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CIRCULAR ECONOMY IN THE *Agave tequilana* Weber VALUE CHAIN

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ABSTRACT

The blue variety of *Agave tequilana* Weber is a product of great economic and cultural importance in Mexico, although it faces fluctuations in the prices of agave and environmental challenges. In this study, diversification strategies were evaluated using investment portfolios in the agave value chain, aimed at the production of inulin, bioethanol, and biogas from residual biomass, as well as tequila, under a circular economy approach. The hypothesis proposed is that expanding into innovative products derived from the tequila agave enhances returns and mitigates risks throughout the sector's value chain. The biorefinery approach within a circular economy model makes it possible to use the entire agave plant, create high-value products, and reduce the risk of price fluctuation and the environmental impact. The diversification of products and the management of the residual biomass increased the production income and contributed to the dispersion of risk.

Keywords: Tequila agave, residual biomass, investment portfolios, biogas, agave inulin, bioethanol.

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INTRODUCTION

Agave is a crop of agro-industrial importance due to its use in the production of foods, beverages, medications, construction material, and fibers. In 2023, tequila agave production in Mexico reached 2.125 thousand Mg, which represents a 30 % increase in regard to the previous year (SIAP, 2024a). The production was concentrated mostly in the states of Jalisco (59 %), Guanajuato (19 %), and Michoacán (12 %). These three states contributed 90 % of the domestic volume and registered production increments of 22.3, 20.4, and 187.1 %, respectively.

Agave production has become established as a highly lucrative activity due to its demand in international markets, associated with the recognition of tequila's designation of origin. This situation coincides with the growing trend in exports of this beverage, due to the increase in the preference of consumers in countries like the United States (SIAP, 2024a). In 2023, beverages derived from agave, including tequila, ranked second in export value at USD 4159 million, representing a 2 % increase compared to 2022. The main destinations were the United States (USD 3831 million), Japan (USD 78 million), and Spain (USD 69 million) (SIAP, 2024a). Tequila is currently sold in 141 countries, making it the second most significant agro-industrial product by value, following beer.

However, despite its economic importance and the growing rise in its consumption, the value chain for tequila faces environmental and social challenges. Among the main cyclic problems is the scarcity or oversupply of agave in the face of high demand, which causes volatility in the prices of the raw material (Herrera-Pérez *et al*., 2018). In addition, the increase in real prices of agave has boosted the expansion of its production, causing the displacement of less profitable crops such as maize and contributing to deforestation to expand the area under cultivation (Cruz-Ramírez *et al*., 2023a).

The productive processes of agave lead to a large amount of waste that, when disposed of in open areas, causes soil degradation. For every liter of tequila produced, between 10 and 12 L of vinasse and between 3.5 and 7 kg of bagasse are generated (Hoz-Zavala and Nava-Diguero, 2017). The tequila industry annually pollutes with over 4 billion L of vinasse, composed of organic acids, nitrogen, and sulfates, with a high organic matter content and high temperatures, which makes its treatment costly and difficult (CRT, 2019). Additionally, nearly 40 % of the weight of agave used as raw material corresponds to bagasse. Altogether, both waste products represent an economic, social, and environmental problem for the tequila sector.

Nevertheless, these residues have the potential to become valuable products through biorefineries, such as enzymes, biofuels, bioactive molecules, biomedications, construction materials, composts, paper, boards, substrates for vegetables, and feed for ruminants (Cardona-Alzate *et al*., 2023). Currently, these residues pose challenges for the agri-food system due to their contribution to greenhouse gas emissions, unpleasant odors, and potential health risks for people. However, new business models are emerging that adhere to the principles of circular economies. With the concept of biorefineries, this waste may become an opportunity to mitigate pollution and reduce the environmental footprint.

A biorefinery is a complex system designed to process biomass and obtain bioproducts that gradually replace oil by-products to satisfy the needs of different sectors, which requires the incorporation of technology and innovation (Cardona-Alzate *et al*., 2023). Likewise, it also allows the use of a single raw material to produce diverse products with multiple applications. Given the emphasis on the development of products with more added value, it is necessary to adapt and design financial instruments that diversify the risk and increase profitability, such as investment portfolios (Rojas-Rojas *et al*., 2025b). These business models are characterized by their innovative nature, although they also involve greater risk due to price volatility, which is offset by a higher potential profitability (Brambila-Paz *et al*., 2019).

However, based on the above and despite the importance of research that integrates theoretical aspects of bio-economics, biorefineries, and investment portfolios that strengthen the empirical evidence on the topic, these types of studies continue to be limited. Among the most closely related studies are those by Brambila-Paz *et al*. (2013, 2019), focused on bio-economics, biorefineries, portfolios, and real options, as well as those by Carrillo-González and Ponce-Sánchez (2019) on circular economy, bio-economics, and biorefineries, among others.

In this sense, the aim of this investigation was to evaluate diversification mechanisms in the blue agave production process to obtain tequila, the use of waste generated in the process, and the convenience of adopting a biorefinery system for the production of inulin with the use of investment portfolios. As a hypothesis, it is proposed that the development of innovative products derived from tequila agave will increase the yield of the value chain of the sector and reduce its risk.

MATERIALS AND METHODS

The investment portfolio is a tool used for asset diversification, whose function it is to disperse risk for a specific profitability or maximize return at a given level of risk. This methodology was proposed by Markowitz (1952), who developed portfolio optimization techniques by combining different assets. The risk of a portfolio is measured through its volatility, which depends on the covariance or correlation among the returns of the assets. When the assets display correlated returns, the portfolio risk can be reduced by allocating adequate investment weights (Muñoz-González *et al*., 1992).

To propose a product diversification scheme in the agave value chain, the methodology proposed by Brambila-Paz *et al*. (2013) and Rojas-Rojas *et al*. (2025b) was applied, using the investment portfolio tool. Under the concept of biorefineries, the investor decides to invest in the production of tequila or inulin based on the availability of raw material. In the agave value chain, following the circular economy approach, the investor can diversify their production by using the waste generated in the processes. Estrada-Maya and Weber (2022) point out that the bagasse from the tequila production process can be used in the production of bioethanol and biogas through subsequent batch fermentations.

In this study, the design of investment portfolios was proposed, in which the investor has the option of developing a biorefinery and taking full advantage of the waste products of the tequila production process. Inulin, biogas, and bioethanol were considered differentiated products, whereas the traditional or commodity product was the tequila. The diversified portfolio includes the production of all the products mentioned; the portfolio under a biorefinery scheme contemplates the production of inulin and/or tequila, and the traditional portfolio only considers the production of tequila.

An investor in the agave sector was assumed to have a certain amount of capital (*Z*), which is distributed in *n* assets. Each asset was assigned different investment weights $\alpha_1, \alpha_2, ..., \alpha_i$, in such a way that $Z\alpha_i$ represents the amount of capital invested in the *i*-th asset:

$$(\alpha_1 + \alpha_2 + \cdots + \alpha_i)Z = Z$$

Due to , $\alpha_1 + \alpha_2 + ... + \alpha_i = 1$, all investment weights are positive and comply with $0 \leq \alpha_i \leq 1$.

$\bar{R}_1, \bar{R}_2, ..., \bar{R}_n$ were considered to represent the returns obtained for each of the assets or products that make up the investment portfolio. The expected returns follow a normal distribution, therefore the expected profitability of the portfolio $E(\bar{R}_p)$ was modelled as a randomized variable with a normal distribution, mean $E(\bar{R}_p)$ and a constant variance (Muñoz-González *et al*., 1992):

$$E(\bar{R}_p) = \sum_{i=1}^{n} \alpha_i E(R_i)$$

In turn, the portfolio risk was estimated with the return variance. The return variance of a product's returns is defined as the weighted sum of the quadratic deviations of the gains in regard to its mean (Díaz-Carreño *et al*., 2007).

Markowitz (1952) points out that a portfolio with administrative risk must present a lower risk than the weighted sum of the individual risks, which is possible when the assets display a negative or very low covariance. The portfolio variance for *n* assets is described in the following equation:

$$VarP = \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_i \alpha_j CovR_i R_j$$

where *VarP* is the variance of the portfolio and α_i and α_j are the investment weights allocated to each asset. If $i = j$, $CovR_iR_j$ is the variance of each asset or product. If $i = j$, $CovR_iR_j$ represents the covariance of asset *i* with product *j*.

The standard deviation of portfolio $StDevP$ represents the portfolio risk and is calculated as follows:

$$StDevP = \sqrt{VarP}$$

The risk and return of the portfolios analyzed were estimated using Microsoft Excel. Proxy annual variables were used from the 2000–2023 period. The statistical data for amounts (kg, L) and the value of the exports of each product (USD) were obtained from the National Statistics and Geography Institute (INEGI, 2024a). In particular, the prices of inulin (Pr_{1t}, USD kg^{-1}), tequila (Pr_{2t}, USD kg^{-1}), and ethanol (Pr_{3t}, USD kg^{-1}) were considered. For the biogas, the price of LP gas (Pr_{4t}, USD kg^{-1}) was used as a proxy variable, with information obtained from the Secretariat of Energy (SENER, 2015) and the Energy Regulating Commission (CRE, 2024). For subsequent calculations, the prices of Pr_{1t}, Pr_{2t}, Pr_{3t}, and Pr_{4t} were transformed into real prices using the National Index for Prices to Consumers (INPC), based on 2023 = 100, as published by INEGI (2024b).

To estimate the return of each asset or product, yield data were required as a measure of the production quantity (Q_i). An inulin yield of θ_1 = 4.87 kg was considered for every 48.9 kg of agave (Montañez-Soto *et al*., 2011). The tequila production coefficient was defined as θ_2 = 1 L of tequila per 7 kg of agave. The agave yield ($\theta_3 t$) was obtained from data reported by SIAP (2024b). Yields were calculated considering an ethanol yield of θ_4 = 2.9 % per kilogram of bagasse waste and a biogas yield of θ_5 = 4.5 % per kilogram of bagasse waste. (Estrada-Maya and Weber, 2022). Waste generation during tequila production was estimated assuming θ_6 = 2 kg of bagasse per liter of tequila and θ_7 = 10 L of vinasse per liter of tequila. The conversion factor for vinasse was defined as θ_8 = 0.06 kg of chemical oxygen demand (COD) per liter of vinasse. Methane generation through the anaerobic process was estimated using θ_9 = 0.35 m^3 of CH_4 per kilogram of COD. Both parameters were obtained according to del Real-Olvera and López-López (2012). Finally, a density of ϱ = 540 kg m^{-3} was assumed for LP gas.

The gross income (I_{it}), defined as the profit of the product or asset *i* in the year *t*, was estimated following the methodology by Rojas-Rojas *et al*. (2025b), which consists of multiplying the price of asset *i* in year *t* (Pr_{it}) by the amount produced of asset *i* (Q_{it}). In a biorefinery system, the value of I_{it} is based on the investment weights assigned to the production of inulin (α_1), tequila (α_2), or both activities (Table 1).

The yield of each asset (θ_i) and income (I_{it}) were determined for one hectare of tequila agave. For inulin, income was estimated as $I_{1t} = Pr_{1t}Q_{1t} = Pr_{1t}\theta_1\theta_{3t}\alpha_1$, where $Q_{1t} = \theta_1\theta_{3t}\alpha_1$. In the case of tequila, income was calculated as $I_{2t} = Pr_{2t}Q_{2t} = Pr_{2t}\theta_{3t}\theta_2\alpha_2$, where $Q_{2t} = \theta_{3t}\theta_2\alpha_2$.

To estimate the byproducts derived from bagasse, which are residues of the tequila production process (Q_{2t}), the amount of bagasse generated was first calculated:

$$Q_{bagazot} = Q_{2t}\theta_6$$

Table 1. Structure of investment weights of the analyzed portfolios.

Portfolio*	Investment weight		Portfolio*	Investment weight	
	Inulin (α_1)	Tequila (α_2)		Inulin (α_1)	Tequila (α_2)
P1	0 %	100 %	P8	70 %	30 %
P2	10 %	90 %	P9	80 %	20 %
P3	20 %	80 %	P10	90 %	10 %
P4	30 %	70 %	P11	100 %	0 %
P5	40 %	60 %	P12	50 %	50 %
P6	50 %	50 %	P13	0 %	100 %
P7	60 %	40 %			

*P1 corresponds to portfolios of tequila that use bagasse and vinasse for bioethanol and biogas. P2–P10 represent portfolios under a biorefinery scheme that produce inulin and tequila, with waste valorization. P11 only produces inulin; P12 produces inulin and tequila without the use of waste; and P13 produces exclusively tequila.

The income from ethanol was estimated as $I_{3t} = Pr_{3t}Q_{3t} = Pr_{3t}Q_{bagazot}\theta_4$, where $Q_{3t} = Q_{bagazot}\theta_4$. Similarly, the income from biogas derived from bagasse was calculated as $I_{4t} = Pr_{4t}Q_{4t} = Pr_{4t}Q_{bagazot}\theta_5$, where $Q_{4t} = Q_{bagazot}\theta_5$.
To estimate the biogas of the vinasses, which is also a waste product of the tequila production process (Q_{2t}), the amount of vinasse produced was estimated:

$$Q_{vinazast} = Q_{2t}\theta_7$$

The corresponding income was estimated as $I_{5t} = Pr_{4t}Q_{5t} = Pr_{4t}Q_{vinazast}\theta_8\theta_9\rho$, where $Q_{5t} = Q_{vinazast}\theta_8\theta_9\rho$.

From the above equations, the average income from asset *i* was calculated as a measure of profitability or return ($\bar{R}_i$), the variance of asset *i* as a measure of volatility (Var_i), and the standard deviation of asset *i* as a measure of risk ($desvest_i$):

$$\bar{R}_i = \sum_{t=1}^{n} I_{it}\, n^{-1}$$

$$Var_i = \sum_{t=1}^{n} (I_{it} - \bar{R}_i)^2\, n^{-1}$$

$$desvest_i = (Var_i)^{1/2}$$

where $(\bar{R}_i)$ is the weighted profit of the product or asset i (i = 1, 2 ... 4), I_{it} is the weighted real gross income of product i in year t, and n is the number of observations.

The profitability or return of the portfolio (R_p) was obtained with the sum of the weighted profitability of the assets:

$$\bar{R}_p = \sum_{i=1}^{n} \bar{R}_i$$

The variance of the portfolio (*VarP*) was calculated with the matrix of variances (Var_i) and covariances ($CovR_iR_j$) of the assets that were included for each portfolio. The investment weights (α_i) were determined based on the weighted profitability ($\bar{R}_i$) in regard to the profitability or return of the portfolio ($\bar{R}_p$):

$$\begin{aligned} VarP = {} & \alpha_1^2 Var_1 + \alpha_2^2 Var_2 + \alpha_3^2 Var_3 + \alpha_4^2 Var_4 + \alpha_5^2 Var_5 + 2X_1X_2CovR_1R_2 + 2\alpha_1\alpha_3CovR_1R_3 \\ & + 2\alpha_1\alpha_4CovR_1R_4 + 2\alpha_1\alpha_5CovR_1R_5 + 2\alpha_2\alpha_3CovR_2R_3 + 2\alpha_2\alpha_4CovR_2R_4 \\ & + 2\alpha_2\alpha_5CovR_2R_5 + 2\alpha_3\alpha_4CovR_3R_4 + 2\alpha_3\alpha_5CovR_3R_5 + 2\alpha_4\alpha_5CovR_4R_5 \end{aligned}$$

With the estimations of $\bar{R}_i$, Var_i and $CovR_iR_j$ for each asset, the measure of risk (*StDevP*) and profitability ($\bar{R}_p$) of each portfolio was calculated following the methodology by Rojas-Rojas *et al*. (2025b) (Figure 1).

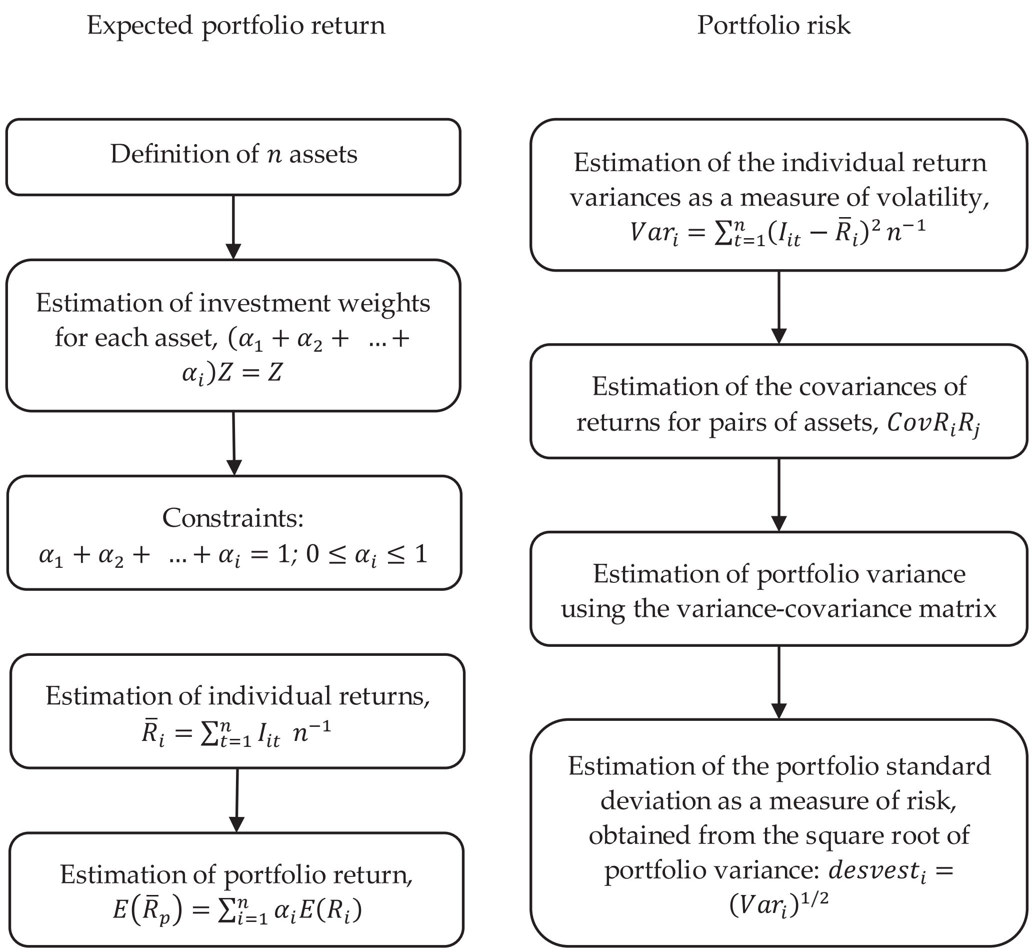

Figure 1. Estimation of the return on investment and risk of the traditional and the biorefinery portfolios.

RESULTS AND DISCUSSION

The tequila industry has proven to be highly productive and profitable due to its dynamism in the export market, mainly to the United States, where the presence of Mexican nationals has increased its consumption as a traditional beverage. As a result, the true price of tequila displayed an average annual increase of 4 % between 2000 and 2023, with a relatively low risk (Table 2).

However, in terms of profitability, the income per hectare of agave production as a raw material displayed a downward trend (-1 %), mainly due to the reduction in crop yield (-1.5 %) (SIAP, 2024b), despite the real price of agave having recorded a marginal growth in its average annual rate of 0.5 % between 2000 and 2023. This reduction in return is associated with the increasing demand for agave as an input for the production of tequila, which has led to soil overexploitation, nutrient depletion, and

Table 2. Return and risk analysis of prices for selected products (2000–2023).

Variable	Agave	Inulin	Tequila	Bioethanol	Biogas
Return	0.005	0.09	0.04	0.05	0.01
Volatility	0.19	2.05	0.02	2.52	0.01
Risk	0.43	1.43	0.13	1.59	0.10

the consequent adverse effects on plant health (Quezada-Chico *et al*., 2022). Likewise, the intensive use of agave has prevented plants from reaching an adequate maturity level, reducing the amount and quality of the raw material (Acosta-Salazar *et al*., 2021). Nevertheless, in the first half of 2024, the tequila agave value chain faced a raw material oversupply problem (Rojas-Rojas *et al*., 2021). Agave consumption for the production of tequila decreased by 25 % from January to July, 2024, in comparison with the same period of the previous year (CRT, 2024). As a consequence, the reduction in demand in the export market (-6 %) was reflected in an equivalent slowdown in the production. This situation led to an oversupply of agave in the first half of 2024 and anticipates a downward trend in the price of agave hearts in upcoming years (Cruz-Ramírez *et al*., 2023b; Díaz-Castellanos, 2023). In this scenario, the possibility of implementing a biorefinery system opens up to implement the use of the available raw material and generate products with a higher added value, such as inulin, while continuing to produce tequila. Inulin is a dietetic fiber with prebiotic effects that favors the reduction of blood cholesterol and the absorption of calcium in bones (Montañez-Soto *et al*., 2011).

On the other hand, to evaluate the normality of the individual returns, the Shapiro-Wilk test was used. Its decision criterion establishes that the null hypothesis (H_0) assumes a normal distribution of returns and is rejected when $p < 0.05$. In addition, a value of W close to 1 suggests normality in the distribution (Gujarati and Porter, 2010) (Table 3).

The results confirmed the normality of inulin and biogas. By contrast, bioethanol and tequila did not satisfy the normality criterion. Nevertheless, its W values were close to 1, which can be explained by the fact that, although the methodology assumes normality, the actual data do not reflect it, as they present fat tails or high peaks in the returns (Francis and Kim, 2013).

Table 3. Normality tests in the individual returns of the products selected.

Product	*p*-value	W
Inulin	0.0856	0.9275
Tequila	0.0140	0.8911
Bioethanol	0.0189	0.8973
Biogas	0.6198	0.9681

Portfolios were developed to utilize agave for the production of inulin and/or tequila. Tequila displayed a high return, as shown in portfolio P13, which has a return three times higher than portfolio P11, which only produces inulin. However, in light of scenarios of oversupply of agave and price volatility, an alternative is to allocate part of the raw material to the production of inulin. By diversifying production, such as in portfolio P12, the risk decreases (Table 4). These results are consistent with those reported by Valencia-Sandoval *et al*. (2020) through evaluation using real options.

Table 4. Risk and return on investment portfolios in the agave value chain.

Portfolio*	Investment weight		Portfolio risk (*StDevP*, \$)	Portfolio variance (*VarP*, \$²)	Portfolio return (E ($\bar{R}_p$), \$)	Portfolio return (E ($\bar{R}_p$), USD)
	α_1	α_2				
P1	0 %	100 %	3 323 290.57	11 044 260 194 181.70	31 076 720.69	1 751 392.56
P2	10 %	90 %	2 983 294.61	8 900 046 736 753.88	28 041 219.40	1 580 320.63
P3	20 %	80 %	2 643 425.23	6 987 696 924 997.75	25 005 718.11	1 409 248.71
P4	30 %	70 %	2 303 734.99	5 307 194 898 730.34	21 970 216.83	1 238 176.79
P5	40 %	60 %	1 964 310.47	3 858 515 613 910.67	18 934 715.54	1 067 104.87
P6	50 %	50 %	1 625 305.26	2 641 617 197 272.32	15 899 214.25	896 032.94
P7	60 %	40 %	1 287 021.54	1 656 424 439 067.60	12 863 712.96	724 961.02
P8	70 %	30 %	950 152.52	902 789 818 683.79	9 828 211.67	553 889.10
P9	80 %	20 %	616 764.58	380 398 548 059.89	6 792 710.39	382 817.17
P10	90 %	10 %	297 988.43	88 797 103 976.98	3 757 209.10	211 745.25
P11	100 %	0 %	347 363.28	120 661 249 896.97	721 707.81	40 673.33
P12	50 %	50 %	192 966.10	37 235 916 569.12	1 425 687.23	80 347.54
P13	0 %	100 %	469 849.67	220 758 714 376.24	2 129 666.64	120 021.75

*P1 corresponds to portfolios of tequila that use bagasse and vinasse for bioethanol and biogas. P2–P10 represent portfolios under a biorefinery scheme that produce inulin and tequila, with waste valorization. P11 only produces inulin; P12 produces inulin and tequila without the use of waste; and P13 produces exclusively tequila. α_1 and α_2 represent the investment weights on inulin and tequila, respectively.

On the other hand, portfolios P1 to P10, designed to use the residual biomass such as vinasses and bagasse, represent a business opportunity and an alternative to mitigate the environmental problems of the sector. When comparing portfolio P1, which produces tequila and manages the waste to generate biogas and ethanol, with portfolio P13, which only produces tequila, profitability increased 14.5 times when the waste is used. Rodríguez-Hernández *et al*. (2016) found similar results, reporting cost-benefit ratios of 13.3 for *Agave angustifolia* and of 6.47 for *A. tequilana* in the production of bioethanol, although they pointed out that profitability depends on the price of agave and bioethanol in the market.

The management of waste in the tequila industry shows the generation of additional income (Figure 2). This can be observed in portfolio P6, corresponding to a biorefinery

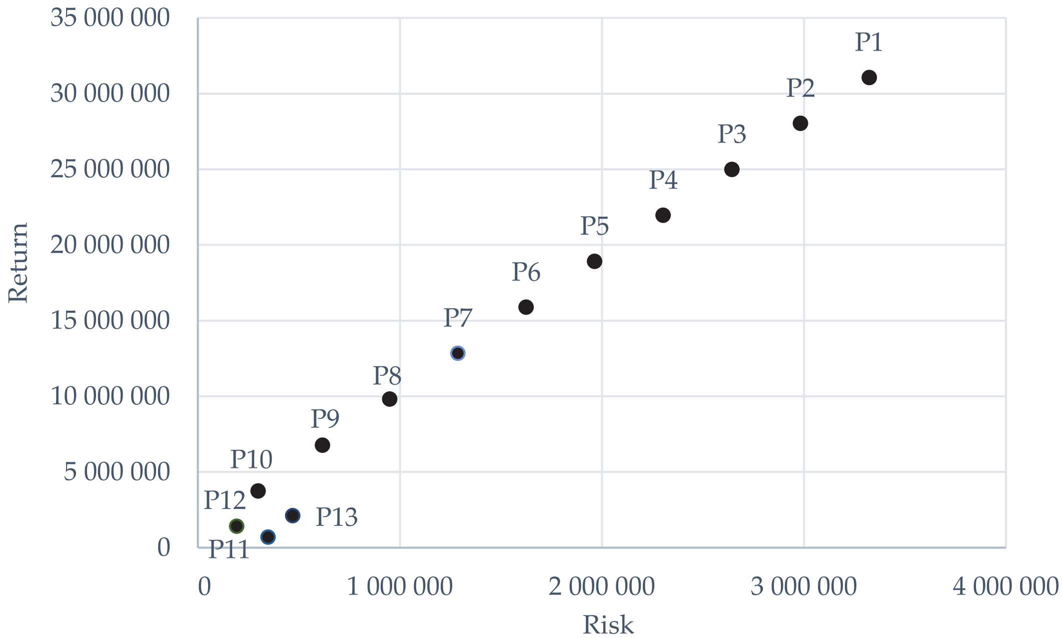

Figure 2. Behavior of the return on investment and risk of the portfolios evaluated.

system in which 50 % of the raw material was destined to the production of inulin and 50 % to the production of tequila, with the use of residues to obtain biogas and bioethanol, in comparison with portfolio P12, with the difference being that the vinasse and bagasse residues were not managed.

It is important to note that P12 was the portfolio with the lowest risk compared to the others. The use of residues increased its risk but also its return. The products with the highest added value maintained a higher risk, since they imply innovation, technological development, access to new markets, greater funding, and new regulations (Brambila-Paz *et al*., 2019; Feng *et al*., 2024; Pender *et al*., 2024). The prices of bioethanol and inulin (Table 2) turned out to be the most expensive, with values of 1.59 and 1.43, respectively, which elevates the level of risk of the portfolios that use waste to manufacture these products.

These results show that the production system in a biorefinery can be implemented in other value chains, such as cereals (ElMekawy *et al*., 2013), oil crops (Chojnacka, 2023), and citrus fruits (Rojas-Rojas *et al*., 2025a), among others. Nevertheless, it is important to have enough information, since a limitation of this investigation was the availability of a robust database.

CONCLUSIONS

The tequila industry is highly profitable. However, diversification in the use of agave as a raw material for the production of inulin and tequila, within a biorefinery system, helps disperse risk. The hypothesis was confirmed that managing waste from the biomass generated during the processing of agave for tequila production enhances the return on investment portfolio and increases risk. This increase in risk is attributed to innovations in production processes and the development of higher-value products. Nevertheless, this risk can be effectively managed in scenarios involving price volatility.

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