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# Effect of Rock Fragment Proportion on Soil Water Availability and Maize Growth in Sandy Clay Loam Soil

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## ABSTRACT

The presence of rock fragments in soil significantly impacts the soil's ability to retain water and other hydrological functions such as water storage, infiltration, evaporation, and hydraulic properties. This study evaluated soil water retention, penetration resistance, maize (*Zea mays* L.*)* growth, biomass and leaf gas exchange across five rock fragment proportions (0%, 10%, 30%, 50% and 60%; M0-M60). This experiment was conducted in a Randomised Complete Block Design (RCBD) with five treatments and three replicates, for a total of 15 experimental units. Rock fragments were 2-4 mm in diameter and were mixed with soil described as sandy clay loam. Reported plant available water capacity declined from approximately 9.00% in M0 to 3.11% in M60; M30 recorded 6.15%. In contrast, M30 had the highest mean ear weight (370.60 g plant$^{-1}$), root dry biomass (25.97 g plant$^{-1}$) and net photosynthetic rate (25.17 µmol $CO_2$ $m^{-2}$ $s^{-1}$). Ear weight in M30 exceeded M50 but did not differ significantly from M0, M10 or M60, whereas root biomass in M30 exceeded all other treatments. In conclusion, the mixture of 30% rock fragments with sandy clay loam has the best proportions that ensure the Plant Available Water Capacity (PAWC) for maize (*Zea mays* L.*)* growth.

*Keywords:* Plant Available Water Capacity (PAWC), rock fragment, sandy clay loam, soil water retention, *Zea mays* L

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## INTRODUCTION

A rock fragment is defined as a soil particle that is larger than 2 mm in diameter. The presence of rock fragments in soil has a substantial impact on water retention and other hydrological functions such as water storage, infiltration, evaporation, and hydraulic properties.

In many Mediterranean nations where natural environment deterioration is a major issue leading to desertification, a substantial proportion of soils contain rock pieces both at the soil surface and in the soil profile (Poesen & Lavee, 1994; Tétégan et al., 2011). Earlier studies demonstrated that rock fragments influence infiltration and crop responses to water supply (Kosmas et al., 1994). Rock fragments contents in soil may hinder the growth of plant roots and cause the soil to be unable to retain water for plant uptake. Certain proportions of rock fragments may decrease water-holding capacity. Appropriate proportions of rock fragments will provide an adequate amount of water for root uptake. The percentage of rock fragments in soil influences water availability and, by extension, plant traits. Plants cultivated in soil containing rock fragments have lower transpiration rates, particularly when well-watered. The ability of a soil to absorb water rises with its particle size. The presence of rock fragments has a major impact on hydrological processes such as water storage, infiltration and evaporation, and soil hydraulic characteristics (Ma & Shao, 2008). More recent work has shown that plants can use water stored in porous rock fragments during drought (Korboulewsky et al., 2020), and that even hard sandstone fragments can contribute to field-capacity water storage (Robertson et al., 2021). Field observations also show that fragment content modifies the spatial and seasonal distribution of soil water and temperature (Huang et al., 2023). This study addresses that question by comparing water retention, penetration resistance, maize morphology, biomass and leaf gas exchange across five proportions of 2-4 mm rock fragments.

The objectives of this study were to evaluate the effect of different rock fragments proportion on plant available water capacity (PAWC), evaporation rate, biomass, morphology growth and growth performance of maize (*Zea mays* L.*)* planted in a mixture with sandy clay loam and to evaluate the effect of rock fragment mixtures on gas exchange characteristics of maize (*Zea mays* L.). The hypothesis of this experiment is to observe the effect of different proportions of rock fragments (0%, 10%, 30%, 50% and 60%) towards the plant available water capacity (PAWC), evaporation rate, biomass, morphology, growth and growth performance and gas exchange characteristics of maize (*Zea mays* L.) planted in a mixture of sandy clay loam soil and rock fragments.

## MATERIALS AND METHODS

This experiment was conducted at the University Agriculture Park, Universiti Putra Malaysia (UPM), Serdang, Malaysia. GPS coordinates: latitude 2.585660 and longitude.

101.425469. The rock fragments used in this experiment are between 2.0 mm and 4.0 mm. The sieve sizes 2 mm and 4 mm were used to ensure the range size for the rock fragments.

The soil texture used is sandy clay loam collected at UPM Serdang campus, Selangor. The soils were sieved with a 2 mm sieve size and collected for media preparation, then mixed with the rock proportion. The soil was described as sandy clay loam; its reported particle-size distribution and water-holding capacity are presented in Table 1. The sandy clay loam and rock fragments were mixed evenly and transferred into respective (16 × 16 × 16) polybags according to the treatments, with 3 replications (Table 1).

## Experimental Design

The experimental design used is a Randomised Complete Block Design (RCBD) with five rock fragment proportions and three replicates, giving 15 experimental units. The treatments were M0, M10, M30, M50 and M60, corresponding to 0%, 10%, 30%, 50% and 60% rock fragments, respectively (Table 2).

Table 1
*Properties of the experimental soil*

| | |
|---|---|
| Sand (%) | 56.8 |
| Silt (%) | 21.6 |
| Clay (%) | 21.6 |
| Water-holding capacity (%) VWC | 66 |

Table 2
*Treatment composition of soil and rock fragment mixtures*

| Label | Treatments |
|---|---|
| M0 | 100% sandy clay loam soil + 0% rock fragments (control) |
| M10 | 90% sandy clay loam soil + 10% rock fragments |
| M30 | 70% sandy clay loam soil + 30% rock fragments |
| M50 | 50% sandy clay loam soil + 50% rock fragments |
| M60 | 40% sandy clay loam soil + 60% rock fragments |

Maize (*Zea mays* L.) was used as a test crop. One seedling was transplanted into each polybag at 7 days after sowing (DAS), and the crop duration was reported as 75 DAS (Table 3). Fertiliser application began at 14 DAS and was repeated weekly until 75 DAS at the reported rate of 5 g per polybag per application. The fertiliser type used is shown in Table 3.

## Soil Properties Analysis

### *Soil Water Retention and Plant Available Water Capacity (PAWC)*

Soil water retention was measured using the water retention pressure plate and pressure membrane method (Richards, 1941). Materials used were pressure chambers, a pressure control manifold, an air compressor and ceramic plates (100 kPa, 500 kPa and 1500 kPa plates). Determination of PAWC was done at soil water pressure of 0.1 kPa

(saturation capacity/point), 1 kPa, 10 kPa, 33 kPa (field capacity), and 1500 kPa (permanent wilting point).

### *Evaporation Rate*

Evaporation rate is determined by the rate at which water can be conducted to the surface rather than by atmospheric conditions (Tian & Philpot, 2015). The Penman-Monteith formula is used for calculating the potential rate of evaporation, which is based on the energy balance. The resultant equation is as shown in Equation 1:

Table 3
*Fertiliser recommendation for maize*

| Item | Value |
|---|---|
| Nitrogen (N) (kg/ha) | 130 |
| Phosphorus ($P_2O_5$) (kg/ha) | 57 |
| Potassium ($K_2O$) (kg/ha) | 130 |
| Fertiliser application rate | 5 g/ polybag/ week |
| Plant Population Density (PPD per ha) | 53 333 |

*Source: Department of Agriculture Malaysia (DOA) (2008)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [1]$$

Where:
$ET_o$ reference evapotranspiration [mm $day^{-1}$],
$R_n$ net radiation at the crop surface [MJ $m^{-2}$ $day^{-1}$],
G soil heat flux density [MJ $m^{-2}$ $day^{-1}$],
T mean daily air temperature at 2 m height [°C],
$u_2$ wind speed at 2 m height [m $s^{-1}$],
$e_s$ saturation vapour pressure [kPa],
$e_a$ actual vapour pressure [kPa],
$e_s$ - $e_a$ saturation vapour pressure deficit [kPa],
D slope vapour pressure curve [kPa $°C^{-1}$],
g psychrometric constant [kPa $°C^{-1}$].

### *Soil Electrical Conductivity (EC)*

The EC of the soil extract is obtained immediately from the digital display of a temperature-compensating conductivity meter. The electromotive force (EMF) generated by the platinum/epoxy electrode arrangement varies linearly with the EC. Plotting the measured EMF against the EC of several standard concentrations reveals this linear relationship.

### *Soil Compaction*

Soil compaction was measured using a soil penetrometer, and readings were recorded in kilopascals (kPa). In addition, supporting soil physical properties, such as bulk density, were assessed to complement the compaction data.

## Plant and Growth Performance Analysis

The maize plant's fresh weight and dry weight were taken after the cobs of maize were harvested. Maize cobs, stems, leaves, and roots were taken. To get the dry weight, the maize plant parts were put into the oven to dry. The temperature was maintained at 70 °C for 7 days. After 7 days, the plants were weighed using an electronic balance. The moisture content in the plant was also calculated based on the fresh weight and dry weight.

### *Plant Biomass*

Biomass analysis is the dry weight of the maize plant. The maize plants were divided into 4 parts, that is, stem, leaf, ear and root. The biomass was taken to calculate the relative growth rate and absolute growth rate of the maize plant throughout the experiment.

### *Absolute Growth Rate (AGR)*

Absolute growth rate refers to a plant's size and represents an increase in mass per unit period. AGR is also used to describe the growth of the plant, as it is based on the roots, leaves, and stem mass of the plant. The AGR was measured by the following Equation 2:

$$\text{AGR (g day}^{-1}) = \frac{(\text{fresh weight} - \text{dry weight})}{75 \text{ days planting}} \quad [2]$$

### *Specific Leaf Area (SLA)*

(Evans and Poorter (2001) define specific leaf area (SLA) as the anticipated leaf area per unit leaf dry mass. SLA is a key characteristic in many agronomic and ecological processes, such as photosynthesis, transpiration, and field energy balance, but it can be difficult and costly to quantify. The SLA was measured using the following, Equation 3:

$$\text{SLA (cm}^2\text{g}^{-1}) = \frac{\text{Leaf area}}{\text{Leaf biomass}} \quad [3]$$

### *Root-shoot Ratio (RSR)*

Root-shoot ratio (RSR) is important for the growth and development of plants (Andrews et al., 1999). Root-shoot ratios are thus indicative of plant response to growing conditions of maize (*Zea mays* L.). The formula is based on the dry weight of the root (g) and the shoot (g) per plant. The RSR was measured by following Equation 4:

$$\text{RSR (cm}^2\text{g}^{-1}) = \frac{\text{Root biomass}}{\text{Shoot biomass}} \quad [4]$$

### *Leaf Gas Exchange Analysis*

Leaf gas exchange was measured one week before harvest between 08:00 and 11:00 using a LI-COR portable photosynthesis system. The measurements taken were intercellular $CO_2$, stomatal conductance, transpiration rate and photosynthesis. Gas exchange was measured on the same leaf on which the measuring electrode was fixed. Changes in $CO_2$ concentration were detected with a porometer (Li-Cor Li 6000, Lincoln, WA) that simultaneously measured the rate of transpiration during the period 8.00-11:00. Each started at a $CO_2$ concentration of 400 ppm and a relative humidity of 50%. The temperature in the leaf chamber was 25 °C and the light intensity 300 mmol photons $m^{-2}$ $s^{-1}$. The analyser was calibrated prior to each series of measurements; the stability of the zero point was checked by means of an airline that bypassed the chamber with the leaf.

### Statistical Analysis

All experimental data were statistically analysed using the analysis of variance (ANOVA) techniques in the Statistical Analysis software 9.4 (SAS Institute, Inc., Cray, NC, USA). LSD was used to compare treatment means with significant F values ($p<0.05$).

## RESULTS AND DISCUSSIONS

### Soil Properties Analysis

### *Soil Water Retention and Plant Available Water Capacity (PAWC)*

Figure 1 presents the water-retention curves for the effect of rock fragments on the water content of sandy clay loam soil at different suctions. The pressure head and water content (θs) showed the water retention in the M0 (9.00 %), M10 (8.20 %), M30 (6.15 %), M50 (4.16 %) and M60 (3.11 %), which decreased based on the different rock fragment effects. There were many factors that could affect the soil hydraulic conductivity. Soil with a high percentage of clay might indicate a slow infiltration rate compared to sandy soil (Mahmood-ul-Hassan et al., 2013). High bulk density was correlated with low soil porosity and might also cause a low value in soil hydraulic conductivity. The predicted curve indicated excellent fitting for the retention curve data in the models, together with the Van Genuchten - Mualem equation (m=1-1/n), which was extracted from the retention curve model.

Figure 2 shows the plant available water capacity (PAWC) of rock fragment mixtures with soil. At 0% (8.99%) and 10% rock fragment mixtures (8.20%) showed a significant difference compared to 30% (6.15%), 50% (4.16%) and 60% rock fragment mixtures (3.11%). This indicated that the rock fragment mixture with 10% rock fragments was able to retain the highest available water compared to 30%, 50%, and 60% rock fragment mixtures. The presence of rock fragments in the soil significantly decreases Plant Available Water Capacity (PAWC) due to high rock fragments contents, which causes higher heat

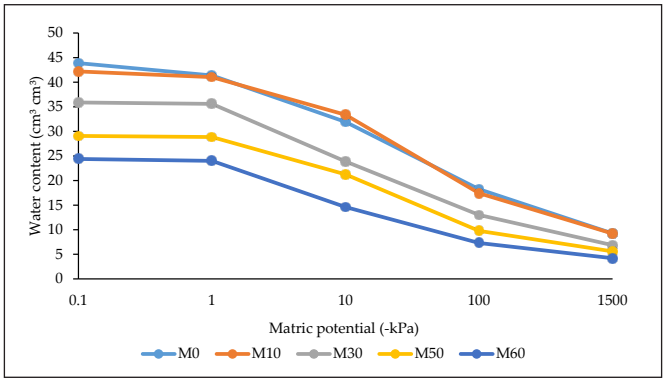


*Figure 1*. Effect of rock fragments on the water content of sandy clay loam soil at different suctions (kPa). Means with the same letter are not significantly different at p<0.05

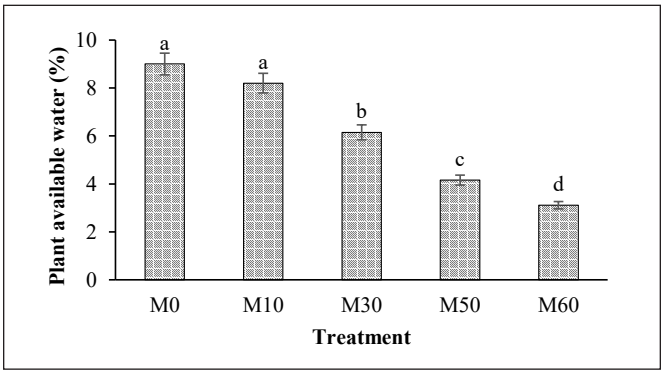


*Figure 2*. Effect of rock fragments on PAW of sandy clay loam soil at different suctions (kPa). Means with the same letter are not significantly different at p<0.05

conduction than stonier soil does, leading to increasing evaporation rates that result in a reduction of AWC (van Wesemael et al., 1996a; van Wesemael et al., 1996b). A thirty percent rock fragments mixture was also able to restore an adequate amount of available water content for maize establishment. Increased rock fragment proportions have been shown to (Fiès et al., 2002) that high rock fragment contents usually give a negative effect on the water-holding capacity of the soil, resulting in less Plant Available Water Capacity (PAWC).

### *Evaporation Rate*

Rock fragment was significantly ($p<0.05$) higher in the M50 (728.50 mm day$^{-1}$), followed by the M60 (637.58 mm day$^{-1}$), M30 (531.00 mm day$^{-1}$), M0 (419.83 mm day$^{-1}$) and M10 mixture (395.08 mm day$^{-1}$), respectively (Figure 3). The result shows that there was no

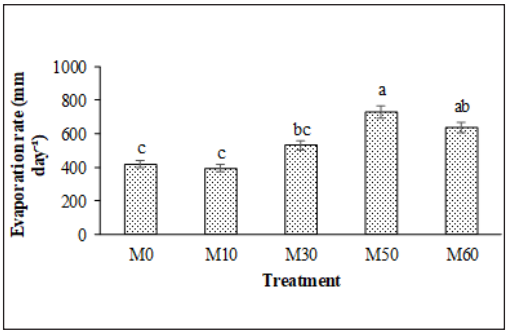


*Figure 3*. Effect of rock fragments on evaporation rate. Means with the same letter are not significantly different at $p<0.05$

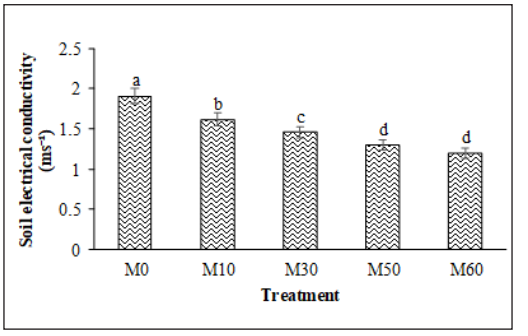


*Figure 4*. Effects of rock fragments on electrical conductivity. Means with the same letter are not significantly different at $p<0.05$

significant difference between the treatments of M0, M10, and M30. There was a significant difference between the M50, M60, and M10 rock fragments mixture. The mean values of M50 and M60 mixtures showed the highest evaporation rate compared to the others. According to the findings, the evaporation rate is dependent on a variety of parameters, including surface area, liquid temperature, and surrounding air. When a system's vapour pressure reaches equilibrium, the evaporation rate slows. The evaporation of soil can be influenced by rock particles. A high concentration of rock particles may increase the evaporation rate. The results of this experiment opposed the findings (Kosmas et al., 1994; van Wesemael et al, 1996b), who discovered that rock fragments induce a decrease in soil evaporation after comparing crop production in soil with and without rock.

### *Soil Electrical Conductivity*

Figure 4 shows the effect of rock fragment mixtures on electrical conductivity (mS $cm^{-1}$). The results showed that there was no significant difference between M50 (1.30 mS $cm^{-1}$) and M60 rock fragment mixtures (1.20 mS $cm^{-1}$), but there was a significant difference between M0 (1.91 mS $cm^{-1}$), M10 (1.52 mS $cm^{-1}$) and M30 (1.46 mS $cm^{-1}$) treatments. This possibly happened because the available water content was high in M0 to M30 mixtures. An EC meter was used to measure the potential electrical conductivity transported through the soil mixtures. The result showed that the increased amount of rock fragment content could possibly affect the EC value or the salinity of the soil. Apparently, EC was highly dependent on soil water content  content  (Mi et al., 2016).

### *Soil Compaction*

Soil compaction tended to decrease as the proportion of rock fragments in the soil increased. The results of comparisons of mean soil compaction for each rock-fragment content

showed that rock-fragment M0 was higher than rock-fragment contents of M10, M30, M50 and M60 (Figure 5). A significant difference was observed in the M0 rock-fragment mixing (539.72 kPa) and M60 rock-fragment mixing (333.02 kPa). However, there was no significant difference in M10 (380.10 kPa), M30 (376.91 kPa) and M50 (355.99 kPa). The decrease in compaction was based on the percentages of mixing rock fragments and soil that based on the pores and structure size. In addition, soil compaction is mostly related to soil bulk density (Panayiotopoulos et al., 2003) and a similar result was observed in this experiment. According to (Horn et al., 1995; Lipiec & Hatano, 2003; Panayiotopoulos et al., 2003), soil compaction can cause the degradation of inter-aggregate pores, as well as a reduction in soil hydraulic conductivity and air permeability. Furthermore, Lipiec and Hatano (2003) stated that in order to obtain an accurate measurement of the effects of soil compaction in all types of soil, it should not only consider soil bulk density but also soil strength, aeration, and moisture.

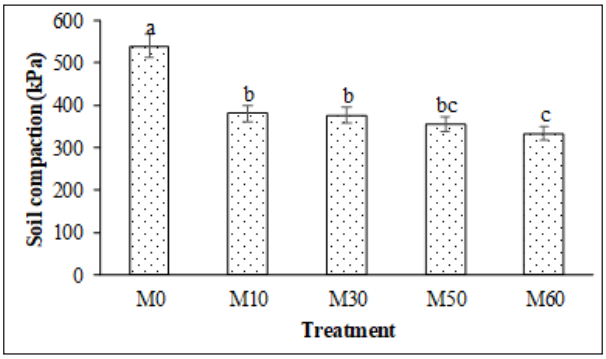


*Figure 5*. Effects of rock fragments on soil compaction. Means with the same letter are not significantly different at $p<0.05$

## Plant and Growth Performance Analysis

### *Maize Growth Morphology*

Table 4 shows the ear weight (g plant$^{-1}$) of M30 (370.6 g plant$^{-1}$), which was identified as the highest compared to M50 rock fragment mixtures (265.9 g plant$^{-1}$). From the results, there was no significant difference between treatments of M0, M10 and M60 rock fragment mixtures, but there was a significant difference between treatments of M30 and M50 rock fragment mixtures. The ear weight differs because the maize plants have more than one ear. Ear weight could be different, correlated to the ability of rock fragment mixtures to hold water. Based on Figure 2, M0 rock fragments were able to retain more water content compared to the other treatments. The ability to retain adequate water content might help plant photosynthesis and increase ear size, and thus increase the ear weight per plant (Sekucia et al., 2020).

Table 4
*Effect of rock fragment on growth morphology of maize (*Zea mays L.*). Means with the same letter are not significantly different at p<0.05*

| Parameter | Percentage of Rock Fragment in Sandy Clay Loam | | | | |
|---|---|---|---|---|---|
| | 0% | 10% | 30% | 50% | 60% |
| Ear Weight (g plant$^{-1}$) | 319.13ab | 295.20ab | 370.60a | 265.88b | 288.66ab |
| Stem Diameter (cm plant$^{-1}$) | 3.45ab | 3.90a | 2.94ab | 2.52b | 2.83b |
| Plant Height (cm plant$^{-1}$) | 113.50a | 115.89a | 117.44a | 89.17b | 97.95ab |
| Leaf Area (cm$^2$ plant$^{-1}$) | 4186.40ab | 3896.00ab | 4846.70a | 2426.30c | 3209.50bc |

Stem diameter in Table 4 shows that there was no significant difference between treatments of M0 and M30 rock fragment mixtures, and there was also no significant difference between M50 and M60 rock fragment mixtures. But the M10 rock fragment mixture showed a significant difference compared to M50 and M60 rock fragment mixtures. This was possibly because 0% to 30% rock fragment mixtures provide adequate water content for maize growth. In contrast, daily stem contraction demonstrated complex and loose interactions with soil and plant water status, as well as stomatal conductance; changes in stem diameter are widely used to measure plant water status (Torres-Ruiz et al., 2013).

Plant height in Table 4 indicated that the plant height (cm plant$^{-1}$) of M30 (117.4 cm plant$^{-1}$) was the highest compared to M50 rock fragments mixture (89.2 cm plant$^{-1}$). From the result, there was no significant difference between the treatments of M0, M10, M30 and M60 rock fragment mixtures. Treatments of M50 and M60 rock fragments mixture were also shown no significant difference. The plant height differs probably because of 0% to 30% rock fragment mixtures had good porosity within the mixtures and better aeration for root growth. The plant height was also related to water holding capacity based on Figure 5. A limited water supply reduced the plant height (Sari-Gorla et al., 1999).

Table 4 shows that the leaf area (cm$^2$ plant$^{-1}$) of M30 (4846.7 cm$^2$ plant$^{-1}$) was the highest compared to M50 rock fragments mixtures (2426.3 cm$^2$ plant$^{-1}$). The M30 rock fragments mixture showed a high amount of leaves present, and the value of leaf area might also increase. These might explain why the leaf area differs between the treatments. Crop plant growth and development are essential for establishing a normal plant structure capable of carrying out all physiological and metabolic activities and providing potential yield. Different ratios of rock fragment mixes resulted in water stress, which may impede maize growth and development. Growth and development include several component parameters that were estimated using various qualities such as plant height, leaf area, root structural and functional attributes, plant biomass, plant fresh weight, plant dry weight, and stem diameter. Drought stress reduces plant height, stem diameter, biomass, and leaf area (Anjum et al., 2017).

### *Biomass and Growth Performance of Maize*

Table 5 shows the leaf biomass (g plant$^{-1}$) of M30 (36.13 g plant$^{-1}$) compared to the M50 rock fragments mixture (23.2 g plant$^{-1}$). The leaf biomass influenced the number of leaves per plant, and the M30 rock fragments mixture of maize plants showed the highest number of leaves and increased their leaf biomass value. It was established that increasing inputs, primarily water content at the farm level, will improve biomass production in addition to boosting the harvest index. (Pandey et al., 2000).

Table 5 shows the ear biomass of M30 (84.7 g plant$^{-1}$) compared to the M60 rock fragments mixture (61.1 g plant$^{-1}$). The ear biomass in this data was influenced by the number of ears per plant. The maize plant from the M30 rock fragments mixture had more than one ear per plant compared to the other treatments. The 10% to 30% rock fragment mixtures of maize plants also received enough nutrients because the presence of rock fragments provided adequate porosity for plant growth. The rock fragment mixtures of 50% and 60% gave unfavourable conditions for maize to grow because water was easily leached due to the high macro-pores present in the maize planting media (Fortin, 1994)

There was the highest stem biomass (g plant$^{-1}$) at the M30 rock fragment mixture (35. 5 g plant$^{-1}$) compared to M50 (22.9 g plant$^{-1}$) (Table 5). The root biomass (g plant $^{-1}$) of M30 (26.0 g plant$^{-1}$) was the highest compared to the M60 rock fragment mixture. The 30% rock fragments mixture gave more aeration and more micropores for maize growth in the mixtures and encouraged the widening of root establishment in the polybag (Chow et al., 2007). Apparently, the 30% rock fragments mixture showed the highest maize root biomass and the biggest root size compared to the other treatments. The presence of rock fragments in soil layers may have an impact on their hydraulic properties. Previous research has demonstrated that rock pieces on the soil surface can have a variety of effects on soil moisture, runoff generation, overland flow hydraulics, and interrill and rill erosion (Poesen & Lavee, 1994; Wang et al., 2012). For example, in cultivated soils, rock fragments affect both moisture content and plant growth. Kosmas et al. (1994) and Tétégan et al. (2011) demonstrated that soils produced from sandstone and conglomerates with rock fragments are less affected by dry periods than soils on marls without rock fragments, resulting in improved maize biomass output. It seems that 0% to 30% rock fragment mixtures in this study might not hinder root and maize growth performance.

Table 5 shows that the M30 rock fragments mixture (221.9%) had the highest moisture content compared to M50 (143.5%). The results, it showed that the 30% rock fragments mixture stored more water content compared to the other treatments. The results of this experiment were comparable to those of Ma and Shao (2008), who discovered that the favourable effect of rock fragments varied according to the range of rock fragment concentration, which might affect biomass between 10% and 50% rock fragment mixtures.

Table 5
*The effect of rock fragments on biomass and growth performance of maize (*Zea mays L. *Means with the same letter are not significantly different at p<0.05*

| Parameter | Percentage of Rock Fragment | | | | |
|---|---|---|---|---|---|
| | 0% | 10% | 30% | 50% | 60% |
| Leaves Biomass (g plant$^{-1}$) | 30.69ab | 26.01bc | 36.13a | 23.17c | 24.99bc |
| Ear Biomass (g plant$^{-1}$) | 75.50ab | 69.79ab | 84.72a | 77.42ab | 61.14b |
| Stem Biomass (g plant$^{-1}$) | 27.63b | 33.27a | 35.45a | 22.92c | 23.2bc |
| Root Biomass (g plant$^{-1}$) | 17.03b | 16.09b | 25.97a | 17.82b | 15.57b |
| Total plant moisture content (% plant$^{-1}$) | 175.01bc | 190.02ab | 221.91a | 143.55c | 160.48bc |

## Specific Leaf Area (SLA)

Figure 6 shows the Specific Leaf Area (SLA), and there was a significant difference in SLA due to different percentages of rock fragment mixtures. There was a significant difference between M30 and M60 rock fragment mixtures. SLA of the M30 rock fragment mixture was the highest recorded in this experiment. SLA was formed by two components, which are leaf area and leaf biomass

## Absolute Growth Rate (AGR)

Figure 7 shows the total absolute growth rate (g day-1) of M30 (8.7 g day-1) compared to the M50 (5.5 g day$^{-1}$) rock fragments mixture, which was the lowest among the other percentages in this experiment. AGR is also used to explain plant growth because it is based on the root, leaf, stem, and leaf mass of the plant. AGR is the most basic metric for measuring plant growth rate. However, limits will arise because it is only used to compare the development of the same plant at the same age or original size. Growth is defined as an increase in plant size, which is directly proportional to an increase in the number and size of cells. According to Romano (2002), the absolute growth rate varied according to the quantity of rock fragments, as did the dry mass of roots, leaves, stems, and fruits.

## Root-Shoot Ratio (RSR)

For the M30, M50 and M60 rock fragment mixtures (means of 0.33, 0.43 and 0.39 g$^{1}$ g$^{-1}$, respectively) was significantly different from M0 and M10 (0.34 g$^{1}$ g$^{-1}$) (Figure 8). In general, the effect of RSR reflects dry matter partitioning between the shoot and root of higher plants, and it has been concluded that changes in RSR occur in response to a wide range of environmental factors, including rock fragments (Andrews et al., 1999; Ding et al., 2025). Furthermore, particular percentages of rock fragments may boost root growth while limiting aboveground biomass production (Du et al., 2017).

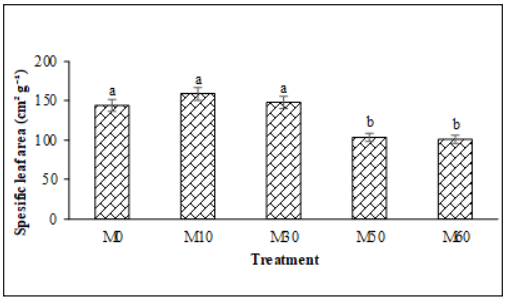


*Figure 6*. Effects of rock fragments on Specific Leaf Area of maize (*Zea mays* L.). Means with the same letter are not significantly different at p<0.05

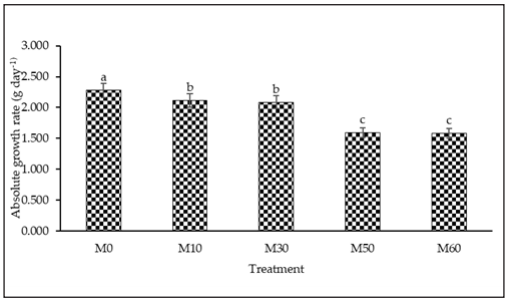


*Figure 7*. Effects of rock fragments on the Absolute Growth Rate of maize (*Zea mays* L.). Means with the same letter are not significantly different at p<0.05

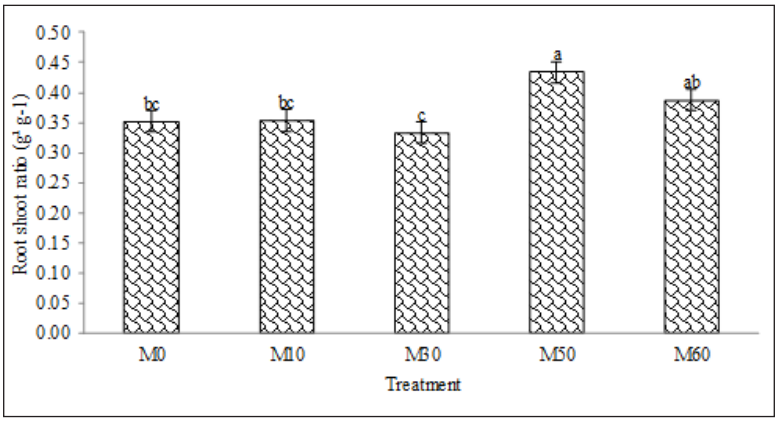


*Figure 8*. Effects of rock fragments on the root-shoot ratio of maize (*Zea mays* L.). Means with the same letter are not significantly different at p<0.05

Rock fragments can influence plant growth by changing soil physicochemical qualities and controlling plant root systems (Carrick et al., 2013; Estrada-Medina et al., 2013), although there is no agreement on the effects of rock fragments on plant growth. For example, Poesen and Lavee (1994) found that rock pieces promote plant growth, particularly in arid conditions. Soils containing rock fragments have been shown to produce high-quality grapes (Seguin, 1971) and to boost blueberry seedling development (Jackson et al., 1972). Munn et al. (1987) discovered a negative effect of rock pieces on grass productivity in irrigated reclaimed areas in Colorado (USA), while Kongsrud and Nes (1999) found a similar effect on strawberry yield. In contrast, Du et al. (2017) found that a rock fragment concentration of 30% had a beneficial effect on korshinsk peashrub growth and biomass, whereas a rock fragment level of 50% had a detrimental effect on plant growth. This disparity is most likely due to variances in plant species, soil conditions, and rock fragment composition. For example, Du et al. (2017) hypothesised that rock shards

would have a negative impact on root development in sandy soil but would be beneficial for air and water circulation in clayey soil, increasing the root growth environment. Similarly, Babalola and Lal (1977) found that rock fragments had a stronger inhibitory effect on root development of maize seedlings in sandy soil than in sandy loam or clay soil.

## Leaf Gas Exchange Analysis

Table 6 shows the photosynthesis rate ($A_{net}$) ($\mu molm^{-2}s^{-1}$) of the 30% (25.17 $\mu molm^{-2}$ $s^{-1}$) rock fragments mixture (highest) compared to the M60 rock fragments mixture (14.70 $\mu molm^{-2}$s-1) (lowest) among the other treatments. The adaptation of photosynthesis to water stress had previously attracted significant interest, and there had been a long-standing debate about which was the primary limitation for photosynthesis. Stomatal closure or metabolic impairment (Galmés et al., 2007).

Stomatal Conductance ($G_s$) in Table 6 presented the $G_s$ ($molm^{-2}$ $s^{-1}$) of the M30 (0.375 $molm^{-2}$ $s^{-1}$) (highest) rock fragments mixture compared to the M60 (0.154 $molm^{-2}$ $s^{-1}$) (lowest) rock fragments mixture. Stomata are plants' major regulatory mechanisms for reducing water loss, and they may do it swiftly. Stomata are responsive to environmental stimuli, which cause them to open or close. The primary function of stomata is to allow carbon dioxide in to stimulate photosynthesis while also allowing water to exit when it evaporates, cooling the leaves. Light, water, temperature, and $CO_2$ level within the leaf all have an impact on stomatal opening and shutting. Stomata will open in the daylight and close in the darkness. However, stomata can close in the middle of the day if water is limited, $CO_2$ builds up in the leaf, or the temperature is too high. (Driesen et al., 2020).

$CO_2$ intercellular concentration ($C_i$ ($\mu molCO_2$ $m^{-2}$ $s^{-1}$) of the M30 (223.67 $\mu$molCO2 $m^{-2}$ $s^{-1}$) rock fragments mixture was the highest, and the M60 rock fragments mixture was the lowest. A plant's stomata were open during transpiration, allowing gas exchange between the atmosphere and the leaf. Open stomata allowed water vapour to leave the leaf while also allowing carbon dioxide ($CO_2$) to enter. Carbon dioxide was required for photosynthesis to occur. Transpiration exceeds $CO_2$ uptake because water molecules diffuse more rapidly, are driven by a steeper concentration gradient from the hydrated leaf to the drier atmosphere, and traverse a shorter diffusion pathway compared to $CO_2$, which has a lower atmospheric concentration and must travel a longer internal distance to reach the chloroplast (Hwang et al., 2012). The greater the stomatal aperture, the easier it is for carbon dioxide to enter the leaf and fuel photosynthesis (Evans & von Caemmerer, 1996). However, this enormous aperture would allow the leaf to lose a significant amount of water, increasing the danger of dehydration or water-deficit stress. Plants with slightly open stomata lose less water per $CO_2$ molecule taken in, resulting in improved water use efficiency (the ratio of water lost to $CO_2$ acquired) (Lawson & Blatt, 2014). Plants with higher water use efficiency could endure periods of low soil moisture (Bassiouni et al., 2023).

Table 6
*Effects of rock fragments on gas exchange of maize (*Zea mays *L.) Means with the same letter are not significantly different at p<0.05*

| Parameter | Percentage of Rock Fragment | | | | |
|---|---|---|---|---|---|
| | 0% | 10% | 30% | 50% | 60% |
| Photosynthesis Rate ($A_{net}$) ($\mu molm^{-2}s^{-1}$) | 21.43b | 22.57b | 25.17a | 18.10c | 14.70d |
| Stomatal Conductance ($G_s$) ($molm^{-2}s^{-1}$) | 0.17b | 0.28 ab | 0.38a | 0.16b | 0.15b |
| $CO_2$ Intercellular ($C_i$) ($\mu molCO_2\ m^{-2}s^{-1}$) | 133.33b | 204.33a | 223.67a | 193.33ab | 140.33b |
| Transpiration Rate ($E_L$) ($\mu molH_2O\ m^{-2}s^{-1}$) | 1.53b | 2.48ab | 3.18a | 1.55ab | 1.47b |

Transpiration Rate ($E_L$) is the evaporation of water from a plant. Roots absorb water from the soil and transfer it as a liquid to the leaves via xylem in the leaf; tiny pores allow water to escape as a vapour (Hwang et al., 2012). From the analysis of variance, there was a significant difference in $E_L$ due to different percentages of rock fragment mixtures. Table 6 shows that the EL ($\mu molH_2O\ m^{-2}s^{-1}$) of M30 (3.18 $\mu molH_2O\ m^{-2}\ s^{-1}$) was the highest, and the M60 (1.47 $\mu molH_2O\ m^{-2}s^{-1}$) rock fragment mixture was the lowest compared to the other treatments. Less than 5% of the water received by plants is retained for growth. (Korboulewsky et al., 2020) studied and explained that the presence of rock fragments can make Plants waste much water, the path water travels through plants, how plants can compensate for excessive water loss to prevent stress circumstances, and how the environment influences plant water loss. As the proportion of rock fragments increases, soil temperature increases, water-holding capacity decreases, transpiration increases, and plant moisture content decreases due to high transpiration (Huang et al., 2023). High vapour pressure deficit is caused by limiting hydraulic conductance in the plant, which restricts the passage of water from roots to transpiration sites on the leaf surface (Schönbeck et al., 2022). A substantial portion of the hydraulic resistance can be located in the leaf, especially the extravascular component (Cochard et al., 2004).

## Relationship between Transpiration and Photosynthesis

Figure 9 shows the positive correlation between transpiration rate ($E_L$) and photosynthesis rate ($A_{net}$). The correlation was 0.53. The relationship was influenced by the total amount of moisture content in maize plants cultivated in different proportions of rock fragment mixtures. Water evaporated from the surface of air-exposed leaf cells in actively growing plants. This water was replaced by extra water absorbed from the earth. Liquid water stretched through the plant from the soil water to the leaf cell surfaces, where it was changed from a liquid into a gas by the process of evaporation and transpiration (Meinzer, 2002). Thus, when photosynthesis increased, the transpiration rate increased, which might also have influenced the increase in total moisture content of the maize plant.

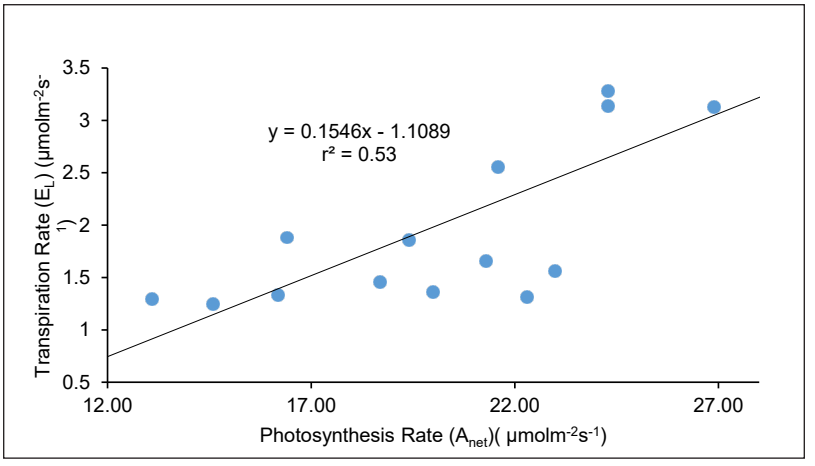


*Figure 9.* Relationship between transpiration rate ($E_L$) and photosynthesis rate ($A_{net}$)

Water consumption was influenced by both the water content and the rock particles. Transpiration first remained consistent, but eventually reduced as the water content fell. Increased rock fragment content in the soil considerably reduced transpiration, particularly under well-watered circumstances (>60% field capacity). Hydrogen bonding between adjacent water molecules maintains a continuous water column within the xylem, enabling transpiration at the leaf surface to generate the tension that pulls water upwards through the plant. This mechanism is described by the cohesion-tension theory of sap ascent (Mott, 2007). Under water stress, increased stomatal resistance limits both water loss via transpiration and $CO_2$ uptake for photosynthesis. Water stress can also affect the biochemical processes of photosynthesis by altering protein hydration and enzyme activity (Zargar et al., 2017).

## CONCLUSION

In general, this study has shown significant differences between the percentage of rock fragment mixtures in soil on water-holding capacity, biomass, growth morphology and the growth performance of maize. The optimal proportion of rock fragments was 30% due to the good performance shown in soil water-holding capacity, maize biomass, growth morphology and growth performance. Soils amended with 30% rock fragments also showed favourable characteristics that enhance the ability to retain available water and good macro- and micropores for aeration. In conclusion, the mixture of 30% rock fragments with sandy clay loam soil was the best proportion that could provide Plant Available Water Capacity (PAWC) for the growth of maize.

## LIMITATION AND RECOMMENDATION FOR FUTURE RESEARCH

This study was conducted under controlled conditions using sandy clay loam soil and maize (*Zea mays* L.) as the test crop, which may limit the direct applicability of the findings to other soil types, crops, and field environments. The experiment also focused on short-term plant growth responses and did not evaluate the long-term effects of rock fragments on soil structure, nutrient dynamics, root development, and crop productivity under varying climatic conditions. Furthermore, the rock fragments used were within a specific size range (2-4 mm), and different fragment sizes, shapes, and mineral compositions may produce different effects on soil physical properties and plant performance. Therefore, future research should investigate the long-term impacts of rock fragments under field conditions across diverse soil types and crop species, while also evaluating different rock fragment characteristics and their interactions with soil moisture, nutrient availability, and plant physiological responses to better understand their role in sustainable soil and water management.

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## REFERENCES

Andrews, M., Sprent, J. I., Raven, J. A., & Eady, P. E. (1999). Relationships between shoot to root ratio, growth and leaf soluble protein concentration of *Pisum sativum*, *Phaseolus vulgaris* and *Triticum aestivum* under different nutrient deficiencies. *Plant, Cell & Environment, 22*(8), 949-958. https://doi.org/10.1046/j.1365-3040.1999.00452.x

Anjum, S. A., Ashraf, U., Zohaib, A., Tanveer, M., Naeem, M., Ali, I., Tabassum, T., & Nazir, U. (2017). Growth and development responses of crop plants under drought stress: A review. *Zemdirbyste, 104*(3), 267-276. https://doi.org/10.13080/z-a.2017.104.034

Babalola, O., & Lal, R. (1977). Subsoil gravel horizon and maize root growth: I. Gravel concentration and bulk density effects. *Plant and Soil, 46*, 337-346. https://doi.org/10.1007/BF00010090

Bassiouni, M., Manzoni, S., & Vico, G. (2023). Optimal plant water use strategies explain soil moisture variability. *Advances in Water Resources, 173*, Article 104405. https://doi.org/10.1016/j.advwatres.2023.104405

Carrick, S., Palmer, D., Webb, T., Scott, J., & Lilburne, L. (2013). Stony soils are a major challenge for nutrient management under irrigation development. In L. D. Currie & C. L. Christensen (Eds.), *Accurate and efficient use of nutrients on farms* (Occasional Report No. 26, p. 8). Fertilizer and Lime Research Centre, Massey University.

Chow, T. L., Rees, H. W., Monteith, J. O., Toner, P., & Lavoie, J. (2007). Effects of coarse fragment content on soil physical properties, soil erosion and potato production. *Canadian Journal of Soil Science, 87*(5), 565-577. https://doi.org/10.4141/CJSS07006

Cochard, H., Nardini, A., & Coll, L. (2004). Hydraulic architecture of leaf blades: Where is the main resistance? *Plant, Cell & Environment, 27*(10), 1257-1267. https://doi.org/10.1111/j.1365-3040.2004.01233.x

Department of Agriculture Malaysia (DOA). (2008). *Pakej teknologi jagung manis*. https://www.doa.gov.my/doa/modules_resources/bookshelf/pt_tnmn_ldg_kontan_jagung_manis_2008/pt_jagung_manis_2008.pdf

Ding, R., Nóbrega, R. L. B., & Prentice, I. C. (2025). Global assessment of environmental and plant-trait influences on root: Shoot biomass ratios. *Global Change Biology, 31*(10), Article e70543. https://doi.org/10.1111/gcb.70543

Driesen, E., Van den Ende, W., De Proft, M., & Saeys, W. (2020). Influence of environmental factors light, $CO_2$, temperature, and relative humidity on stomatal opening and development: A review. *Agronomy, 10*(12), Article 1975. https://doi.org/10.3390/agronomy10121975

Du, Z., Cai, Y., Yan, Y., & Wang, X. (2017). Embedded rock fragments affect alpine steppe plant growth, soil carbon and nitrogen in the northern Tibetan Plateau. *Plant and Soil, 420*(1-2), 79-92. https://doi.org/10.1007/s11104-017-3376-9

Estrada-Medina, H., Graham, R. C., Allen, M. F., Jiménez-Osornio, J. J., & Robles-Casolco, S. (2013). The importance of limestone bedrock and dissolution karst features on tree root distribution in northern Yucatán, Mexico. *Plant and Soil, 362*(1), 37-50. https://doi.org/10.1007/s11104-012-1175-x

Evans, J. R., & Poorter, H. (2001). Photosynthetic acclimation of plants to growth irradiance: The relative importance of specific leaf area and nitrogen partitioning in maximizing carbon gain. *Plant, Cell & Environment, 24*(8), 755-767. https://doi.org/10.1046/j.1365-3040.2001.00724.x

Evans, J. R., & von Caemmerer, S. (1996). Carbon dioxide diffusion inside leaves. *Plant Physiology, 110*(2), 339-346. https://doi.org/10.1104/pp.110.2.339

Fiès, J. C., Louvigny, N. D. E., & Chanzy, A. (2002). The role of stones in soil water retention. *European Journal of Soil Science, 53*(1), 95-104. https://doi.org/10.1046/j.1365-2389.2002.00431.x

Fortin, M.-C., Pierce, F. J., & Edwards, M. (1994). Corn leaf area response to early-season soil temperature under crop residues. *Agronomy Journal, 86*(2), 355-359. https://doi.org/10.2134/agronj1994.00021962008600020027x

Galmés, J., Medrano, H., & Flexas, J. (2007). Photosynthetic limitations in response to water stress and recovery in Mediterranean plants with different growth forms. *New Phytologist, 175*(1), 81-93. https://doi.org/10.1111/j.1469-8137.2007.02087.x

Horn, R., Domżżał, H., Słowińska-Jurkiewicz, A., & van Ouwerkerk, C. (1995). Soil compaction processes and their effects on the structure of arable soils and the environment. *Soil and Tillage Research, 35*(1-2), 23-36. https://doi.org/10.1016/0167-1987(95)00479-C

Huang, L., Bao, W., Hu, H., Traselin Nkrumah, D., & Li, F. (2023). Rock fragment content alters spatiotemporal patterns of soil water content and temperature: Evidence from a field experiment. *Geoderma, 438*, Article 116613. https://doi.org/10.1016/j.geoderma.2023.116613

Hwang, G. S., Parkinson, D., Kusoglu, A., MacDowell, A., & Weber, A. Z. (2012). Water uptake and transport in Nafion®. *ECS Meeting Abstracts, MA2012-02*(13), 1483-1483. https://doi.org/10.1149/MA2012-02/13/1483

Jackson, L. P., Hall, I. V., & Aalders, L. E. (1972). Lowbush blueberry seedling growth as affected by soil type. *Canadian Journal of Soil Science, 52*, 113-115. https://doi.org/10.4141/CJSS72-018

Kongsrud, K. L., & Nes, A. (1999). Effects of fertigation of the black currant cultivar 'Ben Tron' (*Ribes nigrum* L.). *Acta Horticulturae, 505*, 409-413. https://doi.org/10.17660/ActaHortic.1999.505.57

Korboulewsky, N., Tétégan, M., Samouelian, A., & Cousin, I. (2020). Plants use water in the pores of rock fragments during drought. *Plant and Soil, 454*(1-2), 35-47. https://doi.org/10.1007/s11104-020-04425-3

Kosmas, C., Moustakas, N., Danalatos, N. G., & Yassoglou, N. (1994). The effect of rock fragments on wheat biomass production under highly variable moisture conditions in Mediterranean environments. *Catena, 23*(1-2), 191-198. https://doi.org/10.1016/0341-8162(94)90060-4

Lawson, T., & Blatt, M. R. (2014). Stomatal size, speed, and responsiveness impact on photosynthesis and water use efficiency. *Plant Physiology, 164*(4), 1556-1570. https://doi.org/10.1104/pp.114.237107

Lipiec, J., & Hatano, R. (2003). Quantification of compaction effects on soil physical properties and crop growth. *Geoderma, 116*(1-2), 107-136. https://doi.org/10.1016/S0016-7061(03)00097-1

Ma, D., & Shao, M. (2008). Simulating infiltration into stony soils with a dual-porosity model. *European Journal of Soil Science, 59*(5), 950-959. https://doi.org/10.1111/j.1365-2389.2008.01055.x

Mahmood-ul-Hassan, M., Rafique, E., & Rashid, A. (2013). Physical and hydraulic properties of aridisols as affected by nutrient and crop-residue management in a cotton-wheat system. *Acta Scientiarum. Agronomy, 35*(1), 127-137. https://doi.org/10.4025/actasciagron.v35i1.14683

Meinzer, F. C. (2002). Co-ordination of vapour and liquid phase water transport properties in plants. *Plant, Cell & Environment, 25*(2), 265-274. https://doi.org/10.1046/j.1365-3040.2002.00781.x

Mi, M., Shao, M., & Liu, B. (2016). Effect of rock fragments content on water consumption, biomass and water-use efficiency of plants under different water conditions. *Ecological Engineering, 94*, 574-582. https://doi.org/10.1016/j.ecoleng.2016.06.044

Munn, L., Harrington, N., & McGirr, D. R. (1987). Rock fragments. In R. D. Williams & G. E. Schuman (Eds.), *Reclaiming mine soils and overburden in the Western United States: Analytic parameters and procedures* (pp. 259-282). Soil Conservation Society of America.

Mott, K. A. (2007). Leaf hydraulic conductivity and stomatal responses to humidity in amphistomatous leaves. *Plant, Cell & Environment, 30*(11), 1444-1449. https://doi.org/10.1111/j.1365-3040.2007.01720.x

Panayiotopoulos, K. P., Salonikiou, E., Siaga, K., Germanopoulou, V., & Skaperda, S. (2003). Effect of uniaxial compression on water retention, hydraulic conductivity and the penetration resistance of six Greek soils. *International Agrophysics, 17*(4), 191-197. https://www.international-agrophysics.org/Effect-of-uniaxial-compression-on-water-retention-hydraulic-conductivity-and-the,106747,0,2.html

Pandey, R. K., Maranville, J. W., & Chetima, M. M. (2000). Deficit irrigation and nitrogen effects on maize in a Sahelian environment: II. Shoot growth, nitrogen uptake and water extraction. *Agricultural Water Management, 46*(1), 15-27. https://doi.org/10.1016/S0378-3774(00)00074-3

Poesen, J., & Lavee, H. (1994). Rock fragments in top soils: Significance and processes. *Catena, 23*(1-2), 1-28. https://doi.org/10.1016/0341-8162(94)90050-7

Romano, N., & Santini, A. (2002). Water retention and storage: Field. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis: Part 4. Physical methods* (pp. 721-738). Soil Science Society of America. https://doi.org/10.2136/sssabookser5.4.c26

Richards, L. A. (1941). A pressure-membrane extraction apparatus for soil solution. *Soil Science, 51*(5), 377-386. https://doi.org/10.1097/00010694-194105000-00005

Robertson, B. B., Almond, P. C., Carrick, S. T., Penny, V., Eger, A., Chau, H. W., & Smith, C. M. S. (2021). The influence of rock fragments on field capacity water content in stony soils from hard sandstone alluvium. *Geoderma, 389*, Article 114912. https://doi.org/10.1016/j.geoderma.2020.114912

Sari-Gorla, M., Villa, M., Frova, C., Krajewski, P., & Di Fonzo, N. (1999). Genetic analysis of drought tolerance in maize by molecular markers. II. Plant height and flowering. *Theoretical and Applied Genetics, 99*(1-2), 289-295. https://doi.org/10.1007/s001220051234

Schönbeck, L. C., Schuler, P., Lehmann, M. M., Mas, E., Mekarni, L., Pivovaroff, A. L., Turberg, P., & Grossiord, C. (2022). Increasing temperature and vapour pressure deficit lead to hydraulic damages in the absence of soil drought. *Plant, Cell & Environment, 45*(11), 3275-3289. https://doi.org/10.1111/pce.14425

Sekucia, F., Dlapa, P., Kollár, J., Cerdà, A., Hrabovský, A., & Svobodová, L. (2020). Land-use impact on porosity and water retention of soils rich in rock fragments. *Catena, 195*, Article 104807. https://doi.org/10.1016/j.catena.2020.104807

Seguin, G. (1971). Influence des facteurs naturels sur les caractères des vins [Influence of natural factors on the characteristics of wines]. In J. Ribéreau-Gayon & E. Peynaud (Eds.), *Sciences et techniques de la vigne* (Vol. 1, pp. 671-725). Dunod.

Tétégan, M., Nicoullaud, B., Baize, D., Bouthier, A., & Cousin, I. (2011). The contribution of rock fragments to the available water content of stony soils: Proposition of new pedotransfer functions. *Geoderma, 165*(1), 40-49. https://doi.org/10.1016/j.geoderma.2011.07.001

Tian, J., & Philpot, W. D. (2015). Relationship between surface soil water content, evaporation rate, and water absorption band depths in SWIR reflectance spectra. *Remote Sensing of Environment, 169*, 280-289. https://doi.org/10.1016/j.rse.2015.08.007

Torres-Ruiz, J. M., Diaz-Espejo, A., Morales-Sillero, A., Martín-Palomo, M. J., Mayr, S., Beikircher, B., & Fernández, J. E. (2013). Shoot hydraulic characteristics, plant water status and stomatal response in olive trees under different soil water conditions. *Plant and Soil, 373*(1-2), 77-87. https://doi.org/10.1007/s11104-013-1774-1

van Wesemael, B., Poesen, J., de Figueiredo, T., & Govers, G. (1996a). Surface roughness evolution of soils containing rock fragments. *Earth Surface Processes and Landforms, 21*(5), 399-411. https://doi.org/10.1002/(SICI)1096-9837(199605)21:5%3C399::AID-ESP567%3E3.0.CO;2-M

van Wesemael, B., Poesen, J., Kosmas, C. S., Danalatos, N. G., & Nachtergaele, J. (1996b). Evaporation from cultivated soils containing rock fragments. *Journal of Hydrology, 182*(1-4), 65-82. https://doi.org/10.1016/0022-1694(95)02931-1

Wang, X., Li, Z., Cai, C., Shi, Z., Xu, Q., Fu, Z., & Guo, Z. (2012). Effects of rock fragment cover on hydrological response and soil loss from Regosols in a semi-humid environment in South-West China. *Geomorphology, 151-152*, 234-242. https://doi.org/10.1016/j.geomorph.2012.02.008

Zargar, S. M., Gupta, N., Nazir, M., Mahajan, R., Malik, F. A., Sofi, N. R., Shikari, A. B., & Salgotra, R. K. (2017). Impact of drought on photosynthesis: Molecular perspective. *Plant Gene, 11*, 154-159. https://doi.org/10.1016/j.plgene.2017.04.003