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Integrating circular economy strategies into sustainable water management: Regression evidence from the Chinchaycocha Lagoon, Peru

Paulo César Callupe-Cueva[1], Luis Ricardo Flores-Vilcapoma[2*], Marina Angelica Porras-Rojas[3], Luis Antonio Visurraga-Camargo[1], Yadira Yanase-Rojas[4]

[1]*School of Business, Universidad Nacional Altoandina de Tarma, Tarma, Perú.*
[2]*School of Business, Universidad Tecnológica del Perú, Huancayo, Perú.*
[3]*School of Business, Universidad Nacional Daniel Alcides Carrión, Pasco, Perú.*
[4]*School of Business, Universidad Continental, Huancayo, Perú.*

Corresponding author: Luis Ricardo Flores-Vilcapoma (*Email: C28305@utp.edu.pe*)

Abstract

This study analyzes the relationship between circular economy strategies and sustainable water management in the Chinchaycocha lagoon, located in the central highlands of Peru, a basin seriously affected by industrial, mining, and agricultural activities. A quantitative, correlational, and predictive approach is adopted through the application of a structured questionnaire to a sample of 50 local stakeholders involved in water management. The analysis is performed using a multiple linear regression model with ordinary least squares (OLS) estimation, complemented by tests for heteroskedasticity, autocorrelation, normality, and functional specification. The findings indicate that the environmental impact and conservation dimension exert a positive and statistically significant influence on both water use efficiency ($\alpha_{(EWU,1)} = 0.491$; $p < 0.05$) and compliance with environmental regulations ($\alpha_{(CER,1)} = 0.567$; $p < 0.001$). Additionally, perceived community benefits significantly influence regulatory compliance ($\alpha_{(CER,3)} = 0.502$; $p < 0.05$), while financial sustainability does not exhibit a statistically significant association with the dependent variables. The study concludes that integrating environmental and community-based strategies within a circular economy framework is essential for enhancing water governance. These findings contribute valuable empirical evidence to inform the development of resilient and context-sensitive public policies for high Andean ecosystems.

Keywords: Chinchaycocha lagoon, Circular economy, Environmental risks, Sustainable management, Water resources.

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1. Introduction

The circular economy (CE) has emerged as an alternative paradigm to the linear development model, aimed at maintaining the value of resources, products, and materials within production systems for as long as possible [1, 2]. This proposal, still gaining ground in Latin America, seeks to optimize resource use, reduce waste, and regenerate ecosystems. It is especially relevant in contexts of water scarcity and pollution [3, 4].

In regions such as the central highlands of Peru, pressure on water resources has increased due to the expansion of industrial, mining, and agricultural activities, which have progressively deteriorated water quality [5, 6]. This is the case of the Chinchaycocha Lagoon, also known as Lake Junín, which constitutes a strategic source of freshwater in the region, playing a key role in ecological balance and supplying communities and productive sectors [7].

In Latin America, the implementation of circular economy strategies in water management has begun to gain prominence in countries such as Mexico, Colombia, Brazil, and Chile. For example, in Colombia, regional policies have been developed for water reuse in urban areas with water scarcity, while in Brazil, successful experiences of water circularity have been documented in agricultural and industrial areas [8, 9]. However, empirical evidence remains fragmented and scarce, particularly in high-altitude ecosystems such as the Peruvian Andes, where mining, industrial, and agricultural pressures critically converge. This research aims to contribute to closing this gap by providing a localized and quantitative analysis of the Chinchaycocha Lagoon, serving as a representative case of the challenges faced in the Andean region.

Faced with this situation, various studies suggest that the circular economy can offer solutions through wastewater treatment and reuse, the implementation of sustainable technologies, and resource efficiency [10]. However, its effective application in vulnerable ecosystems such as Chinchaycocha remains limited, fragmented, and poorly systematized [11].

In this context, this study aims to empirically analyze the relationship between circular economy strategies and sustainable water management in the Chinchaycocha Lagoon, addressing key aspects such as compliance with environmental regulations, resource efficiency, financial sustainability, and community perceptions of benefits.

Scientific Problem: What factors facilitate or limit the effective implementation of circular economy practices in water management in high Andean contexts with high environmental pressure?

Research Question: What impact do the dimensions of environmental conservation, financial sustainability, and community benefits have on water use efficiency and regulatory compliance in the Chinchaycocha Lagoon?

Objective: To analyze, using a multiple linear regression model, the degree of influence of various dimensions of the circular economy on two key indicators of sustainable water management: resource use efficiency and compliance with environmental regulations.

Hypothesis: Strategies aimed at environmental conservation and strengthening community participation have a positive and significant effect on water use efficiency and regulatory compliance, while financial sustainability presents a less consistent relationship.

2. Theoretical Framework

2.1. Circular Economy

The circular economy is a production and consumption model that aims to optimize the use of natural resources through reduction, reuse, and recycling strategies [12-14]. In contrast to the linear economy, which follows an "extract, produce, and dispose" approach, the circular economy promotes the regeneration of natural systems and the extension of product lifecycles [3]. In the context of water management, this approach involves the implementation of efficient technologies for the treatment and reuse of water resources, minimizing waste and reducing environmental impacts [15-17].

2.2. Resource Use Optimization

Resource use optimization within the framework of the circular economy aims to improve the efficiency of water use in industrial and municipal processes [18, 19]. This is achieved through the use of advanced technologies that reduce consumption, the utilization of wastewater, and the implementation of closed reuse systems [20, 21]. The implementation of water efficiency strategies not only contributes to environmental sustainability but also generates economic benefits by reducing operating costs and ensuring resource availability [22, 23].

2.3. Waste Management Regulations

Waste management regulations in the circular economy establish principles and regulations that encourage the proper disposal and reuse of treated water [24]. These regulations include permissible limits on pollutants in discharges, incentives for the implementation of treatment systems, and penalties for non-compliance with environmental standards [25]. Effective regulation of water waste is critical to ensuring that circular economy strategies are implemented responsibly and sustainably [26-28].

2.4. Sustainable Water Management

Sustainable water management is a comprehensive approach that seeks to balance the supply and consumption of water resources, ensuring their long-term availability for future generations. This model considers environmental, economic, and social factors, promoting efficient water use and the protection of aquatic ecosystems. In the Chinchaycocha Lagoon, sustainable water management is a key element in mitigating the effects of pollution and ensuring the preservation of the aquatic ecosystem.

2.5. Environmental Dimension

From an environmental perspective, sustainable water management involves the implementation of policies and technologies that reduce the ecological impact of human activities on water bodies. This includes the conservation of aquatic ecosystems, the restoration of natural habitats, and the reduction of pollution through advanced wastewater treatment systems. The protection of biodiversity and the regulation of water use are fundamental aspects of this dimension.

2.6. Economic Dimension

The economic dimension of sustainable water management focuses on developing business models that promote the efficient use of water resources. This may include implementing tiered tariffs based on consumption, generating revenue from wastewater recycling, and promoting investment in innovative water treatment technologies. A sustainable water system must balance operating costs with the economic benefits derived from resource optimization.

2.7. Social Dimension

The social dimension of sustainable water management emphasizes the importance of ensuring equitable access to water resources for all communities. This involves including local populations in decision-making, implementing educational programs on responsible water use, and creating participatory mechanisms for resource management. Awareness-raising and citizen participation are key elements for the success of sustainable water management strategies.

3. Population and Sample

The population of this study comprises key stakeholders involved in water management in the Chinchaycocha Lagoon watershed. This includes wastewater treatment plant (WWTP) officials, representatives of municipalities, mining companies, agro-industrial companies, and local communities that directly depend on the lagoon's water resources for their livelihoods and economic activities. The selection of this population responds to the need to analyze the application of circular economy principles to sustainable water management in the region.

To determine the sample, a non-probability convenience sampling design was chosen due to the specific nature of the study subjects and the availability of information from the stakeholders involved. The sample will consist of 50 respondents, ensuring equitable distribution among the different stakeholder groups. This distribution will include WWTP officials, municipal representatives, executives of mining and agro-industrial companies, as well as members of local communities involved in water resource management.

The sample size was determined based on the possibility of obtaining representative information on the perception and application of the circular economy in water management, ensuring that the data obtained is sufficient for the correlation analysis between the variables under study. Data collection will be carried out through structured surveys with Likert-scale questions, which will allow quantifying perceptions and evaluating the relationship between the circular economy and sustainable water management in the Chinchaycocha Lagoon.

Regarding the sample size justification, Green [29] criterion, widely used in studies with multiple regression models, was taken as a reference. According to this empirical rule, the minimum recommended sample size is $N \geq 50 + 8m$, where m represents the number of predictors included in the model. In this study, three predictor variables were considered (environmental impact, financial sustainability, and community benefits), which suggests a required minimum of 74 observations. However, the fact that we worked with 50 cases is recognized as a limitation, justified by the limited availability of strategic actors in the lagoon ecosystem and the application of non-probability convenience sampling. Despite this, the models pass the statistical validity tests (heteroskedasticity, autocorrelation, specification) and maintain adequate levels of significance, which supports the empirical consistency of the analysis.

4. Methodology

The research question:
"What factors drive or hinder the implementation of circular economy practices in water management?"

4.1. Sample

Table 1.
Main variables.

Variable	Dimension	Indicator
Circular economy in water management	Efficiency in water use	Quality control in wastewater treatment plants (WWTPs), waste reduction, and the adoption of modern technologies.
	Compliance with environmental regulations	Environmental audits, coordination between companies and authorities, and alignment with SDGs.
Sustainable water management	Environmental impact and conservation	Reuse of treated water, incentives for sustainable practices
	Financial sustainability	Improvements in water quality, pollutant monitoring, and ecosystem restoration
	Benefits for the local community	Funding sources, cost reduction in water treatment, revenue generation from treated water

4.2. Regression Models

For the results, a multiple linear regression model and correlation analysis are used to determine the impact that exists between the dimensions, as well as their statistical significance. For this, the estimation method will be ordinary least squares, since it is the method that is very important to make a consistent estimate if it meets the conventional assumptions, by minimizing the sum of the squared errors.

$$y_i = \alpha_{i,0} + \alpha_{i,1}x_1 + \alpha_{i,2}x_2 + \alpha_{i,3}x_3 + \alpha_{i,4}x_4 + u_i, \quad \text{for } i = EWU, CER \tag{1}$$

Where
y_{EWU}: Efficiency in water use
y_{CER}: Compliance with environmental regulations
x_1: Environmental impact and conservation
x_2: Financial sustainability
x_3: Benefits for the local community
u_i: Disturbance term, $u_{it} \sim iid(0, \sigma^2)$
The formula shown shows the estimation by Ordinary Least Square (OLS), which is to minimize the Sum of Squared Residuals (SSR) to obtain unbiased, efficient and consistent estimates.

$$SSR = \left(y_i^T - \alpha_i^T X^T\right)(y_i - X\alpha_i) \tag{2}$$

Where SSR is sum square of residuals, $\alpha_i = \left[\alpha_{i,0}, \alpha_{i,1}, \alpha_{i,2}, \alpha_{i,3}\right]^T$ and $X = [1, x_1, x_2, x_3]^T$.

$$\alpha_i = (X^T X)^{-1} X^T y_i \tag{3}$$

This methodological approach ensures a rigorous and reliable analysis, facilitating a deeper understanding of the relationships between the dimensions and their influence within the circular economy in water management.

5. Results

5.1. Descriptive Statistics

Table 2.
Descriptive statistics.

Stats	Efficiency in water use	Compliance with environmental regulations	Environmental impact and conservation	Financial sustainability	Benefits for the local community
N	50	50	50	50	50
Max	4.4	4.429	3.5	3.5	3.167
Min	1.6	1.714	1.5	1.667	2
Mean	2.964	3.057	2.497	2.46	2.49
SD	0.651	0.569	0.444	0.454	0.308
Variance	0.424	0.323	0.197	0.206	0.095
$\mathbf{P_{50}}$	3	3	2.5	2.417	2.5
Skewness	0.055	0.199	0.002	0.299	0.305
Kurtosis	2.501	3.284	2.661	2.459	2.209

Table 2 presents the descriptive statistics for the five key dimensions of sustainable water management: EWU, CER, environmental impact and conservation, financial sustainability, and benefits for the local community. The highest average corresponds to compliance with environmental regulations (3.057), suggesting a relatively positive perception regarding adherence to regulations. However, environmental impact and financial sustainability show lower mean values (2.497 and 2.46, respectively), which could indicate persistent challenges in these areas. The dispersion of data, measured through the standard deviation, is highest in water use efficiency (0.651) and lowest in community benefits (0.308), suggesting that perceptions of efficiency are more heterogeneous among respondents, while community benefits are evaluated more uniformly.

Furthermore, skewness and kurtosis suggest that the distributions of the dimensions are close to normality, with relatively low values across all variables. The kurtosis of compliance with regulations (3.284) and water use efficiency (2.501) indicates that these dimensions have a distribution with slightly heavier tails than a normal distribution, suggesting some extreme values within the sample. In terms of the median (P_{50}), all dimensions have values close to the mean, reinforcing the idea that the distribution of responses is not significantly skewed. These results indicate that, while there is a moderate level of implementation of sustainable water management, certain aspects, such as financial sustainability and environmental impact require greater attention to achieve substantial improvements in water resource management.

5.2. Statistical Analysis

Table 3.
Correlation matrix.

	Efficiency in water use	**Compliance with environmental regulations**	**Environmental impact and conservation**	**Financial sustainability**	**Benefits for the local community**
Efficiency in water use	1.000	-	-	-	-
Compliance with environmental regulations	0.198	1.000	-	-	-
Environmental impact and conservation	0.468	0.573	1.000	-	-
Financial sustainability	0.423	0.373	0.326	1.000	-
Benefits for the local community	0.386	0.479	0.361	0.468	1.000

Table 3 presents the correlation matrix among the five key dimensions of sustainable water management. The highest correlation is observed between CER and environmental impact and conservation (0.573), indicating that greater adherence to regulations is associated with improvements in environmental conservation efforts. Similarly, financial sustainability shows a strong correlation with community benefits (0.468), suggesting that a well-structured financial model enhances local well-being. Moderate correlations exist between EWU and environmental impact (0.468), as well as between efficiency and financial sustainability (0.423), reinforcing the notion that optimized water use contributes to both ecological preservation and economic viability.

Lower correlations, such as between EWU and CER (0.198), suggest that regulatory adherence does not necessarily translate into more efficient water usage. This could indicate a gap between policy implementation and practical improvements in resource management. The correlation between financial sustainability and environmental impact (0.326), while positive, is lower than expected, hinting that economic factors may not be the primary drivers of environmental conservation in this context. Overall, the correlation matrix highlights the interconnectedness of sustainability factors while revealing areas where stronger synergies could be fostered to enhance water resource management.

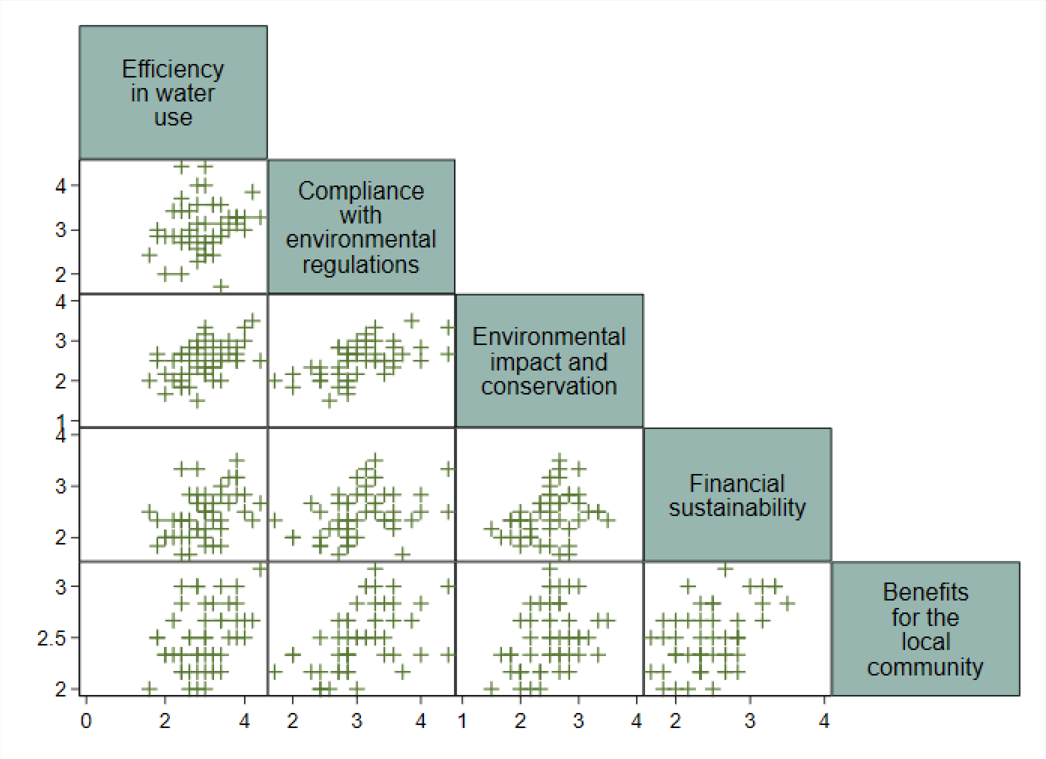

Figure 1.
Scatterplot matrix.

Figure 1 presents a scatterplot matrix illustrating the relationships between the five dimensions of sustainable water management. The patterns observed in the scatterplots suggest varying degrees of correlation between the variables. Notably, the positive linear trends in the relationships between CER and environmental impact and conservation, as well as between financial sustainability and benefits for the local community, support the findings from the correlation matrix. These trends indicate that stronger regulatory frameworks tend to enhance environmental conservation efforts, while financial sustainability is a crucial driver for improving community benefits.

Additionally, the dispersion of points in certain scatterplots, such as the relationship between EWU and CER, suggests a weaker correlation, confirming that regulatory adherence does not directly translate into more efficient water resource utilization. Similarly, the relatively scattered distribution between financial sustainability and environmental impact implies that financial stability alone does not necessarily guarantee improved conservation outcomes. The visualization reinforces the importance of integrated strategies that consider regulatory, financial, and environmental dimensions collectively to achieve a more holistic approach to sustainable water management.

5.2. Modelling

Considering the data previously obtained and according to the proposed objectives, multiple regression models will be conducted to determine the impact of the dimensions and their significance.

Table 4.
OLS results.

	(1) **EWU**	**(2)** **CER**
Environmental impact and conservation	0.491* (2.51)	0.567*** (3.61)
Financial sustainability	0.350 (1.74)	0.127 (0.78)
Benefits for the local community	0.318 (1.06)	0.502* (2.07)
Constant	0.0843 (0.12)	0.0808 (0.14)
F statistic (3,46)	7.14	11.15
Adjusted R-squared	0.2733	0.3832

Note: t statistics in parentheses * p<0.05, ** p<0.01, *** p<0.001.

Table 4 presents the results of two Ordinary Least Squares (OLS) regression models analyzing the determinants of efficiency in water use (Model 1) and compliance with environmental regulations (Model 2). The results indicate that environmental impact and conservation have a statistically significant and positive effect on both dependent variables, with a coefficient of 0.491 ($p < 0.05$) for efficiency in water use and 0.567 ($p < 0.001$) for compliance with environmental regulations. This suggests that improvements in environmental conservation practices contribute positively to both efficiency in water usage and regulatory adherence. Additionally, benefits for the local community are significantly associated with compliance with environmental regulations (0.502, $p < 0.05$) but do not exhibit statistical significance in explaining efficiency in water use. This indicates that local community engagement may play a more crucial role in strengthening regulatory compliance than in enhancing water use efficiency.

The adjusted R-squared values indicate that Model 2 (0.3832) explains more variation in compliance with environmental regulations than Model 1 (0.2733) does for water use efficiency, suggesting that the selected predictors have a stronger explanatory power in regulatory adherence. The F-statistics (7.14 for Model 1 and 11.15 for Model 2) confirm the overall significance of both models, with Model 2 demonstrating higher explanatory power. Notably, financial sustainability does not show a significant effect in either model, implying that financial considerations alone may not be sufficient drivers for improving water use efficiency or regulatory compliance. These findings underscore the importance of environmental conservation efforts and community involvement in achieving sustainable water management, indicating that policies should prioritize these aspects over purely financial incentives.

Table 5.
Model Specification by OLS p-values.

	Heteroscedasticity	**Autocorrelation**		**Normality**	**Identification**
	White test	**Durbin-Watson test**	**Breusch-Godfrey test**	**Jarque-Bera test**	**Ramsey RESET test**
Model 1	0.3849	1.8331	0.1195	0.5922	0.0442
Model 2	0.6915	1.7159	0.0885	0.4148	0.4624

Table 5 presents the diagnostic tests for the Ordinary Least Squares (OLS) regression models used to analyze efficiency in water use (Model 1) and compliance with environmental regulations (Model 2). The White test for heteroscedasticity yields p-values of 0.3849 for Model 1 and 0.6915 for Model 2, indicating that neither model suffers from heteroscedasticity, as the p-values are well above the 0.05 threshold. Regarding autocorrelation, the Durbin-Watson statistics for both models (1.8331 for Model 1 and 1.7159 for Model 2) are close to the ideal value of 2, suggesting no strong presence of serial correlation. Additionally, the Breusch-Godfrey test further supports this conclusion, as its p-values (0.1195 for Model 1 and 0.0885 for Model 2) exceed the conventional significance levels, implying that residuals are not significantly autocorrelated.

Regarding normality, the Jarque-Bera test yields p-values of 0.5922 for Model 1 and 0.4148 for Model 2, suggesting that the residuals are approximately normally distributed, meeting one of the key OLS assumptions. Finally, the Ramsey RESET test, which evaluates model specification and functional form, produces a marginally significant p-value for Model 1 (0.0442) but a non-significant value for Model 2 (0.4624). This indicates that while Model 1 may have minor specification issues, Model 2 does not exhibit significant functional form misspecifications. Overall, these diagnostic tests confirm the statistical validity of both models, with Model 2 demonstrating slightly stronger robustness in terms of specification and functional correctness.

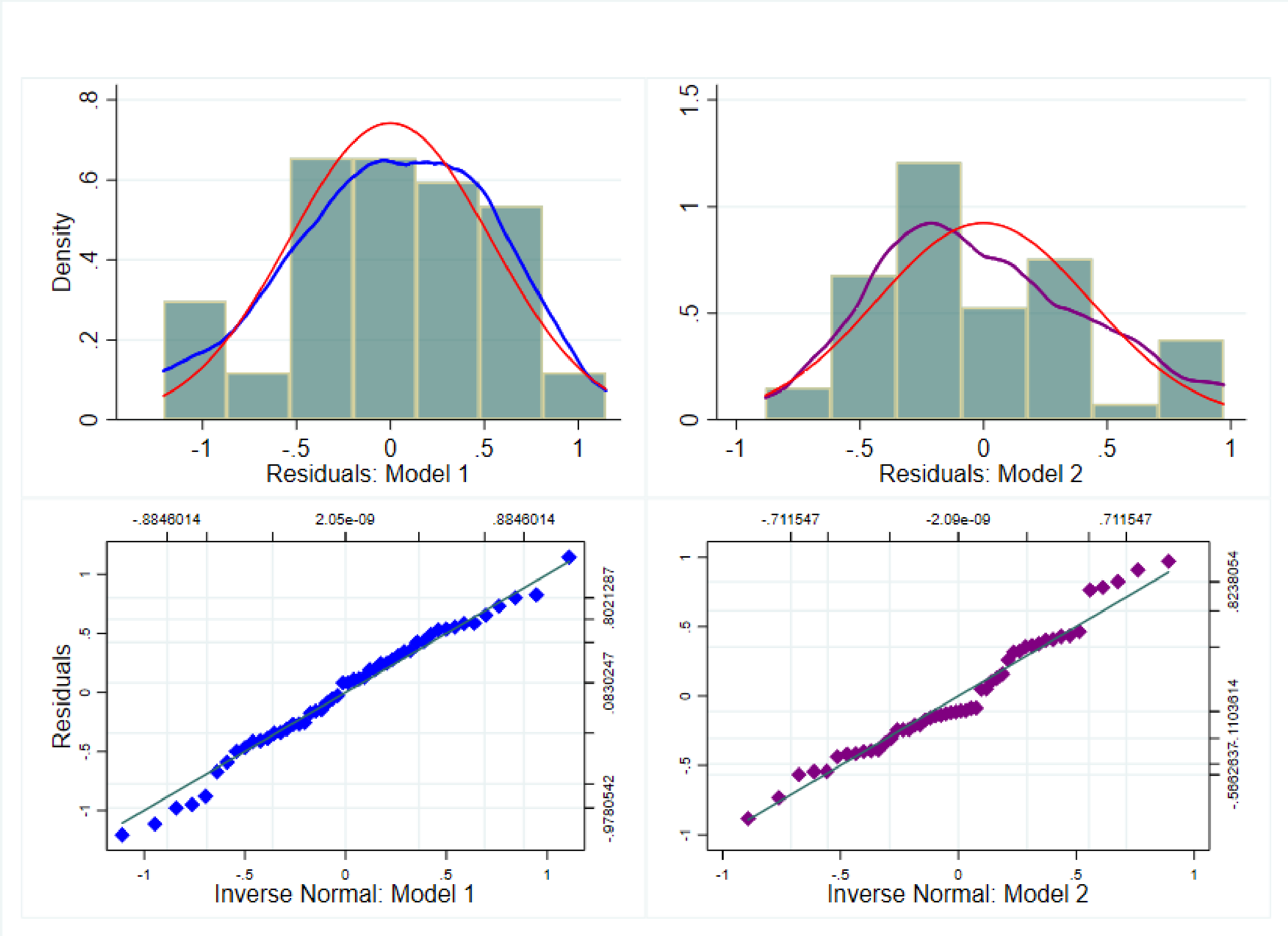

Figure 2.
Estimated kernel density and Q-Q plots.
Note: The normal distribution is represented by the red line. Grid lines are 5, 10, 25, 50, 75, 90, and 95 percentiles.

Figure 2 presents the kernel density estimation (KDE) and quantile-quantile (Q-Q) plots for the residuals of Model 1 and Model 2, allowing for an evaluation of the normality assumption in the OLS regressions. The top panels illustrate the estimated density distributions of the residuals, where the red line represents the ideal normal distribution, and the blue line represents the observed kernel density estimation. In Model 1, the residual distribution closely follows the normal curve, suggesting that the normality assumption is reasonably met. In contrast, Model 2 exhibits slight deviations from normality, particularly at the tails, indicating the potential presence of minor skewness or kurtosis issues. However, given that the deviations are not extreme, the assumption of normality is likely to hold in practical terms.

The bottom panels display Q-Q plots, which further assess the normality assumption by plotting the residuals against the expected normal quantiles. In Model 1, the residuals align well along the 45-degree reference line, reinforcing the conclusion that the normality assumption is satisfied. For Model 2, while most residuals also follow the expected normal trend, some deviations are noticeable at the extremes, suggesting heavier tails in the distribution. These findings align with the Jarque-Bera test results from Table 5, which indicated that residuals in both models were not significantly different from normal. Overall, while both models exhibit acceptable levels of normality, Model 2 shows slightly more deviations, which should be taken into account when interpreting results but are unlikely to compromise the reliability of the regression estimates.

5. Conclusions

The findings of this study highlight the critical role of environmental conservation efforts in promoting circular economy practices within water management. The regression analysis confirms that environmental impact and conservation have a statistically significant and positive effect on both efficiency in water use (EWU) and compliance with environmental regulations (CER). This suggests that initiatives such as treated water reuse, pollution control, and ecosystem restoration are fundamental to improving regulatory compliance and optimizing resource use. Therefore, policy interventions aimed at enhancing circular water management should prioritize integrated environmental strategies, ensuring that conservation efforts are embedded within both regulatory frameworks and industrial practices.

Contrary to expectations, financial sustainability did not demonstrate a statistically significant influence on either EWU or CER, indicating that economic factors alone are insufficient to drive meaningful improvements in water management. This suggests that while financial incentives and investments in sustainable infrastructure are necessary, they must be complemented by strong regulatory enforcement, technological advancements, and institutional capacity-building.

The results imply that simply providing funding mechanisms or reducing operational costs in wastewater treatment plants (WWTPs) does not guarantee more efficient or sustainable water use. Instead, a multi-dimensional approach balancing financial, regulatory, and environmental aspects is required to achieve effective circular economy outcomes.

Moreover, the study underscores the importance of community engagement in enhancing compliance with environmental regulations. A significant relationship was found between community benefits and CER, suggesting that increased public participation, awareness campaigns, and educational initiatives contribute to greater adherence to sustainability policies. This finding reinforces the need for bottom-up approaches, where local communities, industries, and government authorities collaborate to develop inclusive and transparent water management strategies. Strengthening these stakeholder relationships through participatory governance, corporate social responsibility (CSR) programs, and community-based monitoring could bridge the gap between regulatory frameworks and their on-the-ground implementation, fostering a more resilient and inclusive circular water management system.

Based on the findings, it is recommended that public policies in high Andean regions such as Chinchaycocha integrate circular economy approaches into their water management plans, including tax incentives for companies that implement treated water reuse technologies, as well as participatory environmental assessment mechanisms with local communities. Furthermore, the creation of citizen water observatories is suggested to strengthen social oversight of regulatory compliance and the sustainability of water practices. These measures can institutionalize collaborative governance and generate sustainable impacts beyond the short term, aligning with the SDGs and Peru's national climate commitments.

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