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Eco-innovation and agricultural sustainability: empirical evidence from South Africa's agricultural sector

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ABSTRACT
This study explores the role of eco-innovation in promoting environmental sustainability in the agricultural sector in South Africa. The study applies a mixed-methods approach using both qualitative and quantitative data on eco-innovations. The study is guided by the Resource-Based View (RBV) as a theoretical lens and applies a logistic regression model to explore the relationship between various resources and capabilities and four types of environmental sustainability outcomes. The results suggest that agricultural businesses that invest in developing process innovations, acquire knowledge from external sources, leverage different types of technologies such as precision agriculture and sensor technologies are more likely to achieve improved environmental sustainability outcomes. The study suggests a few policy recommendations that emphasize the importance of creating incentives for agricultural businesses to invest in innovative and sustainable agricultural practices, collaborate with higher education and government research institutions and facilitate adoption of advanced ICTs to promote eco-innovation.

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Eco-innovation; Resource-based view; Agricultural sustainability; South Africa; Environmental impact

1. Introduction

In recent years, the concept of eco-innovation has gained significant attention from innovation scholars and policy makers as a strategy to address the environmental challenges faced by the agricultural sector (Arundel and Kemp 2009; Bossle et al. 2016; Díaz-García, González-Moreno, and Sáez-Martínez 2015). The increased regulatory pressures and requirements to implement more sustainable solutions in response to the escalating challenges faced by the agricultural sector (e.g. lowering greenhouse emissions and environmental pollution) has given rise to the idea that sustainable economic development and environmental sustainability are mutually interdependent (Carrillo-Hermosilla et al. 2009). By definition, eco-innovation refers to innovations that are primarily focused on sustainable resource usage, energy efficiency, greenhouse gas reduction, waste minimization, environmental sustainability and the use of novel materials (Gente and Pattanaro 2019; Hellström 2007; Kemp 2011). Furthermore, eco-innovation includes the development and implementation of new or improved products, processes, and services

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that have a reduced environmental impact, or that make efficient use of natural resources (Hazarika and Zhang 2019). The primary difference between eco-innovation and other types of innovations is that it includes products and services that are designed to be more energy-efficient, less polluting, or that use renewable resources (Horbach 2016).

In South Africa, the agricultural sector has been faced with numerous challenges in recent years. For example, the effects of climate change, which include more frequent droughts, unpredictable rainfall patterns, and severe weather events, are considerable (Gulati et al. 2013; Masipa 2017; Pingali and Feder 2017). These climate-related challenges have had direct negative effects on agricultural productivity and have posed serious threats on water availability and food security in the country. As a result, agricultural stakeholder including policy makers, researchers and farmers have been under pressure to find sustainable innovative solutions to address these challenges. Furthermore, the rising input costs faced by agricultural businesses have also added to these challenges. Factors such as escalating fuel prices, rising interest rates, rising fertilizer prices, as well as rising labour costs have placed added to the significant burden farmers already experiencing. All of the above mentioned challenges have called for a comprehensive understanding of how innovation and its dynamics might play a role in tackling the challenges for a more sustainable agricultural sector.

Previous studies have highlighted the importance of the agriculture sector in achieving environmental sustainability goals (Fito and Van Hulle 2021; Lankoski and Lankoski 2023; Yasmeen et al. 2021). Sustainable agricultural practises may improve efficiency and reduce the negative effects on the environment by making the best use of scarce natural resources like water and land (Norse 2012). Furthermore, according to the 2022 South African Government Science, Technology and Innovation (STI) implementation plan (the decadal plan) for the 2019 White paper STI policy, sustainable agriculture has the ability to support South Africa's economic and social growth by providing and creating employment opportunities and promoting community participation (DSI 2022). While the policy debate amongst stakeholders in the agricultural sector has primarily focused on finding a balance between economic growth and maintaining or lowering environmental impact generated by the sector, there seems to be general agreement that coherent policy interventions are necessary to strengthen the agricultural sector's ability to adapt to climate change while also raising its productivity and lowering its greenhouse gas emissions (Karakaya, Hidalgo, and Nuur 2014; Organization for Economic Co-operation and Development [OECD] 2011). Therefore, understanding the dynamics of eco-innovation in the South African agricultural sector is of great practical and policy relevance.

A recent survey of South African agricultural business innovation 2016–2018 (Centre for Science, Technology and Innovation Indicators (CeSTII) 2021), found that a number of agricultural businesses reported that they were engaged in innovations oriented towards environmental sustainability. Yet, despite the critical importance of the agricultural sector with respect to its contribution to environmental sustainability, biofuel production, employment, few studies have attempted to understand the role of eco-innovation in promoting sustainable agricultural practices. Furthermore, the effects of technological innovations on environmental sustainability are still not well understood in the context of the agricultural sector. Therefore, the main objective of this study is to understand the relationship between technological innovations that are intended to reduce environmental impact and innovation outcomes related to environmental sustainability in the agricultural sector. Specifically, the study examined the relationship between the firm's resources, capabilities and innovations intended to reduce environmental impact.

The primary research question guiding this study is formulated as follows: *What is the relationship between technological innovation and eco-innovation outcomes in promoting sustainable agricultural practices in South African agricultural sector, and what are the implications for policy?* The relevance and persistence of this research question is justified by the need to promote sustainable agricultural practices and to reduce the environmental impact generated by the agricultural sector. According to a recent study by Ritchie and Roser (2021), agriculture is one of the key economic sectors with the highest carbon footprint as a result of its direct impact on natural resource use such land and water usage. These have implications on natural ecosystems as well as atmospheric carbon emissions. Furthermore, understanding the role of eco-innovation in the sector is essential for designing effective policy interventions that support the development and adoption of sustainable agricultural practices in the sector (Dudek and Wrzaszcz 2020).

The rest of the paper is structured as follows: The next section provides a review of the literature on eco-innovation. Thereafter, a discussion on the theoretical framework guiding the study is presented. Following that, the research methodology is presented before presenting the findings and discussion. Finally, the paper concludes by presenting the implications of the findings for policy and recommendations for future studies.

2. Literature review

Eco-innovation has emerged as a key concept in the discourse on sustainable development, given that it refers to the development and diffusion of technologies and practices that enhance environmental performance while promoting economic growth. Several perspectives on the concept of eco-innovation and its measurement have been explored by several authors in the literature (e.g. Carrillo-Hermosilla et al. (2009); Díaz-García, González-Moreno, and Sáez-Martínez (2015); Hellström (2007)). This literature review summarizes some of dominant discourses on eco-innovations in order to inform the development of an appropriate theoretical lens to address the research problem in this study.

First, it is necessary to acknowledge the long-standing history of innovation theory and empirical research in the field. The Schumpeterian perspective, along with subsequent developments such as neo or post-Schumpeterian theories, has provided valuable insights into the dynamics of innovation (Abernathy and Utterback 1978; Schumpeter and Nichol 1934). Schumpeter argues that innovation is a dynamic and evolutionary process, driven by entrepreneurs who introduce new products, technologies, or business models that disrupt existing economic structures. According to Schumpeter, innovation drives long-term economic growth and happens in waves or cycles, with periods of intense innovations followed by intervals of relative stability. Building of the rich history and various conceptualizations of innovation that have emerge over time, the Oslo Manual and the Community Innovation Survey (CIS) also provide a comprehensive framework for measuring and assessing innovation (OECD 2005, 2018).

These frameworks, along with the distinction between incremental and radical innovation provide valuable insights into how eco-innovation can be understood.

In defining eco-innovation, various authors argue that there is no single unified definition of eco-innovation because it depends on the context since it is a multidimensional construct that involves technological, social, and institutional dimensions (Hojnik and Ruzzier 2016). The review of literature shows that eco-innovation has been defined in multiple ways, ranging from narrow definitions that focus on the development and commercialization of environmentally friendly technologies to more comprehensive definitions that include broader social and environmental dimensions. For example, Schiederig, Tietze, and Herstatt (2012) define eco-innovation as *an innovation that significantly reduces environmental impact, or provides an entirely new environmental service or improves the sustainability of a product, process or service along its life cycle.* This definition emphasizes the significance of addressing the product and service life cycle in eco-innovation activities. The conceptualization of eco-innovation by Ekins (2010) and Del Río, Carrillo-Hermosilla, and Könnölä (2010) highlight its environmental and economic benefits.

On the other hand, Faucheux and Nicolaï (2011) argue that the concept of eco-innovation commonly used within the ecological economics literature is based on three primary attributes: (1) the issue of double externality, (2) the importance of a regulating framework, and (3) the importance of social and institutional aspects of eco-innovation. This emphasizes the significance of institutional support structures and effective social planning for the effective adoption and diffusion of eco-innovations in businesses.

According to Hellström (2007), sustainable eco-innovation may be conceptualized on three distinctive levels. These are; (a) technological, (b) social, and (c) institutional. While technological eco-innovation is important, it must be supported by relevant social structures and should have the capacity to influence them. Unfortunately, the distinction between eco-innovation and product innovation can be confusing since often eco-innovation can involve both product and process innovations. Kemp and Foxon (2007) suggest that eco-innovations encompass a range of innovations, including products, processes, organizational that result in a reduction of environmental risk, pollution, and the adverse effects of resource use. Arundel and Kemp (2009) discussed several eco-innovation measurement approaches, which include input-output analysis, patent analysis, and survey-based methods. They emphasized the need to synthesize eco-innovation classifications to capture the diverse and multifaceted nature of eco-innovation. Meanwhile, Ekins (2010) advocate for the development of measurement techniques to determine the level of eco-innovation, while Del Río, Carrillo-Hermosilla, and Könnölä (2010) suggest that policy instruments should take into account the maturity of specific eco-innovations. Similarly, Cleff and Rennings (1999) and Rennings (2000) argues that eco-innovation requires interdisciplinary research approaches to identify and assess the role of policy and regulations in stimulating eco-innovation.

The different perspectives of presented above help shed light on the multifaceted nature of eco-innovation. Based on the different perspectives, eco-innovation may take a variety of forms, ranging from incremental improvements to radical innovations that fundamentally improve products and business processes in organizations.

In conclusion, the literature review presented in this study provides useful insights into the conceptual definitions of eco-innovation, its advantages, and policy implications. While there appears to be a lack of consensus on the definition and scope of the concept eco-innovation, however, most authors agree that eco-innovation needs an interdisciplinary approach in order to understand its complexity and determine the role of social and institutional dimensions in fostering eco-innovation in businesses.

3. Theoretical foundations

The Resource Based View (RBV) theory of the firm offers a comprehensive framework for understanding the link between a firm's internal resources and capabilities and its ability to innovate. While neoclassical and evolutionary theories of innovation may provide some insights into specific aspects of eco-innovation, such as stakeholder involvement and knowledge exchange among firms, they fall short in capturing the holistic nature of eco-innovation in agriculture (Newbert 2007; Salvadó et al. 2012). This is because the RBV emphasizes the importance of a firm's unique resources and capabilities in determining its competitiveness and ability to innovate (Lockett, Thompson, and Morgenstern 2009). According to Barney (1991), a firm's resources must be valued, rare, unique, and non-substitutable in order to provide long-term competitive advantage. Over the years, the RBV approach has been further expanded to include the notion of dynamic capabilities, which are essential for firms to adapt and respond to changing environments (Teece, Pisano, and Shuen 1997). In order to understand how businesses may gain and maintain a competitive advantage, it is essential to take into account the idea of capabilities in general.

Dynamic capabilities refer to a firm's ability to integrate, build, and reconfigure its resources and competencies in order to effectively address environmental changes and seize new opportunities (Portillo-Tarragona et al. 2018). In the context of the agricultural sector, the adoption and successful implementation of eco-innovations require not only access to relevant resources but also the ability to effectively integrate and reconfigure these resources. According to Teece, Pisano, and Shuen (1997), dynamic capabilities – which include the capacity to sense market trends and environmental changes, take advantage of opportunities, and transform existing resources to develop and deliver environmentally sustainable products, services, and processes – are crucial for firms to identify and exploit opportunities for eco-innovation.

As such, this study uses the RBV theory to analyse and understand the relationship between technological innovations that are intended to reduce environmental impact and innovation outcomes related to environmental sustainability in the agricultural sector (Carrillo-Hermosilla, Kiefer, and del Río 2019). The RBV theory has previously been used in different contexts to analyse how organizational resources and skills can be used for competitive advantage in businesses (Salvadó et al. 2012). According to the RBV, organizations normally have tangible and intangible resources that help them attain long term competitive advantage. Tangible resources are organizational assets such as technology, raw materials, human capital, financial capital. On the other hand, intangible assets include knowledge and experience, organizational culture. To achieve long term competitive advantage, businesses often purposefully mobilize resources and integrate them well in a way that helps them to build organizational capabilities (Portillo-Tarragona et al. 2018).

Furthermore, the RBV allows to analyse the relationship between a firm’s internal resources and capabilities, and its external environment (Zhang and Walton 2017). In the case of eco-innovation in the agricultural sector, this means that it is possible to examine how a firm’s technological capabilities and its resources interact in order to develop and implement innovations intended to reduce environmental impact (Carrillo-Hermosilla, Kiefer, and del Río 2019; Salvadó et al. 2012). This approach useful because it recognizes that eco-innovations are influenced by a wide range of internal resources and capabilities as well as their interactions. Table 1 illustrates how the RBV theory was operationalized in this study.

From an agricultural sector’s perspective, the RBV offers valuable insights into the dynamics of resource allocation and utilization, which are essentialfor promoting sustainable agricultural practices and achieving environmental sustainability outcomes. In taking into account the dimensions and approach to operationalisation presented in Table 1, this study recognizes the significance of resources and capabilities in enabling agricultural firms to identify, develop, and deploy eco-innovations to achieve sustainable competitive advantage. Furthermore, the incorporation of the different theoretical perspectives presented earlier in this study provides a comprehensive framework for analysing the role of resources and capabilities in driving eco-innovation outcomes and promoting environmental sustainability in agricultural businesses.

4. Logistic regression model

To operationalize the RBV, this study applied a logistic regression model to explore the relationship between various resources and capabilities and four types of environmental sustainability outcomes, namely; *Increased Biodiversity preservation*, *Increased Water preservation*, *Improved Soil fertility*, *Reduced Greenhouse gas Emissions*. The logit model made it possible to estimate the effect of each independent variable on the likelihood of a firm achieving a particular sustainability outcome. By examining the statistical

Table 1. RBV and how operationalized in the context of eco-innovation.

Concept	Definition	How operationalized in eco-innovation context	References
Resources	The tangible and intangible assets that a firm has access to and controls, which are used to achieve its strategic goals.	Innovation activities and are represented by variables such as intra-mural and extra mural innovation activities, access to external knowledge sources, number of skilled employee, Access to advanced ICTs.	Newbert (2007); Salvadó et al. (2012); Arundel and Kemp (2009); Ekins (2010); Carrillo-Hermosilla, Kiefer, and del Río (2019); Chavula et al. (2014)
Capabilities	The firm’s ability to effectively use its resources to achieve its strategic competitive advantage	Technological innovation types. These are represented by variables such as product and process innovation.	Armstrong and Shimizu (2007); Lockett, Thompson, and Morgenstern (2009); Portillo-Tarragona et al. (2018); Cleff and Rennings (1999)
Competitive Advantage	A firm’s ability to achieve superior performance relative to its competitors	Eco-innovation outcomes which are represented by variables such as Increased Biodiversity preservation, Increased water preservation, Improved Soil fertility, Reduced Greenhouse gas emissions	Barney (1991); Teece, Pisano, and Shuen (1997); Carrillo-Hermosilla, Kiefer, and del Río (2019); Lockett, Thompson, and Morgenstern (2009)

significance and magnitude of the coefficients in the logit model, it was possible to identify which specific resources and capabilities were most strongly associated with improved environmental sustainability outcomes as measured in this study. This approach enabled the application of the RBV theory to the agriculture sector and provide empirical evidence for how agricultural businesses can leverage their resources to achieve long term sustainable competitive advantage. The logistic regression model is given below:

$$\text{logit}(p) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k$$

where

- p is the probability of each dependent variable taking the value 1. In otherwords, the probability of achieving the dependent variable associated with a particular sustainability outcome, such as Increased Biodiversity preservation, Increased water preservation, Improved soil fertility, or Reduced greenhouse gas emissions.
- logit(p) is the log-odds of p, which is the natural logarithm of the odds ratio of p. It basically, represents the log-odds of the probability (p) of achieving a specific environmental sustainability outcome. It's modelled as a linear combination of independent variables, such as resources and capabilities ($x_1, x_2, \ldots, x_k$), with associated coefficients ($\beta_0, \beta_1, \beta_2, \ldots, \beta_k$).
- β_0 is the intercept or constant term
- $\beta_1 x_1$, $\beta_2 x_2 \ldots$ are the coefficients of the independent variables x_1, x_2, $\ldots x_k$ respectively.

The logistic function is then applied to the logit(p) to convert it back to the probability scale:

$$p = \frac{e^{\text{logit}(p)}}{1 + e^{\text{logit}(p)}}$$

Essentially, this equation estimates the likelihood that a particular firm will achieve a specific sustainability outcome based on the values of the independent variables (resources and capabilities) and the coefficients derived from the logistic regression model.

5. Methods

This study employed a mixed-methods approach to analyse the relationship between technological innovations and agricultural sustainability outcomes. More specifically, the study used qualitative and quantitative data from the South African baseline Agricultural Business Innovation Survey covering the period 2016–2018 (Agri-BIS 2016–2018). The Agri-BIS 2016–2018 was based on the guidelines of the Organisation for Economic Co-operation and Development's (OECD) Oslo Manual (OECD 2005). By aligning the study design with these established guidelines from the Oslo Manual, this study leverages a well-established framework for assessing eco-innovation outcomes and its interplay with other forms of innovation. The survey used the methodological recommendations for the Community Innovation Survey (CIS) of the European Union (EU) countries, as provided by Eurostat, the Statistical Office of the European Commission. The survey focused on ascertaining how agricultural businesses innovate. Although the survey instrument is standardized, a few changes and adjustments were made to better adapt it to the context of the South African agricultural sector.

In this study, improved environmental sustainability outcomes were assessed by analysing the perceptions of agricultural businesses in relation to the importance of the innovation outcomes related to environmental sustainability. This is because businesses were asked in the survey questionnaire to rate their innovation outcomes in terms of importance from highly significant to not relevant. Rather than directly measuring actual biophysical sustainability outcomes, such as changes in biodiversity or water preservation, the focus was on capturing the perspectives and priorities of the agricultural businesses themselves. By surveying the agricultural businesses and gathering their self-reported perceptions of sustainability outcomes, valuable insights into eco-innovation outcomes were determined. These perceptions provided a valuable indication of the businesses' commitment to environmental sustainability and their recognition of the importance of integrating sustainability practices into their operations. Hence, to determine the outcomes of eco-innovation, the survey included questions on innovation outcomes which were used as indicators of the businesses' eco-innovation outcomes, such as improved biodiversity preservation, reduced environmental impact and improved water preservations and reduced greenhouse gas emissions.

Quantitative data were subjected to statistical analysis using the logistic regression model described in the previous section to examine the relationship between dependent and independent variables. The findings were then integrated with qualitative findings. Thematic analysis was used to gain insights into how organizational capabilities are used in the development and implementation of eco-innovations from qualitative data from the survey responses. These were descriptions and elaborations provided by agricultural businesses regarding the types of innovations used to drive their eco-innovation outcomes. To ensure methodological rigour in analysing the qualitative data, first, a careful reading of the qualitative responses to the survey question was done. Following that, an open coding process was applied to look for patterns, themes, and categories in the data. This required a careful analysis of the responses to find recurrent themes, ideas, and perceptions. Using the axial coding technique, the selected themes were then grouped into significant clusters and subthemes. By establishing linkages and correlations between various topics, it was possible to better understand the data. An iterative strategy was used throughout the process by doing a few more rounds of coding and analysis to improve the accuracy and thoroughness of the detected themes. This ensured the increase in reliability and validity of the findings.

The mixed-methods approach used in this study is consistent with previous studies that have successfully applied this methodology in similar contexts. For example, studies examining eco-innovation in various sectors have employed mixed-methods approaches to gain a deeper understanding of the complex interplay between resources, capabilities, and innovation outcomes (e.g. Gonçalves, Galliano, and Triboulet 2022; Kuntosch et al. 2020; Lee, Wu, and Tseng 2018; Timma, Blumberga, and Blumberga 2015). These studies have demonstrated the value of combining qualitative insights with quantitative analysis, leading to novel insights and a deeper understanding of the dynamics of innovation.

Table 2. Dependent variables.

	Dependent variables	Type	Description
1	Increased Biodiversity preservation	Binary	Dummy = 1 if a business indicated that they considered *Increased biodiversity preservation* as either high or medium successful innovation outcome, otherwise 0
2	Increased Water preservation	Binary	Dummy = 1 if a business indicated that they considered *Increased water preservation* as either high or medium successful innovation outcome, otherwise 0
3	Improved Soil fertility	Binary	Dummy = 1 if a business indicated that they considered *Improved soil fertility* as either high or medium successful innovation outcome, either otherwise 0
4	Reduced Greenhouse gas emissions	Binary	Dummy = 1 if a business indicated that they considered *Reduced Greenhouse gas emission* as either high or medium successful innovation outcome, otherwise 0

Table 3. Independent variables.

Independent variables	Type	Description
Product_innovation	Binary	Dummy = 1 if the business performed product innovation, 0 otherwise
Proccess_innovation	Binary	Dummy = 1 if the business performed process innovations related to eco-innovation, 0 otherwise
Innov_act_Intramural_RD	Binary	Dummy = 1 if a business invested in intramural R&D otherwise 0
Innov_act_Extramural_RD	Binary	Dummy = 1 if a business invested in extramural R&D otherwise 0
Acquisition_external knowledge	Binary	Dummy = 1 if a business invested in acquisition of external knowledge otherwise 0
Adv_ICTs_Sensors technologies	Binary	Dummy = 1 if a business used either Air and Soil sensors, crop sensors, Livestock biometrics knowledge otherwise 0
Adv_ICTs_Precision_agriculture	Binary	Dummy = 1 if a business used precision agriculture, otherwise 0
Adv_ICTs_Drones_Robotics	Binary	Dummy = 1 if a business used Drones or Robotics, otherwise 0
Info_Source_Internal	Binary	Dummy = 1 if a business indicated that they considered internal sources of information as high or medium, either otherwise 0
Info_Source_Market	Binary	Dummy = 1 if a business indicated that they considered internal sources of information as high or medium, either otherwise 0
Info_source_education & research institutions	Binary	Dummy = 1 if a business indicated that they considered information sources from higher education and research institutions of information as high or medium, either otherwise 0
Info_other_sources (conferences, journals, etc.)	Binary	Dummy = 1 if a business indicated that they considered other information sources such as journals and conferences as high or medium, either otherwise 0
Log of number of skilled employees	Continuous	Control variable. The log of the number of skilled employees involved in innovation activities.

6. Dataset and variables

Although the survey covered three main subsectors of commercial agricultural businesses at the higher level of classification: the agriculture subsector (e.g. crop producers, wineries, livestock and poultry), forestry subsector, and fisheries subsector, this study was confined to the agriculture subsector. These were businesses that were in the Standard Industrial Classification (SIC) 11 of the South African agricultural sector. These businesses were involved in animal and crop farming. The rationale of excluding the forestry and fisheries subsectors is that they included very few observations and would have potentially caused spurious associations. Furthermore, the analysis only included innovation-active businesses. The dependent and independent variables used for the analysis are shown in Table 2 and Table 3.

Table 4. Regression model output.

	Dependent Variables			
Independent Variables	Increased Biodiversity Preservation	Increased Water Preservation	Improved Soil Fertility	Reduced Greenhouse Gas Emissions
Product Innovation	−0.1325 (0.881)	−0.8867 (0.232)	1.2902 (0.215)	0.2713 (0.685)
Process Innovation	1.9799 (0.069)*	0.5067 (0.524)	2.3718 (0.040)*	0.0923 (0.895)
Innovation Activity (Intramural R&D)	−1.3414 (0.229)	0.2514 (0.794)	−2.7559 (0.098)*	−0.6693 (0.418)
Innovation Activity (Extramural R&D)	0.7234 (0.456)	0.9309 (0.332)	0.6229 (0.623)	0.7811 (0.334)
Innovation Activity (Acquisition of Knowledge)	0.3056 (0.705)	0.4502 (0.549)	1.7587 (0.124)	2.2036 (0.000)***
Advanced ICTs (Sensors Technologies)	−1.7022 (0.197)	2.2515 (0.006)**	−0.2135 (0.863)	0.6558 (0.398)
Advanced ICTs (Precision Agriculture)	3.9443 (0.003)**	−0.7923 (0.374)	2.8035 (0.042)*	1.1840 (0.117)
Advanced ICTs (Drones Robotics)	−0.0373 (0.970)	0.6089 (0.459)	0.6103 (0.674)	−0.0105 (0.987)
Information Source (Internal)	0.1709 (0.898)	1.1500 (0.313)	−22.9928 (1.000)	0.2034 (0.866)
Information Source (Market)	−1.8952 (0.404)	−0.5994 (0.755)	23.5748 (1.000)	−1.4084 (0.461)
Information Source (Education & Research)	1.6013 (0.073)*	−0.6217 (0.458)	0.3334 (0.769)	1.9261 (0.018)*
Information Source (Other Sources)	0.8543 (0.479)	−0.0498 (0.967)	−0.6742 (0.644)	−1.7972 (0.095)
Log of Number of Employees	1.6360 (0.007)**	0.4186 (0.187)	0.5048 (0.306)	0.0362 (0.887)

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

7. Analysis and discussion

This study applied a logistic regression model that analysed the relationship between different resources and capabilities and their effects on environmental sustainability outcomes. The results from the logistic regression model are presented in Table 4. The findings provide valuable insights into how organizational resources and capabilities can lead to improved environmental sustainability outcomes in the agricultural sector.

The results of the logistic regression model shown in Table 4, consolidates a series of logistic regressions and offer valuable insights on the role of eco-innovation in the agricultural sector. The analysis was guided by the RBV theoretical lens and provides a good understanding of how internal resources and capabilities of agricultural businesses contribute to distinct environmental outcomes.

Each column in Table 4 corresponds to a different outcome or dependent variable related to environmental outcomes (e.g. Increased Biodiversity Preservation, Increased Water Preservation, etc.) while each row corresponds to a different independent or predictor variable. These include variables such as Product Innovation, Process Innovation, different types of innovation activities, etc. The table reports the coefficients and *p*-values for each independent variable's effect on the dependent variables. In interpreting the table, the significant *p*-values indicate that certain independent variables have a significant impact on the dependent variables.

One important finding in the table is that product innovation was found not to be associated with any environmental outcomes with coefficients ranging from −0.1325 to 1.2902 and *p*-values not less than 0.215. This suggests that agricultural businesses that focus on developing new products alone may not be sufficient to achieve environmental benefits. This may warrant a more comprehensive approach to eco-innovation strategies. In this case, the ability to develop and introduce new innovative agricultural products may not necessarily be considered as a valuable resource for agricultural businesses seeking to improve their environmental sustainability outcomes. In contrast, process innovation shows a significant relationship with increased biodiversity preservation (coeff = 1.9799, *p*-value = 0.069) and improved soil fertility (coeff = 2.3718, *p*-value = 0.040). This suggests that innovation in operational processes can lead to tangible ecological value, echoing the core RBV principle of internal efficiencies driving competitive advantage. This finding is consistent with previous findings by Scherr and McNeely (2008) as well as Bennett et al. (2014) and is also commensurate with the RBV theory which suggests that firms with unique and valuable resources can leverage them to achieve superior performance. However, the RBV theory suggests that resources and capabilities must be rare, valuable, and difficult to imitate to provide a competitive advantage (Carrillo-Hermosilla, Kiefer, and del Río 2019; Portillo-Tarragona et al. 2018).

Another finding as illustrated in Table 4 was the role of advanced ICTs, with sensor technologies significantly associated with increased water preservation (coeff = 2.2515, *p*-value = 0.006) and precision agriculture significantly linked with improved soil fertility (coeff = 2.8035, *p*-value = 0.042). This underscores the significance of ICTs as resources in the context of eco-innovation. The use of advanced ICTs, specifically precision agriculture technologies, was found to be a significant predictor of increased biodiversity preservation (coeff = 3.944, *p*-value = 0.003), and improved soil fertility (coeff = 2.8035, *p*-value = 0.042). This finding suggests that agricultural businesses that are able to leverage advanced ICTs to enhance their production processes are more likely to achieve improved environmental outcomes. The positive coefficients for precision agriculture technologies are consistent with the RBV theory, which emphasizes the importance of strategic investments in unique and valuable resources and capabilities. The finding implies that agricultural businesses should prioritize the adoption of precision agriculture as part of their sustainability strategies. By investing in advanced ICTs, agricultural businesses are more likely to gain a competitive advantage by reducing their environmental impact while increasing their productivity and profitability. This finding is consistent with previous studies that suggest that the capacity to harness advanced ICTs may likewise be considered as a valuable resource for agricultural businesses looking for ways to enhance their environmental sustainability outcomes (Barber, Mangnus, and Bitzer 2016; Chavula et al. 2014; Fielke, Taylor, and Jakku 2020).

The influence of acquisition of knowledge and the sources of information have also notable influences in achieving eco-innovation outcomes. For example, Acquisition of knowledge as an innovation activity was found to have a significant effect on reduction of greenhouse gas emission. Meanwhile, sources of information for innovation from education and research institutions showed a positive impact on reduction of greenhouse gas emissions (coeff = 1.9261, *p*-value = 0.018). This highlights the importance of leveraging external knowledge resources, such as academic institutions and research bodies, in formulating eco-innovation strategies. This finding is commensurate with previous findings in literature (Cruz-Cázares, Bayona-Sáez, and García-Marco 2013) and is also consistent with the RBV theory as it suggests that businesses with unique and valuable external knowledge may use it to outperform their competitors (Hullova, Trott, and Simms 2016; Newbert 2007). This finding suggests that agricultural businesses are more likely to enhance their environmental sustainability outcomes if they seek to acquire external sources of knowledge for innovation.

Interestingly, the findings show that the number of skilled employees involved in innovation activities significantly influences biodiversity preservation (coefficient = 1.6360, p-value = 0.007). This suggests that agricultural businesses that may have more skilled human resources to devote to eco-innovation training programmes for professional/skilled employees in environmentally friendly agricultural practices may be valuable in achieving sustainable environmental practices. This may explain why the number of skilled employees had a significant effect on biodiversity preservation as an outcome.. Agricultural businesses may find unique and valuable resources and capabilities by investing in re-skilling their farming employees in modern and up to date sustainable farming practices to enable them to achieve these outcomes. Despite the commonly held narrative that internal R&D drives innovation in businesses, the results show that intramural R&D activities (coeff = −2.7559, p-value = 0.098) may not be as effective as extramural R&D and acquisition of knowledge in achieving superior environmental outcomes.

Finally, the results showed that depending on the source, the influence of information sources maybe valuable. Education and research sources demonstrate a positive impact on reducing greenhouse gas emissions (coeff = 1.9261, p-value = 0.018). This highlights the importance of leveraging external knowledge resources, such as academic institutions and research bodies, in formulating eco-innovation strategies.

However, the apparent lack of significant relationship between internal and market information sources with environmental outcomes contradicts common expectations. One would anticipate that agricultural businesses leveraging internal or market-driven insights would have an edge in driving eco-innovations. Similarly, the negative coefficient of intramural R&D on improved soil fertility suggests that internal research may not always translate into expected environmental performance. The negative coefficient for market sources of information is also surprising and contrary to expectations. Nevertheless, it is possible that businesses that rely heavily on market-based information for innovation may be more focused on short-term financial gains than long-term sustainability outcomes. This finding highlights the need for agricultural businesses to balance financial and environmental sustainability goals in their decision-making processes. These unexpected findings from the quantitative analysis invite further triangulation and integration with qualitative findings.

8. Analysis of qualitative survey responses

The Resource-Based View (RBV) theory suggests that a firm's resources and capabilities are the primary sources of its competitive advantage (Peng 2001). It is also argued that firms with unique and valuable resources and capabilities can use them to achieve superior performance (Lockett, Thompson, and Morgenstern 2009). In the context of eco-innovation in the agricultural sector, agricultural businesses can leverage their resources and capabilities to improve biodiversity preservation, water preservation, soil fertility, and reduce greenhouse gas emissions.

While the logistic regression model quantifies the relationship between the independent variables and the environmental sustainability outcomes, the qualitative analysis offers a deeper understanding of the mechanisms and practical implications behind these relationships. The qualitative findings help to therefore shed light on the quantitative results by providing additional context, examples, and real-world experiences. According to Rennings (2000), using a mixed methods approach to understand eco-innovation is essential. Hence, it was therefore necessary to corroborate the statistical analysis with qualitative survey data.

Respondents were asked two open ended questions related to eco-innovation in the questionnaire. The first question was whether they had introduced new or improved processes to reduce any negative environmental impacts generated? If Yes, respondents were asked to elaborate in detail by describing these new or improved processes. The second question asked whether agricultural businesses had introduced a new or significantly improved methods or practices to deal with the effects of climate change (e.g. droughts, floods, etc.) – If Yes, respondents were also asked to describe these new or significantly improved methods or agricultural practices. As previously mentioned in the methodology section, the responses to the two open ended questions were analysed using thematic analysis. Axial coding was used to organize the identified themes into meaningful clusters and subthemes. This helped to establish relationships and connections between different themes and allowed for a deeper understanding of the data. Table 5 summarizes the themes from the analysis of the first open ended question.

One interesting finding from the logistic regression model was the significant positive impact of process innovation on increased biodiversity preservation and improved soil fertility. This aligns with the resource-based view theory, which suggests that agricultural businesses with the ability to develop new and innovative processes have a competitive advantage in achieving environmental sustainability outcomes (Nagano 2020). The qualitative analysis further supports this finding by providing specific examples of sustainable process innovation practices implemented by agricultural businesses.

As illustrated in Table 5, farmers mentioned the adoption of Soil Conservation and Erosion Control to minimize negative environmental impacts. It includes initiatives such as soil repair after heavy rain and damage, erosion control through bush clearing, and the use of cover crops for better soil management. Farmers also mentioned the use of soil moisture probes for efficient water usage. These examples demonstrate how process innovation can directly contribute to preserving biodiversity and improve soil fertility in the agricultural sector.

Findings show that water management was and remains a major problem for farmers, especially in light of climate change and strict government regulations on water usage. Agricultural businesses emphasized the necessity of drip irrigation and probes for more efficient water consumption and better control of low-quality irrigation water under drought conditions.

> *Water management through improved monitoring and scheduling*
>
> *We introduced probes in our irrigated fields resulting in a much better understanding of the moisture requirements of all the crops under irrigation.*

Table 5. Summary of thematic analysis from qualitative responses.

Themes	Analysis	Examples of Responses
Sustainable Practices and Environmental Preservation	The responses in this theme revolved around to adoption of sustainable farming practices and implementation of measures to preserve the environment. The theme includes mostly practices such as nature-friendly farming, adoption of organic methods, waste management, and compliance with environmental standards and certifications.	*"Introduction of farming practices focused on sustainability and environmental preservation"* *"Nature-friendly farming activities"* *"Better waste management and recycling"*
Technology Implementation	This theme focuses on the adoption and integration of technology in agricultural processes to reduce negative environmental impacts. The trend in responses include the use of drone technology, implementation of management information systems, and the application of precision farming techniques.	*"Use of drone technology"* *"Implementation of management information systems"*
Resource and Energy Efficiency	A number of efforts to improve resource and energy efficiency on farms are mostly discussed in this theme. Most responses in this theme include the installation of solar energy plants, the use of solar panels for water pumps, and the implementation of energy-saving measures such as heat recovery.	*"Installation of solar energy plants"* *"Use of solar panels for borehole pumps"*
Water Conservation and Irrigation Practices	Responses include the adoption of drip irrigation systems, pulse irrigation to limit sunburn on crops, and monitoring and managing water usage for improved efficiency. In otherwords, Water conservation practices and optimising irrigation techniques are central to this theme.	*"Adoption of pulse irrigation to limit sunburn on apples"* *"Use of drip irrigation systems"*
Waste Management and Recycling	This theme highlights efforts to manage and reduce waste on farms through proper waste control and recycling practices. The responses highlights initiatives such as better control over waste products, composting, and the implementation of recycling programmes to minimize environmental impact.	*"Better control over waste products"* *"Implementation of composting and organic fertilizers"*
Reduced Chemical Usage	A frequent attribute highlighted in this theme is the reduction of chemical usage in agricultural practices to minimize environmental harm. Most responses include the introduction of biological control-oriented pest programmes, the reduction in spray chemical usage, and the adoption of organic farming practices.	*"Introduction of biological control-oriented chemical pest programmes"* *"Reduction in spray chemical usage"*
Infrastructure Upgrades	The focus of this theme is on infrastructure upgrades aimed at reducing negative environmental impacts and improving overall efficiency. Initiatives such as biosecurity upgrades, better waste management systems, and upgrades to irrigation and water treatment facilities are some of the most recurring answers in this theme.	*"Upgrades to improve biosecurity"* *"Upgrades for better waste management and recycling"*
Soil Moisture Monitoring and Conservation	A common feature in the responses in this theme are related to soil moisture monitoring and conservation practices to address the impacts of climate change. Some responses mention the use of soil moisture probes, cover crops, and improved soil moisture measurement techniques to optimize water application and conserve moisture in the soil.	*"Using soil moisture probes for efficient water usage"* *"Implementing cover crops for soil moisture conservation"* *"Improved soil moisture measurement techniques"*

Farmers also mentioned the use of precision irrigation scheduling systems, sensor technologies, and research into water storage solutions. This finding corroborates the results from the logistic regression which showed that the use of advanced ICTs, in particular, sensor technologies, can be considered as important innovations aimed at improving water management and resource efficiency.

As illustrated in Table 5, the thematic analysis of responses showed that there is a growing trend towards the implementation of sustainable and environmentally friendly farming practices among agricultural businesses in South Africa. Some of the most notable sustainable technologies cited in the data include the use of no-till farming, cover crops on fields and the chipping of invader trees to produce mulch under fruit trees.

> *No-till farming to improve water conservation*
>
> *Pulse Irrigation through irrigation computers and radio controlled valves.*

The adoption of these sustainable and environmentally friendly practices was mainly in response to the need for reduction of negative environmental impacts, improvement in soil moisture conservation, and overall better usage of scarce of natural resources. Moreover, some farmers were planting new cultivars with reduced cold requirements due to climate change and using selection indices to breed animals that deal with limited resources.

In the logistic regression model, it was noted that, apart from improved bio-diversity preservation, the number of skilled employees did not have a significant effect on the other environmental sustainability outcomes. However, the qualitative analysis revealed that farmers recognized the importance of re-skilling their employees in sustainable farming practices and investing in training programmes. They mentioned the use of advanced irrigation scheduling tools, better water management techniques, and the adoption of online tools for monitoring and decision-making, which require skilled employees to operate effectively. For example, many farmers indicated that they used online tools such as ***Fruitlook*** which is web-based system with near real-time data based on remote sensing data modelling which was developed for the Western Cape province agricultural sector.

> *We used online tools for example Fruitlook.*

This finding from qualitative analysis indicates that the quality of skills and the adoption of modern practices are crucial for achieving eco-innovation. While the number of skilled employees involved in innovation activities alone may not be sufficient, their re-skilling and ability to implement sustainable farming practices can contribute to improved environmental sustainability outcomes.

The analysis and integration of both quantitative and qualitative findings provide complementary insights that together contribute to a more nuanced understanding of the complex dynamics and practices driving eco-innovation in the South African agricultural sector.

9. Conclusion and policy implications

The main objective of this study was to understand the relationship between technological innovations that are intended to reduce environmental impact and innovation outcomes related to environmental sustainability in the agricultural sector. Specifically, the study examined the relationship between the firm's resources, capabilities and innovations intended to reduce environmental impact. This study showed that eco-innovation is a multi-dimensional concept that has been explored from various perspectives by different scholars. The findings presented in this study provide valuable insights into how organisational resources and capabilities can lead to improved environmental sustainability outcomes in the agricultural sector. The findings are largely consistent previous studies as well as with the RBV theory, which emphasizes the importance of unique and valuable resources and capabilities in achieving sustained competitive advantage.

The results from both the logistic regression and the thematic analysis of descriptive responses suggest that agricultural businesses that invest in developing innovative processes, acquire knowledge from external sources, leverage advanced ICTs, and balance financial and environmental sustainability goals are more likely to achieve improved environmental sustainability outcomes.

As such, based on the findings from this study, there are several policy recommendations that can be suggested to encourage agricultural businesses to improve their environmental sustainability outcomes by leveraging their resources and capabilities.

First, given that process innovation was revealed to be associated with environmental sustainability outcomes, it would make sense to promote and create incentives for businesses that develop new process innovations. The results in this study showed that process innovation positively contributes to increased biodiversity preservation and increased water preservation. Policy makers can develop policy instruments that incentivize agricultural businesses to invest in process innovations by offering tax breaks, subsidies, or grants. New policy instruments that require businesses to publicly disclose their sustainability efforts or establish sustainability standards can also encourage process innovation.

This study showed that enhancing biodiversity preservation and soil fertility in agricultural businesses relies on promoting advanced ICT integration, particularly precision agriculture. Policymakers can play a key role by facilitating training, funding research, and establishing responsible technology usage regulations.

However, it is important to note that the adoption of advanced ICTs in agriculture should not be seen as standalone solutions but as enablers that require supportive processes and governance mechanisms (Jakku et al. 2019). As such it is necessary for policy makers to ensure that the adoption and implementation of advanced ICTs in the agricultural sector is accompanied by appropriate regulatory frameworks and guidelines that safeguard the interests of all stakeholders (Klerkx and Rose 2020). This includes promoting transparency in data ownership and usage, protecting farmers' rights, and facilitating open access to information and knowledge sharing.

Finally, encouraging internal initiatives together with market-based solutions, such as certification programmes and eco-labelling, can incentivize sustainable practices among agricultural businesses. Promoting a market environment that values and rewards sustainability can motivate agricultural businesses to embrace it as a competitive advantage. This can help to create a market-driven transition towards long-term sustainable agricultural practices that benefit both the environment and farms.

10. Limitations and recommendation for future studies

The findings of this study represent a snapshot in time and relies on self-reported perspectives of agricultural businesses. While the findings presented in this study provide valuable insights into eco-innovation, they do not allow for a comprehensive assessment of actual biophysical environmental outcomes or long-term trends. Moreover, although using a single statistical model, such as logistic regression, has its potential drawbacks, it was selected as a good modelling approach for studying binary outcomes and examining relationships between variables. Future studies could consider other techniques such as seemingly unrelated regressions (SUR) as potential alternatives. SUR may offer additional advantages in capturing the interdependencies, collinearity, and interrelationships within the dataset. SUR, as a modelling approach, could cater for the simultaneous estimation of multiple equations that account for the potential mutual exclusivity and interrelationships among different aspects of eco-innovation and their impacts on environmental sustainability outcomes. Future studies could also explore the integration of biophysical data such as biodiversity indices, water quality measurements, soil fertility assessments, and greenhouse gas emissions data to further strengthen the validity and reliability of our findings.

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