Technological and Biological Strategies for Increasing Profitability in Integrated Aquaculture Farms in Romania

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Abstract

Optimizing the profitability of aquaculture farms by integrating valuable species and modern production technologies is a fundamental strategic approach, capable of improving economic efficiency, diversifying the productive structure and strengthening the sustainability of farming systems. This study evaluates the evolution of the physicochemical parameters of sediments from an experimental aquaculture farm in Galați County, Romania (January 2024 –September 2025), correlating their dynamics with the local meteorological context, in order to optimize productive management and the integration of valuable species. The pH of the sediments decreased from 9.29 (May) to 8.36 (September), indicating a moderate alkaline stabilization towards the end of the warm season. The organic matter content varied strongly (63.81–118.71 mg $KMnO_4$/100 g), with a maximum in July; calcium reached 60.12 mg/100 g in June, and magnesium increased to 29.16 mg/100 g in September; the Ca/Mg ratio went from 6.60 (August) to 0.96 (September), suggesting relevant changes in mineralization. Nitrogen indicators revealed intense microbiological activity (nitrates max. 5.66 mgN/100 g in August; nitrites max. 0.331 mgN/100 g in July), while phosphates (0.063–0.373 mg/100 g) and sulfates (53.1–197 mg/100 g) showed seasonal variations in nutrient intake. The meteorological context was synthesized on two contrasting benchmarks: January 2024, with monthly Tmed ~1.17°C, RHmed ~89.4%, Ptot ~8.6mm (12 days with precipitation; daily maximum 4mm on January 8), respectively September 2025, with Tmed ~18.9°C, RHmed ~71.9%, Ptot ~11.6mm (5 days with precipitation; peak of 9.2mm on September 17). These conditions — from cold and wet winters to warm autumns with punctual rainy episodes — can influence nutrient mobilization, organic matter decomposition and benthic habitat quality, partially explaining the variations observed in sediments. The results support that integrated sediment–meteorology monitoring provides a solid basis for calibrating rearing, feeding and recirculation technologies, facilitating the implementation of an integrated aquaculture farm model with increased economic efficiency and sustainable resource use.

Keywords: *aquaculture farms; valuable species; economic efficiency; sustainability of farming systems*

1. Introduction

In recent decades, the global agricultural sector has been subjected to unprecedented systemic pressures, generated by accelerated population growth and the intensification of the effects associated with climate change [1]. Recent studies show that increased climate variability, manifested by extreme weather events, increasing average temperatures and instability of rainfall patterns, leads to a significant decrease in the predictability of traditional agricultural systems, affecting crop productivity and production stability [2]. In addition, the ongoing degradation of natural resources and increasing pressure on natural capital accentuate the vulnerability of open field production, generating the need for alternative technological paradigms. [3]

In this context of climate instability and increased volatility, horticultural production in protected spaces — especially in controlled greenhouses — is emerging as one of the most robust strategies for ensuring global food security. Current research indicates that smart horticulture, based on advanced digital systems, sensors, automation and artificial intelligence, allows crops to be decoupled from external weather conditions and production processes to be managed in an optimized manner [4]. Also, the integration of digital technologies provides a significant advantage in terms of resource efficiency, loss reduction and increased production capacity in areas where conventional agriculture is limited [5].

Within this conceptual framework, the applicability of a specific technological system, integrated under the conditions of efficient use of exploitable agro-horticultural resources, becomes fundamental for the modernization and resilience of agro-ecosystems. Current literature highlights that integrated systems — which combine smart sensors, cyber-physical automation, IoT platforms and optimization algorithms — lead to real-time monitoring of critical environmental parameters, facilitating adaptive and predictive management of resources such as water, energy, nutrients and arable land [6]. In addition, these systems allow the fine correlation

of biological processes with technological inputs, optimizing the physiological performance of crops and increasing the efficiency of exploitable resources in agro-horticultural farms [7].

By implementing such integrated technological architectures, not only an increase in production yield and stability is achieved, but also a significant reduction in pressure on natural ecosystems, by reducing the need to expand agricultural land and by promoting sustainable management, in accordance with the principles of circular agriculture [8]. Consequently, integrated technological systems, oriented towards the efficient use of agro-horticultural resources, are asserting themselves as essential elements in the agri-food architecture of the 21st century, contributing to the development of resilient, efficient and environmentally sustainable production models [9].

Agriculture and horticulture are essential pillars of contemporary agri-food systems, directly contributing to food security, the socio-economic stability of the rural environment and the maintenance of ecosystem functionality [10]. In recent decades, the accelerated transformations of the global context — manifested by the intensification of climate change, the progressive diminution of natural resources and the expansion of pressures on natural capital — have generated a pressing need to reconfigure the technological paradigms used in agricultural and horticultural farms [11]. In this context, sustainability, resource efficiency and the resilience of agro-ecosystems become defining criteria for the development of production models adapted to the new economic and ecological realities [12].

Against the background of these challenges, the optimization of technological systems applied in agro-horticultural farms acquires increased strategic relevance. The integration of advanced technological solutions — from cyber-physical systems and integrated sensors to digital monitoring infrastructures and algorithmic platforms — allows not only to improve operational performance, but also to configure more efficient resource management models [13]. At the same time, the development and testing of experimental models based on integrated technological systems provides a methodological framework necessary for the rigorous evaluation of the performance, feasibility and sustainability of proposed technologies, under conditions similar to the real operational environment [14].

Such experimental models focus on capitalizing on the synergies between agricultural and horticultural processes, by designing systemic structures that aim to optimize input and output flows, minimize losses and increase resource circularity [15]. Rational management of essential elements — soil, water, energy and biodiversity — becomes an indispensable condition for improving the performance of agroecosystems, being aligned with the principles of the circular economy and sustainable agriculture [16]. The integration of emerging technologies also contributes to increasing the capacity of agro-horticultural systems to respond to external disturbances, strengthening operational resilience and adaptability to climatic and economic variability [17].

In this sense, the present study focuses on testing an experimental model of an integrated technological system, applicable to agro-horticultural farms, in order to evaluate the efficiency of resource use, operational functionality and replication potential in various productive contexts [18]. The research aims to develop a systemic and interdisciplinary approach, capable of providing relevant empirical data to substantiate decisions in the field of technological innovation and sustainable development of the agro-horticultural sector.

The purpose of this paper is to investigate the potential for converting a disused fish pond into a functional agricultural area, by assessing the agro-productive feasibility and the ecological impact of this transformation. Given that many fish farms in Romania are underutilized, the valorisation of these lands represents a strategic direction for increasing the efficiency of land resource use and for expanding arable agricultural areas. This study is dedicated to the systematic analysis of a fish pond, after the cessation of fish farming activities, can be reintegrated into the agricultural circuit, taking into account the pedological, hydrological and agro-ecological characteristics specific to this type of land. The transformation is approached as a sustainable solution, with economic (by expanding productive land), ecological (by revitalizing and stabilizing the local ecosystem) and social (by diversifying agricultural activities and increasing regional productivity) benefits.

To assess the agricultural applicability of the basin, three crop species with strategic importance and significant weight in the agricultural structure of Galați County, Romania was selected — wheat, peas and corn — species that allow a relevant comparative analysis of the capacity of the reconverted soil to support crops with distinct agrotechnical requirements. The study follows the growth performance, the adaptability of the species to the new edaphic conditions and the productive potential of the land resulting from the conversion.

Therefore, the main purpose of the research consists in the scientific substantiation of the process of reconversion of a fish basin into a functional agricultural system and in the assessment of the opportunities for sustainable integration of these areas into the regional agricultural landscape, contributing to the improvement of natural resource management and the optimization of agricultural production.

2. Materials and Methods

The methodology applied in the study aimed to evaluate the agronomic potential of a disused fish pond, with a view to its reconversion into agricultural land. To achieve this objective, detailed physico-chemical analyses were carried out on the sediments, through a systematic sampling program carried out over several months and in different representative locations within the experimental pond, but also from natural aquatic areas used as reference points. The sediments were collected from areas with distinct spatial characteristics, such as Brateș area from Galati County, Romania, in order to capture the edaphic variability specific to abandoned fish ponds (figure 1). The sampling was carried out from the superficial layer of the sediments (0–20 cm), considered the most relevant for the subsequent installation of agricultural crops. The samples thus obtained were stored in sterile containers, quickly transported to the laboratory and processed within 24 hours, to prevent alteration of the chemical composition.

In the laboratory, the sediments were homogenized and prepared for the analysis of physicochemical parameters, by drying, sieving and grinding until obtaining a fine fraction suitable for gravimetric and spectrophotometric determinations. A series of indicators considered essential for the evaluation of the potential fertility of the substrate were analysed: pH, humidity, organic matter content, Ca^{2+} and Mg^{2+} concentrations, Ca^{2+}/Mg^{2+} ratio, levels of different forms of nitrogen (nitrites, nitrates, total nitrogen, ammonium, ammonia), phosphates, sulphates, potassium, humic substances and hydrolytic acidity. The pH was determined electrochemically, using calibration buffer solutions, and the humidity was established gravimetrically, by drying the samples to constant mass. The organic matter content was determined by oxidation with potassium permanganate, a method widely used in agrochemistry to assess the degree of mineralization and nutritional potential. The macroelements Ca^{2+}, Mg^{2+} and K^{+}, as well as the anionic ions (NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-}) were determined by spectrophotometric and titrimetric methods, while total nitrogen was established by procedures specific to the determination of nutrients in sediments.

Fig. 1. The location of the fish farm - Brateş research and development fish farm
source: I.C.D.E.A.P.A. Galați — Research and Development Institute for Aquatic Ecology, Fisheries and Aquaculture

The analyses were carried out periodically, in the months of January 2024 – September 2025, to capture the seasonal changes of the sediments in their stabilization process after the cessation of fishing activity. This approach allowed the assessment of the edaphic dynamics and the degree to which the substrate spontaneously adapts towards a profile compatible with agricultural use. The results of each series of measurements were compared both between sampling points and between time intervals, in order to identify trends of uniformity, accumulation or depletion of certain nutrients.

The interpretation of the chemical and physical parameters was correlated with the agrobiologically requirements of the three experimentally cultivated species — wheat, peas and corn — which represent crops of major interest for Galați County. Thus, the pH values, nitrogen, phosphorus, potassium, Ca/Mg ratio, as well as the organic matter content were analysed in relation to the physiological tolerances and nutritional preferences of these plants, in order to realistically evaluate the productivity potential of the reconverted land. Through this integrated methodology, the study aimed not only to characterize the sediments, but also to substantiate the scientific arguments necessary to validate the conversion of a fish pond into a functional agricultural system.

The characterization of the regional climatic conditions that influenced the evolution of the processes analysed in the study was carried out based on daily meteorological data provided by the National Meteorological Administration (ANM). The information used comes from the operational sets M101, M201 and M401, integrated into the INSPIRE infrastructure of the ANM and developed in accordance with the standards of the World Meteorological Organization, as well as with the European technical specifications on atmospheric observations and monitoring of meteorological conditions. The M101 set provides basic synoptic observations, including air temperature, relative humidity and precipitation, while M201 provides daily climatological data regarding minimum, maximum and average temperature values, as well as daily precipitation totals. In addition, the M401 product provides validated information on accumulated precipitation in 24-hour intervals, which are commonly used for regional-scale climate and hydrological analyses [19].

The data selected for this study correspond to Galați County, a region where representative meteorological stations are found for both the Brateș Lake area and the lower Prut River sector. The analysed interval covers the years 2024–2025, and the observations were collected entirely at daily resolution, according to the standardized acquisition and quality control procedures implemented by the ANM. These procedures include automatic validations and statistical checks aimed at eliminating possible instrumental or transmission errors, so that the resulting datasets accurately reflect the real atmospheric variability reported to the local context.

The analysed climatic parameters included air temperature (average, maximum and minimum values), relative humidity and daily precipitation amounts. This structure of variables allows the description of the thermal and hygrometric regime characteristic of the period, representing an essential support for the interpretation of the seasonal variations observed in the evolution of the monitored ecological and agronomic parameters. In the study, meteorological information was used both to contextualize the evolution of the physico-chemical properties of sediments and soil, and to understand the relationship between climatic phenomena and the dynamics of the processes observed in the studied systems. The integration of these data provides the climatic foundation necessary for a rigorous interpretation, contributing to the reproducibility and solidity of the presented results.

Principal Component Analysis (PCA) is one of the most widely used multivariate statistical methods for dimensionality reduction and the detection of latent structures in complex data sets. PCA transforms the original variables, often correlated with each other, into a new coordinate system formed by orthogonal principal components, each component representing a linear combination of the original variables. This transformation aims to maximize the explained variance, so that the first components capture most of the information contained in the data. From a methodological point of view, PCA starts from the standardization of the variables, followed by the calculation of the covariance

or correlation matrix, depending on the nature and scaling of the data. Subsequently, the eigenvalues and eigenvectors are determined, which define the directions of maximum variation in the multivariate space. Each eigenvalue indicates the proportion of the total variance captured by the corresponding component, allowing the selection of a small number of components that preserve the essential information.

Projecting observations and variables onto principal component plots provides an intuitive graphical representation of the relationships between the analysed elements, facilitating the identification of natural clusters, ecological gradients, or variables with major influence. In ecological and biogeochemical contexts, PCA is particularly valuable because it allows for the synthesis of multifactorial variations and the highlighting of the dominant mechanisms that structure the studied system. Overall, PCA is a robust and elegant technique for exploring multivariate data, reducing complexity, and supporting the interpretation of fundamental processes that govern the dynamics of the analysed variables.

Random Forest Feature Importance Analysis is a standard technique in computational statistics and machine learning, used to assess the relative contribution of each predictor to the performance of a regression model. Random Forest is an ensemble algorithm that builds a large number of independent decision trees, each trained on random subsets of data and variables. By aggregating the predictions of all trees, the model obtains a robust estimate that is less sensitive to variations in the data.

The importance of variables is calculated by quantifying the contribution of each predictor to reducing the impurity in the tree nodes. In other words, variables are evaluated according to how much they improve the separation of data when they are selected for splitting a node. The final importance value is obtained by weighting the contributions across all trees in the decision forest. Variables with high importance are those that consistently produce significant reductions in prediction error, while variables with low values have little predictive impact.

The method provides a direct insight into the hierarchy of factors influencing the target variable, allowing the relative interpretation of the role of each parameter. In addition, the analysis of the importance of variables is an essential step in the selection of predictors, the optimization of models and the understanding of the ecological and biogeochemical mechanisms reflected by the data. Thus, Random Forest Feature Importances constitutes a rigorous and efficient tool in assessing the predictability of variables in a complex multivariate framework.

3. Results and Discussions

The analysis of the relationships between sediment parameters and meteorological variables for the period January 2024–September 2025 highlights a well-defined climate pattern, reflected in the structure of the Pearson coefficients in the figure 2. At the level of the data set, air temperatures – regardless of whether the average, maximum or minimum values are considered – exert a predominantly negative effect on the organic and acid-base parameters of the sediments. Humic substances are most strongly influenced, with correlation values of –0.63 in relation to the average temperature, –0.59 in relation to the maximum temperature and –0.61 in relation to the minimum temperature, indicating a constant decrease in humic content under higher thermal conditions. A similar behaviour occurs in the case of oxidizable organic matter, for which the coefficients remain around the value of –0.49, both in relation to the average and maximum temperature, suggesting a systematic reduction in stable organic matter as the thermal regime intensifies.

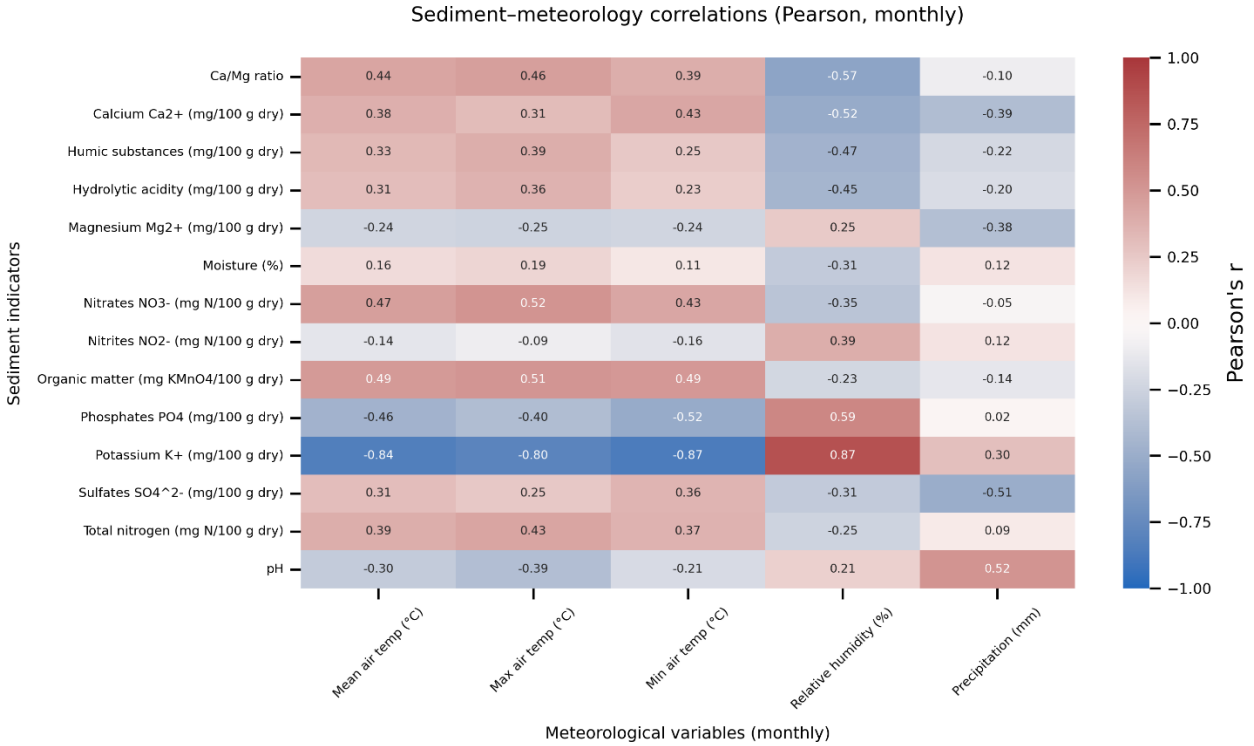

Fig. 2. The Pearson correlation between sediment and meteorological parameters

Hydrolytic acidity follows the same direction, with moderate correlations, between –0.36 and –0.34 for the three thermal variables, complemented by a more discreet decrease in sediment moisture, which varies between –0.16 and –0.19. The phenomenon is also visible in the behaviour of nitrites, where the minimum temperature correlates negatively in proportion to –0.46, while the relationships with the maximum temperature remain weak (–0.10). These results indicate a pronounced climatic gradient, in which variables sensitive to mineralization processes or to the evolution of organic matter respond consistently to high temperatures. In contrast to these parameters, calcium and the Ca/Mg ratio are distinguished by positive correlations with the thermal variables. Calcium presents values ranging between +0.31 and +0.38, and the Ca/Mg ratio is between +0.39 and +0.45, suggesting a concomitant increase in these indicators in the months marked by higher temperatures. The potassium ion is by far the most sensitive to temperature, recording some of the highest positive

correlations in the entire matrix: +0.80 with both mean and maximum temperature, and +0.87 with minimum temperature, which places it in a distinct category in terms of seasonal response.

As for the hygrometric variables, the direction of the relationships is reversed. Relative air humidity shows very clear positive correlations with organic parameters: +0.74 for humic substances, +0.23 for oxidizable organic matter, +0.45 for hydrolytic acidity and +0.21 for sediment moisture. The K^+ ion remains the most responsive from this point of view as well, with a correlation of +0.87, suggesting that air humidity variability coincides with pronounced changes in the mobility of this element in sediments. In contrast, phosphates show an inverse relationship, with a negative correlation of –0.46, indicating a decrease in their concentrations under conditions of high atmospheric humidity.

The correlation with precipitation partially confirms the patterns induced by relative humidity, but with lower magnitudes. Organic parameters show moderate positive values, of approximately +0.14 for humic substances and organic matter, and +0.20 for hydrolytic acidity. The K^+ ion also has a marked positive correlation here (+0.30), while phosphates (–0.51) and sulphates (–0.51) are negatively correlated with the monthly amount of precipitation, representing the most pronounced negative relationships in this category.

Indicators associated with reactive forms of nitrogen remain weakly correlated with climatic variables; nitrates vary between –0.47 (average temperature) and +0.02 (precipitation), and nitrites between –0.46 and +0.12, without a clear directional trend. pH shows moderately negative values with temperatures (between –0.21 and –0.39), but becomes positive with relative humidity (+0.39) and precipitation (+0.52), indicating a greater influence of the water regime on the acid-base balance than of the thermal regime. Overall, the figure 2 demonstrates the existence of a clear seasonal climatic gradient, in which the organic and acid-base parameters of the sediment are closely linked to the thermal and hygrometric regime of the air, while the major ions react predominantly to temperature, and the reactive nitrogen species remain largely independent of monthly meteorological variations.

The first two principal components (PC1 and PC2) capture a substantial proportion of the multivariate variability of the combined sediment–meteorology dataset, according to the PCA Scores plot. PC1 explains most of the variation, representing the major gradient associated with climatic and geochemical changes from May 2024 to September 2025, while PC2 captures a second, well-structured gradient related to secondary variation in atmospheric conditions and sedimentary parameters.

Together, the two components reduce the complexity of the entire set of variables to two interpretable axes, synthesizing the main common processes governing sediment dynamics in relation to meteorological factors. The projection of months in the PCA plane shows a clear separation according to seasonal characteristics. The month of May 2024 is positioned in a space associated with higher values of organic parameters and hydrolytic acidity, reflecting colder and wetter conditions. The peak summer months (July and August 2025) are markedly separated from the rest in the direction of PC1, corresponding to a pronounced thermal regime and a sedimentary composition influenced by high temperatures, low atmospheric humidity and ionic variations specific to the warm season. The month of September occupies an intermediate position, suggesting a transition towards a partial return to thermal-hydric conditions close to the beginning of the season. This spatial distribution confirms the coherent seasonal structure of the data.

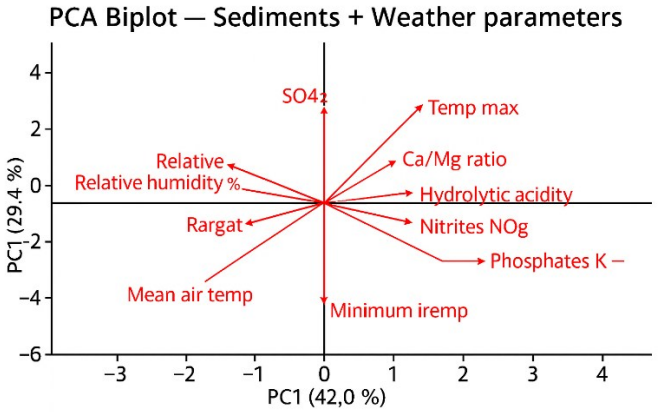

Fig. 3. The PCA Biplot sediments and weather parameters

The analysis of the loading vectors shows that PC1 is dominated by thermal variables (mean, maximum and minimum temperature), oriented in the same direction in the component space, together with major ions such as potassium and the Ca/Mg ratio. In the opposite direction are found the organic parameters (oxidizable organic matter, humic substances), as well as hydrolytic acidity, indicating an inverse relationship between the thermal regime and the organic-acid state of the sediments. PC2 is mainly influenced by water variables, especially relative humidity and precipitation, in partial opposition to variables such as phosphates and sulphates. The biplot brings these relationships together, highlighting how the vectors of climatic and sedimentary align.

The figure 4 illustrate two complementary approaches to assessing the contribution of variables to the prediction of organic matter content, using advanced machine learning methods. The first image shows the importance of the variables obtained by the Random Forest model, and the second represents the distribution of SHAP values, which provides an interpretable perspective on how each predictor directly influences the model output.

In the first image (Top 12 Feature Importances), the variables are ordered according to their overall importance in the model. Random Forest calculates this indicator by quantifying the reduction of statistical impurity in the decision trees that compose the model. Thus, variables such as Hydrolytic Acidity, Humic Substances, Potassium (K) and Nitrites (NO_2) appear with high values, which indicates their major role in explaining the variation of organic matter. These variables are influential because they frequently contribute to decisive splits in the regression trees, determining an efficient structuring of the data and a substantial reduction in the prediction error.

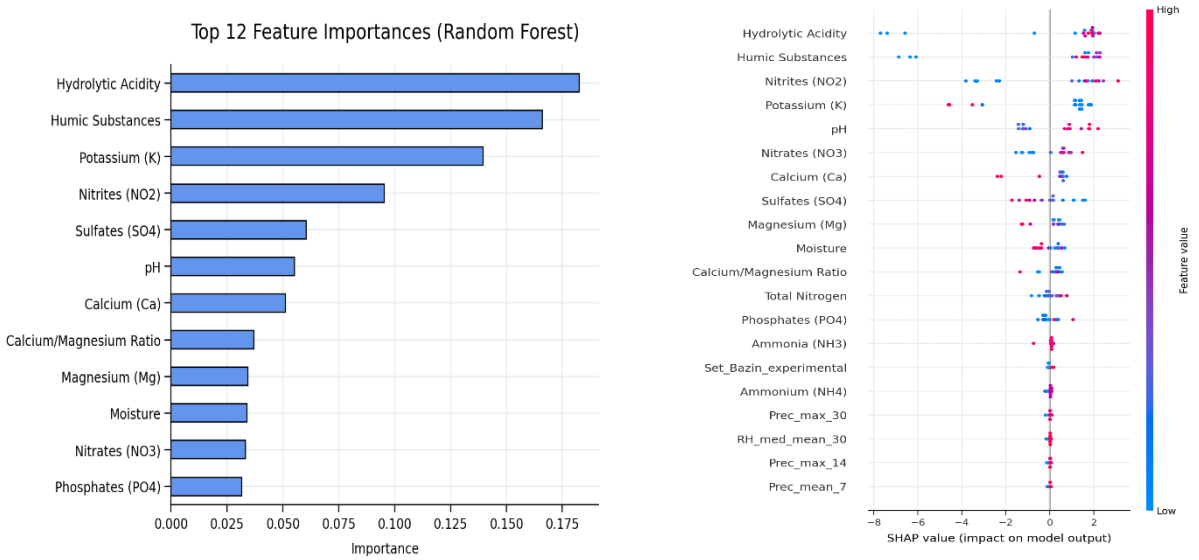

Fig. 4. The Top 12 Feature Importances and SHAP Summary Plot

The second image (SHAP Summary Plot) does not limit itself to the global importance of the variables, but describes their individual impact on the predictions, through SHAP values. This type of analysis is based on cooperative theory and allows the decomposition of each prediction into the contributions of the component variables. The coloured points represent individual observations, the position on the horizontal axis indicates the magnitude of the effect on the prediction, and the colour signals a high or low value of the predictor. For example, high values of Hydrolytic Acidity or Humic Substances tend to increase the prediction of the level of organic matter, which reflects a positive relationship between these parameters and the biogeochemical processes associated with the accumulation of organic matter. In contrast, other parameters, such as Sulphates (SO_4) or Calcium (Ca), can have variable positive or negative effects, suggesting a complex interaction between the chemical composition of the sediments and the dynamics of organic matter.

By combining the two approaches—global importance (Random Forest) and local influence on predictions (SHAP)—a comprehensive picture of the determining mechanisms in the data set is obtained. Random Forest provides a robust hierarchy of predictors, while SHAP clarifies the direction and consistency of their effects. Together, these methods allow both the assessment of the predictability of each variable and the ecological interpretation of how these parameters contribute to the observed variability in sediment organic matter.

The figure 5 presents a comparative analysis of sedimentary parameters for soils associated with the three crops — pea (Pea), corn (Corn) and wheat (Wheat) — highlights major differences in organic and mineral composition, suggesting the distinct functioning of biogeochemical processes in each type of crop. The measured values allow a robust interpretation of the soil condition and local ecological mechanisms.

Regarding organic matter, the soil from the wheat crop presents the highest value (65.47 mg $KMnO_4$/100 g), followed by pea (62.69) and corn (48.79) 1. This distribution suggests a superior capacity for accumulation of organic matter in soils cultivated with wheat, possibly associated with the root structure and the mineralization rate in these areas. The high values for peas are compatible with the beneficial effects of legumes on the carbon cycle, while maize reflects a low level of organic matter, suggesting a more intense consumption of organic compounds or an accelerated mineralization.

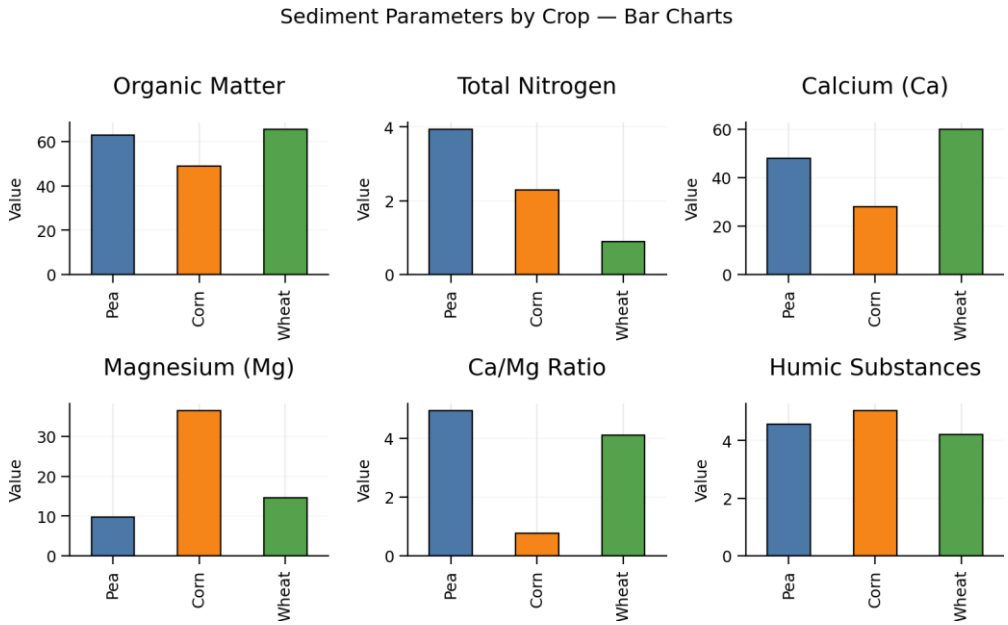

Fig. 5. The sediments parameters by crop

For total nitrogen, the differences are even more pronounced: peas present the highest concentration (3.94 mg N/kg), maize an intermediate level (2.29), and wheat a much lower value (0.904). These data correspond to the specific behaviour of legumes, which fix atmospheric nitrogen, thus increasing the availability of this element in the soil. The low levels for wheat may indicate a more intense consumption of nitrogen or a reduced availability in the analysed interval.

The analysis of major cations reveals significant contrasts. Calcium (Ca) is dominant in wheat (60.12 mg/100 g), moderate in peas (48.10) and low in maize (28.06). In contrast, magnesium (Mg) reaches very high values in maize soil (36.45 mg/100 g), compared to peas (9.72) and wheat (14.58) — a marked imbalance that directly influences the Ca/Mg ratio. This ratio, an indicator of soil structural stability, is well represented in pea (4.95) and wheat (4.12) soils, but extremely low in maize soil (0.77), indicating an ionic regime dominated by Mg and potential difficulties in the mobility of other nutrients.

Regarding humic substances, the distribution is relatively uniform: corn has the highest value (5.04 g/100 g), followed by peas (4.56) and wheat (4.20). This closeness in values suggests that, despite differences in total organic matter, humification processes remain similar between crops, reflecting a comparable level of organic stabilization in the soil.

Generally, the analyses highlight three clearly differentiated sedimentary profiles between the investigated crops. The soil associated with the wheat crop is distinguished by a high calcium content, high levels of organic matter and a favourable Ca/Mg ratio, which suggests a well-structured soil, with a high buffering capacity and a pronounced potential to support organic stabilization processes. In contrast, the soil associated with peas presents a balanced profile, characterized by very high values of total nitrogen, a substantial content of organic matter and a Ca/Mg ratio close to optimal, confirming the agronomic role of legumes in the natural enrichment of the soil and the maintenance of a stable nutritional regime. On the other hand, the soil from the maize crop is distinguished by a very high level of magnesium and an extremely low Ca/Mg ratio, indicating significant cationic imbalances, with a potential impact on fertility and bioavailability of essential nutrients. These differences, consistently observable between the analysed variables, demonstrate that each crop imprints a distinct biogeochemical signature on the soil, with direct implications on the functioning and quality of the agricultural ecosystem.

Thus, the graphical comparison supports the conclusion that crop type strongly influences sediment chemistry, outlining specific biogeochemical signatures relevant for fertility management and assessing the functioning of agricultural ecosystems.

The z-score heatmap analysis (figure 6) highlights clear differences between the three crops, providing a standardized perspective on how each sedimentary parameter deviates from the overall average. Positive values indicate above-average levels, while negative values signal below-average concentrations, allowing for a rigorous comparative assessment.

For pea (Pea), the profile is predominantly positive, suggesting balanced sedimentation, but with marked enrichment elements. Organic matter scores +0.51, indicating a slight over-average, and total nitrogen stands out with its highest value, +1.26, confirming the biological contribution specific to legumes. Calcium has a z-score of +0.20, while magnesium is below-average (–0.91). The Ca/Mg ratio is strongly positive (+0.92), highlighting a favourable cation balance. Peas also show the highest relative levels of humic substances (+0.65) and hydrolytic acidity (+1.41), suggesting active humification processes and a well-developed buffer capacity.

Corn shows a different profile, dominated by sharp contrasts. Organic matter is strongly below average (–1.40), and calcium is also low (–1.31). In contrast, magnesium reaches the highest relative value of all crops, with a score of +1.39, reflecting a strongly Mg-dominated soil. This magnesium preponderance correlates with a very low Ca/Mg ratio (–1.39), suggesting significant imbalances that may affect cation mobility and nutrient availability. Humic substances are slightly above average (+0.77), while pH (–0.81) and moisture (+0.75) indicate a moderately variable environment. Potassium is also below average (–0.72), completing an ionic profile characterized by internal imbalances.

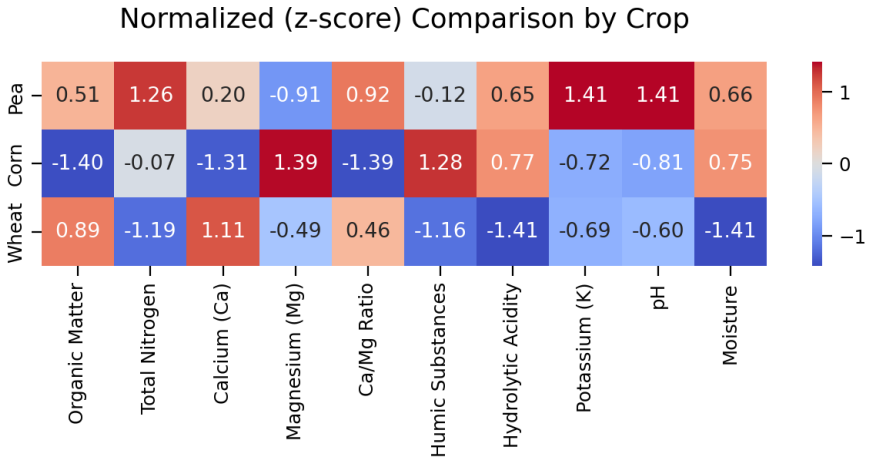

Fig. 6. The normalized z-score comparison by crop type

In the case of Wheat, the normalized profile highlights dominant positive values for the key nutrients: organic matter (+0.89), calcium (+1.11) and potassium (–0.60, but close to the average). These values confirm the trend also identified in the raw analyses, according to which wheat is associated with a soil rich in Ca and with a high level of organic matter. Total nitrogen is strongly below average (–1.19), suggesting limited availability or intense consumption in the period prior to sampling. Magnesium has a negative value (–0.49), while hydrolytic acidity presents one of the lowest scores (–1.16), indicating a lower buffer capacity compared to peas. Moisture has a score of –1.41, the lowest of the three crops, suggesting drier soil in the area associated with wheat at the time of sampling.

Taken together, these normalized profiles confirm the existence of distinct biogeochemical signatures for each crop analysed. The pea soil is characterized by an exceptional nitrogen supply, indicated by a z-score of +1.26, as well as an optimal Ca/Mg ratio (+0.92), suggesting a cationic balance favourable to nutritional processes. In parallel, the humic activity is intense (+0.65), reflecting an advanced level of organic matter stabilization, characteristic of soils with robust biogeochemical functioning. In contrast, the maize soil presents a chemical signature dominated by very high magnesium values, highlighted by a score of +1.39, indicating a pronounced accumulation of this cation. This abundance correlates with a very low Ca/Mg ratio (–1.39), suggesting a major cationic imbalance, likely to affect calcium mobility and the efficiency of nutrient absorption processes. At the same time, corn has a low level of organic matter, marked by the value of –1.40, which may signal accelerated mineralization processes or a low capacity for retaining organic carbon. Wheat is characterized by a sedimentary

signature oriented towards the accumulation of calcium, reflected by a score of +1.11, in parallel with high values of organic matter (+0.89). These elements indicate a well-structured soil, with consistent buffer potential and favourable organic dynamics. However, this crop has a low level of total nitrogen (–1.19) and a low hydrolytic acidity (–1.16), suggesting a lower buffer capacity compared to leguminous crops and a limited availability of some nutrient fractions.

Overall, these differences synthesize the particular way in which each crop influences and is influenced by the local sedimentary structure. They emphasize that crop type is a major determinant of soil ecological functioning, contributing to the definition of specific biogeochemical profiles, with direct implications for fertility, chemical stability and resilience of agroecosystems.

4. Conclusion

The analysis included in this study highlights that the processes influencing the dynamics of organic matter in sediments are the result of complex interactions between biogeochemical parameters and environmental conditions. The internal chemical variables of the sediments prove to have a determining role, reflecting the slow and cumulative processes of mineralization, transformation and accumulation of organic matter. These results suggest that the local chemical structure and ionic composition represent primary factors in controlling the observed variation, while external variables, such as meteorological ones, exert secondary influences, more dispersed and difficult to capture in short time windows. At the same time, the analysis shows that data from different ecosystems, with distinct ecological and hydrological particularities, can introduce large variations in predictive models, limiting their overall performance. This diversity emphasizes the need to develop models specific to each type of system, in order to adequately capture the directions and intensities of the relationships between variables.

The comparative analysis of sedimentary parameters reveals the existence of significant differences between the soils of the three crops, differences that reflect both physiological particularities of the plants and the distinct way in which they influence local pedological and biogeochemical processes. The soil associated with the wheat crop is distinguished by high concentrations of calcium and organic matter, indicating an environment with high buffering potential and a pronounced capacity for accumulating organic matter. This profile suggests advanced mineralization and humification processes, compatible with a constant and efficient soil supply regime. In contrast, the soil from the corn crop is characterized by an abundance of magnesium and a very low Ca/Mg ratio, which may indicate both cationic imbalances and potential effects on the mobility of essential nutrients. The low values of organic matter and total nitrogen in this crop highlight a possible higher consumption of nutrients, associated with the high physiological requirements of the plant. Pea, known for its nitrogen-fixing capacity, presents the most balanced profile, with high levels of total nitrogen and a stable Ca/Mg ratio, suggesting positive contributions to soil fertility and nutrient cycling. Overall, the results indicate that crop type directly influences sediment structure and functionality, leading to distinct chemical signatures. These variations have important implications for both agronomic management and understanding the dynamics of agricultural ecosystems, suggesting the need for differentiated soil monitoring and improvement practices depending on the dominant crop.

General, the study confirms that the use of modern machine learning and multivariate analysis methods provides deep insight into the mechanisms governing sediment functioning, but the performance and interpretability of these models depend crucially on the quality, homogeneity and granularity of the data. Strengthening datasets, refining integrated ecological concepts and improving monitoring design will contribute to the development of more robust predictions and a broader understanding of the biogeochemical processes underlying the dynamics of aquatic ecosystems. Viewed synthetically, the normalized profiles of the three crops highlight clearly differentiated biogeochemical signatures. The soil cultivated with peas stands out for its highest nitrogen enrichment (+1.26) and an optimal Ca/Mg ratio (+0.92), supported by a superior humic activity (+0.65), which outlines a well-balanced nutritional and structurally stable soil. In contrast, maize expresses a profile dominated by excess magnesium (+1.39) and a deeply unfavourable Ca/Mg ratio (–1.39), concomitant with a marked deficit of organic matter (–1.40), signalling a soil under the pressure of cationic imbalances. In turn, wheat shows higher accumulations of calcium (+1.11) and organic matter (+0.89), but with low values of total nitrogen (–1.19) and hydrolytic acidity (–1.16), suggesting moderate fertility and a lower buffer capacity compared to legumes. Overall, these differences synthesize the particular way in which each type of crop modulates sedimentary composition, confirming the determining role of plant structure on the chemical and ecological functioning of the soil.

Optimizing the profitability of aquaculture farms by integrating valuable species and adopting modern technologies is a fundamental direction for increasing economic efficiency and strengthening the sustainability of production systems. Diversifying the species portfolio allows for superior valorisation of biological resources and reducing economic vulnerability, while technological innovations — from digital monitoring of environmental parameters to advanced recirculation systems — contribute to optimizing operational costs and improving zootechnical performance. By combining these two directions, aquaculture acquires the ability to operate more stably, more competitively and better adapted to market requirements, while integrating the principles of sustainability and efficient resource management.

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