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Review Article

The Effects of Agricultural Tire Technologies on Soil Compaction, Traction Performance and Agricultural Productivity

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ABSTRACT

This review article examines the impact of agricultural tire technologies on soil compaction, traction performance, and agricultural productivity. Topics such as the stress distribution of low-inflation pressure tires on soil, the effects of tire profiles on performance and soil compaction are discussed in depth. Moreover, the impact of tires on traction and soil compaction under different inflation pressures is explored. A thorough analysis of the existing literature reveals significant contributions to improving the efficiency of agricultural tires and reducing the risk of soil compaction. The findings reveal that low-inflation pressure next-generation tires (IF/VF tires) significantly reduce soil compaction by providing a larger contact area. Furthermore, it was concluded that selecting the appropriate inflation pressure and load distribution is critical for optimizing traction and energy efficiency. This review provides valuable insights for future studies and contributes to sustainable agricultural practices.

Keywords: Agricultural tire technology, Soil compaction, Traction, Agricultural productivity

1. INTRODUCTION

Soil compaction is one of the main problems that reduces productivity and negatively affects soil health in modern agricultural practices [1, 2]. Intensive use of agricultural machinery, especially tractors and other heavy equipment, causes the soil pore structure to deteriorate and water-air permeability to decrease due to the stresses they create on the soil. This situation restricts plant root development and negatively affects agricultural production potential [22]. In recent years, agricultural tire technologies developed to minimize these negative effects have provided significant improvements in reducing soil compaction with tires having lower inflation pressure and larger contact surfaces [3].

In the current management system, engine powers reaching 500 KW in tractors are constantly increasing and demands for fuel consumption and greenhouse emissions are increasing. For this reason, tire manufacturers carry out intensive R&D studies on tire designs. The design of agricultural tires not only reduces soil compaction, but also plays an important role in traction, energy efficiency and sustainability of agricultural activities [4]. The distribution of stress applied to soil by tires at various inflation pressures and its effects at different soil depths have been extensively studied in the literature [5]. Research shows that low-inflation-pressure tires distribute soil surface stress over a wider area, reducing compaction and increasing agricultural yields [6]. These types of tires provide a large contact area, allowing the stress applied to the soil surface to be distributed more homogeneously, thus reducing compaction in the lower soil layers. New generation tires with low inflation pressure (for example, Advanced Elasticity (IF) and Very High Elasticity (VF) technology) can operate with lower pressure compared to traditional tires and cause less damage to the soil structure under the same load [7, 8].

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By analyzing the relationship between the performance characteristics of agricultural tires and their capacity to prevent soil compaction, important results were obtained for the sustainability of agricultural activities [9]. In this review, the effects of agricultural tire technologies on soil compaction, traction performance and agricultural productivity were examined and the potential contributions of these technologies in future agricultural applications were discussed in the light of existing literature. In particular, further investigation of subsoil layers, calculation of long-term soil compaction effects, and more comprehensive modeling of the effects of tires on energy efficiency could contribute to future studies. The study aims to summarize the current status of the literature on the development of new generation tire technologies in order to guide applications that aim to increase efficiency in agricultural production and minimize soil compaction.

2. EFFECT OF PRESSURE, LOAD, GROUND CONDITIONS ON SOIL STRESS IN AGRICULTURAL TIRES

2.1 Effect of Low Inflation Pressure Tires on Soil Stress

Damme and colleagues [3] studied the effects of tires with low inflation pressure on soil stress. Soil stress is measured by dividing the force applied to a specific area of soil by the area itself and is expressed as force per unit area (Pa or kPa). The study examined the effect of three different tire types (AxioBib, CerexBib and EvoBib) with similar dimensions, wide and low inflation pressure, on the average stress in the soil profil (Figure 1). They tested the tires under different inflation pressures and wheel loads. The average normal stress was measured at six different locations using probes.

a-) b-) c-)

Fig 1. Different types of Michelin brand agricultural tires, a-) AxioBib, b-) CerexBib, c-) EvoBib [10]

The results showed that the tire structure had no significant effect on the stress applied to the soil, but reducing the inflation pressure reduced the stress in the upper soil layers. It was found that the effect of inflation pressure was limited in the lower soil layers. It has been noted that there is no significant difference in the center of the front and rear tires. At normal stress values of the rear wheels only at a depth of 0.2 m, the AxioBib tire produced 16-20% lower stress than other tires. This difference was said to be due to testing the CerexBib with low inflation pressure. Lowering the inflation pressure of the EvoBib tire has been shown to decrease mean normal stress, particularly in the upper soil layers. It was emphasized that when it was reduced from 80 kPa to 60 kPa, the stress caused by the front and rear tires decreased by 22%, and when it was reduced from 60 kPa to 40 kPa, the stress caused by the rear tires decreased by 11%. They observed that when the EvoBib tire load was reduced by 20% and the inflation pressure was reduced by 25%, the average normal stress was reduced by 10-14%. However, this decrease was not found to be statistically significant.

The average normal stress on the soil is calculated using Equation 1. In this calculation, the maximum internal pressure P_{i-max} and the proportionality coefficient k_s, which is a function of the Poisson ratio, are used. Maximum internal pressure refers to the highest pressure measured in the ground under the load applied by the tire to the ground.

$$\sigma_m = P_{i-max} k_s \approx \frac{P_{i-max}(1-3\upsilon)}{(1+\upsilon)} \quad (1)$$

Here υ is the Poisson ratio and is obtained from the mechanical properties of the soil. Poisson's ratio (υ) expresses the ratio of the transverse expansion of the material to the longitudinal compression.

The study shows that tires with low inflation pressure significantly reduce soil compaction in the upper soil layers. It was concluded that the tire load was more decisive in the lower soil layers. These findings highlight that inflation pressure is a critical factor. The EvoBib tire in particular has been identified as the most effective tire in reducing stress in the upper soil layers at low inflation pressure. One of the strengths of the study is that it quantitatively models the effect of different inflation pressures. However, the models focus on only the upper soil layers resulted in a less comprehensive examination of the effects on the lower layers. It is thought that future studies should include more in-depth analysis of the subsoil layers.

2.2 Tire Slippage Under the Influence of Inflation Pressure in Agricultural Tires

How to optimize the slip and traction efficiency of tractor tires on the ground is an important issue. Janulevičius and Damanauskas (2022) developed an equation to predict tractor tire slippage under different inflation pressures. Traction efficiency reflects the proportion of engine power transferred to the ground as tractive force. High traction efficiency allows the tractor to operate more efficiently with less energy. Tire slippage indicates how much of the force applied to the ground is not being used effectively. High slip rates reduce productivity and cause soil compaction. While low pressure provides a wider contact area, reducing slippage, very low pressure can damage the tire structure. Traction efficiency η_t in tractors can be calculated with Equation 2 depending on the traction coefficient κ, rolling resistance coefficient ρ, and slip coefficients [11].

$$\eta_t = \frac{\kappa}{\kappa - \rho}(1 - s) \quad (2)$$

The traction coefficient equation (κ) is calculated with the traction force (F_t) and tractor weight (W) using Equation 3 [11, 12].

$$\kappa = \frac{F_t}{W} \quad (3)$$

The rolling resistance coefficient (ρ) is calculated with the rolling resistance force (F_f) and tractor weight (W) using Equation 4 [11, 12].

$$\rho = \frac{F_f}{W} \quad (4)$$

The tire slip coefficient (s) equation is calculated with the help of the maximum slip value (s_{lim}), the critical traction coefficient (F_t^{lim}) and a coefficient (b) depending on the soil and tire properties, using Equation 5 [4].

$$s = s_{lim}\left[1 - (1 - \frac{F_t}{F_t^{lim}})^b\right] \quad (5)$$

The empirical equation they proposed predicted the average slip rate with a 5% error margin. The findings of the study reveal that different inflation pressures have a significant effect on tractor tire slippage. Low inflation pressure allows the tire to contact the ground on a larger surface, reducing slippage and increasing traction efficiency. However, very low pressures can damage the structural integrity of the tire and cause deformation. Future studies should aim to improve these models with larger data sets and under different soil conditions.

Fig 2, generated by the above equations, shows the effect of traction force on traction efficiency and tire slippage. As traction force increases, efficiency increases, but if slippage also increases, efficiency decreases. In Fig 3, it is seen that increasing traction force increases slippage and decreases efficiency.

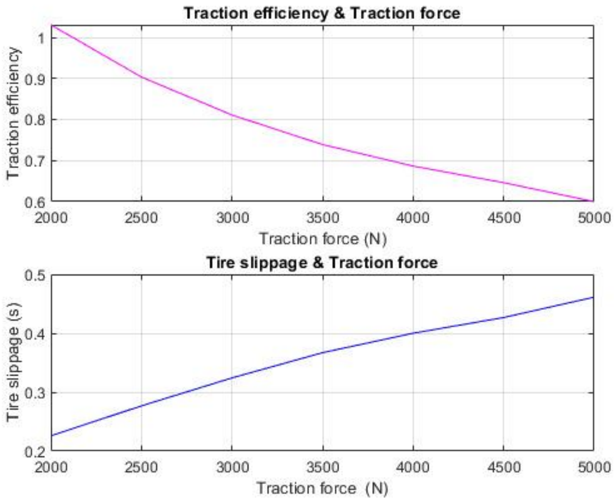

Fig 2. Effect of traction force on traction efficiency and tire slip [4]

2.3 Effect of Ballast on Different Types of Agricultural Tires

Kumar et al.[13] studied the performance of bias-ply and radial tires in different ballast conditions. Bias-Ply and Radial tire shapes are shown in Fig 3. Ballast is water or iron weights used to increase the weight of the tractor and reduce slipping. In the study, tires of sizes 13.6–28 were tested under different ballast and inflation pressures (68.9–206.8 kPa).


a-) b-)

Fig 3. Different types of tires, a-) Bias-Ply, b-) Radial [14]

In their study, they tested 13.6–28 Bias-Ply and Radial tires (empty, 50% water, 50% iron, 75% water, 75% iron) and inflation pressures (68.9 - 206.8 kPa) (Fig 4). In their tests, they evaluated the vertical deflection and contact area. Vertical deflection indicates how much the tire flexes in the vertical direction. It varies with the load acting on the tire and inflation pressure. Contact Area refers to the surface area of the tire that comes into contact with the ground. This area changes with the inflation pressure of the tire and the load applied to it.


Fig 4. Test tires used in the study, a-) Bias, b-) Radial

Radial tires demonstrated a 13% larger contact area and a 6.5% greater deflection compared to Bias-Ply tires. The results showed that using low inflation pressure and high ballast creates a large contact area for the tire and increases

efficiency. Water ballast provided lower deflection and contact area than iron ballast, while iron ballast performed better under load. Optimization of ballast type and inflation pressure is critical to maximizing tractor efficiency.
In the evaluations made using the Commando model, tire performance was analyzed with tire deflection and contact area equations (Equations 6 and 7). The Komandi model [15, 16] is a model used in the analysis of ground-vehicle interactions and evaluates performance by taking into account variables such as normal load (W), tire section width (b), tire diameter (d), and inflation pressure (P_i). This model performs performance analysis based on the surface area (A) where the tire is in contact with the ground and the amount of vertical deformation of the tire (deflection, δ). It has been found that radial tires provide better load distribution under high weight and low pressure conditions and can be preferred in agricultural applications. It has been observed that radial tires create a more balanced contact area, especially as the load applied to the tire and the tire section width increase. The expanding contact area under low inflation pressure can optimize traction by increasing the amount of deformation (deflection) while reducing soil compaction.

$$\text{Tire deflection } (\delta)\ (\%) = \left(\frac{Vertical\ tire\ deflection}{Carcass\ section\ height}\right) \times 100 \tag{6}$$

$$\text{Tire deflection} \quad \delta = C1 \times \frac{W^{C2}}{b^{C5} d^{C6} P_i^{C7}} \times (C3 \times b + C4)$$

$$\text{Contact area} \quad A = C1 \times W^{C2} \times \left(\frac{b}{d}\right)^{C3} + p_i^{C4} \tag{7}$$

The findings of the study show that the use of ballast has a significant impact on the performance of both bias and radial tires. However, it is emphasised that the long-term effects of iron and water ballasts need further investigation. The study provides significant contributions to the optimization of tire performance by providing a wide data set obtained with different ballast types and tire types.

2.4. Reducing the Risks that may Arise from Soil Compaction with the Developments in the Tire Industry

Soil compaction disrupts the physical structure of the soil and reduces its water and air permeability, as noted by Damme et al.[17]. Investigated how new generation tires can minimize this situation on five generations of tires (1970-2018). In the study, tire loads of 2900 kg and 4300 kg were applied to the tires and the inflation pressure was varied between 240 and 60 kPa. The tire-soil contact area and stress distribution were calculated with the FRIDA model, and the results were compared with the vertical stresses in the soil profile using the Söhne model. The FRIDA model gives the shape and stress distribution of the tire-soil contact area. The Poisson ratio was obtained from the Uniaxial confined compression test (UCCT) slope and Young's modulus.

In their study, the Poisson ratio was determined by a method based on the work of Eggers and colleagues [18]. In this method, the slope of the reloading section (UCCT) and Young's modulus are combined. The load was converted to stress and log10-transformed. Displacement was converted into unit deformation (Equation 8).

$$\upsilon = \frac{1}{4}\left[\frac{d\varepsilon_z}{d\sigma_z}E + \left\{\left(1 - \frac{d\varepsilon_z}{d\sigma_z}E\right)\left(9 - \frac{d\varepsilon_z}{d\sigma_z}E\right)\right\}^{0.5} - 1\right] \tag{8}$$

The results show that the new generation of tires with low pressure and large contact area significantly reduces soil stress. In particular, the EvoBib tire provided the best stress distribution and low soil compaction. FRIDA model calculations revealed that soil compaction was reduced even at a depth of 0.6 m.

These findings demonstrate the potential for innovations in tire design to both reduce soil compaction and contribute to agricultural sustainability. Tires with large contact surface support plant root development. However, the long-term effects of these technologies in different soil types and load conditions need to be investigated further. Future studies can increase the effectiveness of these technologies with larger data sets under different climate and soil conditions.

2.5. Research on Soil Compaction for Effective and Efficient Production in Agricultural Fields

The force applied to the soil by heavy machinery used in agricultural areas disrupts the soil structure and negatively affects productivity and environmental quality. To prevent this situation, Shaheb and et al. [9] examined the methods recommended for sustainable agriculture. While agricultural machinery increases productivity, it can cause soil compaction, which can lead to yield losses of up to 50%. To reduce this negative impact, strategies such as the use of low inflation pressure tires, controlled traffic agriculture and planting of deep-rooted plants are recommended. Low inflation pressure tires minimize soil compaction with a larger contact area.

In parallel with the rapid increase in the world population, food production must also be increased rapidly. New generation agricultural machinery developed for this purpose has become quite widespread. While new generation agricultural machinery facilitates agricultural production, it also damages the soil and causes soil compaction. Soil compaction disrupts the structure of the soil, negatively affecting plant root development, overall plant growth and yield. To prevent soil compaction, which can cause yield losses of up to 50%, the use of low inflation pressure tires, controlled traffic farming and the planting of deep-rooted plants are recommended [9]. Standard and high inflation pressure tires cause more soil compaction than low inflation pressure tires. The use of low inflation pressure tires reduces compaction by creating a larger contact area on the soil.

The negative effects of agricultural machinery on the soil constitute a significant obstacle to sustainable production. Soil compaction prevents the development of plant roots, makes it difficult for water and nutrients to reach the plants, and as a result, leads to productivity losses. Studies by Shaheb et al. [9] have shown that methods such as controlled traffic farming, use of low inflation pressure tires and planting of deep-rooted plants significantly reduce the risk of soil compaction. These strategies are particularly critical to the viability of sustainable agriculture.

The management strategies discussed in this study provide valuable approaches to support sustainable production and minimize the long-term of soil compaction. However, more research is needed on how these methods perform in different soil types and climate conditions. Moreover, the economic viability of these strategies and the rate at which farmers adopt these methods should also be the subject of future studies.

2.6. Soil Compaction in Tires Used in Different Conditions

Rodriguez and et al. [6] studied the effects of different types of tires used during sugarcane harvesting and transportation on soil compaction. Factors that determine soil compaction include tire contact area, inflation pressure, tire hardness, load and soil conditions. Four different tire types (block pattern, rib pattern, low tread profile and high tread profile) were tested at three different inflation pressures (207, 276, 345 kPa) and six load levels (20-60 kN) (Fig 5). The contact surface of the tires was measured by leaving marks on the cardboard, and their vertical deflections were recorded with a hydraulic system. Vertical tensions in the soil were monitored with sensors placed at depths of 10, 30, 50 and 70 cm. These stresses were simulated using the Boussinesq equation.

a-) b-) c-) d-)

Fig 5. Effect of different types of tires on soil compaction. a-) block patterned lug profile, b-) rib patterned lug profile, c-) low lug profile, d-) high lug profile tire

The Boussinesq point load equation is the stresses created by a vertical point load of magnitude P on a surface point at any point at a horizontal distance r in a semi-infinite elastic half-space at a depth of z. Equality 9 expresses the stresses at any point at a horizontal distance r in a semi-infinite elastic half-space [19, 20].

$$\text{Vertical tension}(\sigma_z): \sigma_z = \frac{3P}{2\pi z^2}\left(\frac{z^3}{(r^2+z^2)^{5/2}}\right)$$

$$\text{Horizontal tension } (\sigma_r) = \sigma_r = \frac{P}{2\pi}\left(\frac{3z^3 r}{(r^2+z^2)^{5/2}}\right) \quad (9)$$

$$\text{Shear stress } (\tau_{zr}) = \tau_{zr} = \frac{3P}{2\pi}\left(\frac{z^2 r}{(r^2+z^2)^{5/2}}\right)$$

The contact surface area (A_t) was calculated based on the tire width (B_s) and diameter (D_e) with the McKyes model (McKyes 1985). Type A (block pattern) and type B (rib pattern) tires create lower contact pressure and vertical tension, causing less damage to the soil. As the load increases, the contact surface expands, and as the pressure increases, the contact area shrinks. While the B type tire stands out as the most sensitive tire to different pressure and load changes, the D type tire produced high contact pressure on hard surfaces. A and B type tires minimize soil compaction during transportation.

$$A_t = \frac{B_s \times D_e}{k} \quad (10)$$

k = Although there is a fixed value for the surface type, it is used as 4 for hard surfaces and 2 for loose soils.

The measurement results of soil compaction agreed with the simulation data by 87-92%, demonstrating the reliability of the mathematical models. It was determined that A and B type tires offered better performance in sugar cane transportation with lower contact pressure and more balanced stress distribution.

As a result, A and B type tires are among the best choices for agricultural applications, with less damage to the soil under low inflation pressure and high load conditions. However, further investigation of the performance of these tires in different soil conditions and their long-term effects are required. Future studies should examine the effectiveness of these tires in different agricultural practices and evaluate their contributions to sustainable agriculture.

2.7. Effect of Change in Tire Inflation Pressure on Rating Cone Curve (RCI) Index

It is important to correctly assess the impacts of agricultural machinery on the soil and the soil's response to these impacts. Oh et al. [21] studied the effects of tire inflation pressure on the rating cone index (RCI). RCI is an indicator that determines the impact of machinery on the soil and the strength capacity of the soil. In their study, tire inflation pressure was changed between 50-150% and real-time tire penetration depth was measured using laser distance sensors. Wheel rotations were monitored using a rotary encoder, and tire slippage was calculated by comparing theoretical and actual travel distances.

The RCI value was calculated depending on the tire load (W), tire slip ratio (s), tire indentation depth (z), tire width (b), diameter (d) and tire deflection amount (δ) (Equation 11). As inflation pressure increased, tire penetration depth and slip rate increased, but beyond the optimum pressure level these changes slowed down. The study showed that the RCI value increased with increasing tire inflation pressure, but these changes stabilized outside the optimum pressure range (90-120%). The average estimation error rate in RCI calculations was found to be 1.59%.

$$RCI = 2{,}6265\left(\frac{W(1-\frac{\delta}{h})^{3/2}}{bd^{2/5}}\right)\left(\frac{s}{z^3}\right)^{1/3} \quad (11)$$

The distance of the rear sensor to the tire tread profile (h_r), the average vertical distance of the front sensor to the tread profile (h_f) and the vertical distance between the ö and rear sensors (Δ) are calculated with Equation 12 for the tire penetration depth (z).

$$z = \frac{h_r - (h_f \pm \Delta)}{2} \quad (12)$$

Tire slip (s) is calculated with the help of Equation 13 using the equation of the actual movement distance of the tractor (S_a) and the theoretical movement distance of the tractor (S_t).

$$s = 1 - \frac{S_a}{S_t} \quad (13)$$

These equations and calculations are used to better understand soil and machinery interactions and to minimize the negative effects of agricultural machinery on the soil. Accurate RCI estimates are important to prevent soil compaction and increase agricultural productivity.

The results showed that as inflation pressure increases, the risk of soil compaction increases, but more consistent and lower deflection values are obtained within the optimum pressure range. Low inflation pressure below the optimum pressure level increased tire deflection and sinking. The change of RCI values at different pressure levels revealed that inflation pressure is an important parameter in minimizing the negative impact of agricultural machinery on the soil.

This study highlights the impact of tire inflation pressure on RCI and how strategies should be developed to reduce the negative impacts of agricultural machinery on soil. However, these findings need to be extended under different soil types and field conditions. It is also recommended to investigate the potential to increase energy efficiency in agricultural production by optimizing inflation pressure.

2.8. Estimation of Carcass Stiffness in Agricultural Tires

The increase in the power and weight of agricultural machinery increases soil compaction and reduces productivity. Misiewicz et al. [22] compared four different methods to estimate the carcass stiffness of agricultural tires. The methods examined are: footprint area, tire load and deflection, pressure mapping, and manufacturer specifications.

i. Contact Area Method: The contact area of the tire is determined using ink and the average contact pressure is calculated. The contact pressure values obtained with this method were found to be 30-40% lower than the pressure mapping method.

ii. Tire Load and Deflection Method: As the load increases, the deflection increases and the slopes show a linear relationship with the pressure.

iii. Pressure Mapping Method: Average and maximum contact pressure is measured using a commercial system. It has been found to be the most accurate and effective in measuring carcass hardness.

iv. Manufacturer Specification Method: Carcass hardness is estimated from data provided by the manufacturer. This method provided simple and rapid results and showed agreement with other methods within ±20%.

The results showed that the pressure mapping system provided the most accurate estimates, while the method based on manufacturer data provided a simple and fast alternative. However, the methods need to be tested with large data sets and different tire types. Additionally, it is important to evaluate the accuracy of the methods in real-world conditions in the field.

2.9. Effects of Tire Systems Used in Different Agricultural Vehicle Types on Soil Compaction and Traction Power

Arvidsson et al. [23] studied the effects of rubber track systems used in agricultural tractors on soil compaction and traction performance. An example rubber track system is given in Figure 6. The study was carried out in Sweden in 2009 on two different clay soils with an 85 kW tractor. Tractor equipped with four track units, compared with single and twin wheel configurations. In measurements made at depths of 15, 30 and 50 cm, it was found that tracks and double wheels created similar soil stress, while single wheels caused higher soil stress.

Fig 6. Tractor track tire system [24]

Track systems provide a larger contact area, reducing soil stress and significantly reducing slippage. Dual wheels reduced slip rates in compact soils, but this effect was limited in loose soils. Single wheels created higher stress levels at all depths, increasing the risk of soil compaction. The stress difference created by the pallets and double wheels at a depth of 50 cm was minimal.
The study results show that rubber track systems increase the efficiency of tractors while causing less damage to the soil and minimizing compaction. With their large contact surface, the pallets distributed the pressure applied to the soil and reduced the risk of soil compaction, which provided a significant advantage in terms of agricultural sustainability.
However, further investigation of the performance of these systems under different soil types and operating conditions is required. Assessing the long-term cost and sustainability impacts of pallet systems could enable greater adoption of these technologies in agriculture.

2.10. Modelling of Compressive Strength Between Rubber and Soil in Different Soil Types

Soil compaction occurs as a result of the pressure exerted on the soil by heavy machinery and negatively affects plant root development, making it difficult to absorb water and nutrients. High flexibility (IF) and very high flexibility (VF) tires have been developed to reduce soil compaction with low ground pressure and support heavy loads. Jjagwe et al. [25] studied the pressure-sinkage relationship using plates of different geometric shapes (circular, rectangular and square) on artificial soil. Pressure-sinking data were analyzed with Bekker and Reece models in experiments conducted in loose and dense soil conditions.

While the Bekker model estimates the pressure-sinking relationship by taking into account the cohesion (k_c) and friction moduli (k_φ) of the soil, the Reece model examines the compatibility of these parameters to geometric scaling. In loose soil, the pressure increase follows a more linear course, while in dense soil an exponential increase is observed. Both models were able to predict pressure and subduction depths successfully, with the Reece model giving better results in plate-soil interaction.

Bekker Model

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n = k_{eq} z^n \tag{14}$$

Reece Model

$$p = \left(Ck'_c + \gamma_s b k'_\varphi\right)(z/b)^{n'}$$

The parameters used in the equations are as follows: p represents the pressure (kPa), b represents the small size of the plate (in meters) and z represents the subduction depth (in meters). While k_c, which defines the mechanical properties of the soil, is the cohesion modulus of the soil and is shown in the unit $[kN/m^{n-1}]$, k_φ defines the friction modulus as $[kN/m^n]$. k_{eq}, represents the equivalent parameter between the soil and the plate. The apparent cohesion of the soil is expressed as C (in kPa) and the soil weight density is defined as γ_s $[kN/m^3]$. The parameters of the Reece model, k_c'' and k_φ'^', denote the dimensionless soil cohesion and friction modul, respectively. Finally, n' is the parameter representing the soil exponent in the Reece pressure-sinking relationship.

The results showed that plate geometry and soil density have significant effects on the pressure-sinking relationship. Circular and rectangular plates produced lower compressive strength than square plates. These studies provide useful data for minimizing soil compaction in the design of agricultural machinery. However, the validity of these models needs to be tested in real agricultural areas. Future studies should improve the accuracy of model predictions with larger data sets and evaluate their long-term effects.

2.11. Modelling of Footprint and Vertical Stress Distribution in Agricultural Tires

When vehicles move over the ground, the ground surface is exposed to mechanical stresses from the tires. This stress varies depending on tire inflation pressure, wheel load, tire dimensions and soil conditions. To accurately predict the impact of agricultural machinery on soil, modeling of the tire-soil contact area and vertical stress distribution is necessary. Keller [5] developed an approach that models the contact area and stress distribution based on tire parameters. The model describes the contact area with a super ellipse, the longitudinal distribution of vertical stress with a power law function, and the transverse distribution with a decay function.

In this model, pressure sensors placed on the soil surface were used to calculate vertical stress and the obtained data were analyzed with Boussinesq and Fröhlich equations [19, 26]. The maximum vertical stress is related to the tire inflation pressure (P_{tyre}), wheel load (F_{wheel}) and the logarithm of the recommended tire pressure ($P_{recommended}$) and is described by the equation:

$$\sigma_{max} = 34.4 + 1.13P_{tyre} + 0.72F_{wheel} - 33.4\ln\left(\frac{P_{tyre}}{P_{recommended}}\right) \quad (15)$$

According to this equation, the maximum stress increases as tire pressure and wheel load increase, and decreases as it approaches the recommended pressure.

The contact area was calculated with the super ellipse model developed by Hallonborg and estimated using the contact width (w_A) and contact length (l_A) in this model [27]. The vertical stress distribution between the center and the edge of the contact area is modeled by Equation 17

$$A = kw_A l_A \quad (16)$$

$$\sigma_y = C\left(\frac{w(x)}{2} - y\right)e^{-\delta\left(\frac{w(x)}{2} - y\right)} \quad (17)$$

$$0 \le y \le \frac{w(x)}{2}$$

This equation is used to predict the stress distribution in the contact area and has been reported to give high agreement with the measured stress values.

The model was successful in predicting the stress distribution and soil compaction of agricultural tires, providing accurate results with practically accessible data. However, the validity of this model needs to be tested in different soil types and field conditions. Future studies should aim to expand this model and make it applicable in the field to more accurately predict the impacts of agricultural tires.

2.12. Effects of Stress Zones Caused by Agricultural Vehicles on Soil Structure

The pressure exerted by agricultural machinery on the soil causes soil compaction and deterioration of the pore structure. The pore system that provides water and air permeability of the soil shrinks as a result of compression, negatively affecting plant root development Berisso et al. [28] investigated the change in the stress effects of tires on the soil pore structure and carried out this study with four wheel passes in a clayey soil. A forage harvester with a width of 80 cm carrying a total load of 6100 kg was used and normal and horizontal stresses were measured with load cells. Pore continuity index and air-filled porosity degree were calculated using different air permeability values.

As a result of the study, it was found that air filling and air permeability were at the lowest level in the center of the tire track, while these values were higher outside the tire track. It has been determined that the pore structure in the center of the tire track is tighter and distorted due to pressure. On the short edges, pore continuity is disrupted but air permeability is preserved. The average normal stress was calculated using the internal pressure (PI) with the help of Equation 18 [29]:

$$\sigma_m = \frac{PI}{2(1-\upsilon_m)} \quad (18)$$

When the Poisson ratio (υ_m) is taken as 0.3, the σ_m value is found to be 40% more than the internal pressure. Air permeability (k_a) was calculated using the height of the soil sample (l_s), dynamic air viscosity (η), air pressure difference (ΔP), cross-sectional area (A_s) and volumetric flow rate (ϕ). These data show that the stresses exerted by tires on the soil significantly alter the pore structure and impede water/air circulation.

$$\sigma_m = \frac{PI}{1,4} \quad (19)$$

$$k_a = \frac{-\varphi l_s \eta}{\Delta P A_s} \quad (20)$$

These studies have revealed that agricultural tires reduce the pore continuity index and lower air permeability. High pressure in the centre of the tire causes the pores to become less connected and the air transmission capacity to decrease. These findings highlight critical points to consider in the design and use of agricultural machinery and indicate the need for strategies aimed at preserving the pore structure. Future studies could investigate the long-term effects of different tire types and inflation pressures to develop recommendations for more sustainable agricultural practices.

2.13. Calculating Tire Footprint Area on Hard Ground

Grečenko [30] tried to calculate the tire footprint area on hard ground. Many existing formulas include load deformation as a parameter to calculate tire tread area. A user can only see the data of usage pressure, usage rim and the amount of load the tire can carry from the tire catalog. In his study, Grecenko [30] aimed to evaluate the tire tread area with arbitrary loading and inflation pressure, using existing formulas and a tire catalogue, suggesting the application of a specific correction factor. This provides an accurate estimate of the average contact pressure.

In the developed model, the track area (A_o) was calculated using the tire track length (l_o), track width (b_o) and shape coefficient (k) (Equation 21). The shape coefficient, k, defines the geometric shape of the wake field: $k = \pi$ If , it indicates an ellipse, if π<k<4 it indicates an oval and if k=4 it indicates a rectangular shape. The section height (h_k) and total diameter (d_k) of the tire are other basic parameters used in the equations. Nominal load deflection is the deformation of the tire under a certain load and is calculated using the static radius (r_s) and rim diameter (d_r). The nominal load deflection (f_{kj}) is shown with the ratio (a) symbols.

$$A_o = k \frac{l_o}{2}\frac{b_o}{2} \quad (21)$$

$$k = \frac{4A_{om}}{l_o b_o} \quad (22)$$

$$h_k = \frac{d_k - d_r}{2} \quad (23)$$

$$a = \frac{h_k}{b_k} = \frac{d_k - d_r}{2b_k} \tag{24}$$

$$f_{kj} = \frac{d_k - 2r_s}{2} \tag{25}$$

$$\frac{f_{kj}}{h_k} = \frac{d_k - 2r_s}{d_k - d_r} \tag{26}$$

This model accurately predicts tire footprints in hard ground conditions, providing engineers with better data for vehicle design and tire selection. Taking into account parameters such as percentage nominal deflection (Equation 26) and section width (b_k) allows for more accurate prediction of tire footprint at different pressure-load combinations. However, further testing of experimental data on different ground conditions and load cases is required.

This approach proposed by Grecenko [30] provides an important model for accurately calculating tire footprint area, especially in hard ground conditions. The model can be used to assess the potential for soil compression and compaction of the tire track area. However, future studies could test the accuracy of this model in agricultural and variable ground conditions, providing more comprehensive data to optimize tire choices and soil conservation.

2.14. Modelling of Stress and Compaction in Soil Caused by Agricultural Field Traffic

Soil compaction is the physical deterioration caused by the pressure applied to the soil by agricultural machinery, and this causes the soil pores to decrease, water and air permeability to decrease, thus negatively affecting plant growth. Keller and colleagues [31] conducted a modeling study to evaluate the effects of agricultural land traffic on soil and developed a model that estimates the stress and compression caused by the passage of agricultural machinery.

The developed SoilFlex model is a two-dimensional contact model and for using to calculate the tire-soil interaction. The contact area and contact stress are obtained from parameters such as tire load, inflation pressure and tire width and normal (vertical) stresses and shear (horizontal) stresses are examined separately. Soil properties such as soil density and volumetric strain are included in the parameters of this model. They used different methods in measuring volumetric stress in their studies. Three different methods were investigated for the calculation of soil density and volumetric stress: Larsson et al. [32], Bailey and Johnson [33], O'Sullivan and Robertson [34]. The stress distribution was calculated using the Boussinesq [19] and Cerruti [35] equations.

The SoilFlex model was able to successfully predict the stress distribution and displacement in the contact area due to tire load. The model was found to accurately predict stress distribution and compression effects when compared with real-world data. The study showed that the size and shape of the tire-soil contact area directly affects the depth and spread of soil compaction. Therefore, optimum tire inflation pressure and reduction of machine passes are important to minimise damage to the soil.

These modeling studies provide critical data to assess and minimize the negative impacts of agricultural activities on soil. However, these models need to be tested under different soil types and climatic conditions. Future work should focus on improving the prediction accuracy of the SoilFlex model under different soil conditions and machine loads. In addition, this model can be optimized in the design and usage processes of agricultural machinery through long-term field studies.

2.15. Investigation of the Pressures Created by Tractor Tires on the Ground

The interface pressure of tractor drive tires on the soil is an important parameter affecting soil compaction and traction performance. Thomas and Kishimoto [2] investigated the interface pressures of different combinations of dynamic load and inflation pressure in clay and sandy soils using 18.4R38 radial-ply tires. In structured clay soil, the pressures on the tire tread surface were found to be higher than the inflation pressure, while the pressures under the tire tread were found to be lower. In loose sandy and clayey soils, the pressures were close to or below the inflation pressure. On different ground types, the tire tread area varied, which directly affected the pressure applied to the soil and the risk of compaction.

The research revealed that the tire footprint area was 10% wider in loose sandy soil and 4% wider in loose clay soil. As tire inflation pressure and load increased, the interface pressure in clay soil reached higher values on the tread surface, which increased the tendency for soil compaction. However, the effect of similar load and pressure changes on the interface pressure in loose soils was more limited.

Results show the effect of tractor tire pressure and load condition on soil compaction and traction performance. By optimizing inflation pressure, the efficiency of tractors can be increased and soil compaction can be minimized. However, more comprehensive studies conducted under different soil types and climate conditions could increase the accuracy of these findings in application in agriculture. A better understanding of the interaction mechanism with soil will contribute to the planning of more efficient and environmentally friendly agricultural activities.

2.16. Comparison of Soil Stresses Caused by Agricultural Machinery with Simulation Model

Keller and colleagues [36] conducted experiments under different soil types and loading conditions to measure and simulate the vertical stress effects of agricultural machinery on the soil. In the study, data obtained during wheel passes in five different soil types (13-66% clay content) were used and the results were compared with the Boussinesq and Frohlich solutions based on classical elasticity theory. The Boussinesq model describes the vertical stress distribution caused by a single normal force on the surface, while Frohlich added a "concentration factor" to this model and defined it from a broader perspective.

Boussinesq [19] developed a model to describe the normal stress distribution on a homogeneous isotropic elastic half-space surface due to a single normal force applied to a surface, and explained the vertical stress (σ_z) on the surface with the following equation:

$$\sigma_z = \frac{3P}{2\pi}\frac{z^3}{r^5} \quad (27)$$
$$r = (x^2 + y^2 + z^2)^{1/2}$$

Here, σ_z is the simulated vertical soil stress (Pa), P is the point load on the surface (N), z is the depth of the load (m) and r is the distance from the point of impact of the point load to the desired location (m). r the value is defined as the square root of the sum of the squares of the horizontal (x, y) and vertical (z) coordinates of the load point.
Frohlich [26] added a concentration factor (υ) to this model to describe the stress distribution more broadly:

$$\sigma_z = \frac{\upsilon P}{2\pi}\frac{z^\upsilon}{r^{\upsilon+2}} \quad (28)$$

Here, the coefficient υ controls the intensity of the stress distribution and when υ = 3, the equation agrees with Boussinesq's solution based on classical elasticity theory. This parameter affects the distribution of the load applied to the surface along the depth and the spread of the stress curves.

To evaluate the impact of agricultural machinery on the soil, each small element of the load in the tire-soil or track-soil contact area can be treated as point loads. In this case, the total stress is calculated by summing the stress values of all the small elements in the contact area of the surface load (Söhne 1953). In this approach, developed by Söhne and using similar principles, the total stress (σ_z) is expressed as:

$$\sigma_z = \sum_{i=0}^{n} \frac{\upsilon P_i}{2\pi}\frac{z_i^\upsilon}{r_i^{\upsilon+2}} \quad (29)$$

In this equation, P_i represents the point load (N) on each small point element, z_i^υ represents the depth of this element (m), r_i^υ represents the distance of the element from the point load to the desired location (m), and υ represents the concentration factor. This formula summarizes how stress varies with depth and the effect of each point load at different depths. Therefore, such models are used to understand how soil stresses under surface load change with depth and to minimize stress effects in the design of agricultural machinery.

In the simulations, each small area where the tire contacts the ground is treated as point loads and the vertical stress is estimated by calculating the sum of these loads. The vertical stress values measured with simulations based on the Boussinesq solution showed agreement above 90%. This high degree of agreement enabled accurate modeling of tire width, load and contact patch parameters.

The results showed that vertical stresses in elastic-plastic layered soils with weak upper layers were higher than in homogeneous soils, but this difference remained limited. Study recommends better modeling of tire-soil interactions and optimizing tire design parameters to minimize soil compaction by agricultural machinery.

This research shows that the effects of agricultural tires on soil can be reliably predicted by simulations and that such modeling studies can be an important guide in the design of agricultural machinery. However, the validity of the model needs to be tested under different soil types and more complex loading conditions. Future field tests can be used to increase the accuracy of these simulations and minimize the negative effects of agricultural machinery on soil structure.

2.17. Effect of Different Tire Load and Different Inflation Pressure on Soil Tension

Arvidsson and Keller [1] studied the effects of different tire loads (11, 15 and 33 kN) and inflation pressures (70, 100 and 150 kPa) on the stress distribution in the upper and lower soil layers. In the experiments, five stress sensors at 10 cm depth and sensors at 30, 50 and 70 cm depth were used to measure subsoil stresses. The data obtained showed that the maximum stress at 10 cm depth was 39% higher than the tire inflation pressure and that the stress increased with increasing tire load. In the subsoil, the effect of inflation pressure decreased, but tire load stood out as a determining factor on subsoil tension.

Vertical stresses (σ_z) were calculated with the model developed by Söhne [37] and formulated based on the Boussinesq equations. Tire load and inflation pressure are the most important parameters affecting the pressure distribution applied to the soil surface. Söhne's model describes the stress distribution on the surface using the tire's load and contact area parameters with the following equation:

$$\sigma_z = \sum_{i=0}^{n} \frac{\upsilon P_i}{2\pi Z^2} \cos^{\upsilon+2} \theta_i \tag{30}$$

Here, σ_z is the vertical stress (kPa), P_i is the load of each point element (kN), Z is the depth (m), θ is the angle between the point load vector and the position vector. The equation is used to calculate how the tire load and contact pressure change the stresses through the soil depth.

The study found that tire inflation pressure affects stress distribution in the topsoil, but this effect decreases in the subsoil and tire load plays a greater role. As the tire load increases, it has been observed that the stress values in the subsoil decrease linearly or parabolically from the center of the tire track to the edges. The results show that tire load and inflation pressure should be carefully optimised to reduce the risk of soil compaction.
This study highlights that tire load and inflation pressure are of great importance to correctly understand and minimize the impacts of agricultural machinery on the soil. While the inflation pressure is decisive in the topsoil, the effect of the load is more critical in the subsoil. Future field studies can test the validity of these models under different soil types and loading conditions, helping develop strategies to increase long-term agricultural productivity and prevent soil compaction.

3. CONCLUSIONS

In this review, the effects of agricultural tire technologies on soil compaction, traction performance and agricultural productivity in agricultural activities were comprehensively investigated. Findings from the literature reveal that new generation tires with low inflation pressure significantly reduce soil compaction by providing a large contact area. The use of such tires has the potential to reduce soil compaction and damage, while also increasing agricultural productivity. Findings show that low inflation pressure tires create a large contact area in agricultural activities, spreading the stress distribution more evenly and thus providing favorable conditions for plant root development [3, 6]. Moreover, it has been determined that optimum tire design and inflation pressure setting improves tractor performance by increasing traction and energy efficiency. Notably, radial tires exhibit a higher deflection capacity compared to bias tires, which makes them more effective at preventing soil compaction [13]. The ballast effect stands out as a critical factor in controlling soil compaction and increasing net traction power. The use of ballast provides an effective solution for preserving soil fertility by providing a more balanced load distribution, especially in radial tires.

Findings based on modeling studies highlight that accurately simulating tire and soil interactions plays an important role in planning agricultural activities and increasing productivity. Simulations have shown that the effects of tires on soil can be reliably predicted under different inflation pressures and soil conditions [21, 25]. However, existing models need to be tested with larger data sets under field conditions. Future modelling studies should be expanded to increase the accuracy of predictions for more complex soil structures and variable climatic conditions.

This review demonstrates that appropriate tire selection and use is critical to ensuring the sustainability of agricultural operations. In particular, the use of low inflation pressure tires creates a large contact area, increasing agricultural productivity and preserving the long-term health of the soil. As a result, it is recommended that tire load, inflation pressure and ballast applications be carefully optimized to minimize the negative impacts of agricultural machinery on the soil and ensure efficient use of the soil.

In future studies, testing the potential of new generation tire designs to increase energy efficiency and reduce soil compaction in agricultural machinery is thought to provide significant progress in agricultural machinery technologies. In this regard, in addition to field studies, the development of advanced modeling methods that can more accurately simulate soil compaction and traction force is also of great importance.

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CONFLICT OF INTEREST

The authors declare that this study has no financial or commercial relationship with any organization or people working with them.

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