SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Relationship between soil chemical properties and rice yield under multiple stresses in the coastal agricultural land of Pangandaran, Indonesia

Nasrudin[1], Budiastuti Kurniasih[1]*, Eka Tarwaca Susila Putra[1], Eko Hanudin[2], Elisa Azura Azman[3]

[1] Department of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia
[2] Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia
[3] Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, Malaysia

ARTICLE INFO

Keywords:
Coastal land;
Rice productivity;
Salinity;
Soil properties;
Waterlogging;

Article history
Submitted: 2024-09-18
Revised: 2024-12-10
Accepted: 2024-12-19
Available online: 2025-01-17
Published regularly: June 2025

* *Corresponding Author*
Email address:
tuti_b@ugm.ac.id

ABSTRACT

Seawater intrusion causes salinity and waterlogging in the coastal agricultural land of Pangandaran, Indonesia. Both limiting factors cause a decrease in soil chemical properties. The decline in rice yield occurred due to the low soil chemical properties. The study aims to identify the soil's chemical properties based on limiting factors and to reveal its relationship with rice productivity in the coastal agricultural land of Pangandaran. Soil sampling was conducted using a purposive sampling method, and the samples were analyzed in the laboratory. Various soil properties are grouped into three clusters using hierarchical clustering. The cluster of waterlogging high salinity has very high Na-exchangeable with EC ranging from 0.21 - 4.93 dS m^{-1}, while the other two clusters contain high Na-exchangeable and EC ranging from 0.101 - 0.581 dS m^{-1}. Rice productivity under waterlogging-low salinity is <1 t ha^{-1}, no waterlogging-low salinity is 3.63 t ha^{-1}, and waterlogging-high salinity is 2.48 t ha^{-1}. There are negative correlations between Na-exchangeable, water depth, and duration of waterlogging to rice yield (R^2= -0.33; R^2= -0.58; R^2= -0.90). Multiple stresses cause limiting factors, and low soil chemical properties can inhibit plant development. The presence of waterlogging-low salinity has a strong impact on decreasing rice yield. Finally, our study provides an overview of the coastal agricultural land of Pangandaran based on multiple stresses. Furthermore, improved soil properties are needed with good management techniques to make it suitable for rice cultivation.

How to Cite: Nasrudin, N., Kurniasih, B., Putra, E.T.S., Hanudin, E., Azman, E.A. (2025). Relationship between soil chemical properties and rice yield under multiple stresses in the coastal agricultural land of Pangandaran, Indonesia. Sains Tanah Journal of Soil Science and Agroclimatology, 22(1): 12-22. https://doi.org/10.20961/stjssa.v22i1.98275

1. INTRODUCTION

The coastal agricultural land has many limiting factors, but it has the potential to be used in rice cultivation due to an area of 954.39 million hectares worldwide (Tang et al., 2023). Generally, it has low organic matter (Jia et al., 2024), as well as low nutrient content and cation exchange capacity (CEC) (Andrade et al., 2020). In addition, the coastal agricultural land has a high salt concentration and increased electrical conductivity (EC), low water retention capacity, and poor soil structure (Zhang et al., 2024). Furthermore, the proximity of the land to the sea allows sea-water intrusion to occur, causing puddles or floods and impacting reduced soil respiration (Li et al., 2022), and low soil microorganism activity (Helton et al., 2019). This condition will be a stress for plants, affecting a decrease in growth and yields reaching 18-40% (Zhang et al., 2022).

Pangandaran is one of the regencies in West Java, located in the southern coastal area. Based on data from BPS (2023), Pangandaran has the potential for rice production with a harvest area of 30.521 hectares. Nevertheless, most agricultural land has multiple stress constraints due to its location close to the coast. One of the villages, namely Karangjaladri, has at least 109 hectares and is located at a distance of 0.1 - 0.7 m from the coast, which often causes growth disorders and crop failure. Two stresses that occur on this agricultural land are salinity and waterlogging. Salinity is a condition of soil and water with a high salt content that causes an EC value of > 4 dS m^{-1} (FAO, 2018). Xiaoqin et al. (2021) stated that salinity causes a decrease in the hydraulic system, soil productivity, and organic matter content. Salinity in the soil is influenced by various factors such as agricultural

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v22i1.98275

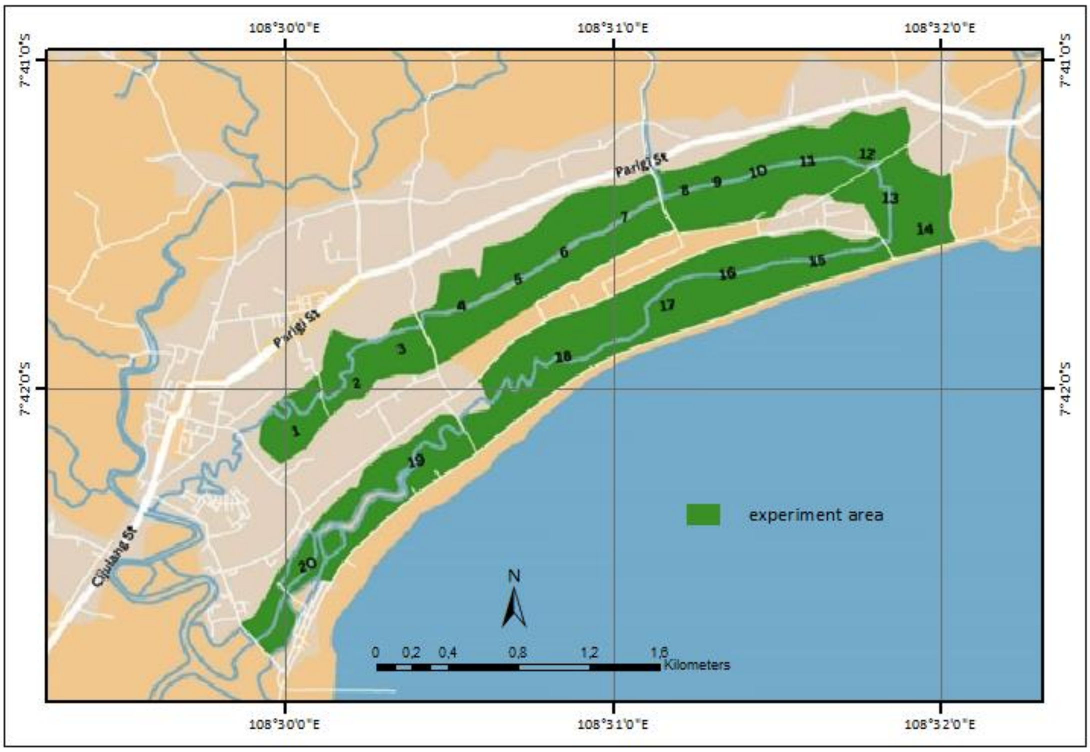

Figure 1. Study site in Karangjaladri Village, Parigi District, Pangandaran, Indonesia

land vegetation, topography, climate, and sea tides (Ibarra-Villarreal et al., 2021). Salinity can be a limiting factor and will decrease rice production by more than 65% (Shafi et al., 2013).

Waterlogging in plants is the situation when soil becomes saturated with water, leading to an environment with reduced O_2 or a complete lack of O_2 (Lin et al., 2024). This condition typically occurs in poorly drained soils, after heavy rainfall, or due to flooding. Furthermore, flooding and waterlogging on the agricultural land have a depth of more than 1 m. This condition causes the soil to contain low O_2 (hypoxia) (Panda & Barik, 2021), soil compaction, and poor drainage (Ploschuk et al., 2018). Limited O_2 and high water volume can reduce rice yield (Anshori et al., 2023) due to low light interception, low soil respiration, and failure to grow optimally (Yang et al., 2017). Yamauchi et al. (2017) stated that limited O_2 in the soil due to waterlogging will have an impact on Potassium deficiency and affect the decline in root development, as well as limited gas diffusion and Nitrogen deficiency, which contribute to rice crop failure (Kim et al., 2024).

In coastal agricultural land, the presence of organic matter in the soil is crucial, affecting the soil respiration rate (Miao et al., 2017). Moreover, soil respiration is influenced by the availability of nutrients, especially Nitrogen, temperature, and humidity (He et al., 2024). Generally, coastal soils have low fertility with a sandy texture, low potential hydrogen (pH), low C-organic, and high Al-exchangeable (Sigua et al., 2016). These conditions will be a limiting factor in soil fertility and impact reduced rice productivity (Tian et al., 2024). Sea tides often occur in coastal agricultural areas, and they can cause multiple stresses for plants. Flooding and waterlogging due to sea-water intrusion affect soil compaction, decrease Potassium, and increase Sodium in the soil (Kumar et al., 2021). Several studies have revealed that salinity and waterlogging will reduce rice production (Fukao et al., 2019; Win et al., 2022). Nasrudin and Kurniasih (2021) reported that the rice planted under the water depth of coastal areas can reduce photosynthetic rate, increase proline content, and decrease rice yield. However, the study reveals that rice production under multiple stress conditions is still limited.

The chemical soil properties are crucial ways to support paddy cultivation in coastal agricultural land with abiotic stresses such as salinity and waterlogging. Therefore, at present, we are studying the chemical soil properties of soil under multiple stress conditions. As we know, coastal agricultural land allows for waterlogging with low salinity, no waterlogging with low salinity, and waterlogging with high salinity. Three multiple stresses certainly have different soil chemical properties and will affect rice production. Soil chemical properties evaluation under three multiple stress conditions is needed for information mitigation strategies to produce optimal rice yield. Previous studies have not thoroughly investigated the relationship between soil chemical properties and rice production under multiple stress conditions. Additionally, the absence of similar studies focused on the coastal agricultural land of Pangandaran underscores the significance of this study. We hypothesize that soil chemical properties are affected by multiple stresses in coastal agricultural land, and these conditions will also produce different rice yields. The study aims to identify the soil's chemical properties based on limiting factors and to reveal its relationship with rice productivity in the coastal agricultural land of Pangandaran.

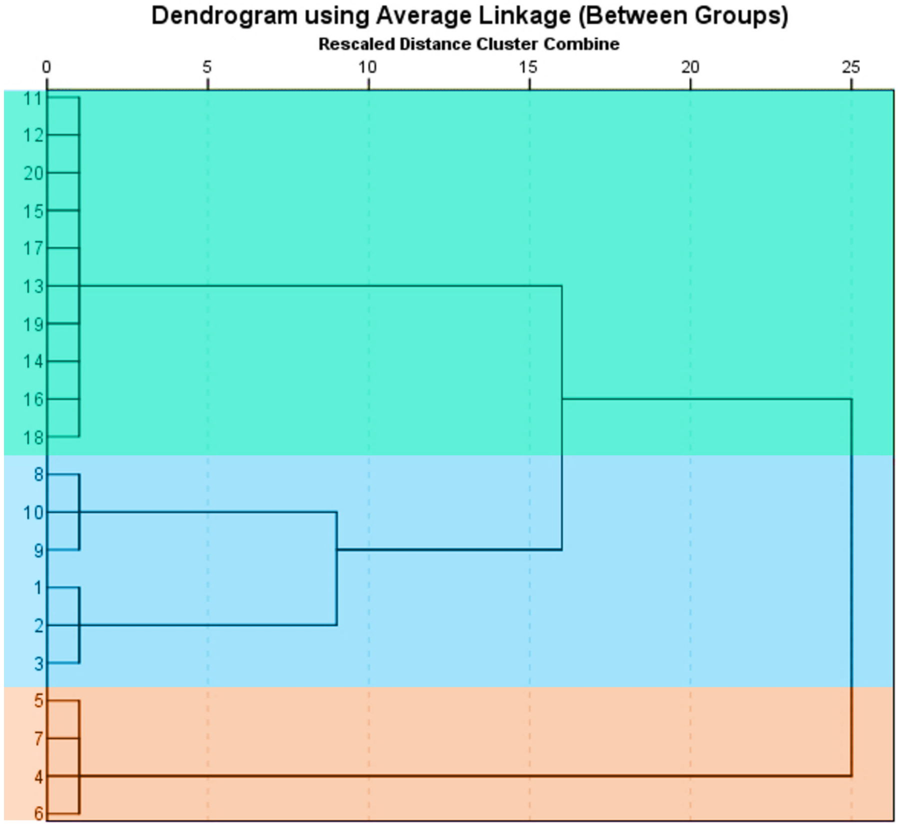

Figure 2. Dendrograms of hierarchical clustering in the study site

2. MATERIAL AND METHODS

The study was conducted from August until December 2023 in the coastal agricultural land of Pangandaran, located in Karangjaladri Village Parigi District (Figure 1). The land used in this study was 109 hectares, and the distance from the coast was between 0.1 - 0.7 km.

General information about agricultural land conditions used in this study is in Table 1. The classification of the study site is lowland (0 - 50 msl) with a land area of 109 hectares. Various limiting factors are due to sea tides close to the coast causing salinity and waterlogging. Based on some information about climate conditions, the agricultural area has an average monthly rainfall of low to high. (BMKG, 2023) records that average monthly rainfall is categorized as low at 0 - 100 mm and as high at 300 - 500 mm.

Land clustering analysis was based on purposive sampling and then continued by dividing it into 20 plots. The division of plots used the method by FAO (2020); each plot covers an area ranging from 5 – 7 hectares. Furthermore, clustering is done using data from the direct observation method, namely by measuring Electrical conductivity (EC) water and soil, water level, and duration of waterlogging. The EC measurements were analyzed using the HANNA HI 98304 EC meter. The water level measurement was determined using a tape measure, and the information about the duration of waterlogging was collected by interviews with farmers. Based on the clustering analysis, three clusters were obtained, namely waterlogging-low salinity (plots of 4, 5, 6, and 7), no waterlogging-low salinity (plots of 1, 2, 3, 8, 9, and 10), and waterlogging-high salinity (plots of 11 until 20), as shown in the dendrogram in Figure 2.

Further, soil samples were taken at each plot in a composite manner using five locations of diagonal sampling. The soil was cleaned by weeds and taken using a hoe with a depth of 0 - 20 cm (topsoil), as much as 1 kg, respectively, then composited and put into a plastic bag. Collects the soil sample information, including the sampling date, soil code, and plot coordinates. Then, soil samples were analyzed in the soil science laboratory of the Agricultural Instruments Standardization Agency of Yogyakarta. Interviews using the questionnaire method were conducted to collect information about rice cultivation and rice productivity aspects in each plot.

The soil chemical properties variables observed include N-total (%) using the Kjeldahl method, P_2O_5 (ppm) using the Bray method, cation exchange capacity (CEC) (cmol kg^{-1}), Na-exchangeable (cmol kg^{-1}), K-exchangeable (cmol kg^{-1}), Mg-exchangeable (cmol kg^{-1}), and Ca-exchangeable (cmol kg^{-1}) using the DTPA extraction method, and exchangeable sodium percentage (%) using the same method of Seilsepour et al. (2009), and dissolved oxygen (mg L^{-1}) using the dissolved oxygen analyzer DO9100.

The clustering analysis uses the hierarchical clustering method and Pearson correlation to determine the relationship between soil chemical properties and rice productivity. The data are presented in the form of tables and dendrograms. The data analysis was performed using R Studio software version 4.1.3, Statistical Tools for Agricultural Research version 2.0.1, and Microsoft Excel.

Table 1. General condition of the study site

Indicators	Details
Location	Karangjaladri Village, Parigi District, Pangandaran Regency, West Java
Altitude	0-50 meters above sea level
Distance from the coast	± 0.1 - 0.7 km
Average rainfall	80 - 400 mm month^{-1}
Average temperature	25 - 26 °C
Land area	109 hectars

3. RESULTS

3.1. Rice Cultivation Aspects and Limiting Factors in The Three Clusters

Based on the interviews with farmers in the three clusters, we get some information about rice cultivation activities (Table 2). Generally, in clusters 1, 2, and 3, farmers cultivate rice on land of less than 1 hectare. The land type is rice fields, and the varieties used are Maros and Mawar, respectively. Farmers obtained rice seeds from the stores, and then the seeds were sowed using the dry land method. Usually, farmers do not add organic matter during soil processing and only use NPK 15:15:15 and urea fertilizers for plant nutrients.

The land used in cultivation activities has a type of irrigation, namely the presence of a river that flows into the sea so that it is affected by tidal activity. This condition causes water to enter cluster 1 with poor drainage, causing waterlogging with a depth of up to 1.5 m. In cluster 2, we found this land passed by sea water from tidal activity. Proximity to the estuary and some located in the part after the barrier causes no waterlogging and the impact of low salinity. Furthermore, cluster 3 has two limiting factors, namely waterlogging and salinity, which are close to the coast (0.1 km).

Based on direct observation of several limiting factors, EC water and soil in clusters 1 and 2 were classified as non-saline, whereas cluster 3 classified them as slightly saline - moderately saline. The categories made by FAO (2018), which group salinity based on EC values including 0 - 2 dS m^{-1} (non-saline), 2 - 4 dS m^{-1} (slightly saline), 4 - 8 dS m^{-1} (moderately saline), and 8 - 16 dS m^{-1} (strongly saline). Other limiting factors on land in the three clusters are the depth and duration of waterlogging. Based on the observations, the water depth in cluster 1 has the potential to reach 1.5 m for 336 hours, cluster 2 can reach 1 m with a duration of 0 - 48 hours, and in cluster 3, the water depth reaches 0.5 m for 168 hours. These various limiting factors affect the rice yield obtained by farmers. The data shows that the average rice yield in cluster 1 is < 1 t ha^{-1}, cluster 2 is 3.63 t ha^{-1}, and cluster 3 is 2.48 t ha^{-1}.

3.2. Soil Chemical Properties

Soil chemical properties can support rice growth and production (Suntoro et al., 2024). Soil with low chemical quality affects plants not being supplied with their nutritional needs, which causes a decrease in rice yield or crop failure (Rendana et al., 2021). The analysis showed that the soil chemical properties in the three clusters are present in Table 3. In the waterlogging-low salinity cluster, the average pH was 6.08, the average N-total was 0.26%, and the average P_2O_5 was 12.37 ppm. Furthermore, the average exchangeable cations of K, Na, Mg, and Ca were 1.09 cmol kg^{-1}, 9.13 cmol kg^{-1}, 3.61 cmol kg^{-1}, and 2.43 cmol kg^{-1}, respectively. The exchangeable cations affect the CEC as an indicator of soil fertility that can provide essential nutrients for plants such as K, Mg, and Ca (Sasongko et al., 2022). The results showed that the average CEC was 23.55 cmol kg^{-1} and the average Exchangeable Sodium Percentage (ESP) was 41.30 cmol kg^{-1}.

In the waterlogging-low salinity cluster, the average pH was 5.88, the average N-total was 0.31%, and the average P_2O_5 was 9.11 ppm. Furthermore, in the value of exchangeable cations, the average K, Na, Mg, and Ca were 2.10 cmol kg^{-1}, 7.83 cmol kg^{-1}, 3.31 cmol kg^{-1}, and 2.63 cmol kg^{-1}, respectively. These conditions affect the average CEC and ESP, which were 25.20 cmol kg^{-1} and 30.73 cmol kg^{-1}, respectively.

In the waterlogging-high salinity cluster that often causes crop failure, the average pH was 5.88, the average N-total was 0.50, and the average P_2O_5 was 9.28. Additionally, the average concentrations of exchangeable cations in the soil were 1.85 cmol kg^{-1} for K, 15.65 cmol kg^{-1} for Na, 3.14 cmol kg^{-1} for Mg, and 2.96 cmol kg^{-1} for Ca. These conditions affect the average CEC and ESP, which were 20.64 cmol kg^{-1} and 74.24 cmol kg^{-1}, respectively.

3.3. Correlation among rice yield to soil chemical properties and limiting factors in the three clusters

Correlation analysis to reveal the relationship between rice yield and soil chemical properties and limiting factors (Table 4). The study results illustrate that the high Na-exchangeable is positively correlated to EC water (R^2= 0.80) and EC soil (R^2= 0.76), which indicates that the increase in Na-exchangeable causes an increase in EC water and soil. Additionally, Na- exchangeable negatively correlated to Mg-exchangeable (R^2= -0.57) and rice yield (R^2= -0.33), which illustrates that the increase in Na causes a decrease in Mg and rice yield.

Furthermore, water depth negatively correlated to EC water (R^2= -0.42), EC soil (R^2= -0.36), dissolved oxygen (R^2= -0.93), and Ca-exchangeable (R^2= -0.31). This condition indicates that water depth causes a decrease in the EC water and soil, dissolved oxygen, and Ca-exchangeable. Based on the data, water depth causes an increase in the duration of waterlogging (R^2= 0.68) but causes a decrease in K-exchangeable (R^2= -0.35). Hence, water stress also has an impact on decreasing rice yield. This condition is illustrated by the water deeper with a longer duration negatively correlated (R^2= -0.58) and (R^2= -0.90), respectively.

4. DISCUSSION

The existence of limiting factors on agricultural land will affect the condition of soil chemical properties and rice yield. Based on the clustering analysis, we found three clusters, i.e.

Table 2. Information on rice cultivation aspects and limiting factors in the three clusters' area

Indicators	Cluster 1 (waterlogging-low salinity)	Cluster 2 (no waterlogging-low salinity)	Cluster 3 (waterlogging-high salinity)
Average land by farmers	< 1 ha	< 1 ha	< 1 ha
Types of irrigation	Path of tidal river	Path of tidal river	Path of tidal river
Limiting factors	Flooding due to poor drainage and water level can reach 1.5 m	Path of low drainage and potentially passable by tidal swamp	High salinity and pools of seawater with depths up to 0.5 m
EC water (dS m^{-1})	0.250 - 0.580	0.250 - 0.980	0.680 - 5.590
EC soil (dS m^{-1})	0.126 - 0.212	0.102 - 0.528	0.112 - 4.930
Water level (m)	1.5	1	0.5
Duration of waterlogging (hours)	336	0 - 48	168
Dissolved oxygen (mg L^{-1})	0.70 - 1.20	2.10 - 8.00	5.10 - 8.50
Varieties	Maros dan Mawar	Mawar	Maros dan Mawar
Sowing process	Sowing on land area	Sowing on land area	Sowing on land area
Types of fertilizer	NPK 15:15:15 and urea	NPK 15:15:15 and urea	NPK 15:15:15 and urea
Rice yield (t ha^{-1})	< 1	3.63	2.48

Remarks: Data were collected through interviews with farmers in each cluster using a questionnaire method. Additionally, data on various indicators, including EC in the water and soil, water level, duration of waterlogging, and dissolved oxygen, were obtained through direct field observation.

waterlogging-low salinity, no waterlogging-low salinity, and waterlogging-high salinity. The limiting factors on the agricultural land include land crossed by tidal rivers, poor drainage, and strong wind. Velmurugan et al. (2016) stated that land close to the sea has the potential to experience waterlogging and salinity influenced by seawater intrusion.

The data shows that all plots in cluster 1 are affected by seawater intrusion into the land, and the position of the land is lower than the river flow (Table 2). This condition makes it difficult for water to exit the land so that the water depth can reach 1.5 m with a duration of 336 hours. The agricultural land condition is lower than the river and has a great potential to experience flooding and disadvantages in rice production (Fan et al., 2024). Water depth causes a limited O_2 in the soil and affects low soil respiration (Pampana et al., 2016). Based on the value of dissolved oxygen (DO) in cluster 1 being in the range of 0.70 - 1.20 mg L^{-1}. The condition is also in line with the correlation analysis in Table 4, which illustrates that increasing water depth and duration of waterlogging impact decreasing DO. Ali et al. (2022) stated that DO with a value of less than 2 mg L^{-1} is classified as heavily polluted. Water depth and duration of waterlogging also influence the EC soil between 0.126 - 0.212 dS m^{-1} and EC water between 0.250 - 0.580 dS m^{-1}. This value belongs to non-saline soil (P. Kumar et al., 2024). These conditions are caused by the leaching of salt levels, especially when rainy reasons occur. Generally, the water depth reaches 1.5 m on this land during the rainy season due to the land type belonging to rainfed rice fields. So, this land has two water sources, i.e. rainwater and seawater intrusion.

Rice yield on cluster 1 only produces <1 t ha^{-1}. Waterlogging with a long duration causes a low rice yield and affects the low Ca-exchangeable. Naz et al. (2024) reported that low Ca will cause root dysfunction due to toxins in the soil. Root dysfunction due to that obstacle and limited O_2 in the soil will make it difficult for plants to absorb nutrients that support their growth and production (Basu et al., 2020). This condition describes the CEC value as moderate, indicating that the soil's ability to provide essential nutrients such as Mg, Ca, and K cannot be optimal. Additionally, waterlogging will worsen the conditions for plants to grow, such as the activation of the chlorophyllase enzyme, which degrades chlorophyll (Biswajit et al., 2017), accumulation of reactive oxygen species (ROS), and decreased antioxidants (Foyer, 2018). Furthermore, based on the study by S. Kumar et al. (2024) reported that waterlogging for a long time and in-depth has the potential to reduce pollen viability, which causes low rice yields.

In cluster 2, there is multiple stress in the form of no waterlogging-low salinity. This cluster causes seawater intrusion into several plots close to the water inlet, but the receding process is relatively faster. Data shows that water ingress can reach 1 m, but the duration of waterlogging is fast moving to recede, namely 0 - 48 hours. The salt content in water and soil is relatively low (P. Kumar et al., 2024), which ranges from 0.250 - 0.980 dS m^{-1} and 0.102 - 0.528 dS m^{-1}, respectively.

Due to these limiting factors, the soil's content of N-total and P_2O_5 belongs to the medium. We predict this cluster has slight obstacles like waterlogging and/or salinity. The content of N-total will affect the vegetative growth of rice plants (Rossatto et al., 2023), while the presence of Na-exchangeable causes an impact on the availability of limited P_2O_5. It will reduce the energy in the form of Adenosine triphosphate (ATP) (Waani et al., 2021). Additionally, in the soil of cluster 2, Ca-exchangeable also becomes limited due to osmotic stress (Cheng et al., 2023). According to the correlation analysis between Ca and water depth (R^2= -0.31). This process will impact the ability of plants to absorb nutrients and root function disorders (Peduzzi et al., 2024). Therefore, the average rice yield obtained in this cluster tends to be 3.63 t ha^{-1}.

Table 3. Soil chemical properties and rice yield in three clusters area

Plot	pH	N-total (%)	P_2O_5 (ppm)	K-exchangeable (cmol kg^{-1})	Na-exchangeable (cmol kg^{-1})	Mg-exchangeable (cmol kg^{-1})	Ca-exchangeable (cmol kg^{-1})	CEC (cmol kg^{-1})	ESP (%)	Rice yield (t ha^{-1})
Cluster 1 (waterlogging-low salinity)										
4	5.78^{SA}	0.24^{M}	1.03^{VL}	0.77^{H}	9.13^{VH}	3.42^{H}	2.30^{L}	28.00^{H}	32.61^{VH}	< 1.00
5	6.12^{SA}	0.32^{M}	21.65^{VH}	1.28^{VH}	9.57^{VH}	3.75^{H}	2.15^{L}	31.00^{H}	30.86^{VH}	< 1.00
6	6.13^{SA}	0.19^{L}	5.15^{L}	1.03^{VH}	9.13^{VH}	3.67^{H}	2.55^{L}	19.00^{M}	48.06^{VH}	< 1.00
7	6.30^{SA}	0.29^{M}	21.65^{VH}	1.28^{VH}	8.70^{VH}	3.58^{H}	2.70^{L}	16.20^{M}	53.68^{VH}	< 1.00
Average	**6.08^{SA}**	**0.26^{M}**	**12.37^{H}**	**1.09^{VH}**	**9.13^{VH}**	**3.61^{H}**	**2.43^{L}**	**23.55^{M}**	**41.30^{VH}**	**< 1.00**
Cluster 2 (no waterlogging-low salinity)										
1	5.28^{A}	0.21^{M}	2.06^{VL}	3.59^{VH}	10.43^{VH}	3.33^{H}	2.65^{L}	24.00^{M}	43.48^{VH}	3.20
2	5.19^{A}	0.21^{M}	3.09^{VL}	3.33^{VH}	3.04^{VH}	3.42^{H}	2.65^{L}	18.70^{M}	16.28^{VH}	4.00
3	5.85^{SA}	0.23^{M}	3.09^{VL}	0.77^{H}	8.26^{VH}	3.42^{H}	1.90^{VL}	30.00^{H}	27.54^{VH}	4.00
8	6.97^{N}	0.53^{H}	20.62^{VH}	2.31^{VH}	8.26^{VH}	3.58^{H}	3.90^{L}	29.20^{H}	28.29^{VH}	3.80
9	5.95^{SA}	0.28^{M}	15.46^{VH}	1.54^{VH}	8.26^{VH}	3.33^{H}	2.00^{L}	24.60^{M}	33.58^{VH}	3.50
10	6.06^{SA}	0.39^{M}	10.31^{M}	1.03^{VH}	8.70^{VH}	2.75^{H}	2.65^{L}	24.70^{M}	35.21^{VH}	3.30
Average	**5.88^{SA}**	**0.31^{M}**	**9.11^{M}**	**2.10^{VH}**	**7.83^{VH}**	**3.31^{H}**	**2.63^{L}**	**25.20^{H}**	**30.73^{VH}**	**3.63**
Cluster 3 (waterlogging-high salinity)										
11	6.13^{SA}	0.46^{M}	7.22^{L}	1.54^{VH}	10.43^{VH}	2.92^{H}	2.45^{L}	19.50^{M}	53.51^{VH}	2.80
12	6.28^{SA}	0.36^{M}	2.06^{VL}	1.03^{VH}	9.57^{VH}	3.00^{H}	2.80^{L}	25.40^{H}	37.66^{VH}	2.80
13	6.11^{SA}	0.37^{M}	15.46^{VH}	1.54^{VH}	5.22^{VH}	3.67^{H}	3.10^{L}	22.80^{M}	22.88^{VH}	2.80
14	5.98^{SA}	0.34^{M}	15.46^{VH}	2.82^{VH}	22.61^{VH}	3.00^{H}	3.10^{L}	23.50^{M}	96.21^{VH}	2.00
15	5.97^{SA}	0.35^{M}	23.71^{VH}	2.56^{VH}	21.30^{VH}	2.92^{H}	2.90^{L}	23.40^{M}	91.04^{VH}	2.00
16	5.76^{SA}	0.40^{M}	5.15^{L}	2.56^{VH}	38.70^{VH}	2.67^{H}	5.10^{L}	24.40^{M}	158.59^{VH}	2.00
17	6.01^{SA}	2.09^{VH}	1.03^{VL}	1.28^{VH}	13.04^{VH}	2.50^{H}	2.90^{L}	20.30^{M}	64.25^{VH}	2.00
18	5.73^{SA}	0.41^{M}	11.34^{H}	2.82^{VH}	20.43^{VH}	3.00^{H}	2.55^{L}	22.00^{M}	92.89^{VH}	2.00
19	5.52^{SA}	0.10^{L}	2.06^{VL}	1.54^{VH}	7.83^{VH}	3.50^{H}	2.65^{L}	15.00^{L}	52.17^{VH}	3.20
20	5.34^{A}	0.15^{L}	9.28^{M}	0.77^{H}	7.39^{VH}	4.25^{H}	2.00^{L}	10.10^{L}	73.18^{VH}	3.20
Average	**5.88^{SA}**	**0.50^{M}**	**9.28^{M}**	**1.85^{VH}**	**15.65^{VH}**	**3.14^{H}**	**2.96^{L}**	**20.64^{M}**	**74.24^{VH}**	**2.48**

Remarks: A (Acidic); SA (slightly acid); N (neutral); VL (very low); L (low); M (medium); H (high); VH (very high). The soil criteria are based on Eviati et al. (2023).

Table 4. Pearson correlation among soil chemical properties, limiting factors, and rice yield

Parameters	EC-W	EC-S	pH	N	P	Na	K	Mg	Ca	CEC	WD	D-W	DO	RY
EC-W	1^{**}	0.95^{**}	-0.16^{ns}	0.23^{ns}	-0.01^{ns}	0.80^{**}	0.47^{*}	-0.51^{**}	0.59^{**}	-0.08^{ns}	-0.42^{*}	-0.01^{ns}	0.30^{*}	-0.17^{ns}
EC-S		1^{**}	-0.17^{ns}	0.37^{*}	-0.002^{ns}	0.76^{**}	0.41^{*}	-0.53^{**}	0.58^{**}	-0.09^{ns}	-0.36^{*}	0.04^{ns}	0.27^{*}	-0.21^{ns}
pH			1^{**}	0.23^{ns}	0.514^{ns}	-0.02^{ns}	-0.29^{*}	-0.10^{ns}	0.26^{*}	0.42^{*}	-0.09^{ns}	0.09^{ns}	0.05^{ns}	-0.19^{ns}
N				1^{**}	-0.14^{ns}	0.12^{ns}	-0.08^{ns}	-0.54^{**}	0.18^{ns}	0.02^{ns}	-0.24^{ns}	-0.03^{ns}	0.10^{ns}	-0.12^{ns}
P					1^{**}	0.08^{ns}	0.10^{ns}	0.20^{ns}	0.07^{ns}	0.16^{ns}	-0.06^{ns}	0.09^{ns}	0.09^{ns}	-0.21^{ns}
Na						1^{**}	0.39^{*}	-0.57^{**}	0.68^{**}	0.13^{ns}	-0.24^{ns}	0.09^{ns}	0.14^{ns}	-0.33^{*}
K							1^{**}	-0.26^{*}	0.42^{*}	0.04^{ns}	-0.19^{ns}	-0.35^{*}	0.19^{ns}	0.19^{ns}
Mg								1^{**}	-0.41^{*}	-0.24^{ns}	0.41^{*}	0.23^{ns}	-0.25^{*}	0.05^{ns}
Ca									1^{**}	0.13^{ns}	-0.31^{*}	-0.09^{ns}	0.29^{*}	-0.06^{ns}
CEC										1^{**}	0.09^{ns}	-0.16^{ns}	-0.15^{ns}	-0.012^{ns}
WD											1^{**}	0.68^{**}	-0.93^{**}	-0.58^{**}
D-W												1^{**}	-0.61^{**}	-0.90^{**}
DO													1^{**}	0.54^{**}
RY														1^{**}

Remarks: ns: not significant, *: significant at α 5%, **: significant at α 1%, EC-W: electrical conductivity in the water, EC-S: electrical conductivity in the soil, pH: potential hydrogen, N: N-total, P: P2O5, Na: Na-exchangeable, K: K-exchangeable, Mg: Mg-exchangeable, Ca: Ca-exchangeable, CEC: cation exchange capacity, WD: water depth, D-W: duration of waterlogging, DO: dissolved oxygen; RY: rice yield

Furthermore, multiple stress occurs in cluster 3, namely waterlogging-high salinity. The closeness of the rice field plot in cluster 3 to the sea causes seawater seepage, and the presence of water flow from the sea in two directions causes this land to experience two stresses at once. The water depth in this plot is not too high, but the duration can reach 168 hours. Additionally, the EC values in water and soil are 0.680 - 5.590 dS m^{-1} and 0.112 - 4.930 dS m^{-1}, respectively. These values indicate the high salt content (Radanielson et al., 2018). The presence of puddles originating from seawater for a long duration causes low soil respiration (Chen et al., 2022). This condition impacts root disorders and cannot develop optimally (Loudari et al., 2022). The dual stressor will worsen to absorb the essential nutrients that support plant growth and development. As we know, in salinity and waterlogging, plants will experience ionic, osmotic, and aeration stresses (Acosta-Motos et al., 2017), which will reduce rice yield.

The various limiting factors affect other soil chemical properties. An increase in EC affects a rise in Na-exchangeable but will cause a decrease in Mg and affect plant physiological activity and chlorophyll formation (Gao et al., 2024). The decline of chlorophyll content affects the ability of plants to light interception for photosynthesis (Liu et al., 2022), so the assimilates produced will be reduced (Huanhe et al., 2024). The low assimilates cause low translocating activity to the permanent sink (Xiong, 2024), lowering the rice yield by 2.48 tons ha^{-1}.

Generally, rice fields close to the sea have the potential to experience multiple stresses. This condition will cause changes in soil chemical properties and affect the decline of rice growth and production. This study shows multiple stresses in the form of waterlogging and salinity. Waterlogging is indicated by increasing water depth for a long time and the salt content in the form of EC water-soil and Na-exchangeable. In the present study, we observed that cluster 1 faced a limiting factor in the form of prolonged waterlogging, resulting in a harvest of <1 ton ha^{-1}. In contrast, cluster 2 exhibited no apparent limiting factors, with a harvest yield of 3.63 tons ha^{-1}. In cluster 3, salinity and waterlogging become limiting factors, leading to a harvest yield of only 2.48 tons ha^{-1}. Regarding the soil's chemical properties, no significant differences were observed across the three clusters. However, certain chemical properties, such as Na and EC required a decrease, while Ca needed to be increased. Additionally, the pH tended to be acidic across all clusters.

Based on our study, the coastal agricultural land of Pangandaran has several limiting factors, including salinity and waterlogging, that contribute to fluctuations in EC values, water levels, and the duration of waterlogging. Some of these variations are attributed to seasonal influences. These conditions render certain soil properties less conducive to rice cultivation, resulting in decreased harvest yield. We recommend further study focused on enhancing soil quality through organic ameliorants. Additionally, it is crucial to implement effective strategies for managing irrigation and drainage to prevent prolonged waterlogging.

5. CONCLUSION

The coastal agricultural land of Pangandaran, covering an area of 109 hectares, is categorized into three clusters based on distinct limiting factors. Cluster 1 is characterized by waterlogging-low salinity, cluster 2 by the absence of waterlogging and low salinity, and cluster 3 by waterlogging-high salinity. The soil chemical properties across all three clusters exhibit minimal variation, with all having slightly acid pH, low Ca-exchangeable, and high Na-exchangeable. In cluster 1, prolonged waterlogging results in a harvest yield of less than 1 ton ha^{-1}. In contrast, cluster 2, which lacks significant limiting factors, produces the highest harvest yield at 3.63 tons ha^{-1}. In cluster 3, the combination of high salinity-waterlogging produces a harvest yield of 2.48 tons ha^{-1}. These findings indicate that limiting factors such as salinity and waterlogging influence soil chemical properties and significantly impact crop yield.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

Acosta-Motos, J. R., Ortuño, M. F., Bernal-Vicente, A., Diaz-Vivancos, P., Sanchez-Blanco, M. J., & Hernandez, J. A. (2017). Plant Responses to Salt Stress: Adaptive Mechanisms. *Agronomy*, *7*(1), 18. https://doi.org/10.3390/agronomy7010018

Ali, B., Anuska, & Mishra, A. (2022). Effects of dissolved oxygen concentration on freshwater fish: a review. *International Journal of Fisheries and Aquatic Studies*, *10*(4), 113-127. https://doi.org/10.22271/fish.2022.v10.i4b.2693

Andrade, R., Silva, S. H. G., Weindorf, D. C., Chakraborty, S., Faria, W. M., Mesquita, L. F., . . . Curi, N. (2020). Assessing models for prediction of some soil chemical properties from portable X-ray fluorescence (pXRF) spectrometry data in Brazilian Coastal Plains. *Geoderma*, *357*, 113957. https://doi.org/10.1016/j.geoderma.2019.113957

Anshori, M. F., Purwoko, B. S., Dewi, I. S., Suwarno, W. B., & Ardie, S. W. (2023). Systematic selection to adaptive doubled haploid rice lines under different environments of submergence screening methods. *Journal of Agriculture and Food Research*, *14*, 100775. https://doi.org/10.1016/j.jafr.2023.100775

Basu, S., Kumar, G., Kumari, N., Kumari, S., Shekhar, S., Kumar, S., & Rajwanshi, R. (2020). Reactive oxygen species and reactive nitrogen species induce lysigenous aerenchyma formation through programmed cell death in rice roots under submergence. *Environmental and Experimental Botany*, *177*, 104118. https://doi.org/10.1016/j.envexpbot.2020.104118

Biswajit, P., Sritama, K., Anindya, S., Moushree, S., & Sabyasachi, K. (2017). Breeding for submergence tolerance in rice (Oryza sativa L.) and its management for flash flood in rainfed low land area: A review.

Agricultural Reviews, *38*(02). https://doi.org/10.18805/ag.v38i02.7938

BMKG. (2023). *Prakiraan hujan bulanan*. BMKG (Meteorological, Climatological, and Geophysical Agency), Indonesia. https://www.bmkg.go.id/iklim/prakiraan-hujan-bulanan.bmkg?lang=ID

BPS. (2023). *Luas panen tanaman padi (Ha) (Hektar), 2021-2023*. Badan Pusat Statistik (BPS-Statictics Indonesia). https://jabar.bps.go.id/indicator/53/300/1/luas-panen-tanaman-padi-ha-.html

Chen, G., Bai, J., Wang, J., Liu, Z., & Cui, B. (2022). Responses of soil respiration to simulated groundwater table and salinity fluctuations in tidal freshwater, brackish and salt marshes. *Journal of Hydrology*, *612*, 128215. https://doi.org/10.1016/j.jhydrol.2022.128215

Cheng, C., Steinman, A. D., Xue, Q., Zhang, L., & Xie, L. (2023). The osmotic stress of Vallisneria natans (Lour.) Hara leaves originating from the disruption of calcium and potassium homeostasis caused by MC-LR. *Water Research*, *245*, 120575. https://doi.org/10.1016/j.watres.2023.120575

Eviati, Sulaeman, Herawaty, L., Anggria, L., Usman, Tantika, H. E., . . . Wuningrum, P. (2023). *Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air, dan Pupuk* [Technical instructions for chemical analysis of soil, plants, water, and fertilizer] (3rd ed.). Balai Pengujian Standar Instrumen Tanah dan Pupuk. Kementerian Pertanian Republik Indonesia. https://tanahpupuk.bsip.pertanian.go.id/storage/assets/uploads/publikasi/Ho07w2htwf9OzGNVgMnfb1rsJrfxzYAjN687bbNC.pdf

Fan, Y., Amgain, N. R., Rabbany, A., Manirakiza, N., Bai, X., VanWeelden, M., & Bhadha, J. H. (2024). Assessing flood-depth effects on water quality, nutrient uptake, carbon sequestration, and rice yield cultivated on Histosols. *Climate Smart Agriculture*, *1*(1), 100005. https://doi.org/10.1016/j.csag.2024.100005

FAO. (2018). *Handbook for saline soil management*. Food and Agricultural Organization the United Nations and Lomonosov Moscow State University: Rome. https://openknowledge.fao.org/handle/20.500.14283/i7318en

FAO. (2020). *Soil testing methods manual*. Food and Agriculture Organization of the United Nations: Rome. https://openknowledge.fao.org/handle/20.500.14283/ca2796en

Foyer, C. H. (2018). Reactive oxygen species, oxidative signaling and the regulation of photosynthesis. *Environmental and Experimental Botany*, *154*, 134-142. https://doi.org/10.1016/j.envexpbot.2018.05.003

Fukao, T., Barrera-Figueroa, B. E., Juntawong, P., & Peña-Castro, J. M. (2019). Submergence and Waterlogging Stress in Plants: A Review Highlighting Research Opportunities and Understudied Aspects [Review]. *Frontiers in Plant Science*, *10*. https://doi.org/10.3389/fpls.2019.00340

Gao, F., Guo, J., & Shen, Y. (2024). Advances from chlorophyll biosynthesis to photosynthetic adaptation, evolution and signaling. *Plant Stress*, *12*, 100470. https://doi.org/10.1016/j.stress.2024.100470

He, Y., Bond-Lamberty, B., Myers-Pigg, A. N., Newcomer, M. E., Ladau, J., Holmquist, J. R., . . . Falco, N. (2024). Effects of spatial variability in vegetation phenology, climate, landcover, biodiversity, topography, and soil property on soil respiration across a coastal ecosystem. *Heliyon*, *10*(9), e30470. https://doi.org/10.1016/j.heliyon.2024.e30470

Helton, A. M., Ardón, M., & Bernhardt, E. S. (2019). Hydrologic Context Alters Greenhouse Gas Feedbacks of Coastal Wetland Salinization. *Ecosystems*, *22*(5), 1108-1125. https://doi.org/10.1007/s10021-018-0325-2

Huanhe, W., Xiaoyu, G., Xiang, Z., Wang, Z., Xubin, Z., Yinglong, C., . . . Qigen, D. (2024). Grain Yield, Biomass Accumulation, and Leaf Photosynthetic Characteristics of Rice under Combined Salinity-Drought Stress. *Rice Science*, *31*(1), 118-128. https://doi.org/10.1016/j.rsci.2023.06.006

Ibarra-Villarreal, A. L., Gándara-Ledezma, A., Godoy-Flores, A. D., Herrera-Sepúlveda, A., Díaz-Rodríguez, A. M., Parra-Cota, F. I., & de los Santos-Villalobos, S. (2021). Salt-tolerant Bacillus species as a promising strategy to mitigate the salinity stress in wheat (Triticum turgidum subsp. durum). *Journal of Arid Environments*, *186*, 104399. https://doi.org/10.1016/j.jaridenv.2020.104399

Jia, P., Zhang, J., Liang, Y., Zhang, S., Jia, K., & Zhao, X. (2024). The inversion of arid-coastal cultivated soil salinity using explainable machine learning and Sentinel-2. *Ecological Indicators*, *166*, 112364. https://doi.org/10.1016/j.ecolind.2024.112364

Kim, Y.-U., Webber, H., Adiku, S. G. K., Nóia Júnior, R. d. S., Deswarte, J.-C., Asseng, S., & Ewert, F. (2024). Mechanisms and modelling approaches for excessive rainfall stress on cereals: Waterlogging, submergence, lodging, pests and diseases. *Agricultural and Forest Meteorology*, *344*, 109819. https://doi.org/10.1016/j.agrformet.2023.109819

Kumar, A., Nayak, A. K., Hanjagi, P. S., Kumari, K., S, V., Mohanty, S., . . . Panneerselvam, P. (2021). Submergence stress in rice: Adaptive mechanisms, coping strategies and future research needs. *Environmental and Experimental Botany*, *186*, 104448. https://doi.org/10.1016/j.envexpbot.2021.104448

Kumar, P., Tiwari, P., Biswas, A., & Kumar Srivastava, P. (2024). Spatio-temporal assessment of soil salinization utilizing remote sensing derivatives, and prediction modeling: Implications for sustainable development. *Geoscience Frontiers*, *15*(6), 101881. https://doi.org/10.1016/j.gsf.2024.101881

Kumar, S., Basu, S., Choudhary, A. K., Shekhar, S., Mishra, J. S., Kumar, S., . . . Kumar, G. (2024). Sequential submergence and drought induce yield loss in rice by affecting redox homeostasis and source-to-sink sugar transport. *Field Crops Research*, *310*, 109362. https://doi.org/10.1016/j.fcr.2024.109362

Li, Y.-L., Ge, Z.-M., Xie, L.-N., Li, S.-H., & Tan, L.-S. (2022). Effects of waterlogging and salinity increase on CO2 efflux in soil from coastal marshes. *Applied Soil Ecology*, *170*, 104268. https://doi.org/10.1016/j.apsoil.2021.104268

Lin, C., Zhang, Z., Shen, X., Liu, D., & Pedersen, O. (2024). Flooding-adaptive root and shoot traits in rice. *Functional Plant Biology*, *51*(1), -. https://doi.org/10.1071/FP23226

Liu, B., Zhang, X., You, X., Li, Y., Long, S., Wen, S., . . . Xu, Y. (2022). Hydrogen sulfide improves tall fescue photosynthesis response to low-light stress by regulating chlorophyll and carotenoid metabolisms. *Plant Physiology and Biochemistry*, *170*, 133-145. https://doi.org/10.1016/j.plaphy.2021.12.002

Loudari, A., Mayane, A., Naciri, R., Zeroual, Y., Colinet, G., & Oukarroum, A. (2022). Root morphological and anatomical responses to increasing phosphorus concentration of wheat plants grown under salinity. *Plant Stress*, *6*, 100121. https://doi.org/10.1016/j.stress.2022.100121

Miao, G., Noormets, A., Domec, J.-C., Fuentes, M., Trettin, C. C., Sun, G., . . . King, J. S. (2017). Hydrology and microtopography control carbon dynamics in wetlands: Implications in partitioning ecosystem respiration in a coastal plain forested wetland. *Agricultural and Forest Meteorology*, *247*, 343-355. https://doi.org/10.1016/j.agrformet.2017.08.022

Nasrudin, & Kurniasih, B. (2021). The agro-physiological characteristics of three rice varieties affected by water depth in the coastal agricultural land of Yogyakarta, Indonesia. *Biodiversitas Journal of Biological Diversity*, *22*(9). https://doi.org/10.13057/biodiv/d220907

Naz, M., Afzal, M. R., Raza, M. A., Pandey, S., Qi, S., Dai, Z., & Du, D. (2024). Calcium (Ca2+) signaling in plants: A plant stress perspective. *South African Journal of Botany*, *169*, 464-485. https://doi.org/10.1016/j.sajb.2024.04.047

Pampana, S., Masoni, A., & Arduini, I. (2016). Grain Yield of Durum Wheat as Affected by Waterlogging at Tillering. *Cereal Research Communications*, *44*(4), 706-716. https://doi.org/10.1556/0806.44.2016.026

Panda, D., & Barik, J. (2021). Flooding Tolerance in Rice: Focus on Mechanisms and Approaches. *Rice Science*, *28*(1), 43-57. https://doi.org/10.1016/j.rsci.2020.11.006

Peduzzi, A., Piacentini, D., Brasili, E., Della Rovere, F., Patriarca, A., D'Angeli, S., . . . Falasca, G. (2024). Salt stress alters root meristem definition, vascular differentiation and metabolome in Sorghum bicolor (L.) genotypes. *Environmental and Experimental Botany*, *226*, 105876. https://doi.org/10.1016/j.envexpbot.2024.105876

Ploschuk, R. A., Miralles, D. J., Colmer, T. D., Ploschuk, E. L., & Striker, G. G. (2018). Waterlogging of Winter Crops at Early and Late Stages: Impacts on Leaf Physiology, Growth and Yield [Original Research]. *Frontiers in Plant Science*, *9*. https://doi.org/10.3389/fpls.2018.01863

Radanielson, A. M., Angeles, O., Li, T., Ismail, A. M., & Gaydon, D. S. (2018). Describing the physiological responses of different rice genotypes to salt stress using sigmoid and piecewise linear functions. *Field Crops Research*, *220*, 46-56. https://doi.org/10.1016/j.fcr.2017.05.001

Rendana, M., Idris, W. M. R., Abdul Rahim, S., Ali Rahman, Z., & Lihan, T. (2021). Characterization of physical, chemical and microstructure properties in the soft clay soil of the paddy field area. *Sains Tanah - Journal of Soil Science and Agroclimatology*, *18*(1), 8. https://doi.org/10.20961/stjssa.v18i1.50489

Rossatto, T., Souza, G. M., do Amaral, M. N., Auler, P. A., Pérez-Alonso, M.-M., Pollmann, S., & Braga, E. J. B. (2023). Cross-stress memory: Salt priming at vegetative growth stages improves tolerance to drought stress during grain-filling in rice plants. *Environmental and Experimental Botany*, *206*, 105187. https://doi.org/10.1016/j.envexpbot.2022.105187

Sasongko, P. E., Purwanto, P., Dewi, W. S., & Hidayat, R. (2022). Assessment of soil fertility using the soil fertility index method on several land uses in Tutur District, Pasuruan Regency of East Java. *Journal of Degraded and Mining Lands Management*, *10*(1), 3787-3794. https://doi.org/10.15243/jdmlm.2022.101.3787

Seilsepour, M., Rashidi, M., & Khabbaz, B. G. (2009). Prediction of soil exchangeable sodium percentage based on soil sodium adsorption ratio. *American-Eurasian Journal of Agricultural and Environmental Science*, *5*, 1-4. https://core.ac.uk/download/pdf/11038819.pdf

Shafi, M., Khan, M. J., Bakht, J., & Khan, M. A. (2013). Response of wheat genotypes to salinity under field environment. *Pakistan Journal of Botany*, *45*(3), 787-794. https://www.pakbs.org/pjbot/PDFs/45(3)/10.pdf

Sigua, G. C., Novak, J. M., & Watts, D. W. (2016). Ameliorating soil chemical properties of a hard setting subsoil layer in Coastal Plain USA with different designer biochars. *Chemosphere*, *142*, 168-175. https://doi.org/10.1016/j.chemosphere.2015.06.016

Suntoro, Herdiansyah, G., & Mujiyo. (2024). Nutrient status and soil fertility index as a basis for sustainable rice field management in Madiun Regency, Indonesia. *Sains Tanah - Journal of Soil Science and Agroclimatology*, *21*(1), 10. https://doi.org/10.20961/stjssa.v21i1.73845

Tang, L., Zhan, L., Han, Y., Wang, Z., Dong, L., & Zhang, Z. (2023). Microbial community assembly and functional profiles along the soil-root continuum of salt-tolerant Suaeda glauca and Suaeda salsa [Original Research]. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1301117

Tian, S., Xia, Y., Yu, Z., Zhou, H., Wu, S., Zhang, N., . . . Xia, Y. (2024). Improvement and the relationship between chemical properties and microbial communities in secondary salinization of soils induced by rotating vegetables. *Science of The Total Environment*, *921*, 171019. https://doi.org/10.1016/j.scitotenv.2024.171019

Velmurugan, A., Swarnam, T. P., Ambast, S. K., & Kumar, N. (2016). Managing waterlogging and soil salinity with a permanent raised bed and furrow system in coastal lowlands of humid tropics. *Agricultural Water Management*, *168*, 56-67. https://doi.org/10.1016/j.agwat.2016.01.020

Waani, S. P. T., Irum, S., Gul, I., Yaqoob, K., Khalid, M. U., Ali, M. A., . . . Arshad, M. (2021). TiO2 nanoparticles dose, application method and phosphorous levels influence genotoxicity in Rice (Oryza sativa L.), soil enzymatic activities and plant growth. *Ecotoxicology and Environmental Safety*, *213*, 111977. https://doi.org/10.1016/j.ecoenv.2021.111977

Win, K. T., Oo, A. Z., & Yokoyama, T. (2022). Plant Growth and Yield Response to Salinity Stress of Rice Grown under the Application of Different Nitrogen Levels and Bacillus pumilus Strain TUAT-1. *Crops*, *2*(4), 435-444. https://doi.org/10.3390/crops2040031

Xiaoqin, S., Dongli, S., Yuanhang, F., Hongde, W., & Lei, G. (2021). Three-dimensional fractal characteristics of soil pore structure and their relationships with hydraulic parameters in biochar-amended saline soil. *Soil and Tillage Research*, *205*, 104809. https://doi.org/10.1016/j.still.2020.104809

Xiong, D. (2024). Perspectives of improving rice photosynthesis for higher grain yield. *Crop and Environment*, *3*(3), 123-137. https://doi.org/10.1016/j.crope.2024.04.001

Yamauchi, T., Colmer, T. D., Pedersen, O., & Nakazono, M. (2017). Regulation of Root Traits for Internal Aeration and Tolerance to Soil Waterlogging-Flooding Stress. *Plant Physiology*, *176*(2), 1118-1130. https://doi.org/10.1104/pp.17.01157

Yang, S.-Y., Wu, Y.-S., Chen, C.-T., Lai, M.-H., Yen, H.-M., & Yang, C.-Y. (2017). Physiological and molecular responses of seedlings of an upland rice ('Tung Lu 3') to total submergence compared to those of a submergence-tolerant lowland rice ('FR13A'). *Rice*, *10*(1), 42. https://doi.org/10.1186/s12284-017-0180-3

Zhang, N., Liu, Q., Chen, C., Zhang, C., Atakpa, E. O., Wei, X., . . . Zhou, H. (2024). Deciphering the performance and mechanisms of glycolipids in regulating crop growth in coastal saline-alkali soils: Perspectives on soil properties and microbial communities. *Applied Soil Ecology*, *201*, 105527. https://doi.org/10.1016/j.apsoil.2024.105527

Zhang, Y., Hou, K., Qian, H., Gao, Y., Fang, Y., Xiao, S., . . . Ren, W. (2022). Characterization of soil salinization and its driving factors in a typical irrigation area of Northwest China. *Science of The Total Environment*, *837*, 155808. https://doi.org/10.1016/j.scitotenv.2022.155808