biodigesters can promote, since the country has a high level of dependence on the national electricity grid. The authors also pointed out the potential for sanitation, waste management, and fertilizer production, in addition to the fact that biogas is a high-quality fuel, which can be used for heating and powering vehicles. Another highlight was the lack of control and monitoring devices in most of the biodigesters sampled in Zimbabwe.

Brazil also has examples of eco-innovations aimed at biodigesters, since its economy has as its main driving force, agribusiness, as well as having most of its territory located in the tropical region, with the remaining, located in the region subtropical, and at this point, heat is an important

Fig. 4 Map of Brazil. Source www.iheartbrazil.com/brazil-map, edited by the authors

ingredient to optimize the functioning of biodigesters (Mahmudul et al. 2020), especially the covered lagoon model, characterized by a geomembrane over a pond where the waste is deposited.

In Brazil, despite the identification of several initiatives aimed at the eco-innovation of biodigesters, it is observed that its use is still small, given the potential for application and research that biodigesters have in a country with a continental dimension and a vocation for agribusiness. As the main research in the biodigesters' area in Brazil, we can mention the research that is ongoing in the extreme west of the state of Santa Catarina, in the Uruguay River basin, in the municipality of Itapiranga, under the coordination of CGT Eletrosul, a state-owned federal company that operates in the generation and transmission of electricity. Santa Catarina is a neighboring state to the state of Paraná, both located in the southern region of Brazil, as shown in Fig. 4.

As the municipality of Itapiranga depends economically on the creation of pigs and this production results in animal waste, which was polluting the Uruguay River basin, Eletrosul, through Research and Development (R&D) initiatives, contributed to minimizing these impacts in the municipality, first with the Alto Uruguay Project in 2008, installing 10 covered lagoon biodigesters, and in 2012 with a public call for Strategic R&D ANEEL, called "Technical and commercial arrangements for the insertion of electricity generation from biogas originated from waste and liquid effluents in the Brazilian energy matrix." This R&D was offered by the National Electric Energy Agency (ANEEL), which is the regulatory agency for the Brazilian electricity sector (ANEEL 2021). For the sake of simplification, this Strategic R&D will be called Biogas Project.

Fig. 5 Uruguay River

Figure 5 illustrates the Uruguay River located near the facilities of the Biogas Project.

The source of funds for these actions was Law 9.991/2000, and in this second stage of Eletrosul's R&D actions in Itapiranga, the Biogas Project provided for the construction of a gas pipeline and the construction of other biodigesters built from different materials. The Biogas Project sought to observe through the implementation of different technologies of biodigesters on an industrial scale, to compare which are the best cost–benefit ratios in the generation of energy from swine manure. And so, to compare them with Canadian-type digesters (covered pond), installed in the Alto Uruguay Project. This eco-innovation presents itself as the largest ever carried out in Brazil since it provided for the installation of a piped gas network to interconnect the biodigesters built in the Alto Uruguay Project and the biodigesters built by the Biogas Project, which were: three biodigesters and three wooden digestate ponds, all with industrial size.

The pipeline had a length of about 11 km, and along its entire route, in parallel, it was accompanied by a fiber optic cable, since the system provided for a supervisory system in which the data transmission is done over the network of optical fibers. Of the biodigesters installed in the Biogas Project, there are: one concrete biodigester; one slate stone biodigester accompanied by one wooden digestate pond, and one stainless steel biodigester accompanied by two wooden digestate ponds. All the biogas produced by the biodigesters was interconnected by the piped gas network, and its total production was linked to a mini thermoelectric plant (MCT) so that the biogas is converted into electricity, generating credit to rural producers in proportion to the amount of biogas injected into the network. Table 1 illustrates the types of biodigesters installed in the Biogas Project and their dimensions. Figure 6a and b illustrates the slate stone digester and its wooden digestate tank. Figure 7a and b illustrates the stainless steel biodigester and its two wooden

Table 1 Types of biodigesters installed in the Biogas Project of Itapiranga

Biodigester type	Amount	Dimensions in meters (diameter×height)	Capacity (liters)
Slate stone	01	8.28×4.80	230 thousand
Stainless steel	01	11.49×4.80	680 thousand
Concrete	01	17.40×4.50	951 thousand
Wood digestate	01	8.56×4.50	230 thousand
Wood Digestate	02	11.46×4.50	851 thousand

digestate tanks next to MCT. Figure 8a and b illustrates the concrete biodigester, aerial view.

In the Biogas Project, many construction methods were chosen, as another remarkable innovation, which was the interconnection of all units through a gas pipeline and fiber optic network to an MCT through rural roads. The final Project will have the interconnection of the large biodigesters to eight covered pond-type digesters since two of them were deactivated and therefore the pipeline did not contemplate the connection of these properties, since these two producers gave up the pig breeding activity. At the end of the works of the Biogas Project and after its commissioning, CGT Eletrosul, together with the group of researchers and the rural producers involved, will operate the MCT and perform measurements of the set of facilities for one year, evaluating the performance of the project, in compliance with ANEEL's R&D guidelines.

The business model of the Biogas Project provides for the sustainability of the business, which must be socially, environmentally, and economically fair, and the latter dimension of sustainability represents the greatest challenge to an association of rural producers since the social and environmental dimensions are easily met with the installation of biodigesters. Socially, biodigesters prove to be excellent solutions about the need of labor, unlike photovoltaic energy, which involves few workers in the stages of the construction process. Environmentally, biodigesters are excellent allies in the treatment of environmental liabilities and are still becoming a source of energy that can be thermal or electrical.

Sustainability indicators

The performance of business organizations has improved due to increased awareness of sustainability, so that understanding which performance indicators are best suited to measure the level of environmental innovation allows organizations to develop policies that encourage companies to be more sustainable, implementing green practices more efficiently (García-Granero et al. 2018). For example, Kardec et al. (2002) defined “indicators” as being similar guides for measuring the effectiveness of actions taken and

Fig. 6 **a** Slate stone biodigester and its wooden digestate tank, aerial view. **b** Slate stone biodigester and its wooden digestate tank, seen from the ground

Fig. 7 **a** Stainless steel biodigester and two wooden digestate tanks, seen from the ground; **b** Stainless steel biodigester and two wooden digestate tanks, aerial view

Fig. 8 **a** and **b** Concrete biodigester, aerial view

for identifying any distortions or biases between what was programmed and the concrete result. They stated that, since the indicators are central tools for monitoring aspects of interest about an object of analysis, they make it possible to plan actions to improve performance. Indicators can then be analytical tools for the study of changes in society, which when combined allows the formation of indices.

In this article, the interest falls on the sustainability indicators, which, in the perspective of sustainable development, are a set of parameters to measure and communicate the anthropic impacts of a given system in relation to the established goals (Moura 2002), reinforcing the use sustainability indicators as a planning, monitoring, and evaluation tool. For companies, the concept behind sustainability indicators must be objective and simple enough to identify whether a company is approaching or moving away in terms of sustainability (Veleva and Ellenbecker 2000).

At the beginning of the 1990s, the term sustainable development started to occupy more space in society's daily life, mainly with the signing of the Global Agenda 21 and projects guided by it, and called Local Agenda 21, generating several definitions about indicators, their functions, rules, and principles for use. Institutionally, the event that started to focus on the search for sustainability indicators was the World Conference on the Environment held in Brazil, in the state of Rio de Janeiro, in 1992, Rio-92, in which Chapter 40 of the resulting document emphasized the need for each country to develop indicators in line with their respective realities.

According to Roma (2019), in September 2000, at the United Nations Conference on Sustainable Development, eight Millennium Development Goals (MDGs) were established. They were considered major global goals assumed by the member countries of the United Nations (UN). Goals that, taken as a whole, aimed to make the world move quickly toward the elimination of extreme poverty and hunger on the planet, factors that particularly affected the poorest populations of the least developed countries. The MDG evolved in 2015 toward the Sustainable Development Goals (SDGs) that were approved by the United Nations (Leal Filho 2020), and include issues of social, environmental, and economic development, including poverty, hunger, health, education, global warming, gender equality, water, sanitation, energy, urbanization, the environment, and social justice.

To achieve sustainable development, it is crucial to rely on sustainability indicators, from which the best strategies for decision making toward sustainable business are guaranteed, in its three aspects: environmental, economic, and social. Sustainable development has gained attention in recent years not only among academics but has also spread among companies, who realized that their operation must address environmental and social as well as economic

prosperity. They also realized that to manage them, it is necessary to measure them (Hojnik et al. 2020). For Malheiros et al. (2013), sustainability indicators and measurement systems must be simple and reliable in describing reality, as they are fundamental in the formation of lasting bases for sustainable development.

The sustainability indicators take different qualitative and/or quantitative forms, depending on the research interests and their fields of application. Stanitsas et al. (2020) studied sustainability indicators in construction projects, from a literature review, with a subsequent consultation with experts, and from this research, the authors provided a holistic view of sustainable project management indicators, covering the entire spectrum Triple Bottom Line, known as the sustainability tripod, and also made it possible for project professionals to choose the right combination of indicators, depending on the sustainability focus they want to provide in their projects.

Hojnik et al. (2020) had already pointed out, in their research on sustainability indicators, the need to cover the spectrum of the Triple Bottom Line, aiming to identify "critical points" and for the industry to develop its own sustainability assessment system. Misra and Kumar (2020) believe that it is still necessary to have a fourth parameter, which is the perception of the citizen when it comes to the design of smart and sustainable cities.

In general, the term "indicators" has been widely discussed by researchers from different areas of knowledge and, although there are differences in the approach, the definitions found have common meanings: a measure that summarizes important information about a certain phenomenon; a link between parameters and standards that make up an evaluation system; have reliability, accuracy, and timeliness; assist in decision-making processes.

Methodological procedures

Research characterization

The central assumption of this study is that the impact of eco-innovations can be assessed more objectively, comprehensively, and in a systemic way, which can be explained by the results obtained from the application of a technically adequate model for this purpose and serve as a basis for other organizations in the agribusiness.

Aiming to verify and explain the validation of this assumption, and still fulfill the established objectives, the case study was chosen as the working methodology (Yin 2005), including four companies, of which three are representatives of the starch agro-industry in the State of Paraná and a company that works with Agronomic Advisory and Environmental Planning, the latter being responsible for

the introduction of biodigester technology in the starch plants. The starch plants are linked to the Brazilian Association of Cassava Starch Producers (ABAM) and the Union of Cassava Producing Industries of Paraná (SIMP).

Due to the necessary methodological rigor and in line with the proposed objectives, the methodological procedures defined by Eisenhardt (1989) were adopted for the construction of generic theories and conceptual models based on case studies, namely: detailed structuring of the construction process of study; use of multiple sources for data collection and their interaction with the theoretical constructs studied, in order to obtain the greatest possible validity for the research; to seek generalization and depth.

At the beginning of the research, 50 agribusinesses were identified, including flour and starch plants, which were subjected to a selection process to choose the most typical and common in relation to the whole population, excluding those with significant specificities, which resulted in 45 companies. Then, they were consulted to verify whether they met two research requirements: having a functioning anaerobic digester and to be located in the State of Paraná. Having overcome this phase, the choice of the cases studied took in account only the confirmation of interest and the availability to participate in the research. In the end, three agro-industries agreed to participate, providing information, and setting an agenda for field visits.

Then, visits were made to the three starch plants to monitor on-the-spot processing of cassava and the functioning of biodigesters, and the collection of primary data through semi-structured interviews. The interview script was composed of questions that allowed flexibility and the inclusion of factors not initially considered, mainly for the definition and application of the indicators selected for feeding the INOVA-tec System model.

The interviews were conducted with the person in charge of Agronomic Advisory and Environmental Planning and with the managers of the agro-industries directly involved with the implementation of biodigester technology. One of the common characteristics among the companies studied was the simplicity of the organizational structure and hierarchical levels, making the interviewees invariably the director and/or industrial manager, or one of the owners.

Aiming to deepen the data analysis, the recommendations of Miles and Huberman (1994) were observed so that, as the data were collected, the analysis would occur concurrently, even if still in a preliminary way, searching to identify needs for deepening and complementing with new data, in addition to allowing the first interpretative reports to be produced by the researcher. Everything that has been collected, such as notes, observations, recordings, photos, footage, and conversations, has been transcribed/coded, as it is an additional source for understanding and reinforcing raw data.

The procedures defined by Yin (2005) were also applied at this stage of the study, namely: (1) Each interview report was analyzed and compared in relation to other interviewees, highlighting convergent and divergent points; (2) with the same purpose and also so that peculiarities relevant to the study were identified, the final reports of each company were analyzed among themselves; (3) data analysis was also carried out by crossing the information collected from the proposed sources of evidence with the studied theoretical implications, in order to verify the fulfillment of the objectives of the work, plus secondary data; and (4) after being analyzed, the case study reports served as the main basis for the treatment of the data, analyses, conclusions, and recommendations.

The INOVA-tec system and its evaluation indicators

In its original format, the INOVA-tec System model features 57 impact indicators divided into analysis topics and grouped into seven lines of action. Each of these indicators is detailed in the document Technological Innovation Impact Assessment System (EMBRAPA 2011). According to the INOVA-tec System model, the evaluator must select the indicators most aligned with his research and can insert more specific ones that increase the robustness of the evaluation according to each reality; it is recommended to work with 30 indicators to optimize the results. The indicators presented in the INOVA-tec System are closely aligned with the concepts of eco-innovation presented in the literature review of this work.

By analyzing and comparing each of the 57 indicators of the INOVA-tec system model with the sustainability indicators suggested in the EU Eco-Innovation Index report/2018 (EU 2018), a total of 12 similar indicators were arrived at which were promptly selected specifically for the environmental, social, and economic dimensions. For the remaining indicators of this first analysis and for the other four lines of action treated by the INOVA-tec model (institutional development, training, the introduction of innovation, and unexpected occurrences) but not included in the studies and publications of the EIO, all were evaluated by the interviewed to verify the applicability, considering three premises: reliability, accuracy, and timeliness of the data to be imputed. At the end of this procedure, another 23 indicators were considered, totaling 35 indicators applied to the three starch plants and the advisory company that developed the technology (Table 2).

Results and analysis

The impact matrix generated by the INOVA-tec System (Fig. 9) indicates that the eco-innovation “biodigester technology” applied in the starch plants of the State of Paraná

Table 2 Indicators used to power the Modified INOVA-tec System

Indicators (lines of action)	Source
Environmental	
Water quality (effluents)	Starch plants
Emission of air pollutants (in this case, CH ₄ and CO ₂)	Starch plants
Change in demand for natural resources (firewood burning)	Starch plants
Environmental management or monitoring practices (formal system)	Starch plants
Social	
Influence on working conditions	Starch plants
Decrease in jobs	Starch plants
Generation of jobs	Starch plants
Social classes benefited by innovation (direct benefits to workers)	Starch plants
Economy	
Financial gain resulting from the implementation of innovation (cost reduction)	Starch plants
Increase in foreign exchange (related to international trade)	Advisory company
Market outlook	Advisory company
Possibility of commercializing innovation	Advisory company
Institutional development	
Resource allocation (for the development of innovation)	Advisory company
ISO seal or another quality seal	Starch plants
Regulatory compliance (legislation)	Starch plants
Training	
Number of graduate students involved in research or innovation development	Advisory company and University that coordinated the study
Technical training (employees of starch plants)	Starch plants
Academic and scientific works presented and/or published associated with innovation	University that coordinated the study
Innovation introduction	
Type of innovation	Advisory company
Business incubation	Advisory company
Service provision (post-deployment)	Advisory company
Changing the effectiveness of innovation	Advisory company
Time frame to launch the product on the market (deadline)	Advisory company
Service/demand creation	Advisory company
Impact on the production line (processes)	Starch plants
Need to train the R&D or Production team to be able to develop the innovation or innovative product	Advisory company
Unexpected occurrences	
Adverse effect on the environment	Starch plants
Possibility of misuse of innovation	Advisory company
Damage to human health, fauna, or flora	Starch plants
Judicial demands against innovation	Advisory company
Risks of technology adoption	Advisory company
Specific indicators	
Supply chain environmental practices	Starch plants
Environmental management report	Starch plants
Carbon credit projects	Starch plants
Corporate policy on climate change	Starch plants

presents a favorable scenario for its dissemination in the market, with 124 points in the significance index axis (whose scale ranges from 0 to 210), but the joint performance of its indicators is still low, with 10 points on the magnitude

index axis (on a scale ranging from 1 to 28), pointing to the need for corrective actions to improve this performance. Regarding the significance index, which measures the market perspective, it is possible to verify that all the variables

Fig. 9 Impact matrix determined after processing the research data. Source: Extracted from the modified INOVA-tec System

that compose it contribute to the scenario being conducive to the studied eco-innovation, but with different performances. First, there are the economic, legal, environmental, and human health benefits, followed, respectively, by the political environment, product quality, and social.

The economic gain occurs in the heating phase of the boiler for steam generation, due to the significant reduction, of about 90%, in the consumption of firewood. The biogas captured by the biodigester is channeled to the boiler, where a thermal valve is also installed to control the inlet flow, requiring only a small amount of wood to burn the flame.

As for the legal aspect, the technology of biodigesters fully complies with both the environmental legislation of the State of Paraná and the municipalities where the studied starch plants are installed, including the support regulations, avoiding possible legal sanctions due to the negative externalities generated by the starch plants. Still in the environmental context, the direct benefits refer to the proper treatment of effluents, avoiding the negative effects of eutrophication of the waters, the capture of methane gas instead of releasing it into the atmosphere, thus reducing the negative environmental impacts (Singh et al. 2018), and the reduction in firewood consumption, which contributes to the maintenance of forest areas and, mainly, to the reduction in the emission of pollutants, again minimizing environmental impacts.

Human health is also benefited by the technology of biodigesters, more specifically that of the workers of the starch plants. The lower exposure to soot caused by burning firewood and the reduction in the frequency of cleaning the boilers minimize, respectively, the risks of smoke inhalation and its microparticles, in addition to the negative effects of thermal overload caused by the permanence of these workers

inside the boilers. In the study by Prasara-A and Gheewala (2020), it is pointed out that among the indicators of social sustainability in starch plants, the main ones refer to health and safety and working conditions.

The political environment evaluated the reach, or institutional strength, of biodigester technology on the segment of starch plants in Paraná. The results obtained can directly influence the dissemination of this eco-innovation, but there is still a need for more specific government policies. For example, until the end of this study, the financing of technology with resources from the Special Industrial Financing Agency (FINAME) had not yet been regulated by the National Bank for Economic and Social Development (BNDES) in Brazil.

Regarding the magnitude index, which measures the performance of technology based on the indicators defined for each dimension analyzed, the model indicates low global performance, which is the systemic interaction between all lines of action of the INOVA-tec System. The results obtained are shown in Table 3.

The indicators defined for the environmental dimension include criteria for environmental conservation and water resources, soil, and air. In the first one, environmental management or monitoring practices were evaluated and it was identified that the three starch plants studied carried out some environmental conservation actions, involving a reduction in the consumption of water, electricity, water reuse, and selective collection of industrial waste. For water, soil, and air resources, the benefits refer to the reduction of about 90% in the demand for firewood, a reduction of 34 thousand tons CO₂ equivalent due to the capture of methane gas generated in the first effluent treatment pond, as presented by Guimarães et al. (2014). Lansche et al. (2020) used the life

Table 3 Results determined by INOVA-tec System in all its lines of action

Line of action	Determined result
Environmental	8
Training	38
Institutional development	4
Economy	10
Specific indicators	– 1
Introduction of innovation	16
Unexpected occurrences	0
Social	5

Source Made from the INOVA-tec system

cycle assessment (LCA) tool to compare different scenarios of cassava production and processing and concluded that environmental impacts can be reduced if the biogas resulting from the use of waste is used for production of electricity and heat. Igliński et al. (2020) also point out that one of the basic advantages of agricultural biogas is its versatility, in comparison with other renewable energy sources, to generate electricity and heat.

For the social dimension, the criteria (1) social reach were evaluated, which indicated that the social classes directly benefited by the adoption of biodigester technology are the “C” and “D,” from which the largest number of employees of the starch plants comes, and (2) labor relations, which indicated that the adoption of technology improved working conditions, occupational health, in addition to not causing a decrease in posts, since the employees who handled/controlled the firewood previously used were trained and relocated to the monitoring of the biodigester and biogas boiler feed. However, so far there has been no generation of new jobs.

The economic dimension achieved the best performance among the classic dimensions of the Triple Bottom Line, Environmental, Economic and Social pillars. The interviewees stated that there was a significant reduction in manufacturing costs and a consequent increase in the profit margin, making their products more competitive and allowing growth in sales. Still in this dimension, only the “foreign exchange increase” indicator had a zero result, as there is no prospect of exporting the technology to other countries, even because it is an incremental improvement over a technology of Chinese origin. Regarding the quality of the product, the results achieved so far are direct, but still low, with respondents reporting that the use of biogas provides greater stability in the temperature of the boiler and the steam generated by it, benefiting only the drying process of the starch.

Madeira et al. (2017) concluded, from an economic feasibility study of a large biohydrogen production plant, that

using cassava wastewater makes the business highly competitive. The economic feasibility calculation involved the investment, operation, and maintenance costs of the biogas steam reformer and the cost of hydrogen production, which reached the value of US \$ 0.13/kWh with a 7-year return, demonstrating that this type of hydrogen production is a good option for power generation.

For the other lines of action, the synthesis of the results is: (1) training: obtained the best performance among all, basically due to specific training, training of researchers and scientific production; (2) institutional development: bureaucratic difficulties create obstacles to obtain public resources, both for those who develop the technology and for those who intend to adopt it; (3) introduction of innovation: the technology is already in place and is characterized as incremental innovation. The original model was developed in China and adapted in the canvas anchoring phase, without changing the technological paradigm; and (4) unexpected occurrences: there are no records that the technology causes damage to life, adverse effects on the environment, misuse, legal process against its use, or other associated risks.

Anyhow, it is known that the biodigester technology is not new. However, this research presented a differential that was the use of a model, which in this case was the INOVA-tec System, with 57 indicators. This set of 57 indicators, after being compared to the sustainability indicators, according to the EU Eco-Innovation Index report/2018 (EU 2018), resulted in a total of 12 common indicators covering the environmental, social, and economic dimensions. After interviews with professionals involved in the implementation of the biodigester technology, it was possible to add another 23 indicators, totaling 35, with which it was possible to evaluate the biodigester technology as an eco-innovation, taking into account economic, legal, political, social, and environmental issues. Thus, the 35 indicators fed the INOVA-tec System, demonstrating the feasibility of the biodigester technology in relation to economic gains, compliance with legal aspects, improvements in working conditions, the promotion of more specific government policies, and, finally, mitigation of the environmental impacts of waste from cassava production on the environment.

Final considerations

Considering the need for a model for technology assessment to be able to systematically articulate complex issues and also represent the knowledge and perceptions of different actors involved, the research began with the original model INOVA-tec System (Jesus-Hitzschky, 2007) and a systematic review of the literature that deals with the formulation, validation and use of sustainability indicators by organizations, reaching the definition of 35 indicators that evaluate

several criteria in different lines of action: (1) environmental, (2) social, (3) economic, (4) human resource training, (5) institutional development, (6) introduction of innovation, (7) unwanted occurrences, and (8) characteristics of environmental management.

The application of the INOVA-tec System model brought new and important information that allowed a holistic and systemic analysis. By correlating the results obtained in the two evaluation strands used to assess the general impact of innovation, which culminated in the formulation of the significance index and the magnitude index, the model allowed us to identify that there is an underutilization of the technical potential of the innovation, which is found in a favorable scenario for its dissemination in the market, but with low global performance of the studied indicators, which demands corrective actions internal and external to the companies.

In this sense, it is suggested that companies establish a specific role for environmental management with clearly defined responsibilities. The benefits of this action include: (1) the strategic value that sustainability provides to the business; (2) the evolution towards a proactive environmental stance, including making available to society the results of its socio-environmental practices; (3) the company's greater competitiveness in both the domestic and foreign markets; and (4) expanding the social reach of innovation, since the selection/development of suppliers reduces the possibility of buying manioc from suppliers that adopt practices contrary to the principles of sustainable development, for example, using child labor, inadequate handling soil, indiscriminate use of agricultural pesticides, etc.

The biodigester technology studied is in the commercialization stage, and the demand created has been met by the developing company, but two aspects involving the government are not contributing to accelerate its dissemination. First, legislators and government agencies need to be stricter in relation to GHG emissions since this policy tends to encourage the implementation of biodigesters. Parana law already requires the installation of biodigesters to treat the effluents generated by agribusiness activities, but this requirement does not yet apply to the capture/sequestration of these gases, in the case of this research, methane gas. It should be noted that effluent from biodigester should be treated prior to its discharge into surface water, as in the study by Zahrim (2018). Second, the BNDES needs to regulate the use of FINAME resources as a source of financing for the acquisition of biodigester technology by other starch and agribusiness sectors.

The theoretical contribution of this study, although the biodigester technology is not new, is the proposal of a set of specific indicators to assess the general impacts of an eco-innovation, with the potential to be used by organizations in their decision-making processes involving sustainable technologies. For future work, it is suggested that the model

be replicated in other sectors of agribusiness and/or other starch plants, aiming not only to validate its applicability but mainly to overcome the limitation of this study which was to work with a limited sample due to the low adhesion by most of the companies consulted to participate in the research. In addition, the indicators discarded in this study, according to the criteria described in the subsection indicators used to assess the studied eco-innovation, should be incorporated into future works that will employ the INOVA-tec System model to verify whether changes in the results of the analysis occur.

It is understood that the objective of employing the INOVA-tec System model as an instrument for evaluating eco-innovative processes in leading companies in its segment, seeking evidence to expand its usability to other realities in the agribusiness, processes based on sustainability, has been met and that the research answered its question since it was shown that the INOVA-tec System model, as an instrument for evaluating eco-innovative processes in leading companies in its segment, was capable of showing processes based on sustainability and thus expanding its usability for other realities of agribusiness in Brazil and the world.

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Authors and Affiliations

Marco Antonio Sampaio de Jesus¹ · Ana Regina de Aguiar Dutra¹ · Claudia Brito Silva Cirani² · Katia Regina Evaristo Jesus³ · Ruy Castro Sobrosa Neto¹ · José Baltazar Andrade Guerra¹

Claudia Brito Silva Cirani
claudiabscirani@gmail.com

Katia Regina Evaristo Jesus
katia.jesus@embrapa.br

² Universidade Nove de Julho, São Paulo, São Paulo, Brazil

³ EMBRAPA Centro Nacional de Pesquisas em Meio Ambiente – Jaguariuna, Jaguariúna, São Paulo, Brazil

¹ Present Address: Universidade São Judas Tadeu (USJT), São Paulo, São Paulo, Brazil