Environmental impact assessment of sustainable agricultural practices through structural analysis with the MICMIAC technique

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Received: 19.01.2024 Revised : 21.01.2024 Accepted: 20.01.2024

ABSTRACT
This study assesses the environmental impact of sustainable agricultural practices through a structural analysis using the MICMAC technique to evaluate the key interrelations between variables. Variables were identified and classified, highlighting those with important influences and dependencies. The results showed that Use of agrochemicals, Climate resilience, and Greenhouse gas emissions are variables with a high impact. The results also show the existence of determinant variables such as Energy use, Biological diversity, among others. Autonomous variables, such as Effects on human health and Soil erosion, show direct impacts on human health and soil management. Finally, Economic costs and profitability were variables that were classified as result variables, reflecting the economic impact of sustainable practices. Despite some limitations, the study provides support when making decisions in sustainable agriculture.

Keywords: Sustainable agriculture, environmental impact, MICMAC, decision making.

INTRODUCTION

Sustainable development in agriculture has received increasing attention (Hu et al., 2022) as the agricultural sector plays a fundamental role in improving food availability and achieving food security (FS) (Patel et al., 2020). However, advances in increasing agricultural production lead to challenges of environmental degradation, such as soil pollution, and climate change, among others (Hossain et al., 2020). For example, the massive use of fertilizers has allowed an increase in production capacity, but the inefficiency in the use of these fertilizers is also highlighted, which generates environmental problems, nutritional imbalances in the soil, and a suboptimal food production (FP) (Penuelas et al., 2023).

Given the above, in the face of this challenge, the adoption of sustainable agricultural practices (SAP) emerges as a solution (Alloghani, 2023). These practices have the capacity to increase FP, contributing to the preservation of water and soil, and carbon sequestration (Foguesatto et al., 2020). Despite the benefits they offer, the adoption rate of these practices is low in many countries (Thompson et al., 2022), even with the support of government entities (Tey et al., 2014); this may be due to, among other factors, a lack of knowledge and awareness of the environmental impact (EI) of adopting SAP.

The literature review (LR) shows progress in knowledge in the area of Sustainable Agriculture (SA) and the assessment of its environmental impact. For example, Van der Werf and Petit (2022) have studied various dimensions of this topic, from the analysis of the effectiveness of specific practices to the measurement of Climate resilience and biodiversity in agricultural systems. Similarly, in the study carried out by Hu et al. (2022), it is measured the agricultural production, the rural environment, and the well-being of farmers. German et al. (2017) also studied the relationships between multiple aspects of EI and agricultural productivity, to guide SA. Likewise, current literature also highlights the importance of understanding the relationships between key SA variables to achieve a sustainable balance between agricultural production and environmental health (Tey et al., 2014).

In this context, the MICMAC (Multiplicative Cross-Impact Matrix Applied to a Classification) technique is a beneficial tool in the assessment of the EI, by facilitating the identification of key variables and their relationships in a system as complex as the agricultural system. This technique is used in the present research to understand the interdependencies and influence between the variables of the SA, using advanced analytical tools, to contribute to the understanding of the EI when applying agricultural practices.

METHODOLOGY

The present study was classified as mixed, which uses qualitative and quantitative approaches, as explained by Sampieri (2018). The design was non-experimental, cross-sectional, correlational, and descriptive. Non-experimental since the variables were not manipulated (Frölich et al., 2014), cross-sectional because data was acquired at a certain time (Hernández et al., 2014), to assess the EI of SAP. An LR was carried out, experts were consulted, and a structural analysis was performed following the methodology proposed by Herrera (2017) to identify key variables associated with the EI of SAP.

Key variables associated with the EI of SAP were extracted, such as Biological diversity, Energy use, and other relevant environmental factors. The MICMAC technique was applied to classify each variable into one of the following categories: Key: highly influential variables with a high impact on others; Determinants: variables that have a significant impact, but are influenced by others; Autonomous: variables with limited impact but independent; and Result: variables that are the result of the interaction of others. This technique provides an analysis where the problems presented in the system are distinguished and their behaviors are examined (Arango & Cuevas, 2014).

Method procedure

Documentary review: A systematic review was carried out in scientific journals, academic databases, and other relevant resources to identify studies related to the object of study.

Factor selection: Once the document review was completed, the most common variables associated with the EI of SAP were selected, which served as input for the implementation of MICMAC.

Micmac application: To examine the relationships between the variables, in addition to ranking them, the MICMAC technique was used, which uses a matrix that links the components of a system to describe its operation, and also identifies the influential and dependent variables to highlight the key factors (Arango & Cuevas, 2014). This technique has various applications in determining key variables in numerous fields. For example, in Martelo et al. (2020), factors that impact customer loyalty in e-commerce were determined, and in Martelo et al. (2018) it was used to determine the variables in programmatic proposals in educational institutions. Due to the usefulness of this technique, it was decided to use it in this study.

RESULTS

The categories into which the variables analyzed have been classified are presented: key, determinant, autonomous, and results. These results show the dynamics of the impact of SAP to promote strategic planning and decision-making (DM).

As a first result, a list of the ten (10) main variables associated with the EI of SAP was identified through the review of the bibliography, which can be seen in Table 1. Thus, the header of the table is composed of the number, an assigned code, the name, and the description of each variable, for example, in the first row, variable 1 is identified with the code UA, with the name: Use of agrochemicals, with description: Use of pesticides and fertilizers, evaluating their quantity, type and frequency. In this way, the list of factors is shown in Table 1.

Table 1. Variables related to the EI of SAP

#	Code	Variable	Description
1	UA	Use of agrochemicals	Use of pesticides and fertilizers, evaluating their quantity, type, and frequency.
2	SQ	Soil quality	Analyzes the health of the soil, considering the structure, nutrients, pH, and organic matter content.
3	WRC	Water resources consumption	Examines the amount of water used in agricultural practices and look for methods that optimize water use efficiency, such as drip irrigation.
4	GGE	Green house gases emissions	It evaluates emissions of gases such as carbon dioxide (CO2), nitrogen oxides (NOx), and methane (CH4).
5	BD	Biological diversity	Measures biodiversity in the study area, including the diversity of plant and animal species present.

6	SE	Soil erosion	Research on soil erosion caused by agricultural practices and the implementation of techniques to prevent it, such as direct seeding or vegetative coverage.
7	EU	Energy use	Quantifies the energy used in agricultural operations.
8	CR	Climate resilience	Evaluates the ability of agricultural practices to adapt to and mitigate the effects of climate change, including droughts, floods, and extreme weather events.
9	EHH	Effects on human health	Explores how agricultural practices impact food quality and exposure to harmful substances, taking human health into account.
10	ECP	Economic costs and profitability	Analyzes the costs associated with implementing sustainable practices and their impact on long-term profitability.

Source: Authors

The next step was to resort to the collective reflection of 5 SAP experts to assess the dependency and influence relationships of the variables in a square matrix, which corresponds to the second stage of MICMAC. Thus, Figure 1 presents the matrix of direct dependency and influence (MDDI), which has been completed by consensus and through the collective reflection of experts. It is noted that the first row of the matrix corresponds to the relationships of the variable UA. In the case of the relationship with this same variable, it is null (0), the relationship with the variable SQ was defined as strong (3), with the variable WRC it is moderate (2), the relationship with the variable GGE is strong. In this way, the relationship of direct influence/dependency between each variable is described.

Influence ↱	UA	SQ	WRC	GGE	BD	SE	EU	CR	EHH	ECP
UA	0	3	2	3	2	2	2	2	3	3
SQ	3	0	1	3	2	0	2	3	3	0
WRC	3	1	0	2	2	1	1	3	3	3
GGE	2	2	2	0	1	2	2	3	1	2
BD	3	1	2	3	0	1	3	2	0	3
SE	1	2	0	2	1	0	2	3	1	1
EU	1	2	1	3	2	2	0	2	0	3
CR	2	2	1	3	2	2	2	0	1	3
EHH	3	2	1	1	1	0	1	2	0	0
ECP	3	0	1	0	0	0	1	3	1	0

Figure 1.MDDI
Source: Authors

Once the relationships in the MDDI have been established, the next step involves the classification of the variables. This categorization is represented in a plane of direct dependency and influence (PDDI), exemplified in Figure 2. As a result of this study, three variables were identified in the quadrant of the key variables: UA, CR, and GGE. In the quadrant of the determinant variables, four variables were located: WRC, BD, SQ, and EU. In the quadrant of the autonomous variables, two variables were located: SE and EHH. Finally, in the quadrant of the result variables, the variable ECP was located.

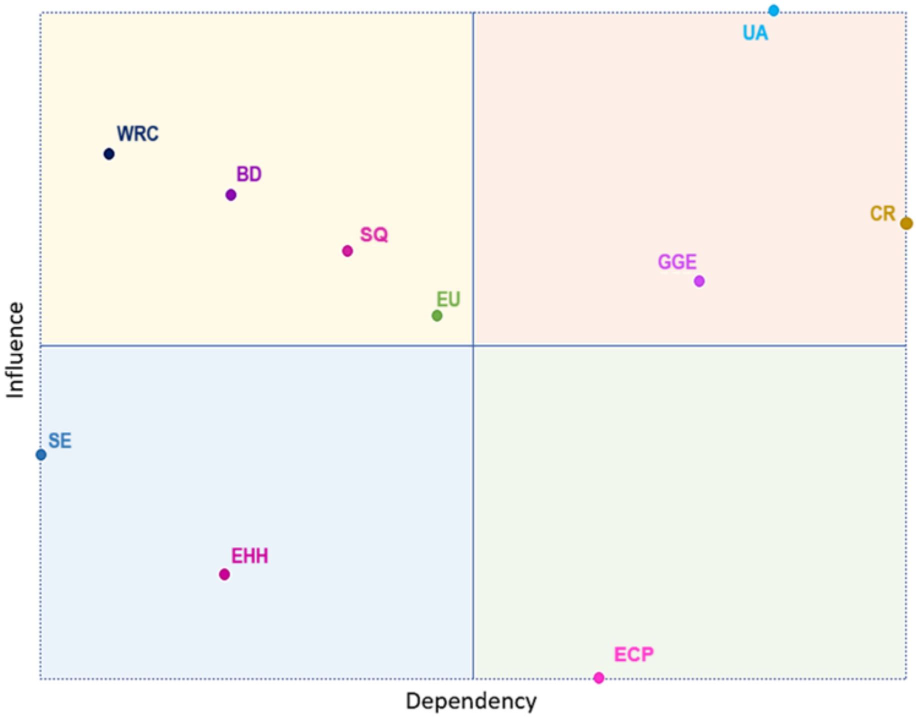

Figure 2. PDDI

Source: Authors

To better explain, these same results are shown in Table 2.

Table 2. Classification of factors by indirect influences and dependencies

Variable Type	Variable	Code
Key, strategic or challenge variables	Use of agrochemicals	UA
	Climate resilience	CR
	Green house gases emissions	GGE
Determinantorinfluencing variables	Energy use	EU
	Biological diversity	BD
	Water resources consumption	WRC
	Soil quality	SQ
Autonomousorexcluded variables	Effects on human health	EHH
	Soil erosion	SE
Dependentorresult variables	Economic costs and profitability	ECP

Source: Authors

Considering the above, the variable UA was classified as a key variable because it exerts a significant influence on multiple aspects of the agricultural system and its environment. For example, this variable can directly affect SQ and biodiversity as mentioned by Penuelas et al. (2023). Due to the variety of impacts that this variable causes, it is classified as a key element in the system.

According to Baweja et al.(2020), agrochemicals alter soil structure and composition, which affects overall soil health and impacts the soil's ability to support crops and long-term sustainability. On the other hand, Aryal et al. (2022) state that the use of certain fertilizers can contribute to GGE, which increases their influence even outside the agricultural context.

This variable is also related to WRC as observed in the MID matrix. This is so because UA can have implications on water consumption, as certain chemicals can affect the soil's ability to retain and distribute water efficiently as confirmed in the study developed by Tudi et al. (2021). Likewise, UA can have consequences on BD, which according to Ankit et al. (2020) can affect non-target organisms such as pollinating insects, soil microorganisms, and other components of the agro-ecosystem.

Finally, this variable is strongly related to ECP, because the cost associated with UA, together with its impact on crop productivity and yield, can be a key factor in the profitability of agricultural practices. In summary, the classification as a key variable suggests that UA not only has a direct impact on various facets of the agricultural system but can also have cascading effects that extend to environmental, economic, and sustainability aspects.

The classification of CR as a key variable suggests that this variable exerts a great influence on the capacity of SA to adapt and recover from climate change. According to Gao et al. (2022), CR can influence UA because practices that promote adaptability to different climatic conditions affect agricultural management strategies. While for Nguyen et al. (2023), the ability to adapt to climatic conditions can affect GGE. On the other hand, Corvalan et al. (2020) state that agricultural practices that improve CR may require less energy resources to recover from adverse climatic events.

The classification of GGE as a key variable implies that it has a significant influence. The interrelation between this variable and the CR variable was highlighted, this may be because GGE affects CR. According to Toor et al. (2020), climate changes caused by GGE affect biodiversity, impacting plants, animals, and microorganisms in agricultural ecosystems. Likewise, Imran &Ozcatalbas (2021) associate GGE with energy efficiency in agriculture, since, according to them, certain practices may require fewer energy resources and, therefore, reduce associated emissions. Lehtonen et al. (2022) associate GGE with costs, economics, and profitability since some consumers have preferences for products with low carbon emissions.

On the other hand, the variables identified as determinants were four. The classification of the variable EU as a determinant variable suggests that it has a significant impact, but is also influenced by other system variables. For example, the choice of renewable energy sources can reduce associated emissions. According to Sarkar et al. (2020), the efficiency in the EU in agricultural practices can be a determinant for the overall sustainability of the system. While, Fenster et al. (2021) state that the cost associated with the EU can be a determinant factor in the profitability of agricultural practices. And for Godde et al. (2021), the choice of energy sources and related practices can affect CR.

The classification of BD as a determinant variable highlights that this variable also has a significant impact, as in the case of ecosystem resilience, since this variable contributes to resilience against environmental changes. BD is influenced by UA. According to Tripathi et al. (2020), a diverse ecosystem is more resistant to pests and diseases, but the use of pesticides and fertilizers affects this diversity. This variable also impacts SQ, according to Bhaduri, et al. (2022), biological activity in the soil, such as the presence of microorganisms and earthworms, contributes to soil health. This is how BD has complex interactions with different variables.

The classification of WRC as a determinat variable implies that it has a direct impact on water availability (WA) in the environment. It should be noted that this variable is essential for developing SAP. On the other hand, this variable is related to other variables. According to Zahoor & Mushtaq (2023), water consumption can affect aquatic ecosystems near agricultural areas, which impacts BD. Likewise, this variable is influenced by GGE, since pumping and transporting water for agriculture requires energy, which in turn implies GGE. According to Corwin (2021), water consumption is also linked to CR, since changing weather patterns can affect WA.

The classification of SQ as a determinant variable also reveals that it has a substantial impact on SAP. SQ is essential for agricultural productivity and is related to other variables. For example, the relationship of this variable with BD, according to Banerjee & Van der Heijden (2023), SQ influences the BD of the agricultural environment. On the other hand, there is a relationship with GGE because certain agricultural practices and SQ influence the emissions of these gases. In contrast, adequate soil management can be key to mitigating these emissions.

Likewise, the relationship with the variable CR is highlighted, according to Altieri & Nicholls (2013), the SQ contributes to the CR of the agricultural system by affecting its capacity to resist and recover from extreme climatic events. The influence on the SE is also highlighted because a good quality soil is more resistant to erosion. The SQ is directly associated with the stabilization and retention capacity of the soil, thus influencing erosion.

Continuing with the results, the variables that resulted as autonomous are presented below, one of which was EHH, which was due to the fact that the security and quality of the processed food are directly related to the EHH. This relationship highlights the autonomy of this variable in influencing the perception of the FS and the health of consumers. According to Baweja et al. (2020), agricultural practices, such as the use of fertilizers, directly impact the quality of food. According to Lee et al. (2023), agricultural practices influence the nutritional quality of the foods produced and, therefore, human health, however, the perception of human health can influence purchasing decisions and consumer interests.

The classification of ES as an autonomous variable suggests that it is directly linked to agricultural practices. Its autonomy is highlighted by being a direct consequence of soil management decisions. According to Tilahun& Desta (2021), ES has a direct impact on soil sustainability. The loss of the topsoil

affects fertility and water retention capacity, which is essential for agricultural productivity. Likewise, ES can have impacts on biodiversity since the loss of fertile soil affects soil microorganisms and can lead to the degradation of surrounding ecosystems.
Finally, the classification of the ECP variable as a result variable reflects the final impact and outcomes of SAP in economic terms. According to Ostaev et al. (2020), ECP are key indicators for assessing investments, competitiveness, and efficiency of agricultural practices. On the other hand, economic outcomes influence the future decisions of farmers. For example, if sustainable practices prove to be economically viable, it may influence their widespread adoption. If these practices prove to be profitable, other farmers are more likely to adopt them.

CONCLUSIONS

This research on the assessment of the EI of SAP has yielded significant results that reveal the interrelations and importance of various variables in the context of SA. Relevant findings were found as Key and Determinant variables: UA, CR, GGE, EU, BD, WRC, and SQ. These results contribute to the formulation of strategies and policies that encourage the adoption of SA because the application of the MICMAC technique has allowed the identification of key variables and their interconnections, providing a valuable guide for DM.
The analysis of environmental, economic, and social aspects highlights the need to address SA in a comprehensive manner. Furthermore, this study establishes a solid foundation for future research by pointing out areas of interest and providing a framework for SAP assessment. On the other hand, despite these findings, it is essential to recognize that the study presents some limitations such as limited data availability in certain areas, or the subjectivity of the MIMCAC technique. However, these limitations suggest future more detailed research in specific regions to improve the applicability of the results and the exploration of new variables or the deepening of the identified relationships to broaden the understanding of SA.

REFERENCES

[1] Alloghani, M. (2023). AI for Sustainable Agriculture: A Systematic Review. . Artificial Intelligence and Sustainability, 53-64.

[2] Altieri, M., & Nicholls, C. (2013). Agroecología y resiliencia al cambio climático: principios y consideraciones metodológicas. Agroecología, 8(1), 7-20.

[3] Ankit , Saha, L., Kishor, V., & Bauddh, K. (2020). Impacts of synthetic pesticides on soil health and non-targeted flora and fauna. Ecological and practical applications for sustainable agriculture, 65-88.

[4] Arango, X., & Cuevas, V. (2014). Método de análisis estructural: matriz de impactos cruzados multiplicación aplicada a una clasificación (MICMAC) .(Doctoral dissertation, Tirant Lo Blanch).

[5] Aryal, B., Gurung, R., Camargo, A., Fongaro, G., Treichel, H., Mainali, B., & Puadel, S. (2022). Nitrous oxide emission in altered nitrogen cycle and implications for climate change. Environmental Pollution, 120272.

[6] Banerjee, S., & Van der Heijden, M. (2023). Soil microbiomes and one health. Nature Reviews Microbiology, 21(1), 6-20.

[7] Baweja, P., Kumar, S., & Kumar, G. (2020). Fertilizers and pesticides: Their impact on soil health and environment. Soil health, 265-285.

[8] Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B., Munda, S., & Dari, B. (2022). A review on effective soil health bio-indicators for ecosystem restoration and sustainability. Frontiers in Microbiology, 13, 938481.

[9] Corvalan, C., Villalobos, E., Sena, A., Campbell-Lendrum, D., Karliner, J., Risso, A., & Vinci, S. (2020). Towards climate resilient and environmentally sustainable health care facilities. . International Journal of Environmental Research and Public Health, 17(23), 8849.

[10] Corwin, D. (2021). Climate change impacts on soil salinity in agricultural areas. . European Journal of Soil Science, 72(2), 842-862.

[11] Fenster, T., LaCanne, C., Pecenka, J., Schmid, R., Bredeson, M., Busenitz, K., & Lundgren, J. (2021). Defining and validating regenerative farm systems using a composite of ranked agricultural practices. . F1000 Research, 10.

[12] Foguesatto, C., Borges, J., & Machado, J. (2020). A review and some reflections on farmers' adoption of sustainable agricultural practices worldwide. Science of the total environment, 729, 138831.

[13] Frölich, M., Landmann, A., Olapade, M., & Poppe, R. (2014). Non-experimental methodologies for quantitative analysis. . A practical guide to impact assessments in micro-insurance, 111-129.

[14] Gao, J., Shahid, R., Ji, X., & Li, S. (2022). Climate change resilience and sustainable tropical agriculture: Farmers' perceptions, reactive adaptations and determinants of reactive adaptations in hainan.

Atmosphere, 13(6), 955.
[15] German, R., Thompson, C., & Benton, T. (2017). Relationships among multiple aspects of agriculture's environmental impact and productivity: a meta-analysis to guide sustainable agriculture. Biological Reviews, 92(2), 716-738.
[16] Godde, C., Mason-D'Croz, D., Mayberry, D., Thornton, P., & Herrer, M. (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. Global food security, 28, 100488.
[17] Hernández, R., Fernández, C., & Baptista, M. (2014). Metodología de la investigación. México: McGraw Hill.
[18] Herrera, J. (2017). La investigación cualitativa. UDGVirtua. Retrieved from http://biblioteca.udgvirtual.udg.mx/jspui/handle/123456789/1167
[19] Hossain, A., Krupnik, T., Timsina, J., Mahboob, M., Chaki, A., Farooq, M., & Hasanuzzaman, M. (2020). Agricultural land degradation: processes and problems undermining future food security. In Environment, climate, plant and vegetation growth. Cham: Springer International Publishing., 17-61.
[20] Hu, S., Yang, Y., Zheng, H., Mi, C., Ma, T., & Shi, R. (2022). A framework for assessing sustainable agriculture and rural development: A case study of the Beijing-Tianjin-Hebei region, China. Environmental Impact Assessment Review, 97, 106861.
[21] Imran, M., & Ozcatalbas, O. (2021). Optimization of energy consumption and its effect on the energy use efficiency and greenhouse gas emissions of wheat production in Turkey. . Discover Sustainability, 2(1), 28.
[22] Lee, C., Zeng, M., & Luo, K. (2023). How does climate change affect food security? Evidence from China. Environmental Impact Assessment Review, 104, 107324.
[23] Lehtonen, H., Huan-Niemi, E., & Niemi, J. (2022). The transition of agriculture to low carbon pathways with regional distributive impacts. Environmental Innovation and Societal Transitions, 44, 1-13.
[24] Martelo, R., Bastidas, M., & Martínez, J. (2018). Determination of key variables for the program proposal to address aspiring undergraduate programs in public universities. Contemporary Engineering Science, 11(15), 707-717.
[25] Martelo, R., Villabona, N., & Bastidas, M. (2020). Factores que influyen en la lealtad del cliente en el comercio electrónico del turismo. . Desarrollo Gerencial, 12(2), 1-24.
[26] Nguyen, T., Grote, U., Neubacher, F., Do, H., & Paudel, G. (2023). Security risks from climate change and environmental degradation: implications for sustainable land use transformation in the Global South. Current Opinion in Environmental Sustainability, 101322.
[27] Ostaev, G., Kondratyev, D., Nechaev, B., & Romanova, A. (2020). Foresight research in management accounting: scenario forecasting and a comprehensive system of expert assessment methods in agricultural holdings. . Amazonia Investiga, 9(29), 188-203.
[28] Patel, S., Sharma, A., & Singh, G. (2020). Traditional agricultural practices in India: an approach for environmental sustainability and food security. Energy, Ecology and Environment, 5(4), 253-271.
[29] Penuelas, J., Coello, F., & Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. . Agriculture & Food Security, 12(1), 1-9.
[30] Sampieri, H. (2018). Metodología de la investigación: las rutas cuantitativa, cualitativa y mixta.México.: McGraw Hill.
[31] Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., & Brahmachari, K. (2020). Management of crop residues for improving input use efficiency and agricultural sustainability. . Sustainability, 12(23), 9808.
[32] Tey, Y., Li, E., Bruwer, J., Abdullah, A., Brindal, M., Radam, A., . . . et, a. (2014). The relative importance of factors influencing the adoption of sustainable agricultural practices: A factor approach for Malaysian vegetable farmers. . Sustainability science, 9, 17-29.
[33] Thompson, B., Barnes, A., & Toma, L. (2022). Increasing the adoption intensity of sustainable agricultural practices in Europe: Farm and practice level insights. Journal of Environmental Management, 320, 115663.
[34] Tilahun, K., & Desta, G. (2021). Impact of Physical Soil and Water Conservation Measures on Soil Erosion Reduction and Associated Constraints in the Highland of Ethiopia. Journal of Soil and Water Science, 5(1), 171-183.
[35] Toor, M., Rehman, F., Adnan, M., Kalsoom, M., & Shahzadi, L. (2020). Relationship between environment and agriculture: a review. . SunText Rev. Biotechnol, 1(2), 1-5.
[36] Tripathi, S., Srivastava, P., Devi, R., & Bhadouria, R. (2020). Agrochemicals detection, treatment and remediation. Butterworth-Heinemann., 25-54.
[37] Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., & Phung, D. (2021). Agriculture development, pesticide application and its impact on the environment. International journal of

environmental research and public health, 18(3), 1112.
[38] Van der Werf, H., & Petit, J. (2022). Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agriculture, Ecosystems & Environment, 93(1-3), 131-145.
[39] Zahoor, I., & Mushtaq, A. (2023). Water pollution from agricultural activities: A critical global review. Biochem. Sci, 23, 164-176.