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Assessment of the Impact of Degree of soil compactness Indicator on Soil Hard-Setting Index and Soil Water Retention Curve in Gypsum-Containing Soils

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ABSTRACT

The insufficient planting materials and lack of technical know-how of *V. volvacea* cultivation is the one of the major problem on technology transfer for mushroom production. This research study was conducted to validate and evaluate the performance of *Volvariella volvacea* with different nutrient sources and substrates. This study was composed of two-parts, mycelial growth performance with different growing media (Study 1) and yield, N-analysis and income potential (Study 2). Study 1 was a single-factor experiment conducted in a randomized complete block design (RCBD) and Study 2 used 3x5 factorial experiment also in RCBD. Test for significant differences among treatment means was done analysis of variance (ANOVA) and pairwise comparison was done with Least Significant Difference test (LSD). Analysis was facilitated by the use of statistical software. Sweet potato has the higher potential as growing media for pure culture of *V. volvacea* fungal inoculation. Some characteristics such as pinhead size, stipe length and biological efficiency were affected by nutrient supplement and kind of substrate. However, the most important variable which is yield was affected by substrate only. Regardless of the nutrient sources *V. volvacea* will grow under different substrates such as banana leaves, corn bagasse, water hyacinth and rice straw except wood shavings. Total nitrogen content converted into protein (%) was undertaken to determine its component for various purposes. Biological efficiency of substrates was higher with banana leaves, rice straw and water hyacinth is significantly different as it is supplemented with inorganic fertilizer (urea) or no nutrient added. Mushroom production under different substrates supplemented with inorganic fertilizer can give promising income. Further research and exploration on the commodity may be conducted to ensure higher efficiency in production that can be used for community acceptability, thus, contribute to increasing the supply of mushroom. As a viable enterprise, mushroom production can be engaged by farmers and households for socioeconomic upliftment.

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KEYWORDS: Degree of soil compactness Indicator ,Hard-Setting , Soil Moisture Retention Curve, Gypsiferous soils

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INTRODUCTION

Gypsum soils are considered to be rigid and stable when in their natural (dry) state, making it difficult or impossible to cultivate them unless they are rehydrated (AL-Kayssi, 2021). It is well-known that these soils cause numerous problems during irrigation, as gypsum dissolves in water, leaving voids and cavities, and leading to an increase in soil compaction. This, in turn, results in soil hardening. Despite this, few studies have been conducted in this area, particularly regarding plant root growth and its relationship with the soil stiffness index and critical apparent soil density. The severe hardening observed in gypsum soils causes several problems that reflect on tillage, root development, and plant growth. This impact may be primarily because of The water bridges formed by soil particles continue to exist between those particles throughout dry conditions. Laboratory tests indicate that the gypsum content and soil moisture level impact soil hardness directly. Soils seem to get denser when their moisture content decreases yet their apparent density increases. These soil types become more easily compacted with repeated heavy machinery activity during farming operations according to (Dexter, 2004) because equipment leaves imprints between soil grains after the soil surface dries according to Dexter (2004b). Field observations showed that gypsiferous soils develop compacted characteristics when they become drier since both their bulk density increases while gypsum content decreases. The soil develops greater soil hardness by reducing its gypsum concentration. These soils become more vulnerable to compaction because mechanical harvest operations along with transportation create significant and widespread activity in the fields. Soil compactness coupled with increasing bulk density from mechanical harvest constitute the main agricultural production challenge found in modern gypsiferous soil farming (AL-Kayssi and Mustafa, 2016). Soil compaction refers to the compression of unsaturated soil, which results in a decrease in the relative volume of air. The fundamental mechanism of soil compaction is the reduction in soil porosity through the partial expulsion of one or both permeable fluids—air and water—from the compacted soil mass. In agricultural practice, soil is considered as a medium for plant growth, and therefore, compaction due to mechanization should be avoided as much as possible, as it makes the soil unsuitable for crop production (Hillel, 1980). The primary effect of soil compaction is an increase in apparent density, which brings soil particles closer together, resulting in a higher mass per unit volume. This reduces the pore spaces filled with water and air, especially the larger pores responsible for the movement of both water and air within the soil, thus reducing the soil's ability to allow water infiltration and increasing surface runoff, leading to water erosion. Root growth in compacted soils is also restricted, extending horizontally, and unable to meet the plant's water and nutrient needs beneath the compacted soil, thereby limiting plant growth (Wolkowshi and Lowery, 2008). Silva et al. (2008) indicated that soil compaction is one of the key processes that directly affect soil structure, as it leads to a reduction in porosity and an increase in apparent density, which impacts the moisture retention curve and soil behavior in terms of water retention and permeability. Aimrun et al. (2004) mentioned an inverse relationship between soil moisture content, apparent density, and soil compaction degree. As the apparent density and compaction degree decrease, the moisture content in the soil increases, due to the closer packing and shrinking of soil particles with reduced moisture content.

The primary objectives of the current investigation were to: Assessment of Impact Degree of soil compactness Indicator on the soil moisture retention curve (SMRC), which represents the relationship between soil water content and water potential, and explain how this relationship changes with increasing soil density. Also study the effect of soil compaction degree (DC%) on the soil Hard-Stening index (H-index) for different soil models with gypsum content (G1-G7).

MATERIALS AND METHODS

Soil samples were obtained from a gypsum-dominated site situated at the Agricultural Research Station of the College of Agriculture, University of Tikrit, located at coordinates 43°38'23" E longitude and 34°40'48" N latitude, with an elevation of 250 meters above sea level. The samples were collected from the surface horizon, at a specified depth of (0-0.1 m), where the gypsum content was 60.12 g kg^{-1}, and from the gypsum horizon at a depth of (0.6-1 m), where the gypsum content was 414 g kg^{-1} (G7). Different soil samples were prepared with varying gypsum contents of (G2) 111, (G3) 155, (G4) 219, (G5) 263, and (G6) 362 g kg^{-1}. These soil samples were prepared The surface soil sample (G1) was mixed with the subsurface horizon (G7) to prepare the composite soil samples. These samples were then moistened by spraying water to achieve approximately two-thirds of their field capacity. The samples were placed in tightly sealed plastic bags and incubated with daily mixing for two months to maintain uniformity and ensure homogeneity. After the incubation period, the soil samples were air-dried, sieved through a 2 mm mesh, and subsequently stored in plastic containers for subsequent experiments. Approximately 200 g of soil from each gypsum soil sample (G1-G7) was taken, then moistened to various gravimetric moisture levels of 5%, 10%, 15%, 20%, 25%, and 30%. The samples were thoroughly mixed and stored in suitable plastic bags to ensure uniform moisture distribution in each soil sample. The compaction process was carried out for each soil sample (G1-G7) at the aforementioned moisture contents using a Proctor compaction device (Proctor bulk density) in metal rings with a diameter of 6.1 cm and a height of 2 cm. The compaction was done with 25 blows using a 2 kg weight over a distance of 500 mm (ASTM Standard, 2007). The Proctor density (Refrence density), which is the highest apparent density at a specific moisture content, was determined using the following equation:

$$Refrence\ bulk\ density(BD_{ref.}) = \frac{dry\ wight\ of\ compacted\ soil}{dry\ \ volume\ of\ compacted\ soil} \qquad ....1$$

If : $Refrence\ bulk\ density(BD_{ref.})$: (Proctor density).

Dry weight of compacted soil: Dry weight of the compacted soil (g).

Dry volume of compacted soil: Dry volume of the compacted soil (cm^3).

The apparent density (natural) was calculated using the following equation:

$$2............ \qquad \frac{M_s}{V_b}\ \mathrm{BD} =$$

BD=Apparent density (Mg m−3).

M_s=Mass of dry soil (Mg).

V_b=Apparent volume of soil (m3).

The measurement of bulk density does not effectively indicate the level of compaction (based on Dexter et al., 2007 research). RBD serves as a valuable measure of compactness since it represents BDnatural divided by BDref. (Håkansson, 1990;Reichert et al., 2009) (Eq. (3)):

$$RBD = \frac{BD_{natural}}{BD_{(ref.)}} \quad \text{……………3}$$

The Proctor standard test determined BDref as its maximum dry bulk density value. (Håkansson, 1990; Reichert et al., 2009). According to Hakansson(1990) the degree of compactness concept (DC) represents the relative density measurement in %. The experiment analyzed the connection between compaction methods and the hardsetting process.

$$Dc = \frac{BD_{natural}}{BD_{(re.)}} \times 100\% \quad \text{…………………4}$$

The moisture content for each soil sample was determined after compacting them to apparent densities of 1.4, 1.5, 1.6, and 1.8 Mg m-3. A suitable amount of soil was moistened to a moisture content corresponding to 100 kPa and left for two days in tightly sealed nylon bags to ensure uniformity and distribution of moisture within the bag. The compaction of each soil sample to the above apparent densities was performed by determining the required weight of the soil sample to fill the metal ring, which had dimensions of 6.1 cm in diameter and 2 cm in height (Eq 5). The samples were moistened through capillary action for a period ranging from 4 to 8 days, depending on the soil's apparent density, until the compacted soils reached the saturation point.

$$Soil\ mass(dry) = bulk\ density \times volume\ [(\frac{dimeter}{2})^2\ \pi \times height] \quad \text{………5}$$

The moisture content corresponding to a water potential of 100 kPa was selected for moistened soils based on a previous study (AL-Kayssi, 2021). At this moisture content, the soil is neither too dry for compaction nor too wet to cause the breakdown of soil aggregates before compaction. The Weighing moisture content of the compacted soils at suction pressures of 7, 33, 100, 200, 500, 1000, and 1500 kPa was determined using The methodology introduced by Klute (1986). As for the moisture content of the gypsum soil samples at suction pressures of 0 and 2 kPa, it was estimated by applying a water column suction using glass funnels with porous discs (centered glass funnels) with pore sizes of 20 micrometers. A moisture retention curve was then plotted for the compacted gypsum soil samples, which links The relationship between gravimetric moisture content and suction pressure is influenced by the soil's moisture content The van Genuchten (1980) function with Mualem (1976) restriction The gravimetric water retention data were analyzed and fitted using the RETC software (van Genuchten et al., 1991).

$$w(h) = w_r + (w_s - w_r)[1 + (\alpha h)^n]^{[\frac{1}{n}-1]} \quad \text{…………6}$$

In the pressure head (h) range of 1–15,000 kPa (Dexter et al., 2008), w_s and w_r represent the fitted saturated and residual soil water contents (kg kg−1). respectively. The parameter α is a scaling factor (kPa−1), whereas n is a shape determines that governs the form of the fitted water retention curve. These fitting parameters were utilized to calculate the coordinates of inflection point of moisture retention curve were calculated using the relevant parameters, as described by Dexter (2004a).from the following equations:

$$w_i = w_r + (w_s - w_r)\left(\frac{2n-1}{n-1}\right)^{[\frac{1}{n}-1]} \quad \text{……………..7}$$

$$\text{8…………..} \quad h_i = \frac{1}{\alpha}\left[\frac{n}{n-1}\right]^{\frac{1}{n}}$$

where hi and wi represent the matric suction (kPa) and water content (kg kg^{-1}) at the inflection point of the semi-logarithmic water retention curve, respectively.. H_{index} was determined using the following equations (Dexter, 2004a, b; RETC, 2008):

$$\text{………. 9}\ H_{index} = \left[\frac{d\sigma}{dw}\right]_i = \left[\frac{h_i}{w_s}\right]\left[1 + \frac{w_i}{s}\right]$$

where σ' The effective stress in unsaturated soils is influenced by matric suction. The HDexter (kPa) index is a measure of soil hard-setting behavior, defined by the rate at which the effective stress (σ') changes with respect to a unit change in water content (w) at the inflection point.

Estimation of Selected Physical and Chemical Properties of Soil Samples

The soil samples were air-dried, ground, and sieved through a mesh with 2 mm openings. Several physical and chemical properties of the study site were then analyzed. estimated, as shown in Table 1:

Table 1: Some Physical and Chemical Properties of Soil Samples

Property	G1	G2	G3	G4	G5	G6	G7
Texture	Loamy	Loamy	Loamy Sand	Loamy Sand	Loamy Sand	*	*
Sand ($g\ kg^{-1}$)	455	492	531	555	637	*	*
Silt ($g\ kg^{-1}$)	325	296	288	275	262	*	*
Clay ($g\ kg^{-1}$)	220	212	181	170	101	*	*
Gypsum content ($g\ kg^{-1}$)	60.12	111	155	219	263	362	474
Apparent density ($Mg\ m^{-3}$)	1.414	1.369	1.313	1.221	1.182	1.143	1.093
Calcium carbonate ($g\ kg^{-1}$)	236.9	212.7	181.9	167.4	123.6	93.6	64.7
pH (1:1)	7.37	7.47	7.66	7.80	7.88	7.91	7.99
Electrical conductivity ($dS\ m^{-1}$)	3.96	3.83	3.70	3.49	3.28	3.13	2.91
Organic matter ($g\ kg^{-1}$)	13.6	12.5	10.7	9.4	7.2	5.5	2.6

* It was not possible to estimate the texture for the soil samples G6 and G7 due to coagulation resulting from the high gypsum content.

The texture was determined according to the developed method for gypsum soils by Pearson et al. (2015). The gypsum content in soil samples was estimated using the method described by Lagerwerff et al. (1965) and modified by Al-Zubaidi et al. (1981). The apparent density was determined using the core method as proposed by Black and Hortge (1986). Calcium carbonate was estimated by calculating the weight loss of CO_2 after treating the soil with 3 N HCl (Richards, 1954). The pH was measured in a soil:water extract (1:1) using a pH-meter (Richards, 1954). Electrical conductivity (EC) was measured in a soil:water extract (1:1) using an EC-meter (Richards, 1954). Organic matter was determined by the Walkley and Black method as outlined in Richards (1954).

RESULTS AND DISCUSSION

Figure (1) shows Soil Water Retention Curve (SWRC) measured and calculated soil moisture retention curves for the relationship between soil water tension (ϕ) and volumetric water content (Θ) for soil samples with different gypsum contents (G1-G7) and compacted to bulk densities of 1.4, 1.5, 1.6, and 1.8 $Mg\ m^{-3}$. The van Genuchten equation (1980) was used to fit the moisture retention data for each gypsum soil sample. It is observed that the volumetric water content decreases as the soil is compacted, with higher bulk density and increased water tension applied to all gypsum soil samples. For example, the volumetric water content for the G1 soil sample at the saturated water tension (0 kPa) decreased from 0.445, 0.418, 0.403, and 0.383 $kg\ kg^{-1}$ for bulk densities of 1.4, 1.5, 1.6, and 1.8 $Mg\ m^{-3}$, respectively. The reason for the decrease in volumetric water content for the same soil sample at the same water tension values is attributed to the reduction in the volume of large and medium-sized pores due to soil compaction, resulting in the dominance of small pores and relatively medium pores, leading to a decrease in water content in the soil. In other words, water retention decreases with increasing bulk density of the soil, as water retention decreases with increasing bulk density of compacted soils at low and medium water tensions for bulk densities ranging from (1.2–1.7 $Mg\ m^{-3}$) (Farahani et al., 2019). Also, the volumetric water content of the soil samples decreased with the increase in gypsum content. For example, the volumetric water content at a water tension of 33 kPa and a bulk density of 1.4 $Mg\ m^{-3}$ was 0.305, 0.285, 0.269, 0.26, 0.24, 0.225, and 0.219 $kg\ kg^{-1}$ for soil samples G1, G2, G3, G4, G5, G6, and G7, respectively. The reason for the reduced water retention capacity of the soil is attributed to the increased content of sand particles in the soil at the expense of clay particles (Table 1), which consequently reduced the pores responsible for water retention (Dexter, 2004).

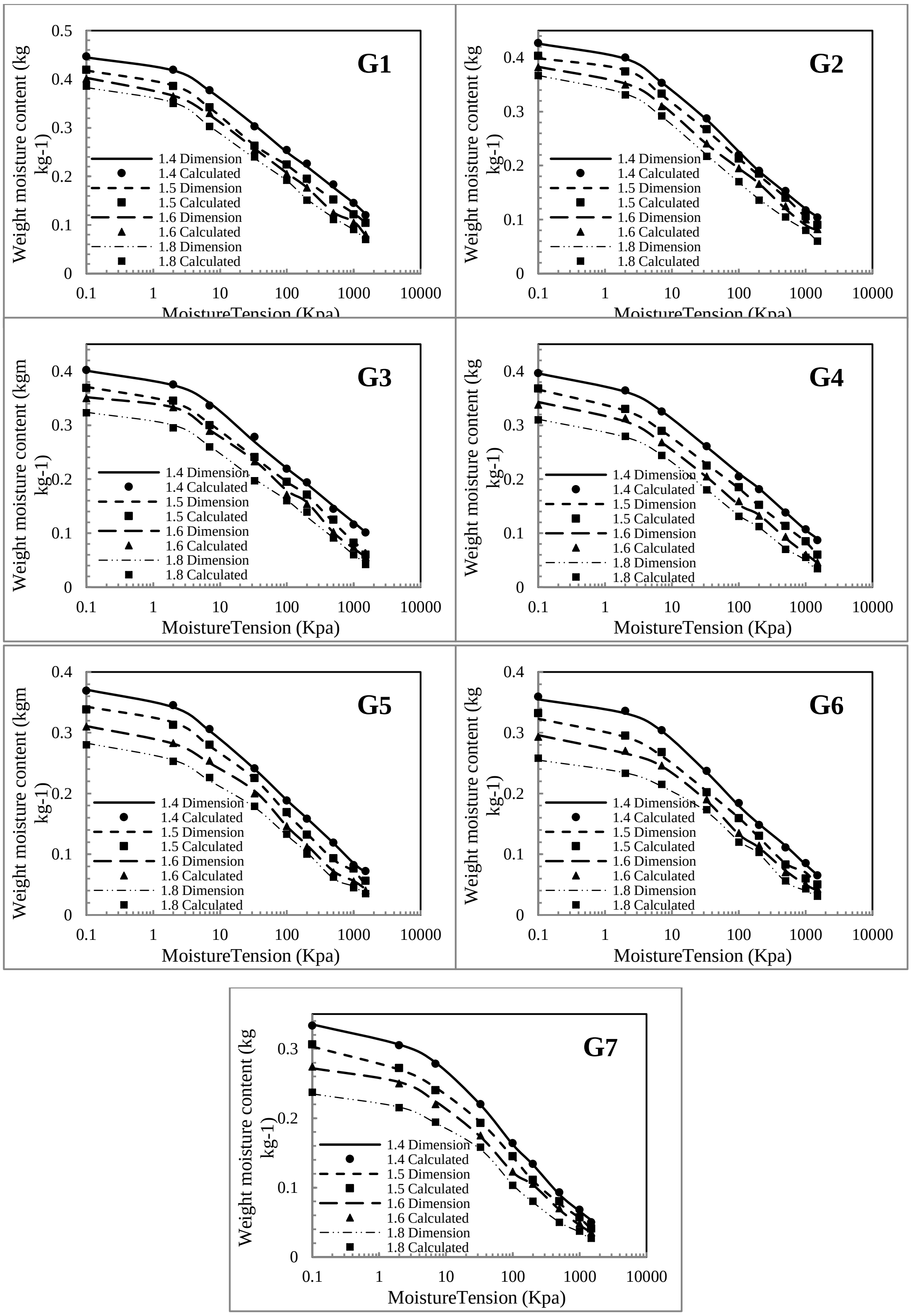

Figure 1. Measured and calculated Soil Water Retention Curve (SWRC) using the van Genuchten equation (1980) for soil samples G1-G7 compacted to bulk densities of 1.4, 1.5, 1.6, and 1.8 Mg m⁻³.

Figure 2. shows the effect of soil gypsum content on soil Hard-Setting index (H-index). The H-index decreased with increasing gypsum content in the soil. Specifically, the reduction was 6.17%, 13.38%, 24.56%, 22.67%, 14.08%, and 24.47% for gypsum soil samples G2-G7 compared to soil sample G1, respectively, at a bulk density of 1.4 Mg m^{-3}. As gypsum content increases in the soil, it forms a weak crystalline layer between soil particles, leading to reduced cohesion. The ability of gypsum to bind soil particles is limited due to the inherent instability of gypsum crystals. This instability leads to a reduction in the soil's mechanical strength, particularly when the soil undergoes drying. (Al-Kayssi, 2016). The figure also shows an increase in H-index values with higher calcium carbonate content in the soil (Table 1). The highest value for the H-index (7889) was recorded for the gypsum soil sample G1 at a bulk density of 1.8 Mg m^{-3}, where the calcium carbonate content was 236.9 g kg^{-1}. Calcium carbonate enhances soil hardness and compaction by acting as a natural binding agent. Over time, calcium carbonate interacts with water and air to form natural

cementing materials, which increase soil stiffness (Farahani et al., 2019). Additionally, the figure highlights the increase in H-index values with higher bulk density for all compacted gypsum soil samples. In high-density soils, the amount of trapped water is reduced, leading to faster drying and the formation of stronger bonds between soil particles (such as physical and chemical bonds between soil minerals). This results in greater soil compaction. Increased soil compaction raises the bulk density, thus increasing the H-index due to the removal of air from the soil, changes in soil structure, reduced pore volume, and changes in pore size distribution, ultimately increasing soil stiffness (Taylor, 1971).

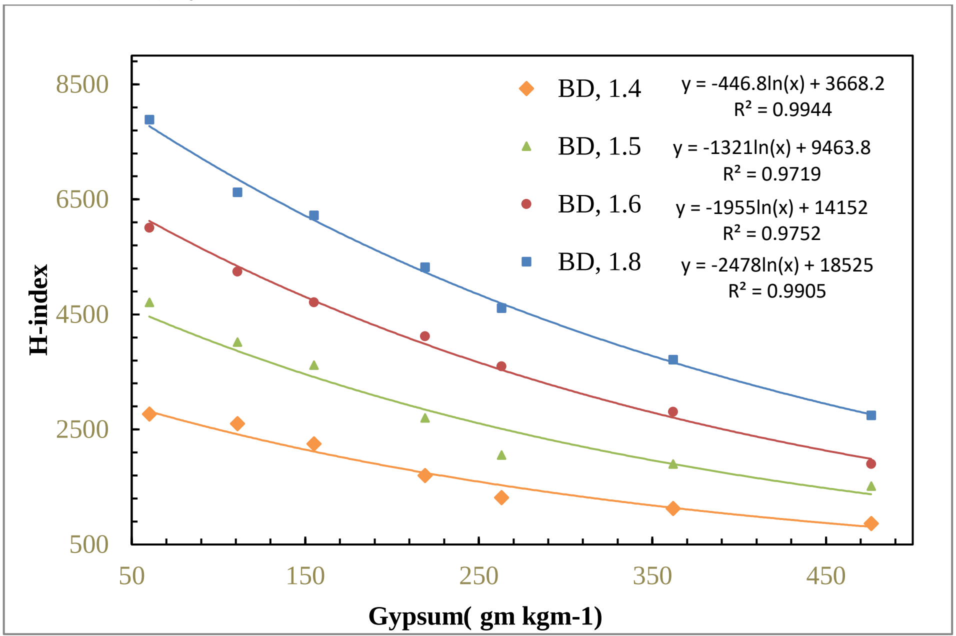

Figure 2: Effect of gypsum content on the compaction index (H-index) for compacted gypsum soil samples (G1-G7(.

Figure 3. The positive polynomial correlation between the Degree of Soil Compactness Indicator (DC%) and the Hard-Setting Index (H-index) indicates that an increase in soil compactness is associated with a rise in the Hard-Setting Index. It can be observed that the H-index increased with the increase in the DC% indicator. The values of the soil compaction index increased by 14.57%, 11.32%, 14.26%, 14.53%, 28.43%, and 47.47% for soil samples (G2-G7) compared to the G1 sample at a bulk density of 1.6 g/cm³. One of the main reasons for the increased soil compaction with higher DC% is the increase in the calcium carbonate content in the soil (Table 1), as calcium carbonate can slightly enhance water retention in the soil. This suggests that the higher The effective stress in carbonated soils is partly attributed to their increased water retention capacity. These two factors can explain the increase in soil hardness and compression indicators with the increase in calcium carbonate content and the decrease in these indicators with The rise in gypsum content within the soil (Mosaddeghi and Mahboubi, 2011).

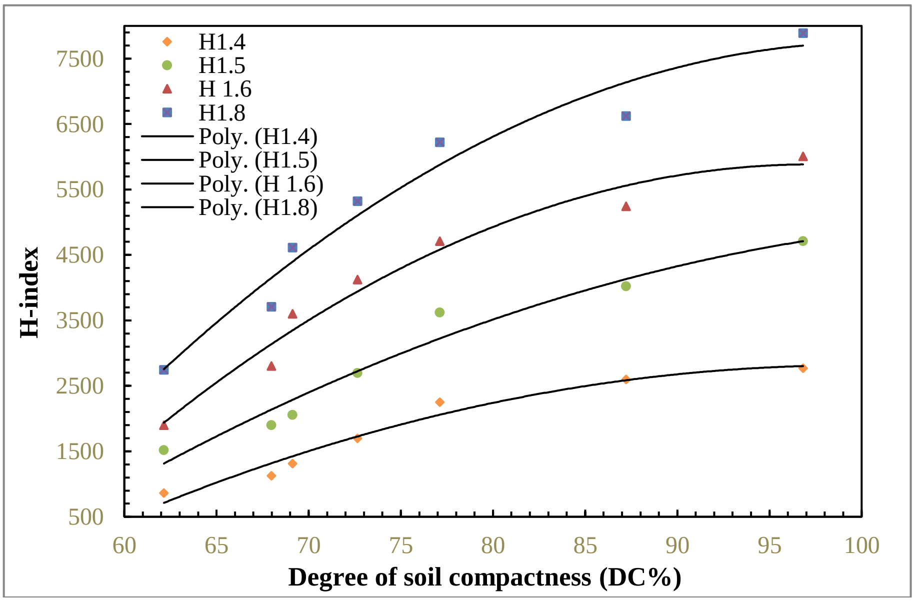

Figure 3. Relationship between (H-index) and the Degree of Soil Compaction (DC%) for bulk densities of 1.4, 1.5, 1.6, and 1.8 Mg m-3 for gypsum soil.

i. Figure4. Shows Relationship between the Hard-Setting Index (H-index) and bulk densities of compacted soils. It is observed that the H-index values increase with the bulk density. For example, the increase for the gypsum soil sample G2 was 70.04%, 27.51%, and 31.31% for bulk densities of 1.4-1.7 mg m-3 compared to a bulk density of 1.8 mg m-3. This can be attributed Soil compaction causes both physical and frictional enhancements through its influence on particle contact points making the particles resist movement better (Vepraskas, 1984). Observational data demonstrate that this phenomenon results from pore size distribution effects that control changes in effective stress produced by internal pressures. It is noted that the H-index values increase with increasing bulk density and relative bulk density. This is also due to the increased degree of compaction, which makes the soil more susceptible to hardening. When soil is compacted or formed, the pore structure is crushed, leading to an increase in the mechanical strength of the soil and an increase in its bulk density due to effective pressures arising from internal forces, thus increasing the tendency of the soil to harden (Dexter2004a).

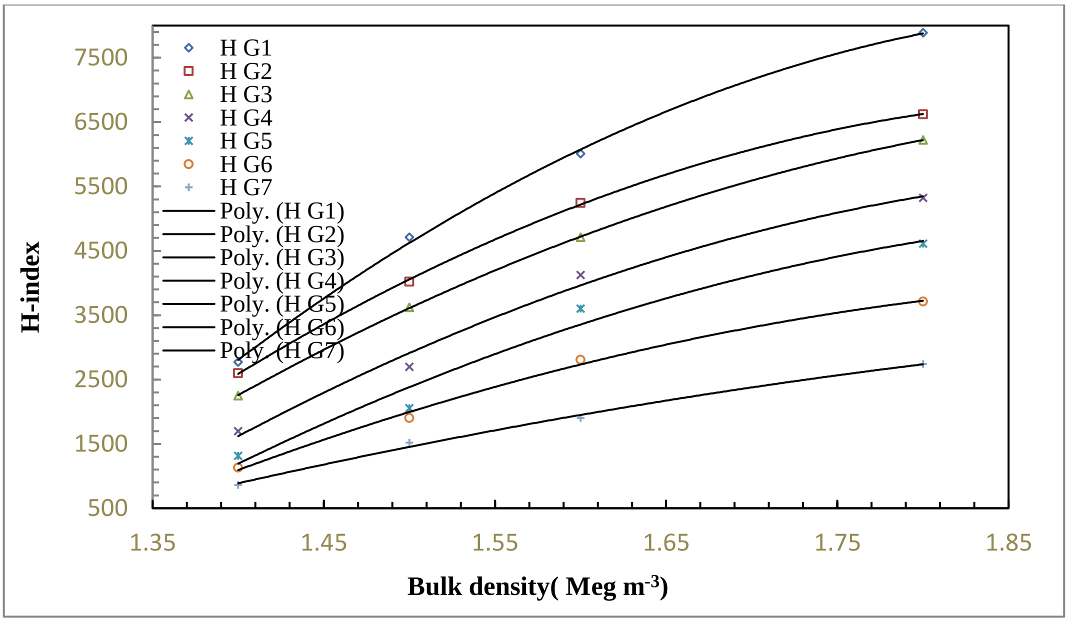

Figure 4. The relationship between the bulk density of compacted soil and (H-index) for gypsum soil samples (G1-G7).

Figure 5. The negative logarithmic relationship between gypsum content and soil compactness degree (DC%) with a high determination coefficient of 0.9726 (R^2). The compactness degree (DC%) decreased with increasing gypsum content in the soil for all gypsum soil samples. The lowest compactness degree value of 62.174 was observed for the gypsum soil sample G7, with a gypsum content of 476 g kg-1, while the highest compaction degree was observed for the gypsum soil sample G1, with a gypsum content of 60.12 g kg-1. This could be attributed to the higher natural bulk density and relative bulk density at lower gypsum content, and the decrease in both densities with increasing gypsum content in the soil. The compaction degree is correlated with both densities, as shown in Equation 4. These findings align with those reported in previous studies by Al-Kayssi (2021).

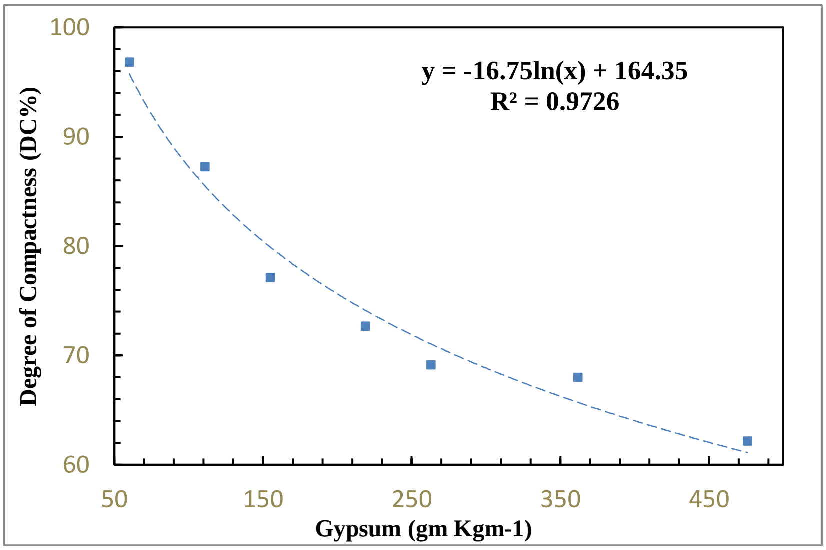

Figure 5: The relationship between gypsum content and soil compactness degree (DC%).

Table 2 shows the values of the Soil Hard-Setting Index (H-index) for gypsum soil samples G1-G7. The highest value of the hardness index was obtained for the gypsum soil sample G1, where the gypsum content was 60.12 g kg-1, and the bulk density was 1.8 mg cm-3, which corresponds to the highest compaction degree index value of 96.822. The lowest value of the H-index was observed for the gypsum soil sample G7, with a gypsum content of 476 g kg-1, at a bulk density of 1.4 mg cm-3 and the lowest compaction degree index. The compaction degree index is strongly and positively correlated with the H-index, while the H-index is negatively correlated with the gypsum content of the soil (Al-Kayssi, 2021).

Table 2. Values of Soil Hardness Index (H-index) and Soil Compaction Degree Indicator

H-index				Degree of soil compactness Indicator (DC%)	Gypsum Soils gm kg-1	Sample
BD, 1.8	BD, 1.6	BD, 1.5	BD, 1.4			
7889	6008	4712	2771	96.822	60.12	G1
6622	5244	4022	2600	87.233	111	G2
6222	4711	3622	2252	77.124	155	G3
5321	4123	2699	1699	72.652	219	G4
4612	3600	2055	1314	69.124	263	G5
3712	2805	1900	1129	67.982	362	G6
2744	1902	1517	864	62.147	476	G7

CONCLUSIONS

1. The Soil Water Retention Curve (SWRC) decreases for different water tensions as the bulk density increases when the soil is compacted to densities of 1.4, 1.5, 1.6, and 1.8 Mg m^{-3}, and with increasing gypsum content in the soil.
2. The values of the Soil Hard-Setting Index (H-index) increase with an increase in the Soil Compactenss Degree Indicator (DC%) and with an increase in the calcium carbonate content in the soil, while the H-index decreases as the gypsum content in the soil increases.
3. The Soil Hard-Setting Index (H-index) increases with the increase in the bulk density of the soil when compacted to the aforementioned densities.
4 .The Soil Compactenss Degree Indicator (DC%) decreases as the gypsum content in the soil increases.

REFERENCES

1. Aimrun, W., Amin, M. S. M., & Eltaib, S. M. (2004). Effective porosity of paddy soils as an estimation of its saturated hydraulic conductivity. Geoderma, 121(3-4), 197-203.
2. Al-Kayssi, A. W., & Mustafa, S. H. (2016). Modeling gypsifereous soil infiltration rate under different sprinkler application rates and successive irrigation events. Agricultural Water Management, 163, 66-74.
3. AL-Kayssi, A. W. (2021). Use of water retention data and soil physical quality index S to quantify hard-setting and degree of soil compactness indices of gypsiferous soils. Soil and Tillage Research, 206, 104805.
4. Al-Kayssi, A. W. (2016). Impact of successive wetting and drying cycles on some physical properties of gypsifereous soils. Journal of Agriculture Food and Development, 2, 5-15.
5. ASTM Standard D698, (2007). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM, International, West Conshohocken, PA
6. Blacke, G.R., and K.H. Hortge. (1986). In methods of soil Analysis, part1. Physical and Mineralogical Methods_ Agronomy Monograph no. 9 (2nd Edition), American Society of Agronomy_ Soil Science Society of America, 677, south segoe Road, Madison, WI 53711, USA.
7. Dexter, A. R., Czyż, E. A., Richard, G., & Reszkowska, A. (2008). A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma, 143(3-4), 243-253.
8. Dexter, A. R., Czyż, E. A., Richard, G., and Reszkowska, A.(2008). A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma, 143(3-4), 243-253.
9. Dexter, A.R., (2004a). Soil physical quality. Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120: 201–214.
10. Dexter, A.R., (2004b). Soil physical quality. Part II. Friability, tillage, tilth and hard-setting Geoderma 120: 215–225.
11. Farahani, E., Mosaddeghi, M. R., Mahboubi, A. A., and Dexter, A. R. (2019). Prediction of soil hard-setting and physical quality using water retention data. Geoderma, 338, 343-354.

12. Håkansson, I. (1990). A method for characterizing the state of compactness of the plough layer. Soil and tillage research, 16(1-2), 105-120.
13. Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York.
14. Klute, A. (1986). Water retension: Laboratory method of soil analysis Part 1, Physical and Mineralogical Method, 2nd ed. Edited. P.635-660.
15. Lagerwerff, J. V., G.W. Akin, S.W. Moses. 1965. Detection and determination of gypsum in soils. Soil Sci. Soc. Am. Proc. 29(5): 535-540.
16. Mosaddeghi, M. R., Morshedizad, M., Mahboubi, A. A., Dexter, A. R., and Schulin, R. 2009. Laboratory evaluation of a model for soil crumbling for prediction of the optimum soil water content for tillage. Soil and Tillage Research, 105(2), 242-250.
17. Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. Water resources research, 12(3), 513-522.
18. Pearson, M. J., Monteith, S. E., Ferguson, R. R., Hallmark, C. T., Hudnall, W. H., Monger, H. C., ... & West, L. T.(2015). A method to determine particle size distribution in soils with gypsum. Geoderma, 237, 318-324.
19. Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Håkansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil and Tillage Research, 102(2), 242-254.
20. RETC (RETention Curve), (2008). RETC model. USDA-ARS U.S. SalinityLaboratory,Riverside,CA,USA.
21. Richards, L.A. (1954). Diagnosis and Improvement of Saline and Alkali Soil. U. S. D. A. Handbook No-60. USA.
22. Silva, S. R. D., Barros, N. F. D., Costa, L. M. D., and Leite, F. P. (2008). Soil compaction and eucalyptus growth in response to forwarder traffic.
23. Taylor, H. M. (1971). Effects of soil strength on seedling emergence, root growth and crop yield. Compaction of agricultural soils, 292, 312.
24. Van Genuchten, M. V., Leij, F. J., & Yates, S. R. (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils.
25. Van Genuchten, M.TH. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44(5): 892-898.
26. Vepraskas, M. J. (1984). Cone index of loamy sands as influenced by pore size distribution and effective stress. Soil Science Society of America Journal, 48(6), 1220-1225.
27. Wolkowski, R., and Lowery, B. (2008). Soil compaction: Causes, concerns, and cures (A3367).