Wavelet-Based Approaches in Agriculture: Applications, Benefits, and Future Perspectives

Funda Dökmen

Kocaeli University, Izmit Vocational School, Department of Plant and Animal Production, Arslanbey Campus, Arslanbey-Kartepe, 41285, Kocaeli, Türkiye.

Orcid No: 0000-0002-0615-2887

Abstract

Wavelet analysis can be described as a type of transformation used for the time-frequency analysis of a signal. Problems encountered during the examination of seismic and repetitive data in particular facilitated the development of the 'Continuous Wavelet Transform'. It was subsequently demonstrated that wavelet analysis could be applied to a wide variety of signal types and repetitive long-term data. Continuous wavelet analyses emerge as a powerful tool for analysing signals that require evaluation based on their time-frequency content, enabling the complete representation of a signal by allowing wavelet scale parameters to vary continuously. In another wavelet analysis, the discrete wavelet transform (DWT) is defined as a transformation performed using an algorithm known as a pyramid algorithm, which calculates a subset of possible scales (usually binary values) and recursively divides and reprocesses data series. These analyses are mathematical tools used in agricultural applications to analyse data that varies at different scales according to agricultural data characteristics. Wavelet analyses can be used in water resource planning and management research, in the assessment of water and soil quality parameters, and in the evaluation of drought, climate and meteorological data. In this study, wavelet analysis applications (Wavelet Transform) will be explained using theoretical information, and the importance and awareness of its use in agricultural applications will be discussed.

Keywords: *Agricultural model applications, signal analysis, transform models, wavelet model*

1. Introduction

Wavelet analysis has emerged as a powerful mathematical tool for analyzing non-stationary and complex signals commonly encountered in agricultural research. Unlike traditional Fourier-based approaches, which assume stationarity, wavelet transforms provide the ability to examine signal behavior simultaneously in both time and frequency domains (Daubechies, 1990; Mallat, 1999). This capability makes wavelets particularly suitable for agricultural datasets, which often exhibit seasonal variability, abrupt changes, noise, and multi-scale patterns.

In agricultural studies, wavelet analysis has been used extensively to evaluate climate–crop interactions, detect drought patterns, analyze soil moisture variability, and interpret spectral signatures from remote sensing platforms (Torrence & Compo, 1998; Labat, 2005). Its multi-resolution framework enables researchers to differentiate short-term fluctuations (e.g., sudden weather changes) from long-term trends (e.g., climate-driven yield shifts), providing deeper insights into agricultural system dynamics.

The increasing availability of high-resolution satellite imagery, UAV-based spectral data, and long-term agro-meteorological time series has further expanded the potential of wavelet methodologies. These tools allow for more accurate monitoring of crop health, early detection of plant stress, improved irrigation scheduling, and enhanced prediction of extreme events such as droughts and heatwaves (Adams et al., 2019; Banerjee et al., 2021; Adamowski, 2011). As agriculture faces growing challenges due to climate change, water scarcity, and the need for sustainable resource management, wavelet analysis offers a robust framework for extracting meaningful information from complex datasets and supporting data-driven decision making.

In this study, wavelet analysis applications (Wavelet Transform) will be explained using theoretical information, and the importance and awareness of its use in agricultural applications will be discussed.

2. Wavelet technique

The most important feature of this method is that the signal can be analysed locally (Allen, 2004). This feature of the technique allows a large signal to be analysed in a small area. This analysis method enables the signal to be analysed in the time domain, thereby defining both low-frequency information over a long time interval and high-frequency information over a short time interval.

A time series is a collection of observations that describe the state of a physical quantity in relation to one or more independent variables. In time series, the independent variable is usually time (Chen, 2002; Grinsted, 2004). Mathematically, it is defined as a function g(t) dependent on (t). If the data is recorded continuously, the resulting series is called a continuous series; if it is recorded at specific intervals, it is called a discrete series (Figure 1 and 2).

Due to the large data size in continuous series, samples are taken from them to create discrete sequences. Today, many physical quantities are represented as continuous and discrete signals, and Wavelet analysis is widely used in the analysis of these signals.

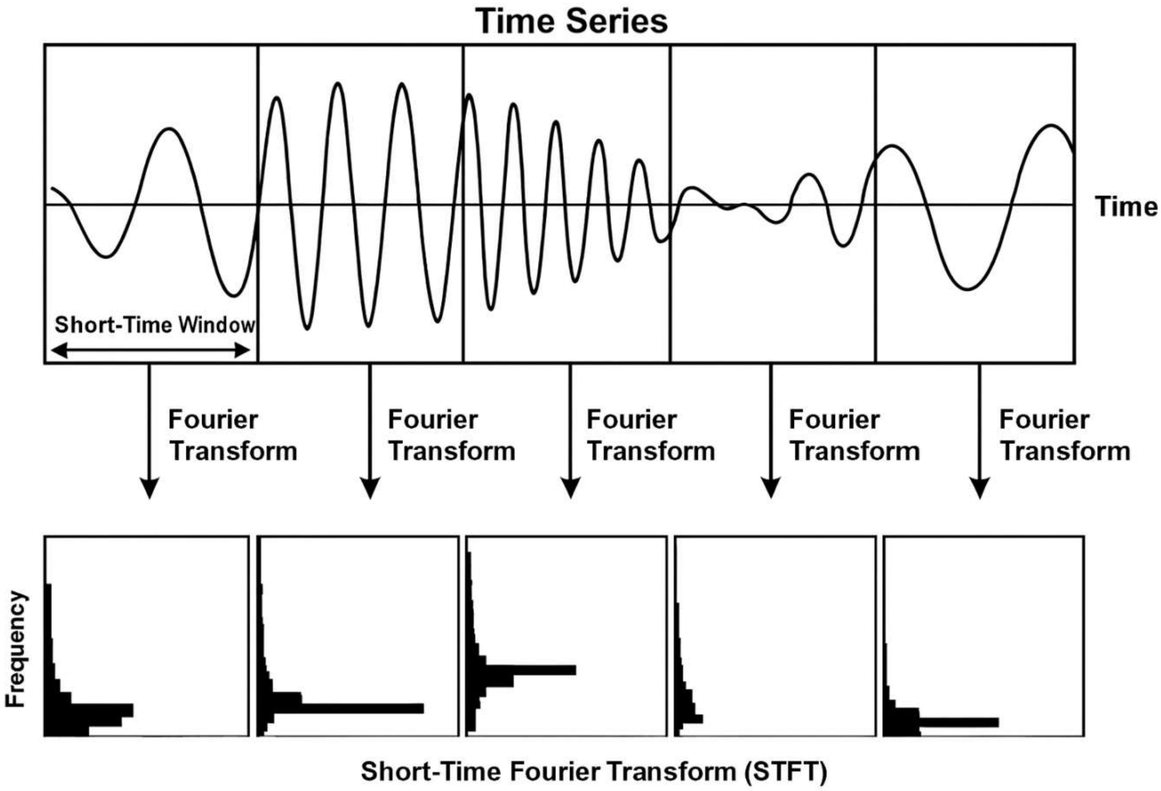

Figure 1: Time series

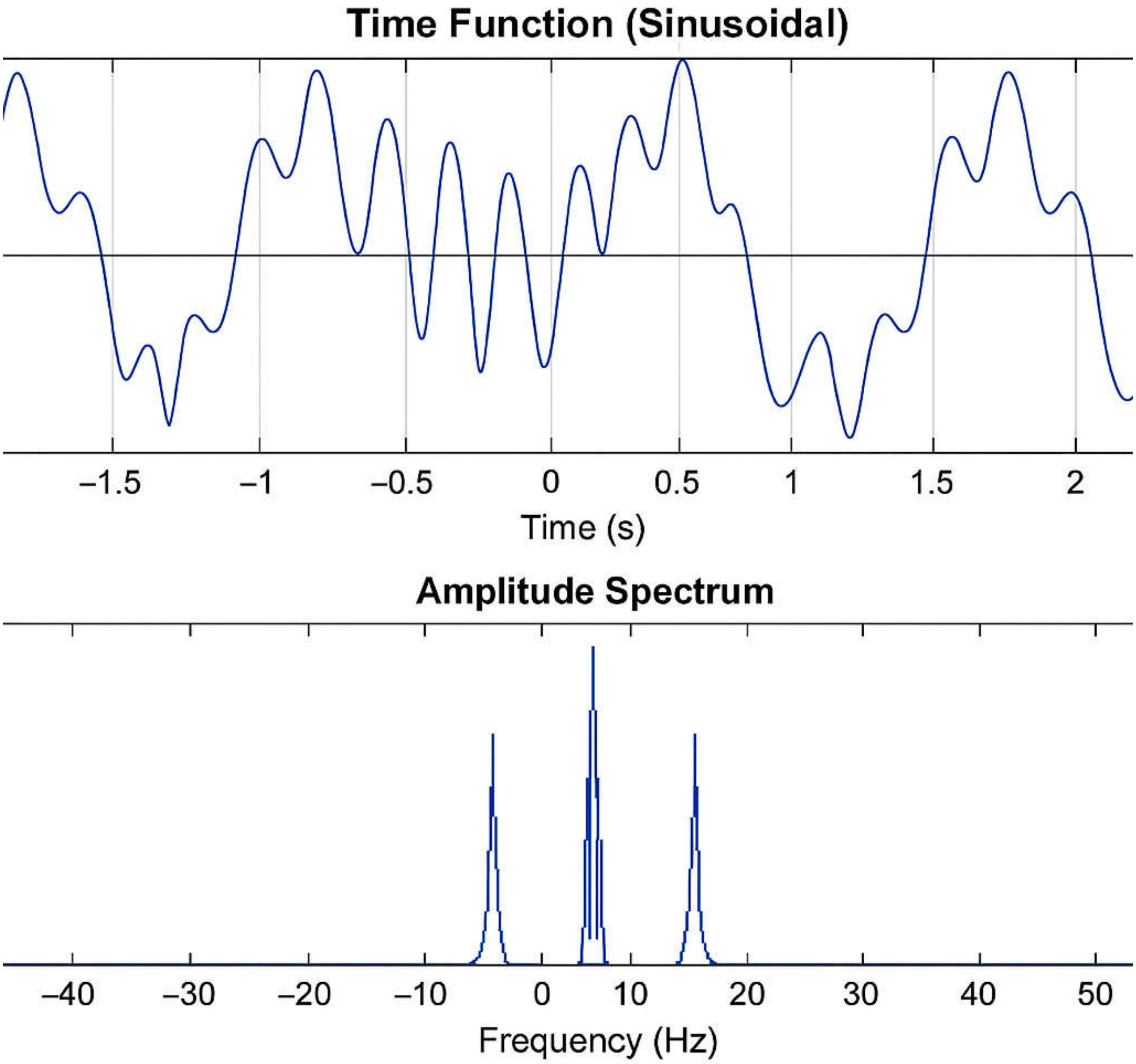

Figure 2: Time series and amplitude

3. Agricultural studies and wavelet Analysis

Agricultural systems are inherently complex, dynamic, and influenced by multiple interacting factors such as climate variability, soil conditions, water availability, and plant physiological processes. These components often produce non-stationary and multi-scale data patterns, which conventional statistical or spectral techniques may fail to capture effectively. In this context, wavelet analysis has emerged as a powerful tool for examining agricultural datasets that fluctuate across time and frequency domains.

Wavelet analysis enables researchers to decompose agricultural time series—such as precipitation, temperature, soil moisture, evapotranspiration, or crop yield data—into different scales, revealing hidden periodicities, abrupt changes, and localized trends. This capability is particularly valuable in agriculture, where environmental drivers operate at various temporal scales, from seasonal and annual cycles to long-term climatic oscillations.

In crop science, wavelets allow the identification of climate–crop relationships, drought periods, pest outbreak signals, and phenological patterns. Hydrological studies use wavelets to investigate river discharge fluctuations, irrigation water demands, and soil–water dynamics (Lahat, 2005; Mishra, 2010). Remote sensing applications also benefit significantly, as wavelet-based filtering and feature extraction improve vegetation index analysis, land-use change detection, and precision agriculture monitoring.

Overall, wavelet analysis offers a robust methodological framework that enhances the interpretation of agricultural datasets by capturing their inherent complexity. As agriculture increasingly relies on high-resolution environmental monitoring and data-driven decision-making, wavelet techniques provide researchers and practitioners with valuable insights for improving sustainability, productivity, and resilience against climate-related risks.

These analyses are mathematical tools used in agricultural applications to analyse data that varies at different scales according to agricultural data characteristics. Wavelet analyses can be used in water resource planning and management research, in the assessment of water and soil quality parameters, and in the evaluation of drought, climate and meteorological data (Zhang, 2006)..

Water is one of the most fundamental resources that meets humanity's energy needs and ensures its survival. The efficient use of existing water potential is essential to optimise water use and management. Future water potential can be estimated using river flow velocity time series. Daily measurements are taken at flow observation stations.

Based on these data, prediction studies are carried out using mathematical models and machine learning systems.

Akbulut and Aslan (2022) were studied by using wavelet , the daily and monthly average flow of the Çatalca Istıranca River, selected as the study area, the daily total precipitation amount for the region, and the daily average air temperature values were taken into account.

Dökmen and Aslan were studied by using wavelet (2013 & 2020), evaluation of oxygen demand in water resources with wavelet modelling and also evaluation of the parameters of water quality with wavelet techniques.

Dökmen, Tokgözlü and Aslan were studied (2023) by using wavelet modelling for standardized precipitation index analyses in drought evaluation. Deniz, Ahi, Aslan, Dökmen and Orta were studied (2025) an analysis of quality parameters changes in agricultural water systems with wavelet transform model.

Başakın, Ekmekçioğlu, Özger ve Çelik were studied (2020) wheat yield prediction in Turkey using the wavelet fuzzy time series method and grey prediction method Turkey wheat yield prediction.

4. Importance of Wavelet Analysis in Agricultural Studies

Wavelet analysis has become a powerful analytical tool in agricultural research due to its ability to examine nonlinear, non-stationary, and multi-scale processes that characterize agro-ecosystems. Agricultural variables such as precipitation, soil moisture, evapotranspiration, temperature, vegetation growth, and crop yield often display temporal and spatial variability that traditional statistical methods cannot fully capture (Torrence,1998; Partal, 2006; Nalley, 2016). Wavelet transforms enable researchers to simultaneously explore both the frequency and time domains, making it possible to detect localized events, periodicities, and abrupt changes in agricultural time series.

One of the major advantages of wavelet analysis is its capacity to evaluate the impacts of climate variability and extreme events—such as droughts, heat waves, or rainfall anomalies—on agricultural productivity. Continuous and discrete wavelet transforms are frequently used to analyze long-term climatic oscillations (e.g., ENSO, NAO) and their lagged effects on crop yields and hydrological variables. This helps improve forecasting accuracy and supports sustainable agricultural planning.

In precision agriculture, wavelet-based filters help reduce noise in remotely sensed data (e.g., NDVI, EVI), enhancing the detection of phenological stages, crop stress, and pest outbreaks (Cazelles, 2008; Lu, 2017). Wavelet decomposition is also applied to model soil properties, detect irrigation anomalies, and improve yield estimation models by extracting relevant multi-scale features. Furthermore, wavelet coherence analysis provides insights into relationships between climatic drivers and agricultural indicators across varying time scales, improving risk assessment and early-warning systems.

Overall, wavelet analysis strengthens agricultural research by offering a robust framework for multi-scale, dynamic, and high-resolution assessment of agro-climatic interactions, thereby supporting climate-smart agriculture, crop management, and decision-making

5. Conclusion and remarks

Wavelet analysis has become an indispensable analytical tool in agricultural research due to its ability to decompose complex, non-stationary signals into time–frequency components with high precision. Unlike classical spectral approaches, wavelet-based methods allow researchers to capture transient patterns, multi-scale processes, and localized variations that are characteristic of agricultural and environmental systems. This flexibility makes wavelet analysis particularly valuable for interpreting climate–crop interactions, soil moisture oscillations, hydrological variability, pest and disease cycles, and remote sensing datasets.

The increasing integration of wavelets with GIS, machine learning, and satellite imagery enhances their analytical power, enabling more accurate drought assessments, crop yield forecasts, and environmental monitoring. These capabilities directly support climate-smart agriculture, early warning systems, and long-term sustainability planning. As agricultural challenges such as climate variability, extreme weather events, and resource scarcity intensify, wavelet analysis offers a methodological framework capable of capturing the nonlinear, multi-temporal dynamics at the heart of these issues.

Overall, the application of wavelet analysis in agricultural studies not only improves data interpretation but also strengthens evidence-based decision making for researchers, practitioners, and policymakers. Continued development of hybrid wavelet approaches and their integration with modern sensing technologies will further expand opportunities for innovation in precision agriculture and environmental monitoring.

Thanks to these methods, used for the first time in agricultural sciences, more accurate decisions are expected to be made. Furthermore, it is thought that the study will shed light on other researchers for the further development of the hybrid models created. Increasing applied studies in this direction would be beneficial.

6. References

1. **Adams, J., Smith, L., & Kwon, H**. (2019). *Wavelet-based analysis of crop stress using multispectral UAV data. Agricultural Remote Sensing Journal,* 12(3), 145–158.
2. **Adamowski, J., Chan, H. F.** (2011). *A wavelet neural network conjunction model for groundwater level forecasting. Journal of Hydrology, 4*07(1–4), 28–40.
3. **Allen, R. L., and Mills ,D. W.** (2004). *Signal analysis: Time, frequency, scale ans structure, IEEE Pres,* p: 712-730.
4. **Akbulut, U., and Aslan, Z**. (2022*). Optimization of the Use and Planning of Water Resources with Advanced Data Processing Methods, Aksaray University Journal of Science and Engineering,* 6(2), 79-94, Aksaray, Türkiye.

5. **Banerjee, S., Patel, N., & Mohanty, B.** (2021). *Time–frequency methods for agricultural drought monitoring. Environmental Modelling & Software,* 140, 105028.
6. **Başakın, E.E., Ekmekçioğlu, Ö., Özger, M., and Çelik, A.** (2020), *Dalgacık Bulanık Zaman Serisi Yöntemi ve Gri Tahmin Yöntemi ile Türkiye Buğday Verimi Tahmini (Forecasting Turkey's Wheat Yield Using the Wavelet Fuzzy Time Series Method and Grey Prediction Method) , Türkiye Tarımsal Araştırmalar Dergisi (Turkish Journal of Agricultural Research) ,* 7(3):246-252, Siirt Üniversitesi Yayınları, Siirt, Türkiye.
7. **Cazelles, B., Chavez, M., Berteaux, D., et al.** (2008). *Wavelet analysis of ecological time series. Oecologia,* 156, 287–304.
8. **Chen, V. C., and Ling, H.** (2002), *Time-frequency transforms for radar imaging ans signal analysis, Atrech House*, p: 29.
9. **Daubechies, I.** (1990). *The wavelet transform, time–frequency localization and signal analysis. IEEE Transactions on Information Theory*, 36(5), 961–1005.
10. **Dökmen, F., and Aslan, Z.** (2013*). Evaluation of the Parameters of Water Quality with Wavelet Techniques,* 27(14), 4977-4988.
11. **Dökmen, F., and Aslan, Z.** (2020). *Evaluation of Oxygen Demand in Water Resources with Wavelet Modelling* , 29, 10078-10087.
12. **Dökmen, F., Tokgözlü, A., and Aslan, Z.** (2023). *Using of Wavelet Modell for Standardized Precipitation Index Analyses in Drought Evaluation, Fresenius Environmental Bulltei*n, 32(10), 3074-3080.
13. **Deniz, O., Ahi, Y., Aslan, Z., Dökmen, F., and Orta, H**. (2025). *An Analysis of Quality Parameters Changes in Agricultural Water Systems with Wavelet: Transform Model, Water,* 17, 662.
14. **Grinsted, A., Moore, J. C., Jevrejeva, S**. (2004). *Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics,* 11, 561–566.
15. **Labat, D**. (2005). *Wavelet analysis of hydrological signals. Water Resources Research,* 41(1), W01001.
16. **Labat, D**. (2005). *Recent advances in wavelet analyses: Part 1 – A review of concepts. Journal of Hydrology*, 314(1–4), 275–288.
17. **Lu, H., Zhang, M., & Guo, B**. (2017). *Wavelet analysis of NDVI time series for vegetation dynamics detection. Remote Sensing*, 9(3), 241.
18. **Mallat, S**. (1999). *A Wavelet Tour of Signal Processing. Academic Press.*
19. **Mishra, A. K., Singh, V. P.** (2010). *A review of drought concepts. Journal of Hydrology, 391(1–2), 202–216.*
20. **Nalley, L., Griffin, T. W., & Bushong, J.** (2016). *The application of wavelet analysis in agricultural economics. Agricultural Economics,* 47(4), 447–457.
21. **Partal, T., & Küçük, M.** (2006). *Long-term trend analysis using discrete wavelet components of precipitation records in Turkey. Theoretical and Applied Climatology,* 90, 155–160.
22. **Torrence, C., & Compo, G**. (1998). *A practical guide to wavelet analysis. Bulletin of the American Meteorological Society,* 79(1), 61–78.
23. **Zhang, Q., Xu, C.-Y., Becker, S.** (2006). *Wavelet-based analysis of precipitation variability in China. International Journal of Climatology,* 26(15), 219–231.