

Biofactories as a strategy to promote sustainable agricultural development

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ABSTRACT

Objective: Explain the factors that most significantly affect the innovation of biofertilizers produced and marketed by biofactories in the agricultural sector of Michoacán.

Design/methodology/approach: The methodology involved structural equation modeling using partial least squares with SmartPLS4 software, a bibliometric study and the logical framework methodology.

Results: Sustainability, productivity and profitability are the key factors that influence the innovation of biofertilizers produced and marketed by biofactories in the agricultural sector of Michoacán. The three constructs explain 78.5% of the variance in Innovation ($R^2=0.785$).

Limitations on study/implications: There are other constructs that can be incorporated into the variables. Each species of agricultural crop needs certain microorganisms as a bioinoculant, so the biofertilizer products market produces new types every year.

Findings/conclusions: For agricultural producers, the search for new markets, higher profits, higher sales, reduction in production costs, and sustainable fertilization alternatives significantly impact the use of biofertilizers. The factors that drive farmers to use bioinoculants are the search for a differentiated organic product for export. The use of biofertilizers has shown growth compared to synthetic ones, between 5 and 10%. In the structural model, Profitability represents 60% of innovation in the agricultural sector of Michoacán, Sustainability 19.2% and Productivity 18.8%. Mexico is innovative in the use of bioinoculants since every year it uses new species of microorganisms in its preparation.

Keywords: Biofactories, innovation, biofertilizers, sustainability.

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INTRODUCTION

Mexico ranks as the 11th largest agricultural producer globally, driven by an export surge facilitated through trade liberalization and the signing of 12 free trade agreements with more than 44 countries (SIAP-SAGARPA, 2018). The fruit sector holds strategic importance, with berries (strawberries, blackberries, blueberries, and raspberries) ranking third after beer and avocado, contributing 10.6% to the total export value (SIAP-SAGARPA, 2018). However, the country's agri-food activity is often predatory, causing extensive pollution of soils, groundwater, rivers, oceans, and the atmosphere. Agriculture accounts for approximately 15% of Mexico's Gross Domestic Product when factoring in environmental degradation and resource depletion (Morales, 2014). For instance, cultivating one hectare of corn typically requires an investment of 4,000 pesos in chemical fertilizers, compared to just 400 pesos for biofertilizers. Incorporating biofertilizers into corn production could generate an additional income of 2,000 pesos per hectare, benefiting nearly 400,000 small-scale producers (Andrade, 2018).

Nitrogen fertilizers Mexico's most consumed and produced have become increasingly costly, with prices rising by 500% in the first decade of the 21st century (Secretaría de Economía, 2012). Their efficiency remains low: crops utilize less than 20% of applied

nitrogen and phosphate fertilizers. The remaining unused portion contributes to significant environmental damage, contaminating soil and water and releasing nitrous oxide, a potent greenhouse gas that exacerbates climate change. Mexico has played a pivotal role in nitrogen fixation research, laying the foundation for the development of biofertilizers. In 1980, the Nitrogen Fixation Research Center (now the Genomic Sciences Center) was established at the National Autonomous University of Mexico, becoming a global pioneer in the field (Morales, 2014). By 2018, biofertilizers were being used on over four million hectares in Mexico. These inputs not only yield economic benefits but also enable access to organic markets, resulting in higher prices and improved sanitary conditions for crops. The National Institute of Forestry, Agricultural, and Livestock Research (INIFAP) conducted experimental trials on high-yield corn, revealing that nitrogen fertilizer use can be reduced by 30% without compromising, and in some cases improving, crop yields (Guzmán, 2018). In 2020, the state of Michoacán tripled its budget for the Sustainable Agriculture Program to 45 million pesos, aiming to incorporate 20,000 hectares into this initiative. According to Rubén Medina Niño, head of the Secretariat of Rural and Agri-Food Development (SEDRUA), the program began in 2019 with three crops over 6,000 hectares. Encouraged by yield increases of 40-80%, the program expanded to cover 12 crops. Innovations under the Sustainable Agriculture Program target a range of products including corn, strawberries, fruit trees (*e.g.*, guava, mango, grapefruit), hibiscus, lentils, and rice. These innovations have successfully lowered production costs by replacing agrochemicals with biofertilizers, fostering healthier crops, and promoting soil conservation and regeneration. Currently, there are 1,129,000 hectares under organic production over 5% of Mexico's total agricultural area with coffee, avocado, safflower, and corn occupying the most land. The primary organic exports are avocado, banana, and coffee (SIAP-SAGARPA, 2018). To further advance agroecological innovation, the Ministry of Agriculture and Rural Development (SADER) has prioritized the replacement of chemical fertilizers with bioinoculants. Governor Alfredo Ramírez Bedolla reported that, through the AGROSANO program, 22,000 tons of biofertilizer were distributed to farmers. Cuauhtémoc Ramírez Romero, head of SADER, described the program as part of a broader agroecological transition aimed at increasing profitability, improving soil fertility and yields, and reducing production costs (SADER, 2022). In 2022, a bioinput production network was established across 113 municipalities in Michoacán, with plans for expansion to decrease costs, protect land, prevent pollution, and reduce foreign dependency (Mendoza, 2022). Biofertilizers are broadly defined as natural organic materials, products of biological recycling, or human-made preparations that enhance soil fertility and productivity, either partially or entirely replacing chemical fertilizers (Vela *et al.*, 2018). A more specific academic definition refers to biofertilizers as products containing microorganisms that, when inoculated into the soil, form associations or symbioses with plants, improving their nutrition and offering protective benefits (Vessey, 2003). Meetings and surveys conducted with avocado and blackberry producers in Ziracuaretiro, Los Reyes, and Peribán, as well as biofactory representatives, helped identify the key variables of this study. Innovation serves as the dependent variable, while sustainability, productivity, and profitability are considered independent variables. International research including studies in the United States, Spain, Italy, China, Cuba,

Brazil, and Mexico has addressed the role of biofactories in agriculture, particularly their environmental implications and relevance to global sustainability efforts. Agrochemicals, though commonly used to increase profitability, have severely detrimental effects on soil health, aquifers, air quality, and human health. Communities relying on chemical inputs face serious health risks due to hazardous waste. In Michoacán, about 90% of farmers use agrochemicals, and approximately 50 million empty containers are improperly discarded each year in ravines, waterways, landfills, and along roadsides (SAGARPA, 2015). Synthetic fertilizer prices continue to climb, with only 20% of the product effectively utilized by crops. Nonetheless, opportunities lie in the expanding demand for organic products in both domestic and international markets. This underscores the importance of continued research on biofertilizers. The primary aim of this study is to identify the key factors that influence the innovation of biofertilizers produced and marketed by biofactories in the agricultural sector of Michoacán. The central hypothesis posits that sustainability, productivity, and profitability are the principal drivers of innovation in this context.

MATERIALS AND METHODS

Based on the 129 questionnaires completed during multiple field visits to producers in Los Reyes and Ziracuaretiro, Michoacán, a data matrix was constructed incorporating 29 indicators. These indicators were organized into three exogenous latent variables and one endogenous latent variable innovation. Structural Equation Modeling using Partial Least Squares (PLS-SEM) was conducted with the SmartPLS4 software to carry out the analysis.

A 5-point Likert scale was employed as the measurement instrument, where a score of 5 indicated complete agreement with a statement and 1 indicated complete disagreement. The Likert-type coding allowed numerical values to be assigned to the responses, facilitating data processing and ensuring symmetrical distribution around a central response category for each item. PLS-SEM does not assume any specific data distribution, making it suitable for exploratory research with complex models and small to medium sample sizes. In this study, respondents evaluated each item using the Likert scale, where higher scores reflected stronger agreement with the corresponding statements. In the constructed data matrix, each row represented an individual respondent, and each column corresponded to a specific questionnaire item. For example, the first row included the complete response set from respondent 1. All analyses were conducted using SmartPLS4. According to Cohen (1992), a minimum of 54 observations is sufficient to detect R^2 values around 0.25, assuming a significance level of 5% and statistical power of 80%. A t-value of 1.96 corresponds to a p-value of 0.05. In formative measurement models, p-values must be below 0.05 to confirm that the external weights are statistically significant at the 5% level.

RESULTS AND DISCUSSION

The following results were obtained using Partial Least Squares Structural Equation Modeling (PLS-SEM). Drawing on data from 129 completed questionnaires collected during multiple visits to producers in Los Reyes and Ziracuaretiro, Michoacán, a data matrix was constructed containing 29 indicators. These indicators were categorized under three exogenous latent variables and one endogenous latent variable innovation. The

statistical analysis was conducted using the SmartPLS4 software to model and assess the structural relationships among the variables in this study.

In the nomogram above, the blue circles on the left represent the exogenous latent variables: productivity (Prod_), sustainability (Sust_), and profitability (Prof_). The blue circle on the right represents the endogenous latent variable, or dependent variable: innovation (Innv_). The yellow rectangles connected to each construct denote the observed indicators or items. The lines linking indicators to constructs, as well as constructs to one another, represent the hypothesized relationships within the model. The numerical values between indicators and their respective constructs indicate the outer weights, reflecting the contribution of each item to its construct. Items with outer weights greater than 0.10 are considered statistically significant. The values between the latent variables represent Cronbach's alpha coefficients, which assess the internal consistency and reliability of the constructs and the overall model. This is a reflective measurement model, as indicated by the direction of the path lines extending from the constructs to the indicators. The model demonstrates a reliability level of 88.4%, based on the constructs and indicators included. These indicators were derived from responses to the survey administered to agricultural producers.

The following image illustrates the structural relationships among the latent variables. The exogenous latent variable Profitability exhibits the strongest influence on the endogenous variable Innovation, with a path coefficient of 0.574 and a total of six associated items. This is followed by Productivity (0.199), which includes eight items, and Sustainability

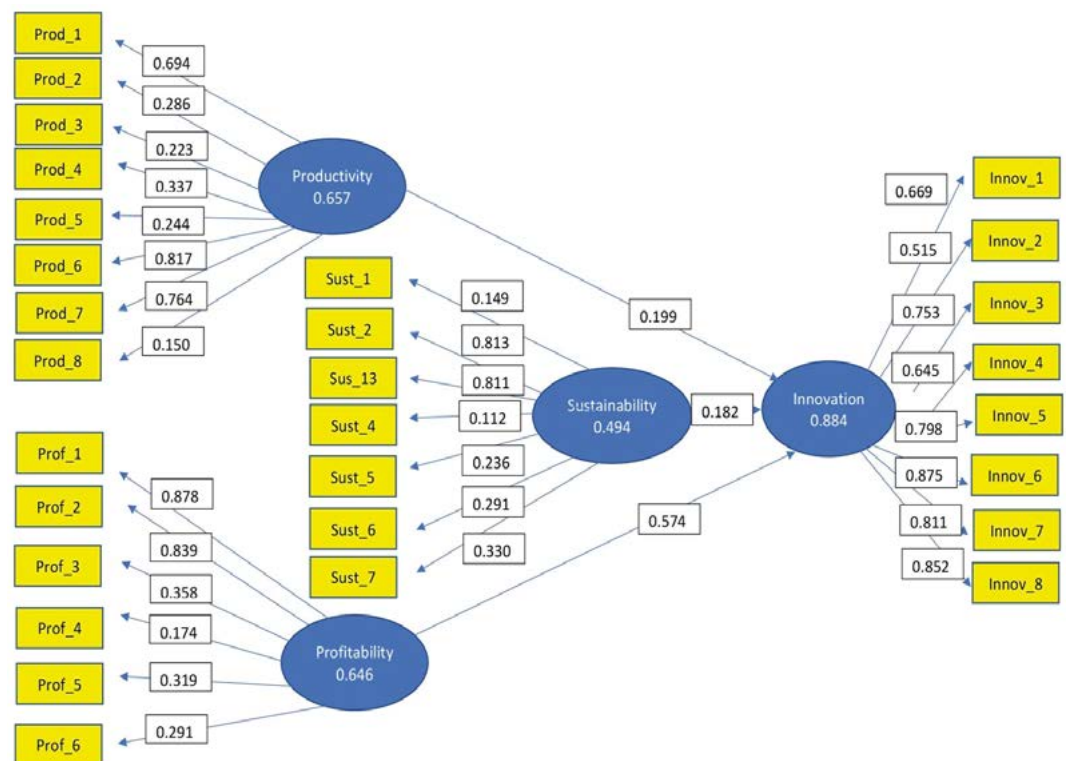


Figure 1. Structural Model with the Endogenous Variable Innovation as the Dependent Variable.

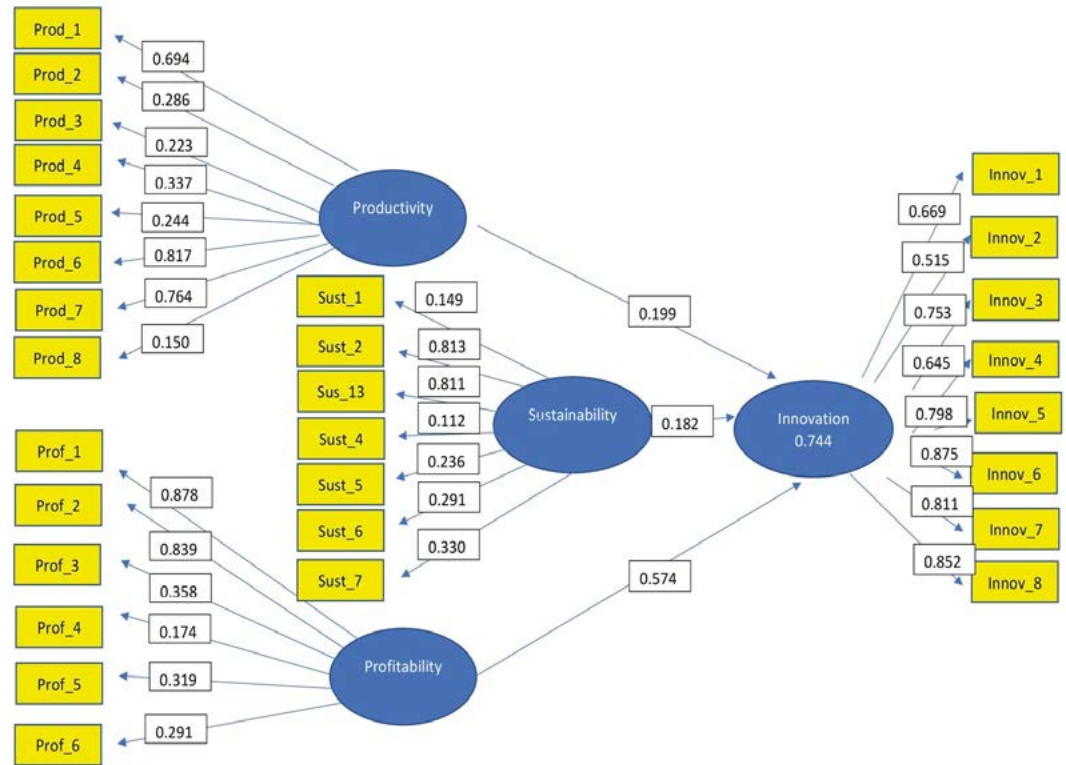


Figure 2. Initial structural model with complete survey indicators.

(0.182), represented by seven items. Collectively, these three constructs account for 74.4% of the variance in Innovation ($R^2=0.744$). These results were obtained prior to refining the measurement model by eliminating items with insufficient contribution. Specifically, indicators with outer weights below 0.10 and external loadings below 0.40 were excluded. Additionally, indicators demonstrating high collinearity often signaled by negative path coefficients were also removed. The final model considered both the relative and partial contributions of each indicator to ensure optimal predictive validity.

Among the exogenous latent variables, Profitability contributes most significantly to the endogenous latent variable Innovation, accounting for 60% of its predictive value. The most influential item within the Profitability construct is item 1 (0.638), which relates to profit gains, as producers seek greater profitability through the use of biofertilizers. Item 2 (0.445) addresses fair pricing, a motivation cited by producers in meetings, who emphasized the potential for higher returns through the marketing of organic products, especially in export markets. Item 5 (0.162) pertains to reduced production costs. Conversely, items 3, 4, and 6 representing sales, biofertilizer pricing, and government support via agricultural programs were discarded due to low external weights and loadings.

For the Sustainability variable, the most significant indicators, as highlighted by both producers and the SmartPLS4 analysis, include sust_2 and sust_3, which reflect the perceived positive environmental impacts of biofertilizers and their role in enhancing soil fertility. Indicators with low predictive power were removed from the model, including those related to groundwater contamination reduction, job creation, perceived health

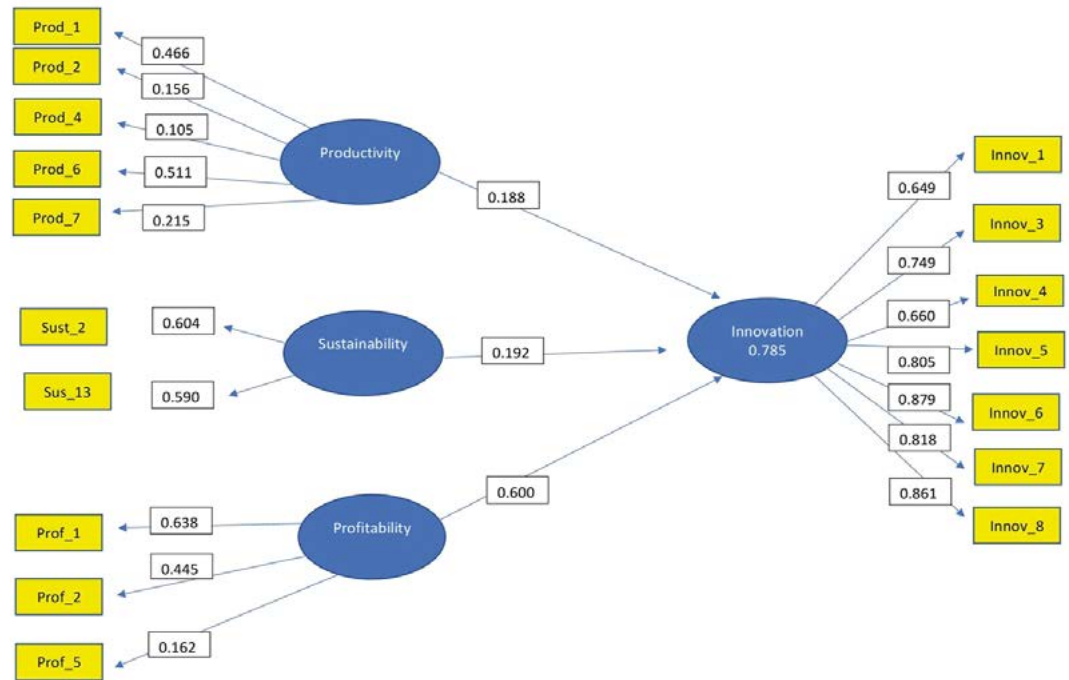


Figure 3. Structural model of innovation-biofertilizers.

benefits, crop adaptability, and issues of packaging and storage. Within the Productivity construct, the most significant items are prod_6 (0.511), which addresses increased productivity through improved soil fertility; prod_1 (0.466), which reflects the belief that biofertilizers enhance yields; and prod_7 (0.215), which indicates a motivation to transition from synthetic fertilizers to bioinoculants. Additionally, prod_2 underscores the advantage of reduced waste generation, as biofertilizers are perceived to be more efficiently utilized compared to conventional fertilizers, which have a utilization rate of only about 20%. Prod_4 highlights the role of government support programs; however, producers noted the lack of effective assistance in the region. The state-level biofactory initiative has failed to provide adequate training, and the few biofertilizers distributed have been largely ineffective due to the absence of viable microorganisms. In a formative-reflective model, a minimum R^2 of 0.50 is required to establish convergent validity. The final model achieved an R^2 of 0.785, indicating strong explanatory power. Together, the exogenous variables Profitability, Sustainability, and Productivity explain 78.5% of the variance in Innovation related to biofertilizer use in the agricultural sector of Michoacán. The remaining 21.5% is attributed to other factors not captured within this model, either due to exclusion during the refinement process or because they were not originally considered. The nomogram demonstrates that Cronbach's alpha increased slightly from 0.884 to 0.889 after removing less significant indicators those with outer weights below 0.10 or low external loadings. Indicators with a weight above 0.10 are considered significant based on their relative contribution, while external loadings reflect their absolute contribution. Although the increase in reliability is marginal, the refinement enhances the structural model's robustness and compliance with statistical thresholds.

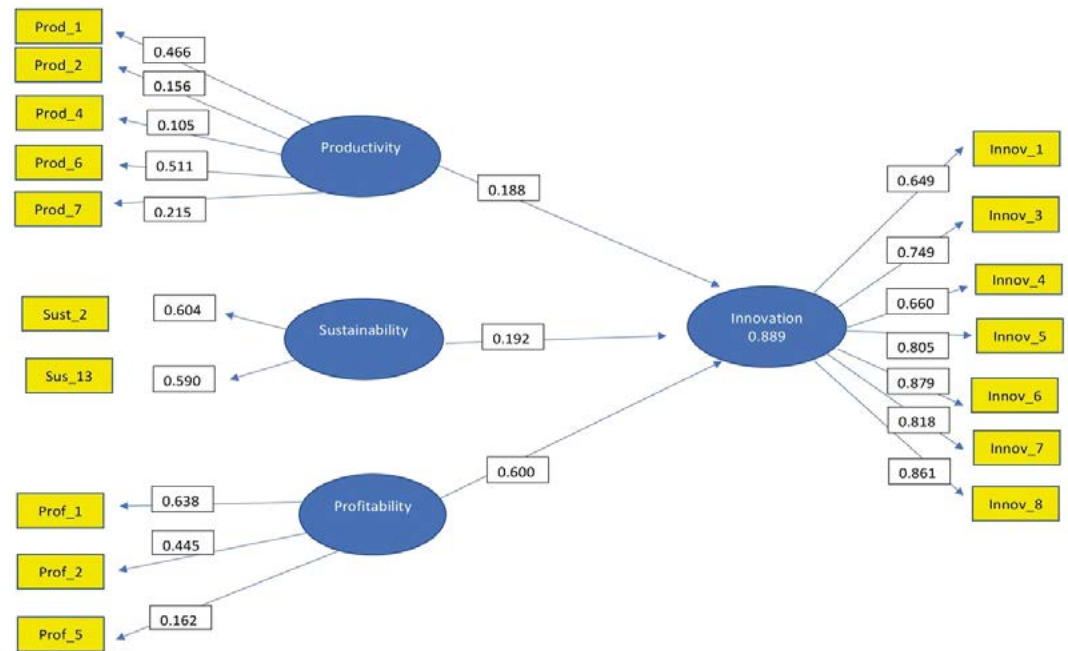


Figure 4. Cronbach’s alpha in the Structural Modeling of Biofertilizer Innovation.

Collinearity does not reach critical levels in any of the formatively measured constructs, indicating that multicollinearity is not a concern in estimating the PLS nomogram of the extended Innovation model. The figure presents the external weights for each indicator contributing to the model’s constructs, all of which are statistically significant, with values exceeding the 0.10 threshold. The lowest observed weight is 0.105, associated with the Productivity construct, suggesting that for producers, the drive to achieve higher productivity is positively associated with biofertilizer use. The highest external weight, 0.638, corresponds to the Profitability construct, underscoring its substantial importance for producers. This weight reflects the motivation to increase profitability through reduced production costs and the opportunity to market a differentiated product. Producers are incentivized to use biofertilizers to access organic export markets, where higher prices perceived as fair can be obtained. Within the Innovation construct, the most significant indicators are *innv_6* (0.879) and *innv_8* (0.861), making them the strongest contributors to the endogenous variable in the structural model. For the exogenous variables, the most significant indicators include *prod_6* (0.842), *rent_1* and *rent_2* (0.837), *sust_2* (0.841), and *sust_3* (0.833). To assess the statistical significance and relevance of these external weights, a bootstrapping procedure will be performed using the Bias-Corrected and Accelerated (BCA) bootstrap method. This analysis will be conducted with a significance level of 0.05, using 5,000 bootstrap samples and a two-tailed test to ensure robust and reliable results.

In the formative measurement model, p-values below 0.05 confirm the statistical significance of the external weights at the 5% level. For agricultural producers in Michoacán, key drivers influencing the use of biofertilizers include the search for new markets, higher profits, increased sales, reduced production costs, the adoption of sustainable fertilization alternatives, the emergence of new biofertilizer brands, and effective knowledge transfer.

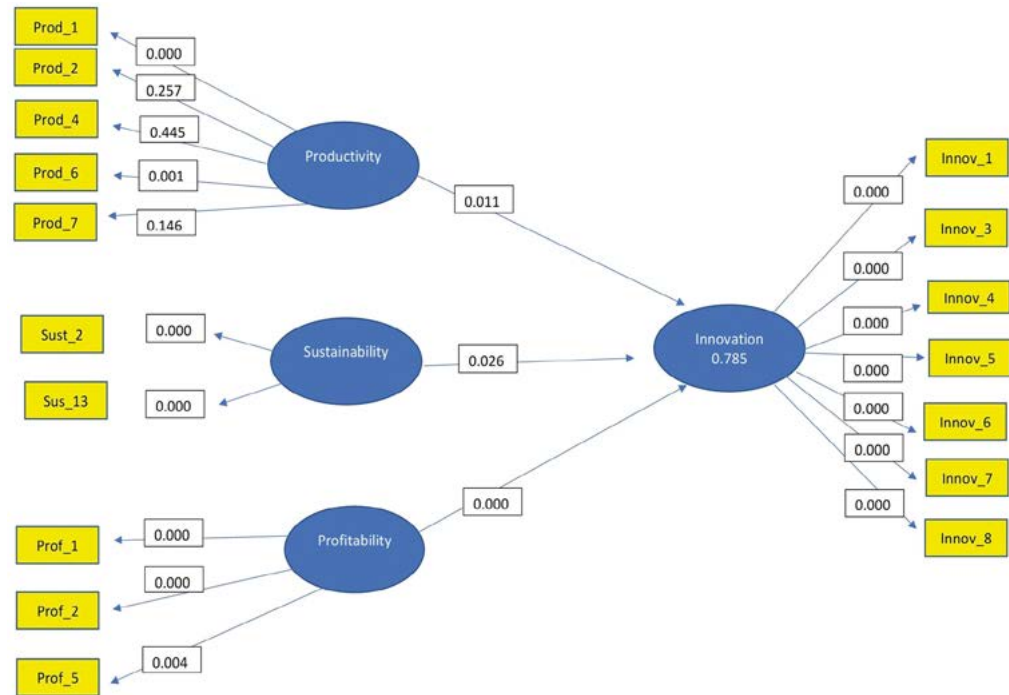


Figure 5. Booststrapping P-values.

The latent variables Profitability, Sustainability, and Productivity exhibit external weights of 0.011, 0.026, and 0.000, respectively each statistically significant in determining Innovation in the context of biofertilizer use in Michoacán’s agricultural sector. These values confirm that the construct measures are both reliable and valid. Furthermore, the p-values for the relationships between the exogenous and endogenous variables are below 0.05, and the t-statistics exceed 1.96, establishing significance at the 5% level. In the importance-performance map, constructs located in the upper-right quadrant those with both high importance and high performance warrant strategic focus. Notably, the exogenous variable Profitability occupies this quadrant, highlighting its potential to drive performance improvement. Therefore, actions aimed at promoting innovation in the use, marketing, and production of biofertilizers should prioritize the indicators under this construct. Specifically, indicators Rent_1 and Rent_2 from the Profitability construct show the highest levels of importance and performance. These findings suggest that strategic efforts should target these indicators to maximize their impact on innovation in the agricultural sector. Profitability emerges as the most influential variable on Innovation, driven by producers’ motivation to access premium organic export markets, secure higher prices, and reduce production costs through more efficient and less expensive alternatives to chemical fertilizers. While Sustainability is also a relevant factor, it ranks below Profitability in impact. The indicators contributing most to Sustainability relate to the enhancement of soil fertility. Although producers recognize the harmful effects of agrochemicals on human health and ecosystems, this awareness is not as strong a motivator. This is reflected in the modest shift toward biofertilizer use, which currently represents only 5% to 10% of total fertilization. Productivity remains a significant driver as well, with producers observing

that biofertilizers restore soil fertility and improve nutrient absorption by crops, thereby increasing yield potential. The pursuit of higher profitability through more productive crops continues to be their primary incentive. Regarding reliability, Cronbach's alpha a conservative measure assuming equal reliability across all indicators supports the model's internal consistency. However, composite reliability, which accounts for the varying external loadings of indicators, offers a more nuanced assessment. Reliability values between 0.60 and 0.70 are considered acceptable, while those between 0.70 and 0.90 are satisfactory. Values exceeding 0.90 may indicate redundancy and are generally discouraged. In this study, all four constructs fall within acceptable or satisfactory reliability thresholds, with especially strong reliability observed in the Innovation and Productivity constructs.

CONCLUSIONS

Based on the hypothesis of this research, sustainability, productivity, and profitability are the key factors influencing biofertilizer innovation produced and marketed by biofactories in the agricultural sector of Michoacán, Mexico. This hypothesis is quantitatively supported by the SmartPLS4 analysis. Within the structural model and its indicators, profitability accounts for 60% of the variance in innovation, while sustainability and productivity account for 19.2% and 18.8%, respectively. Biofertilizers are primarily applied in organic crops intended for international markets, with the United States as the principal destination, followed by Canada, Japan, and European countries such as Germany. The significance of sustainability and productivity in fostering biofertilizer innovation is thus confirmed. Producers recognize the environmental benefits of biofertilizer use, particularly in improving soil fertility, and their non-toxic effects on human health, consumers, field workers, and local ecosystems. Moreover, biofertilizers generate less waste, as they are absorbed more efficiently by crops compared to conventional fertilizers. In the productivity construct, the most impactful indicator is the improvement of soil fertility. Nutrient-enriched soils not only increase yield but also facilitate more effective nutrient absorption by crops. However, a major credibility issue emerged when state-distributed biofertilizers in 2022 were found ineffective due to the absence of viable microorganisms, a core component of biofertilizer efficacy. From a profitability perspective, producers are motivated by the lower cost of biofertilizers relative to chemical alternatives, their greater absorption efficiency, and their potential to reduce long-term production expenses. Unlike synthetic fertilizers, which require larger quantities with each cycle, biofertilizers gradually enrich soil health, enabling recovery in degraded soils within approximately five years. A key incentive is the ability to access organic export markets, which offer premium prices perceived as fair compensation. Several types of innovation are being implemented within agricultural systems, including diversification into export crops such as horticultural and grains, adoption of new and hybrid varieties, use of grafts and patented seeds, reforestation, agro-industrial transformation, application of biotechnology, fertigation, precision agriculture, drones, improved input management, good agricultural practices, agroclimatic monitoring, cold storage, smart machinery, automated packaging, GPS-guided harvesters, and integrated pest and disease management involving cultural, genetic, biological, and

chemical strategies, as well as financial diversification, digitization of administrative systems, flexible labor hiring methods, agricultural machinery rentals, contract farming, direct sales, targeting seasonal market windows, promotional campaigns, upgraded packaging and presentation, global certification, and digital marketing through websites and social media platforms, along with efforts to access government support. One of the main economic incentives for adopting innovations that promote sustainability is the price premium in organic markets, particularly foreign markets. In Mexico, the United States continues to be the main importer of agro-exported goods. Biofertilizers represent a sustainable agricultural input, offering multiple benefits: they enhance productivity, generate profits, and do not harm human health, biodiversity, or agricultural soils. Moreover, they help prevent environmental contamination, especially in water bodies and the atmosphere. They have also become a source of employment through biofactories established in Michoacán, creating jobs in production, distribution, and training-related activities. Their efficacy has been demonstrated in increasing agricultural soil productivity by approximately 40% through enhanced fertility. This contributes to cost reductions, strengthens both national and export-oriented organic markets, and supports premium pricing for sustainable products. As such, biofertilizers represent an innovative bioproduct with a transformative impact across all dimensions of sustainability. They have revitalized the production of traditional staple crops such as corn, beans, rice, coffee, and cocoa, and are also being applied to commercially valuable crops like sugarcane, bananas, limes, berries, and avocados, driving innovation across the agricultural sector.

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