Using a pedotransfer (PTF) model to establish GIS-based maps for the main physical and hydraulic soil properties in the eastern region of the Al-Ahsa Oasis, Saudi Arabia

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Abstract

This study aims to produce digital maps showing the physical and hydraulic soil properties of the Al-Ahsa Oasis in Saudi Arabia by employing the capabilities of the GIS technique. These maps can display the pattern distribution of different physical and hydraulic properties of soil accurately and accessibly. Recently developed local pedotransfer function (PTF) models were applied to the basic soil data of earlier research covering 566 points. An analysis was conducted using a spatial interpolation technique of the GIS program. Maps of spatial patterns described essential soil physical and hydraulic properties such as sand%, silt%, clay%, bulk density ($\rho$), saturation ($\theta_s$), field capacity (FC), wilting point (WP), and soil water characteristic curve (SWCC) fitting parameters $b$, $c$, $d$. Sand dominates most of the study area, particularly in the northeast near Hufof. This may be attributed to the deposition of drifting sand and dune movement. Silt and clay increased in other locations. Bulk density $\rho$ was positively increased with sand and negatively with silt and CaCO$_3$ content. Soil hydraulic properties ($\theta$, FC, WP, and SWCC fitting parameters $b$, $c$, $d$) were positively correlated with silt and $\rho$ and negatively with sand content. This digital map can be employed for a general overview investigation, for the whole studied area, for agricultural expansion and for environmental studies.

1. Introduction

Globally, there has been an increased demand for soil data and information for quantitative environmental monitoring and modeling [1]. To effectively manage food production, environment, and ecosystems at field, catchment, regional, and continental scales, it is crucial to have accurate, up-to-date, and spatially referenced information [2–4]. A geographic information system (GIS), by itself or associated with satellite images, is an effective tool for organizing, analyzing, and presenting the horizontal spatial variables of the soil properties and conditions [4–7]. Soil specialists, irrigation engineers, environmental engineers, and geotechnical...
engineers can use GIS maps for preliminary assessments and final geotechnical designs [4, 8–13]. GIS tools can be used for the following purposes: integrating existing data with project-specific data, identifying potential environmental and geological hazards, planning and tracking fieldwork, producing maps and figures, and improving communication [14, 15]. Early in the design process, these tools can assist in identifying potential barriers that may hinder project completion or agricultural production and avoid costly rework later on [8, 11, 12, 16, 17].

Hydraulic soil properties are integral to hydrological quantification, agriculture resource management, managing pollution transport, geotechnical engineering for construction and road building, and construction of water resource infrastructure, e.g., dam and irrigation and drainage projects [18–20]. Moreover, the soil-water characteristic curve (SWCC) is considered the first step in assessment and the single dominant factor governing changes in the behavior of saturated and unsaturated soils for these applications [21, 22].

The adoption of the GIS technique for drawing an overall map depicting all the hydraulic soil properties (i.e., saturation $\theta_s$, saturated hydraulic conductivity $k_s$, field capacity FC, wilting point WP, and water holding capacity) and some other properties (compaction, soil penetration, etc.) have been reported in many studies during the last two decades [4, 12, 14–16, 23–29].

Al-Ahsa is one of the oldest agricultural settlements in the Arabian Peninsula, dating to 4000 B.C [30].

Today, Al-Ahsa is the largest agricultural area dominated by date palms, with more than three million trees [31]. Recent studies [32, 33] showed that the Al-Ahsa Oasis consists of two parts, the old and new oasis, with a total area of approximately 20,000 ha. It is L-shaped toward the north and east, of which 8200 ha are irrigated and divided into 25,000 farms. Therefore, this study employs the GIS technique to produce digital maps for the measured physical and hydraulic soil properties of the Al-Ahsa Oasis in Saudi Arabia. The resulting maps display the distribution and variability of soil physical and hydraulic properties accurately and easily accessible manner.

2. Material and methods

2.1. Study area

Al-Ahsa is located approximately 70 kilometers west of the Arabian Gulf, within latitude 25° 21’ and 25° 37’ N and longitude 49° 33’ and 49° 46’ E (Fig 1). The city of Hufof, the provincial capital, is situated in the southeast corner of the province at 150 meters above mean sea level (MAMSL). Towards the east and north, the slope drops to 105 MAMSL on the northern border and 122 MAMSL on the eastern border. Morphologically, the land surface of Al-Ahsa is flat except for the Al-Qarah Mountain, 13 km east of Hufof, which is composed of reddish-colored sedimentary rocks of the Upper Miocene to the Lower Pliocene Hufof Formation, which consists of calcareous sandstone, marl and clay.

The mountain has a flat top at 210 MAMSL, covering approximately 1400 hectares [34]. Outside the palm belt, the landscape is dominated by a mantle of eolian sand with a thickness of over 100 feet, interrupted by sabkha and low mesa, the strata of which are nearly horizontal. The great northern sabkhas, 6000 hectares, serve as catchment basins for highly saline drainage water that accumulates due to access irrigation [35]. The geological characteristics of Al-Ahsa outcrops consist of Tertiary and Quaternary period sedimentary rocks [34].

The pedogenesis and characteristics of soils in Al-Ahsa are determined by the extreme hot tropical climate, which evaporates the soil water and deposits the dissolved salts in the upper soil layers and across the whole profile as saline-sodic soil [36]. The soils of Al-Ahsa exhibit no profile development; they are composed of regosol deposits made up of transported particles.
Six great groups of regosols can be identified, namely Salorthids, Gypsiorthids, Caliciorthids, Psammaquants, Haplargids, and Torripsaments [37]. The area’s climate is characterized by six hot, dry months in the summer and six months of cold and wet in winter. The air temperature can exceed 45°C during the summer, whereas it may reach 5°C in winter. An annual average of 50mm of rainfall falls primarily during the winter [38]. Al-Ahsa’s eastern part was the subject of this study, encompassing 12,860 hectares divided between a residential area and farmland.

2.2. Soil sampling and laboratory analysis

The original soil data (Table 1) were provided by Elprince et al. [40]. The study area was divided into 566 grid cells (380 m × 500 m) to establish a strategy for soil sample collection. Fifty randomly selected soil cores (0–20 cm depth) were crushed and mixed into one sample to collect a composite sample. Samples were air-dried, ground, thoroughly mixed, and passed through a 2 mm sieve to element gravels. Soil texture (percent sand, silt, and clay) was determined following the standard method of the hydrometer [41]. Soil bulk density (\(\rho\)) was
determined using the well-tested local statistical equation (Eq 1) developed by Al-Saeedi (2022) [42] based on the percentage of silt.

\[
\rho (\text{g cm}^{-3}) = 1.5608 - 0.0064 \times \text{silt\%}
\]  

(1)

### 2.3. Soil hydraulic properties and SWCC PTFs

This study addresses the major soil hydraulic properties. Soil water characteristics curve fitting parameters based on an earlier work developed a parametric logistic regression equation (PL4) (Eq 1) and local pedotransfer functions (PTFs) to predict soil moisture at any point of soil retention started from saturation \( \theta_s \), field capacity FC, and wilting point WP (Eqs 2–8) [42]. The results provided excellent fitting and statistical significance [42]. The moisture content \( \theta \) at any soil potential \( \psi \) is written as:

\[
\theta (\psi) = c \left( \frac{a - d}{\psi - d} \right)^{\frac{1}{b}}
\]

(2)

where \( a, b, c, \) and \( d \) are statistical fitting parameters; \( a \) is the maximum value on the \( y \)-axis or estimated moisture \( \theta \) at zero suction (pF scale), which equals \( \theta_s \).

Other soil parameters estimation equations:

\[
\theta_s (\text{cm}^3.\text{cm}^{-3}) = 0.9668 - 0.4437 \times \rho
\]

(3)

\[
\text{FC (cm}^3.\text{cm}^{-3}) = -0.0210 + 0.5690 \times \theta_s
\]

(4)

\[
\text{WP (cm}^3.\text{cm}^{-3}) = 0.0056 + 0.2877 \times \theta_s
\]

(5)

\[
b = 7.3872 + 8.7090 \times \theta_s
\]

(6)

\[
c = 2.3356 - 4.9210 \times \theta_s + 9.3802 \times \text{FC}
\]

(7)

\[
d = 0.0264 - 0.5938 \times \text{FC} + 1.3663 \times \text{WP}
\]

(8)

### 2.4. GIS and interpolation method

GIS (geographic information system) is a computerized system with rules and procedures for analyzing and processing geographical information. These algorithms are utilized to link
geographical data to their coordinates, group data into layers, and then display the data on a map showing the geographical characteristics of an area. Because each sample point contains its own spatial and geotechnical data, these data are arranged and tabulated in an Excel sheet in a manner compatible with the ArcMap 10.4 software program.

Interpolation is the estimation of a value within two known values in a sequence of values; in other words, it is a method for predicting the values of the grid at specific locations where there are no data samples [43]. Because of the high density of data in the study area, the inverse distance weighting (IDW) method is the most suitable for dense data interpolation [43]. IDW is an exact fast deterministic interpolator, estimating values at unmeasured points by a linear combination of values at nearby measured points [44]. The two-dimensional interpolation aims to determine the parameter \( z \) in non-scaled locations based on a specific set of parameter measurements at other sites \( z_i \). The parameter \( z \) represents any of the soil properties. The IDW algorithm is based on the equation:

\[
Z_i = \frac{\sum_{j=1}^{N} Z_j d_i^{-n}}{\sum_{j=1}^{N} d_i^{-n}}
\]

where \( Z_0 \) is the estimation value of the variable \( z \) in point \( i \), \( z_i \) is the sample value in point \( i \), \( d_i \) is the distance of the sample point to the estimated point, \( N \) is the coefficient that determines weight based on distance, and \( n \) is the total number of predictions for each validation case [45].

3. Results and discussion

3.1. Soil texture

Sandy soil covers only 10% of the study area, while sandy loam and loamy sand comprise more than 85% of the total area, with silty loam and loam making up about 5%. According to Fig 2, the sand percentage ranges from 45 to 96.9%. In the northeast corner of the study area, near
Al-Omran city, toward Hufuf, the highest concentration of sand particles exists. This may refer to the deposition of drifting sand and dune movement, horizontally creeping 10 to 15 m annually [46–48].

The southwest part of the study area is also characterized by abundant sand deposits, which could be a continuation of the north wind effect and natural slope direction and aspect, as found by Elprince et al. [40]. The northwest corner and south showed the largest proportion of silt and clay where the area is not affected by sand drifting from the north. It is characterized by a relatively shallow soil profile with some influence of the shallow calcareous hardpan, which is rich in clay, silt, and CaCO$_3$. Silt content shown in Fig 3 ranges from 30% to less than 5%, with the highest concentration in the northwest corner. As shown in Fig 4, the clay percentage varies from 20% in a very rare location to less than 5% [46, 49].

3.2. Bulk density $\rho$

Fig 5, a density variation is correlated with the amount of sand and silt [42]. Areas with sandy texture soils, the northeastern corner and the southwest near Taraf, are characterized by densities ranging from 1.51 to 1.55 gm.cm$^{-3}$. In the northwest corner, an area with a high silt content, the $\rho$ value ranges between 1.46 and 1.43 gm.cm$^{-3}$. In the locations where a high CaCO$_3$ content is expected as high, especially near Al-Qara Mountain, due to the deposit of the solution of the mountain’s highly water-soluble rocks and south and southwest showed low $\rho$ values, 1.33 to 1.37 gm.cm$^{-3}$, which most probably due to the shallow sand layer and high CaCO$_3$ percentage. The low density of CaCO$_3$ can be referred to as the negative effects of CaCO$_3$ content in soil on bulk density $\rho$ values, which have been thoroughly studied and confirmed by numerous researchers [50, 51].

3.3. Saturation $\theta_s$

Saturation $\theta_s$ is highly affected by the ratio of pores and fine particles. Positive correlations always exhibited with silt% and clay% were due to increased pore ratio and, in contrast, a
negative correlation for $\rho$ and sand% [52–54]. As shown in Fig 6, $\theta_s$ ranges from 0.28 to 0.377 cm$^3$.cm$^{-3}$. A highly positive correlation of $\theta_s$ with the percentage of clay and silt is observed, which agrees with many other studies [52, 54, 55]. $\theta_s$ is generally low in oasis soils due to the dominant content of sand combined with rare clay [36, 42].

### 3.4. Field capacity FC and wilting point WP

Figs 7 and 8 show water content distribution at FC and WP. FC ranges between 0.194 and 0.138 cm$^3$.cm$^{-3}$, where the higher values are found at scattered locations in the studied
area, while low contents are found in the area extending within the northwest corner. In these areas, the silt fraction is dominant over sand. The same observation is made with WP. Both properties are negatively related to the value of sand and positively related to silt and saturation $\theta_s$—the pore volume ratio increases as the fine particles, silt, and clay increase. The soil body will store more moisture at FC and WP. Several publications have reported this relationship, showing a negative correlation with sand and a positive one with silt and clay [56, 57].

![Spatial pattern of saturation $\theta_s$ over Al-Ahsa.](https://doi.org/10.1371/journal.pone.0276259.g006)

![Spatial pattern of field capacity FC over Al-Ahsa.](https://doi.org/10.1371/journal.pone.0276259.g007)
3.5. Parameters $b$, $c$, and $d$

Eq (1) is based on the value of $(a)$, equal to $\theta_s$; thus, all factors affect saturation $\theta_s$, consequently affecting these fitting parameters. Figs 9–11 show the fitting parameter values in Eq (1). These results support the findings of another study [55]. A good illustration of SWCC can be made by applying Eq (1) to the map information at any given location, using the simple but robust GIS algebra function, which can be used to perform any spatial correspondence, relation, and geographic analysis.

Fig 8. Spatial pattern of wilting point WP over Al-Ahsa.
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Fig 9. Spatial pattern of $b$ over Al-Ahsa.
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4. Conclusions

GIS-based digital maps can provide field researchers with a rapid method for determining the SWCC and other physical and hydraulic soil properties at any location while maintaining high accuracy. The soil texture of the study area is dominated by sandy loam and loamy sand with $\theta_s$ less than 0.300 cm$^3$.cm$^{-3}$, FC less than 0.160 cm$^3$.cm$^{-3}$, and WP less than 0.098 cm$^3$.cm$^{-3}$.

Eq (1) parameter maps will be an excellent tool for estimating SWCC for agricultural and
geotechnical purposes. A detailed study is necessary to verify the accuracy of the overall values depicted on the maps.

Supporting information

S1 Data.
(XLSX)

Author Contributions

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References

1. Hong SY, Minasny B, Han KH, Kim Y, Lee K. Predicting and mapping soil available water capacity in Korea. PeerJ. 2013; 1(e71):1–20. https://doi.org/10.7717/peerj.71 PMID: 23646290

2. Batjes NH. Development of a world data set of soil water retention properties using pedotransfer rules. Geoderma. 1996 May; 71(1–2):31–52.

3. Dai Y, Shangguan W, Duan Q, Liu B, Fu S, Niu G. Development of a China dataset of soil hydraulic parameters using pedotransfer functions for land surface modeling. J Hydrometeorol. 2013; 14(3):869–87.

4. Jayasuriya H, Al-adawi S, Wardy M al. GIS Mapping of Soil Compaction and Moisture Distribution for Precision Tillage and Irrigation Management. In: The 12th International Conference on Precision Agriculture. Sacramento, CA, USA, 20–23 July; 2014.

5. Zhao T, Shi J, Lv L, Xu H, Chen D, Cui Q, et al. Soil moisture experiment in the Luan River supporting new satellite mission opportunities. Remote Sens Environ. 2020 Apr 1; 240:111680.

6. Tian H, Huang N, Niu Z, Qin Y, Pei J, Wang J. Mapping winter crops in China with multi-source satellite imagery and phenology-based algorithm. Remote Sens (Basel). 2019; 11(7):1–23.

7. Tian H, Pei J, Huang J, Li X, Wang J, Zhou B, et al. Garlic and winter wheat identification based on active and passive satellite imagery and the google earth engine in northern China. Remote Sens (Basel). 2020; 12(21):1–17.

8. Aldefae AH, Mohammed J, Saleem HD. Digital maps of mechanical geotechnical parameters using GIS. Cogent Eng. 2020; 7(1779563).

9. Adam J, Saleh S, Olowosulu AT, Ashara AH, Srividhya S. Mapping of Soil Properties Using Geographical Information System (GIS): A Case Study of Hassan Usman Katsina Polytechnic. Open Journal of Civil Engineering. 2018; 08(04):544–54.

10. Omran ESE. Improving the Prediction Accuracy of Soil Mapping through Geostatistics. International Journal of Geosciences. 2012; 03(03):574–90.

11. Player R S V. Geographic Information System (GIS) Use in Geotechnical Engineering. In: GeoCongress 2006. Reston, VA, USA: American Society of Civil Engineers; 2006. p. 1–6.

12. Mohammed Ali H, Shakir RR. Geotechnical map of Thi Qar governorate using geographical information systems (GIS). In: Materials Today: Proceedings. Elsevier Ltd; 2021.

13. Khatri S and SS. Mapping of Soil Geotechnical Properties Using GIS. In: Indian Conference on GEO-TECHNICAL AND GEO-ENVIRONMENTAL ENGINEERING (ICGGE-2019) [Internet]. MNMIT Allahabad, Prayagraj, India, March 01–02; 2019. https://www.researchgate.net/publication/339109231_MAPPING_OF_SOIL_GEO_TECHNICAL_PROPERTIES_USING_GIS

14. Wan-Mohammad WNS, Abdul-Ghani AN. The use of geographic information system (GIS) for geotechnical data processing and presentation. Procedia Eng. 2011; 20:397–406.

15. Mohammed MS, Hasan MF, Al-Bayati KS. Geotechnical maps for Salah Al-Deen-Iraq. IOP Conf Ser Mater Sci Eng. 2020; 737(012224).
16. Ahmed C, Mohammed A, Tahir A. Geostatistics of strength, modeling and GIS mapping of soil properties for residential purpose for Sulaimani City soils, Kurdistan Region, Iraq. Model Earth Syst Environ. 2020; 6(2):879–93.
17. Kravchenko A, Bullock DG. A comparative study of interpolation methods for mapping soil properties. Agron J. 1999; 91(3):393–400.
18. Zapata CE. Uncertainty in Soil-Water-Characteristic Curve and Impacts on Unsaturated Shear Strength Predictions. Ph.D. Thesis, Arizona State University, Tempe, AZ, USA; 1999.
19. Fredlund DG, Rahardjo H, Fredlund MD. Unsaturated Soil Mechanics in Engineering Practice. Hoboken, NJ, USA: John Wiley and Sons Inc; 2012.
20. Hillel D. Introduction to Environmental Soil Physics. 1st ed. Elsevier; 2003.
21. Fredlund DG, Fredlund MD. Application of ‘estimation procedures’ in unsaturated soil mechanics. Geosciences (Switzerland). 2020; 10(9):1–22.
22. Fredlund DG, Houston SL. Protocol for the assessment of unsaturated soil properties in geotechnical engineering practice. Canadian Geotechnical Journal. 2009; 46(6):694–707.
23. Piedallu C, Gégout JC, Bruand A, Seynave I. Mapping soil water holding capacity over large areas to predict potential production of forest stands. Geoderma. 2011; 160(3–4):355–66.
24. Wu X, Lu G, Wu Z, He H, Zhou J, Liu Z. An integration approach for mapping field capacity of China based on multi-source soil datasets. Water (Switzerland). 2018; 10(728).
25. Srivastava PK, Pandey PC, Petropoulos GP, Kourgialas NN, Pandey V, Singh U. GIS and remote sensing aided information for soil moisture estimation: A comparative study of interpolation techniques. Resources. 2019; 8(70).
26. Xie B, Jia X, Qin Z, Zhao C, Shao M. Comparison of interpolation methods for soil moisture prediction on China’s Loess Plateau. Vadose Zone Journal. 2020 Jan 13; 19(e20025).
27. Nasta P, Assouline S, Gates JB, Hopmans JW, Romano N. Prediction of Unsaturated Relative Hydraulic Conductivity from Kosugi’s Water Retention Function. Procedia Environ Sci. 2013; 19:609–17.
28. Nasta P, Palladino M, Sica B, Pizzolante A, Trifuoggi M, Toscanesi M, et al. Evaluating pedotransfer functions for predicting soil bulk density using hierarchical mapping information in Campania, Italy. Geoderma Regional. 2020; 21:e00267.
29. Dai Y, Shangguan W, Duan Q, Liu B, Fu S, Niu G. Development of a china dataset of soil hydraulic parameters using pedotransfer functions for land surface modeling. J Hydrometeorol. 2013; 14(3):869–87.
30. Bowersock G. Tylos and Tyre: Bahrain in the Graeco-Roman World. In: Haya, Rice M, editors. Bahrain Through the Ages of Archaeology. London: Kegan Paul International; 1986. p. 398–407.
31. Al-Wusaili NA, ben Abdallah A, Al-Husaini MS, Al-Salman H, Elballaj M. A comparative study between mechanical and manual pollination in two premier Saudi Arabian date palm cultivars. Indian J Sci Technol. 2012; 5(4):2487–90.
32. Almadini AM, Ismail AIH, Ameen FA. Assessment of farmers practices to date palm soil fertilization and its impact on productivity at Al-Hassa oasis of KSA. Saudi J Biol Sci. 2021; 28(2):1451–8. https://doi.org/10.1016/j.sjbs.2020.11.084 PMID: 33613072
33. Almadini AM, Hassaballa AA. Depicting changes in land surface cover at Al-Hassa oasis of Saudi Arabia using remote sensing and GIS techniques. Vol. 14, PLoS ONE. 2019. p. e0221115. https://doi.org/10.1371/journal.pone.0221115 PMID: 31725716
34. Hotzl H, Maurin V, Zottl JG. Geologic history of the Al Hasa area since Pliocene. In: Al-Sayari SS, Zottl JG, editors. Quaternary Period in Saudi Arabia. Berlin: Springer-Verlag; 1978. p. 58–77.
35. Al-Hawas IA. Origin and properties of some phyllosilicate minerals in the soils of the Al-Hassa oasis, Saudi Arabia. [Reading]: PhD Thesis, Department of Soil Science, University of Reading, Reading.; 1998.
36. Elprince AM. Model for the Soil Solution Composition of an Oasis. Soil Science Society of America Journal. 1985; 49(5):1121–8.
37. Elprince AM. Model for the Soil Solution Composition of an Oasis. Soil Science Society of America Journal. 1985; 49(5):1121–8.
38. Al-Taher AA. Estimation of potential evapotranspiration in Al- Ahsa Oasis, Saudi Arabia. GeoJournal [Internet]. 1992; 26(3):371–79. Available from: http://www.jstor.org/stable/4114505.
39. U.S Geological Survey (USGS), 2022, Digital Orthophoto Quadrangles (DOQs): U.S. Geological Survey database, accessed November 17, 2021, at http://glovis.usgs.gov/app.
40. Elprince AM, Al-Dakheel Y, Al-Saeedi AH, Hussein A, Massoud MA. National Fertilizer Program for Date Palm: Al-Hassa Phase- Final Report (FRQ704). Alhassa; 2003.
41. Gee GW, Bauder JW. Particle Size Analysis. In: Klute A, editor. Methods of Soil Analysis, Part 1. 2nd ed. Soil Science Society of America: Madison, WI, Agron. 9; 1986. p. 383–411.
42. Al-Saeedi AH. Characterizing physical and hydraulic properties of soils in Al-Ahsa, Kingdom of Saudi Arabia. Saudi J Biol Sci [Internet]. 2022 May; 29(5):3390–402. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1319562X22000717 PMID: 35844401
43. Childs C. Interpolating Surfaces in ArcGIS Spatial Analyts. ArcUser [Internet]. 2004;3235(July-September):32–5. Available from: papers2://publication/uuid/7A4DAFEA-CE6C-44AE-9DC4-AE9B953BB87A
44. Longley PA, Frank Goodchild M. Geographic Information Science and Systems. In: International Encyclopedia of Human Geography. 2020.
45. Setianto A, Triandini T. Comparison of Kriging and Inverse Distance Weighted (Idw) Interpolation Methods in Lineament Extraction and Analysis. Journal of Applied Geology. 2015; 5(1):21–9.
46. Hidore JJ, Albokhair Y. Sand Encroachment in Al-Hasa Oasis, Saudi Arabia. Geogr Rev [Internet]. 1982 Jul; 72(3):350. Available from: https://www.jstor.org/stable/214532?origin=crossref
47. Almuhanna EA. Dustfall Associated with Dust Storms in the Al-Ahsa Oasis of Saudi Arabia. Open Journal of Air Pollution. 2015; 04(02):65–75.
48. Abderrahman WA, Bader TA. Remote sensing application to the management of agricultural drainage water in severely arid region: A case study. Remote Sens Environ. 1992 Dec; 42(3):239–46.
49. Chaudhari PR, Ahire DV, Ahire VD, Chkravarty M, Maity S. Soil Bulk Density as related to Soil Texture, Organic Matter Content and available total Nutrients of Coimbatore Soil. International Journal of Scientific and Research Publications. 2013; 3(1):2250–3153.
50. Chen L, Chen X, Bi P, Ding X, Huang X, et al. Effect of Calcium Carbonate on the Mechanical Properties and Microstructure of Red Clay. Advances in Materials Science and Engineering. 2020; 2020.
51. Al-Qinna M, Jaber SM. Predicting Soil Bulk Density Using Advanced Pedotransfer Functions in an Arid Environment. Trans ASABE [Internet]. 2013 Jul 29; 56(1):963–76. Available from: http://elibrary.asabe.org/abstract.asp?aid=42763&t=3&dabs=Y&redir=&redirType=
52. Du C. Comparison of the performance of 22 models describing soil water retention curves from saturation to oven dryness. Vadose Zone Journal. 2020; 19(1).
53. Sun H, Lee J, Chen X, Zhuang J. Estimating soil water retention for wide ranges of pressure head and bulk density based on a fractional bulk density concept. Sci Rep [Internet]. 2020; 10(16666):1–12. Available from: https://doi.org/10.1038/s41598-020-73890-8 PMID: 33028891
54. Rudiyanto, Minasny B, Chaney NW, Maggi F, Goh Eng Giap S, Shah RM, et al. Pedotransfer functions for estimating soil hydraulic properties from saturation to dryness. Geoderma. 2021; 403 (February):115194.
55. Alnajem FA. Evaluating the degraded agricultural soils at Al-Hassa Oasis, KSA. Master's Thesis, Environment and Natural Resources Dep., King Faisal University, Al-Ahsa, Saudi Arabia; 2021.
56. AlJaloud AA. Effect of reclamation on Al-Hassa saline soil in Saudi Arabia. Master's Thesis, Department of Agriculture and Home Economics, California State University, Los Angels, CA, USA; 1983.