Plant and Soil Science

Journal homepage: https://agriculturalscience.com.ua/en
Plant and Soil Science, 15(3), 30-43
Received: 26.04.2024 Revised: 30.07.2024 Accepted: 15.08.2024

UDC 631.171, 631.434.1

DOI: 10.31548/plant3.2024.30

Volodymyr Kravchuk*
Doctor of Technical Sciences, Professor
Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine
03110, 25 Klinichna Str., Kyiv, Ukraine
http://orcid.org/0000-0003-2196-4960
Mykhailo Ivaniuta
PhD in Technical Sciences
Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine
03110, 25 Klinichna Str., Kyiv, Ukraine
http://orcid.org/0000-0002-2180-1929
Oleksandr Ganzhenko
Doctor of Agricultural Sciences, Senior Researcher
Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine
03110, 25 Klinichna Str., Kyiv, Ukraine
https://orcid.org/0000-0002-8118-1645
Yevhen Zaitsev
Doctor of Technical Sciences, Senior Researcher
Institute of Electrodynamics of the National Academy of Sciences of Ukraine
03057, 56 Beresteysky Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-3303-471X

Density of soil composite composition in a changing magnetic field

Abstract. The advancement of technical means for determining soil density in precision (controlled) agriculture necessitates the enhancement of non-destructive flow interaction methods. There is also a need to improve methods for assessing soil density, as existing deviations from optimal values adversely affect the yield of agricultural crops. This research aims to establish the density of the composites in the granulometric composition of soil by determining the self-induction voltage in a changing magnetic field. The research methods are adapted to determine the relationships of Larmor precession under variable inductive current for the density of each composite in the granulometric soil composition. Experimental investigations were conducted by measuring the self-induction voltage of a solenoid acting as a sensor for each of the composites located within the core. The processing of experimental results was carried out according to the principles of mathematical statistics and probability theory, using approximations in the

Suggested Citation:

Kravchuk, V., Ivaniuta, M., Ganzhenko, O., & Zaitsev, Ye. (2024). Density of soil composite composition in a changing magnetic field. *Plant and Soil Science,* 15(3)*,* 30-43. doi: 10.31548/plant3.2024.30.

*Corresponding author

Excel and Statistica software packages. Based on the results of the experimental investigations, models of the relationships between the density ρ (1.0-1.5 g/cm^3) of soil composites and the self-induction voltage $\varepsilon_L = 184\text{-}192$ mV, with a generator voltage of 5 V and determination coefficients $R^2 = 0.95\text{-}0.99$, have been established. These models enable the assessment of soil density with high accuracy, thereby facilitating the optimisation of agronomic processes. It has been determined that these models can be used with a high degree of reliability as calibration characteristics for the design of technical means for flow-based non-destructive measurement of the density of the main soil types in Ukraine. Furthermore, it has been identified that future research should focus on a more in-depth investigation of the relationships between magnetic permeability and the agrophysical characteristics of soil within the locally defined inductive field of the sensor (solenoid). An applied aspect of the obtained results is the further development of adaptive machinery and monitoring systems for soil conditions, aimed at achieving optimal cultivation indicators, as well as their utilisation by research institutions and instrument-making enterprises

Keywords: soil density; magnetic permeability; self-induction; magnetisation; Larmor precession

INTRODUCTION

Determining soil density in a variable magnetic field is crucial for enhancing the precision of agrophysical characteristic measurements, which directly impacts the efficiency of agricultural processes. This method enables flow-based, non-destructive assessment of soil conditions, facilitating high-speed, intelligent cultivation and monitoring of physicochemical properties. It contributes to the optimisation of cultivation technologies, increased yields, and reduced risks of land degradation. Furthermore, this research opens up new avenues for the development of adaptive machines and control systems that utilise modern methods of continuous non-destructive soil condition assessment.

Research by G. Baranov *et al.* (2022) indicates that modern agricultural technologies are based on the use of intelligent systems for high-quality flow-based soil condition monitoring and the adaptation of machine components to achieve the desired agrophysical parameters, particularly soil density, during pre-sowing cultivation.

The normative requirements for pre-sowing soil cultivation, particularly for sugar beet, are established by DSTU 4819:2007 (2009). According to this standard, the depth of the loosened layer, depending on soil moisture, should be between 2.5 and 4 cm across the entire width of the mechanised unit and should not deviate from the set value. The density of the seedbed should be between 1.2 g/cm^3 and 1.3 g/cm^3. Deviations in soil density from the optimum lead to reduced yields. For example, experimental studies by S. Kartashov *et al.* (2012) have shown that deviations in soil density of 0.1...0.3 g/cm^3 (from the optimum) result in a decrease in yield, particularly for sugar beet, by 20-40%.

The implementation of modern sugar beet cultivation technologies using precision farming methods and electronic maps, as proposed by M. Ivaniuta *et al.* (2023), should guarantee flow-based monitoring of soil density in both time and space, considering its compositional makeup, and allow for corresponding adjustments in the operation of farming implements.

The impact of soil compositional composition on density during flow-based monitoring using electronic devices has not been sufficiently studied. According to J. Ruehlmann *et al.* (2020) and P. Panagos *et al.* (2024), the solid portion of soil is primarily composed of "physical clay" (aluminium oxide) and "physical sand" (silicon dioxide), which are classified as diamagnets and paramagnets, respectively.

Existing methods for measuring soil agrophysical characteristics, as exemplified by the research of M. Abdulraheem *et al.* (2024), rely on the soil's ability to alter its dielectric permittivity between submerged electrodes depending on its condition. These methods are effective for determining parameters such as moisture content, temperature, and cation exchange capacity, and are widely used in agricultural monitoring tools. However, despite the success of these methods in measuring these indicators, they primarily focus on agrochemical properties, neglecting other important characteristics such as soil density, which can be determined through interactions with a changing magnetic field.

In the research conducted by M. Zaouche *et al.* (2017), it was noted that to achieve results in determining agrophysical parameters using non-destructive flow-based methods, the interaction of an electromagnetic field with the soil is utilised. These methods are based on studies of eddy currents and reflectometry (radar sensing) which are applied in soil profiling tools and the determination of soil horizons.

Measurements of soil magnetic susceptibility, as proposed by F. Shirzaditabar & R.J. Heck (2022), are widely used to identify zones with elevated concentrations of contaminants. This approach allows for the effective determination of the content of ferromagnetic minerals of anthropogenic origin, such as iron oxides and heavy metals, commonly found in contaminated soils. Due to its sensitivity to changes in magnetic properties, this method is useful for environmental monitoring, however, its application is primarily limited to the detection of contamination, requiring further development for addressing agricultural tasks.

Promising directions for determining soil density, considering its compositional makeup, were proposed in the research of N. Asgari *et al.* (2018), M.O. Kanu *et al.* (2014) and S. Ayoubi *et al.* (2018), where the adaptation of Larmor precession methods for analysing the interaction of a non-homogeneous magnetic field with soil is considered. This approach involves using induction measurement methods to convert the electronic signal into electrical quantities, opening up new possibilities for the precise determination of the physical properties of soil. This is a relevant area of research, as such methods can significantly improve the accuracy of soil monitoring and cultivation.

This study aimed to investigate the dependencies of the density of the soil's composite composition on the self-induction voltage in a changing magnetic field.

MATERIALS AND METHODS

Experimental research was conducted in 2024 at the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine, a research institution located in Kyiv, Ukraine. For the study, soil composition samples optimal for sugar beet cultivation were selected, specifically sandy loam, light loamy, medium loamy, and heavy loamy.

The essence of the method lies in the fact that when a voltage from a generator, ε, is applied to a solenoid with inductance L, a phase shift in the current occurs due to Larmor precession (the interaction of the magnetic field with the core), as shown in Figure 1. The characteristic of the phase shift of the current can be determined from known values of inductive reactance, X_L, by measuring the current, I, flowing through the solenoid (Fig. 2).

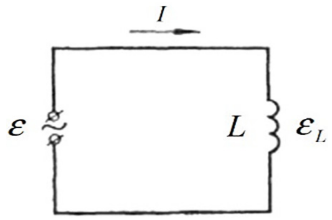


Figure 1. Diagram of connecting a solenoid (coil) with inductance L to an alternating current source

Note: ε – generator voltage, ε_L – self-induction voltage, L – solenoid inductance, I – current

Source: J. Rawlins (2000)

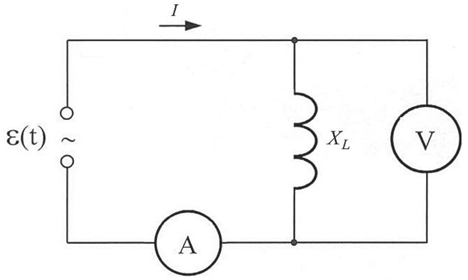


Figure 2. Diagram for determining the inductive reactance X_L

Note: ε – generator voltage, e_L – self-induction voltage, L – solenoid inductance, I – current

Source: J. Rawlins (2000)

Inductive reactance, X_L, depends on the rate of change of current, ω, and the magnetic permeability of the core, which is proportional to the inductance L (Rawlins, 2000; Chakraborty & Majumdar, 2023):

$$X_L = \omega \cdot L, \tag{1}$$

where ω is the angular frequency, *rad/s*; L is the inductance of the solenoid (coil), *H*. Alternatively:

$$X_L = 2\pi f L, \tag{2}$$

where f is the frequency of the alternating current, *Hz*. The inductance of the solenoid can be calculated from known characteristics of the construction and magnetic permeability of the core (Rawlins, 2000):

$$L = \mu \cdot \mu_0 \cdot \frac{N^2 \cdot S}{l}; \tag{3}$$

where S is the cross-sectional area of the core, mm^2, μ is the magnetic permeability of the core, μ_0 is the magnetic permeability of the vacuum, $\mu_0 = 4\pi \cdot 10^{-7}$, N is the number of turns; l is the length of the solenoid, m.

The current in the solenoid, according to Ohm's law, can be found by determining the self-induction voltage ε_L (Fig. 2):

$$I = \frac{\varepsilon_L}{X_L}. \tag{4}$$

The power P consumed by the solenoid in an alternating current circuit can be calculated by determining the self-induction voltage ε_L and the current I (Rawlins, 2000):

$$P = \varepsilon_L \cdot I. \tag{5}$$

The inductive reactance of the solenoid X_L, Ω, expressed through the magnetic permeability μ:

$$X_L = 2\pi \cdot f \cdot \mu \cdot \mu_0 \cdot \frac{N^2 \cdot S}{l}. \tag{6}$$

The power consumption P, W, used for the interaction of the solenoid's induced current with the soil in the core is determined by the relationship:

$$P = \frac{{\varepsilon_L}^2}{2\pi f \mu \mu_0 \frac{N^2 S}{l}}. \tag{7}$$

To establish the relationships between the agrophysical parameters of the soil, it is necessary to conduct research on magnetic permeability at a set magnetisation time of the core of a given density for each soil composition optimal for growing sugar beets (Table 1).

Table 1. Classification of the soil sample compositions by granulometric structure (based on N.A. Kachinsky)

Name by granulometric composition	Content of "physical clay" / "physical sand" (particles < 0.01 mm/particles> 0.01 mm), %
Sandy loam	10/20
Light loam	20/30
Medium loam	30/45
Heavy loam	45/60

Source: developed by the authors based on DSTU 4819:2007 (2009)

Optimal indicators and methods for determining and controlling soil density for sugar beet cultivation have been established by research and relevant regulatory acts, namely: DSTU ISO 11272:2001 (2001), DSTU 4362:2004 (2005), DSTU 11277:2005 (2005), DSTU 4819:2007 (2009), DSTU 7846:2015 (2016).

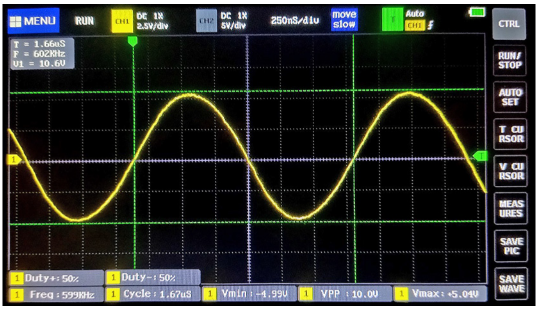
The soil compositions from Table 1 were pre-cleaned, dried to a moisture level of 0.5-1%, and weighed with an accuracy of 0.01 grams. The density range of 1.0-1.5 g/cm^3 was artificially achieved by pressing each composition into a 50 ml volume. For conducting experimental studies, the instruments and equipment depicted in Figure 3 were used. The AC generator 9 was connected to a laboratory power supply with stabilised voltage and a coil 11 (solenoid) functioning as a sensor. The frameless coil consists of 50 turns with a diameter of 32 mm and a length of 65 mm. The AC generator was set to a frequency of 600 kHz, with the ability to generate amplitudes of 3, 4, and 5 V (Fig. 4).

Figure 3. Instruments and equipment for conducting experimental research

Note: 1 – FNIRSI 1013D oscilloscope (FNIRSI Technology Co., Ltd, China), 2 – scales (Digital Pocket, China), 3 – multimeter – DT838 (Avrora LTD, Ukraine), 4 – probes, 5 – sandy loamy soil composition; 6 – light loamy soil composition; 7 – medium loamy soil composition; 8 – heavy loamy soil composition; 9 – AC generator (author's development), 10 – syringe for forming soil composition samples (Jiangsu Zhengkang Medical Apparatus Co., LTD., China), 11 – measuring coil (solenoid) (author's development)

Source: photo by authors

For the experimental research, a classical approach to planning was chosen, in which each factor is changed in turn until a partial maximum is determined while the values of other factors remain constant. The object of the experimental research is the relationships between magnetic permeability and the compositional composition of the soil, which is established by analytical studies of the interactions of the magnetic field with molar mass. The scientific hypothesis is the presence of relationships between the density of soil compositions and the inductive current power of the solenoid under the influence of magnetic flux interactions.



T = 1.66uS
F = 602KHz
V1 = 10.6V

1 Duty+: 50%
1 Duty-: 50%
1 Freq : 599KHz
1 Cycle : 1.67uS
1 Vmin : -4.99V
1 VPP : 10.0V
1 Vmax : +5.04V

Figure 4. Oscillogram of the alternating current (voltage) of the generator *e*

Note: FNIRSI 1013D oscilloscope

Source: photo by authors

RESULTS AND DISCUSSION

In the experimental research, a *first-order* factorial design was used with independent variables $x_1 - x_6$ (density ρ) and $y_1 - y_3$ (generator voltage ε) and dependent variable z_n (self-induction voltage ε_L). (Table 2).

Table 2. Results of experimental studies of self-induction voltage ε_L

Density, g/cm³		Self-induction voltage ε_L, mV (z_n)			
x	**ρ**	**Sandy loamy**	**Light loamy**	**Medium loamy**	**Heavy loamy**
Generator voltage ε (y_1=3 V)					
x_1	1.0	59.3	58.5	58.3	59.2
x_2	1.1	59.3	58.5	58.8	58.8
x_3	1.2	59.0	59.2	59.2	58.7
x_4	1.3	59.3	58.9	59.2	58.5
x_5	1.4	59.0	57.7	58.3	57.3
x_6	1.5	57.6	57.0	57.9	56.9
Generator voltage ε (y_2=4 V)					
x_1	1.0	156.2	154.4	156.1	155.3
x_2	1.1	156.1	155.5	154.0	154.5
x_3	1.2	155.0	154.5	155.1	154.0
x_4	1.3	153.8	153.0	154.3	153.3
x_5	1.4	151.8	151.8	152.0	153.4
x_6	1.5	151.2	150.4	151.8	150.2

Table 2, Continued

Density, g/cm^3		Self-induction voltage ε_L, mV (z_n)			
x	***ρ***	**Sandy loamy**	**Light loamy**	**Medium loamy**	**Heavy loamy**
Generator voltage ε (y_3=4 V)					
x_1	1.0	190	189	191	190
x_2	1.1	190	190	191	190
x_3	1.2	189	189	190	188
x_4	1.3	188	188	189	188
x_5	1.4	186	187	188	186
x_6	1.5	185	184	187	185

Source: developed by the authors

The results of the study of the generator amplitude of 3V determined the range of variation of the self-induction voltage ε_L = 59.3-56.9 mV for density values ρ = 1.0-1.5 g/cm^3 of all soil compositions placed in the solenoid core. It was established that with an increase in the density ρ of soil composition samples, the self-induction voltage ε_L decreased, which is justified by the increase in the specific energy costs of the induction field. For soil compositions, with an increase in their density ρ from 1.0 *g*/cm^3 to 1.5 *g*/cm^3, the self-induction voltage $\Delta\varepsilon_L$ decreased by: sandy loamy – 1.7 mV; light loamy – 2.2 mV, medium loamy – 1.3 mV and heavy loamy – 2.3 mV.

For the generator amplitude of 4V, the change in self-induced voltage ε_L was determined to be 150.2-156.2 mV for all soil compositions placed in the solenoid core within the density range ρ = 1.0-1.5 g/cm^3. It was established that with an increase in the density ρ of soil composition samples, the self-induction voltage ε_L decreased, which is justified by the increase in the current in the sensor (solenoid) supply circuit. For soil compositions, with a change in their density ρ from 1.0 *g*/cm^3 to 1.5 *g*/cm^3, the self-induction voltage $\Delta\varepsilon_L$ changed by: sandy loamy – 5.0 mV; light loamy – 5.1 mV, medium loamy – 4.3 mV and heavy loamy – 4.9 mV.

Experimental investigations using a generator amplitude of 5V revealed a range of self-induction voltage ε_L from 185 to 191 mV for all soil composition densities ρ between 1.0 and 1.5 g/cm^3. Results indicated that as the density ρ of soil composition samples increased, the self-induction voltage ε_L decreased, attributable to the increased induction current required to generate the induction field. For soil compositions, as their density ρ increased from 1.0 *g*/cm^3 to 1.5 *g*/cm^3, the self-induction voltage $\Delta\varepsilon_L$ decreased by: sandy loamy – 5 mV; light loamy – 6 mV; medium loamy – 4 mV; and heavy loamy – 5 mV.

To investigate the influence of various factors based on the results of experimental studies, mathematical models of the parameters of their interrelationships have been developed, along with the determination of their numerical values. The mathematical model was constructed using a set of factors that characterise the conditions under which measurements were taken for each soil composition, following the current plan.

Based on the experimental results, functional relationships between self-induced induction and soil composition density (magnetic permeability) were established. Graphs were plotted to provide a preliminary visual analysis of the interactions of induction current power, resulting in second-degree polynomial equations for each soil composition (Fig. 5):

- sandy loamy:

$$\varepsilon_L = -620.7 + 36.2\rho - 12.34\rho^2 + \\ + 314\varepsilon - 30.67\varepsilon^2 - 3.3\rho \cdot \varepsilon + 0; \quad (8)$$

- light loamy:

$$\varepsilon_L = -632.7 + 66.86\rho - 23.9\rho^2 + \\ + 310\varepsilon - 30.15\varepsilon^2 - 3.5\rho \cdot \varepsilon + 0; \quad (9)$$

- medium loamy:

$$\varepsilon_L = -623.8 + 40.6\rho - 12.8\rho^2 + \\ + 313\varepsilon - 30.4\varepsilon^2 - 3.6\rho \cdot \varepsilon + 0; \quad (10)$$

- heavy loamy:

$$\varepsilon_L = -606.8 + 27.6\rho - 8.68\rho^2 + \\ + 309.45\varepsilon - 29.99\varepsilon^2 - 3.70\rho \cdot \varepsilon + 0. \quad (11)$$

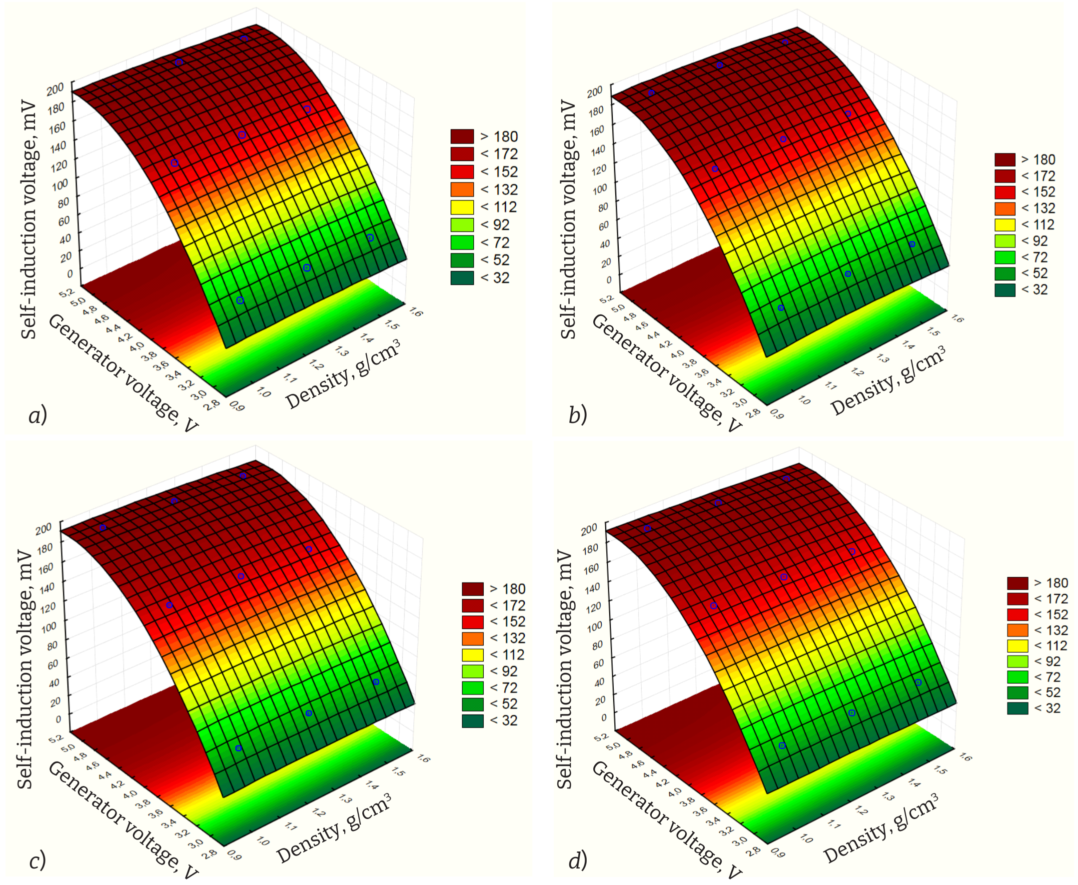


Figure 5. Surface graphs of generator voltage ε, self-induction voltage ε_L, and density ρ for soil compositions

Note: *a* – sandy loamy, *b* – light loamy, *c* – medium loamy, *d* – heavy loamy

Source: developed by the authors

Based on the surface graphs, a dominant influence of the generator voltage ε on the self-induction voltage ε_L was established about the density indicators of the soil compositions. This finding is supported by second-order analytical models of the relationships between the density values and the self-induction voltage for each voltage level of 3.4 and 5 V, with coefficients of determination $R^2 = 0.8 - 0.98$.

From the graph in Figure 6, it can be concluded that the approximation of the measurements using the least squares method (LSM) enabled the characterisation of the numerical values of the change in self-induction voltage ε_L concerning density ρ through second-order equations, yielding coefficients of determination for each soil composition: sandy loamy $R^2 = 0.81$; light loamy $R^2 = 0.89$; medium loamy $R^2 = 0.90$; and heavy loamy $R^2 = 0.95$. The percentage of variation attributed to the influence of the factor characteristics on the overall change in the outcome variable can indicate the *acceptable* prospects for the models of relationships based on the data from the experimental studies. It was established that the coefficient of determination increases as the fractional composition of the examined soil composition decreases.

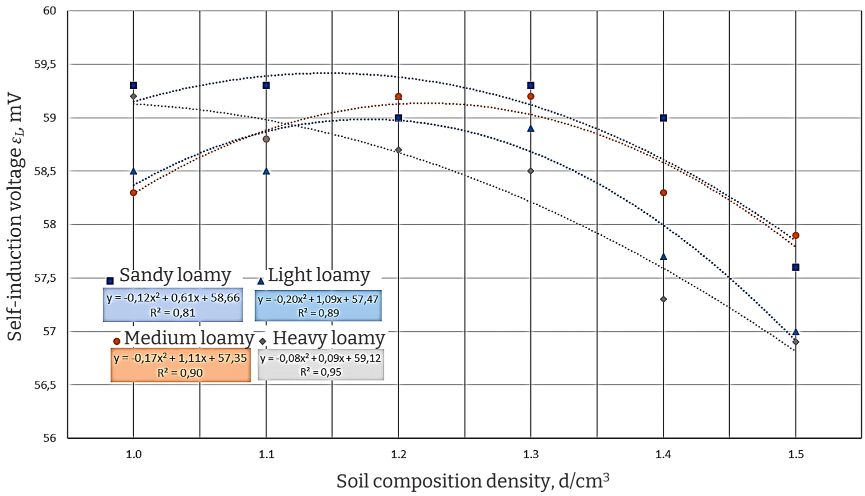


Figure 6. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 3 V)

Source: developed by the authors

As illustrated in the graph in Figure 7, the approximation of the measurements using the LSM enabled the modelling of the dependencies of self-induction voltage ε_L on density ρ through second-order equations, yielding coefficients of determination for each soil composition: sandy loamy $R^2 = 0.97$; light loamy $R^2 = 0.95$; medium loamy $R^2 = 0.99$; and heavy loamy $R^2 = 0.88$. It was established that the coefficients of determination increased with the amplitude of the alternating current for the majority of the soil compositions. The percentage of influence of the factor characteristics on the overall change in the outcome variable can indicate the *acceptable* prospects for the models of relationships based on the data from the experimental studies.

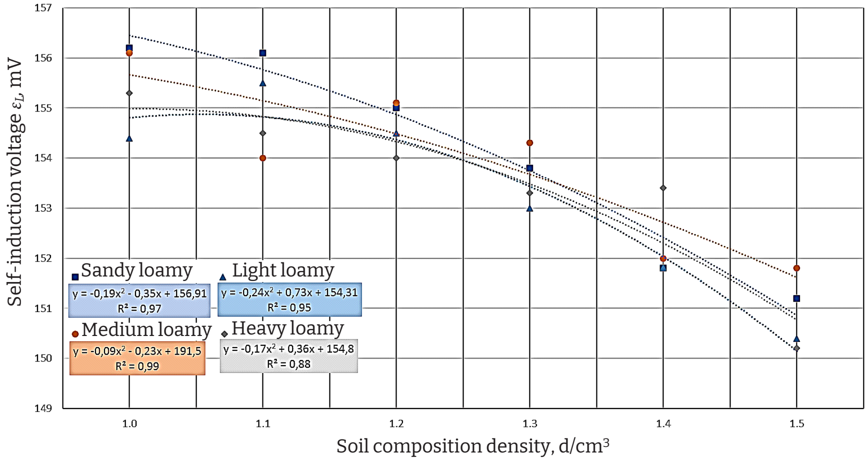


Figure 7. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 4 V)

Source: developed by the authors

The results of the graphical modelling (Fig. 8) indicate that the approximation of the determined parameters using the LSM facilitated the modelling of the relationships between self-induction voltage ε_L and density ρ through second-order equations, yielding coefficients of determination for the soil compositions: sandy loamy $R^2 = 0.98$; light loamy $R^2 = 0.97$; medium loamy $R^2 = 0.99$; and heavy loamy $R^2 = 0.95$. The percentage of influence of the factor characteristics on the overall change in the outcome variable can determine the prospects for the development of relationship models based on data from experimental studies.

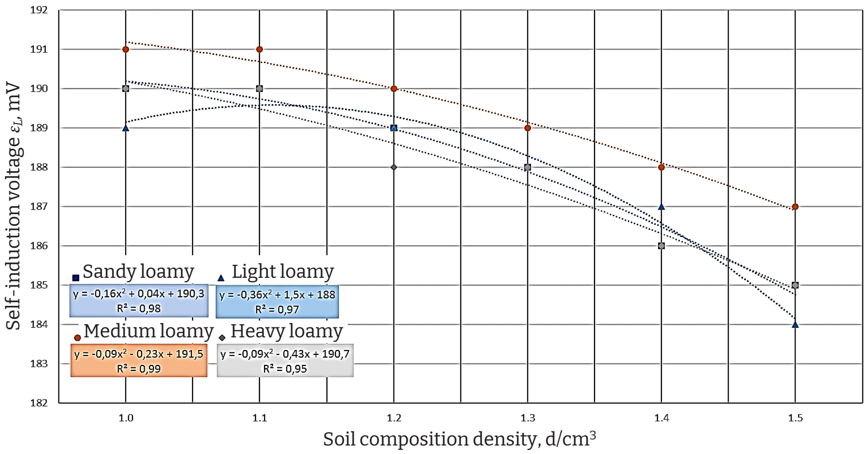


Figure 8. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 5 V)

Source: developed by the authors

Analysis of the graphs (Fig. 6-8) reveals that, with the increase in the amplitude of the generator's alternating current from 3 V to 5 V, the self-induction voltage ε_L of the solenoid (sensor) increased from 59.3 mV to 190 mV for a sandy loamy soil density of $\rho = 1.0$ g/cm^3.

The highest coefficients of determination $R^2 = 0.95 - 0.99$ for the models describing the relationships between the density of soil compositions $\rho = 1.0$-1.5 g/cm^3 and the self-induction voltage $\varepsilon_L = 184 - 192$ mV were observed at a generator voltage of 5 volts. The models featuring these relationships can be employed as calibration characteristics for technical means of non-destructive testing for determining the density of composite soil compositions.

Comparing the results obtained in this research with other similar approaches to this issue, it can be noted that density is one of the critical indicators of soil fertility. Optimal density levels facilitate the faster development of the root system (by an average of 2-3 days) and the increase in vegetative mass, ultimately contributing to higher yields. For most agricultural crops, optimal density levels fall within the range of 1.1 to 1.3 g/cm^3. Overall, a deviation from the optimal density of 1.2 g/cm^3 for sugar beets, as noted by S. Kartashov *et al.* (2012), by 0.1 to 0.3 g/cm^3 may lead to a reduction in yield of 20 to 40 per cent.

In agricultural practice, bulk density serves as a comprehensive indicator of soil physical condition. For most crops grown on medium to heavy loamy soils, optimal growth conditions occur within a density range of $\rho = 1.0$-1.3 g/cm^3, while for sandy and sandy loamy compositions, the optimal range is $\rho = 1.2 - 1.5$ g/cm^3. However, existing methods often fail to provide accurate measurements of soil conditions throughout the entire plough layer, hindering the assessment of tillage equipment performance. According to V. Kravchuk *et al.* (2023), current electronic devices for flow-based density measurement lack the necessary capabilities for precision agriculture and adaptive tillage operations. Notably, non-destructive methods based on electromagnetic interactions with the soil layer are gaining prominence in modern agriculture. These methods encompass both contact and non-contact interactions, as highlighted in the research by V. Kravchuk *et al.* (2023).

One of the approaches to addressing the issues of guaranteed adaptive management of soil cultivation operations is the implementation of automated tools through the use of electronic maps with specified indicators of soil cultivation quality. An important task in designing these automated systems is the development of flow-based measurement tools for agrophysical indicators, as highlighted by I. Trinks & M. Pregesbauer (2016), as well as Y. Zhou *et al.* (2022).

However, the aforementioned tools inadequately respond to the compositional composition of sandy and clay soils, which form the basis of the physical composition according to the classification by Kachinsky, as outlined in DSTU 4730:2007 (2008), and the research conducted by J. Ruehlmann *et al.* (2020) and X. Xu *et al.* (2022).

According to this classification, the division of soils based on their granulometric composition is founded on the complexity of cultivation by the working components of soil tillage machines and the fractional composition, as confirmed by the researcher P. Sanchez (2019). Soils can be classified into light, such as sandy and sandy loamy; medium, including light and medium loams; and heavy, comprising heavy loams and clays. The granulometric composition is one of the factors that influence various physical properties of soils, including density, porosity, plasticity, permeability, swelling, shrinkage, and others.

Research by O. Kruglov *et al.* (2022) indicates that information regarding the agronomic indicators of soil forms the foundation of the modern concept of “precision” (or smart) agriculture. Soils used in agrotechnological production exhibit high levels of differentiation and dispersion. Standard agrochemical surveys do not provide adequate monitoring of the actual situation or the complete realisation of the potential fertility of the soil cover. Consequently, the measurement of magnetic permeability has been proposed as an alternative. It is important to note that conducting the necessary research using standardised agrochemical and agrophysical methods is a labour-intensive procedure, requiring significant time and financial resources to carry out the relevant analyses.

In the study of M. Hanesch & R. Scholger (2005), it is explored that the determination of the characteristics of magnetic susceptibility χ and magnetic permeability *μ* is a widely accepted method in soil science, particularly within the framework of molar mass magnetism, frequency dependence, and thermal behaviour of soils. Furthermore, this study confirmed that fundamental principles of magnetism can be applied to determine parameters relevant to soil contamination studies. The influence of several factors, such as mineralogical composition and particle size, on magnetic field indicators, is analysed, as well as the relationship between the magnetic susceptibility of soil and its parent lithology, climate, organic matter content, topography, sediment sources, and particle size, among others.

According to the research conducted by A. Ouallali *et al.* (2023), a simple, rapid, and cost-effective method for determining magnetic susceptibility χ is essential for the precise mapping of soil erosion. Furthermore, the studies are aimed at identifying the factors that influence the variation in soil susceptibility χ and utilising this susceptibility to assess soil erosion as an inexpensive and efficient means of tracking long-term morphological processes and sedimentation. The results confirm that land use, slope, and soil type significantly affect susceptibility χ values. Current research indicates a high efficacy of magnetic susceptibility values as a rapid, straightforward, and economically viable approach that can serve as an alternative method for assessing soil redistribution.

The research conducted by F. Shirzaditabar & R. Heck (2021) examines the relationships between the volume and bulk density of magnetic permeability μ in soil materials. The study presents a comparison of two types of instruments for measuring soil magnetic susceptibility, based on interactions in a magnetic field and electromagnetic induction (EMI). Magnetochemical investigations encompassed particle size analysis, pollutant detection, organic matter identification, paleoecological studies, archaeology, as well as soil erosion and degradation. The results indicate that the investigated devices, which utilise magnetic fields, can accurately measure the magnetic susceptibility of small soil quantities, thinly applied layers, or exposed soil, but are ineffective at measuring materials beyond 10 cm from the sensor.

The determination of individual soil properties by compositional composition is partially traced in the scientific studies of D. Robinson *et al.* (2004) and P. McLachlan *et al.* (2022), using equipment based on the principles of interaction of the electromagnetic field with the soil and are not intended to solve the goal of research aimed at developing non-destructive flow determination of agrophysical indicators and tillage management systems.

The studies made it possible to develop devices for flow-based non-destructive determination of soil magnetic permeability by measuring the values of self-induction voltage in a changing magnetic field.

CONCLUSIONS

The conducted studies of flow-based determination of soil density by the induction method concerning the compositional composition can be the basis for the development of equipment for guaranteed adaptive control of working bodies, which will ensure the achievement of the specified indicators during the operation of the unit, increase the yield and efficiency of the technological process. The obtained results made it possible to establish the expediency of determining the magnetic permeability of soil for flow-based non-destructive density determination about the compositional composition by using the interaction of the induction field.

It has been established that modern means of determining agrophysical indicators, which use the interaction of the electromagnetic field with the soil, are based on the methods of determining eddy currents and reflectometry. The disadvantages of eddy current methods in the soil during flow-based measurement are the susceptibility to electrochemical corrosion of the root layer and scattering of the probing signal depending on its structure, which complicates the use of reflectometry tools.

It is noted that the development of means for flow determination of soil agrophysical indicators by induction methods will provide an opportunity to obtain operational monitoring of the root layer and respond to changes in the state during cultivation. Studies have shown that the relationships between the density of soil compositions ρ and the self-induction voltage ε_L can be determined by second-order models with determination coefficients $R^2 = 0.80 - 0.98$ at generator voltages of 3.4 and 5 volts. The smallest error of the models of the relationships between the density of soil compositions $R^2 = 1.0 - 1.5$ g/cm^3 and the self-induction voltage $\varepsilon_L = 184 - 192$ mV was observed at a generator voltage of 5 volts.

The obtained models can be used as calibration characteristics for the design of technical means for flow-based, non-destructive determination of the density of various soil structure compositions. It has been established that to improve the accuracy of non-destructive flow-based determination of soil density by induction methods, it is advisable to use second-order models that characterise the compositional composition of the corresponding soil type.

The prospect of research is the introduction of methods for flow-based determination of agrophysical indicators in the system of guaranteed adaptive management of soil cultivation.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Володимир Кравчук
Доктор технічних наук, професор
Інститут біоенергетичних культур і цукрових буряків
Національної академії аграрних наук України
03110, вул. Клінічна 25, м. Київ, Україна
http://orcid.org/0000-0003-2196-4960
Михайло Іванюта
Кандидат технічних наук
Інститут біоенергетичних культур і цукрових буряків
Національної академії аграрних наук України
03110, вул. Клінічна 25, м. Київ, Україна
http://orcid.org/0000-0002-2180-1929
Олександр Ганженко
Доктор сільськогосподарських наук, старший науковий співробітник
Інститут біоенергетичних культур і цукрових буряків
Національної академії аграрних наук України
03110, вул. Клінічна 25, м. Київ, Україна
https://orcid.org/0000-0002-8118-1645
Євген Зайцев
Доктор технічних наук, старший науковий співробітник
Інститут електродинаміки Національної академії наук України
03057, просп. Берестейський, 56, м. Київ, Україна
https://orcid.org/0000-0003-3303-471X

Щільність композиційного складу ґрунту в змінному магнітному полі

Анотація. Розвиток технічних засобів визначення щільності ґрунту в умовах точного (керованого) землеробства потребує вдосконалення методів неруйнівної потокової взаємодії. Існує також необхідність вдосконалення методів визначення щільності ґрунту, оскільки наявні відхилення від оптимальних значень, мають негативний вплив на врожайність сільськогосподарських культур. Мета досліджень спрямована на встановлення щільності композицій гранулометричного складу ґрунту шляхом визначення напруги самоіндукції у змінному магнітному полі. Методи досліджень адаптовані до визначення зв'язків прецесії Лармора за змінного індукційного струму для щільності кожної з композицій гранулометричного складу ґрунту. Експериментальні дослідження виконувались шляхом визначення напруги самоіндукції соленоїда як датчика для кожної з композицій розташованих в осерді. Обробка результатів експериментальних досліджень виконувалась відповідно до правил математичної статистики та теорії ймовірності із застосуванням апроксимації в програмному комплексі Excel та Statistica. За результатами експериментальних досліджень визначено моделі взаємозв'язків щільності ρ (1,0-1,5 г/см^3) композицій ґрунту, напруги самоіндукції ε_L =184 - 192 мВ за напруги генератора 5 В з коефіцієнти детермінації R^2=0,95-0,99. Моделі дозволяють оцінювати щільність ґрунту з високою точністю, що сприяє оптимізації агротехнічних процесів. Визначено, що з високою вірогідністю зазначені моделі можуть бути використані як калібрувальні характеристики для проектування технічних засобів потокового неруйнівного визначення щільності основних типів ґрунтів України. Визначено також, що перспективою подальших досліджень є поглиблене вивчення взаємозв'язків магнітної проникності та агрофізичних характеристик ґрунту в місцевизначеному індукційному полі сенсора (соленоїда). Прикладним аспектом отриманих результатів є подальший розвиток адаптивних машин та засобів моніторингу стану ґрунту для досягнення показників оптимального його обробітку, а також, використаня науково-дослідними установами та приладобудівними підприємствами

Ключові слова: щільність ґрунту; магнітна проникність; самоіндукція; намагнічування; прецесія Лармора