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Experimental Evaluation of Nano Coating on the Draft Force of Tillage Implements and Its Prediction Using an Adaptive Neuro-Fuzzy Inference System (ANFIS)

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Abstract: The effect of coating a flat blade surface with titanium nitride nano coatings (TiN), nano tantalum carbide (TaC), Fiberglass (Glass Fiber-Reinforced Polymer) (GFRP), Galvanized Steel (GAS), and St37 (SST37) was investigated in order to decrease the adhesion of soil on tilling tools, external friction and, ultimately, the draft force. The soil tank, which was filled with soil of the desired conditions, was pulled on the bearing on the rail. A S-shaped load cell was used to measure the draft force. Tests were conducted at a distance of 2 m and speeds of 0.1, 0.2, and 0.3 m·s^{-1} at a depth of 10 cm. A model based on input factors, including blade travel speed, rake angle, and cohesion and adhesion of soil–blade, was developed in an adaptive neuro-fuzzy inference system (ANFIS), and draft force was the output parameter. To verify the performance of the developed model using ANFIS, a relative error(ε) of 6.1% and coefficient of determination (R^2) of 0.956 were computed. It was found that blades coated with Nano (TiN-TaC), due to its hydrophobic surface, flatness, and self-cleaning properties, have considerable ability to decrease adhesion in wet soils and showed a linear relationship with draft force reduction.

Keywords: draft; nano coating; ANFIS; soil; adhesion

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1. Introduction

Tillage operation uses a high percentage of input energy as a preliminary step in crop production [1]. Ren et al. [2] reported that a 30% draft force increment results in a fuel consumption increase of 30–50%. Many factors affect the value of the required draft force; the most important parameters are soil texture, soil moisture, tillage tool geometry, tool rake angle, internal and external soil friction angle, soil cohesion, soil–tilling tool adhesion, operation speed, and tillage tool working depth [3]. Some researchers, to decrease the energy requirement of tillage tools and improve working conditions, investigated tool surface coverage with materials such as Teflon, while today's technology industries have focused on the influence of nanotechnology materials [4]. Titanium Nitride (TiN) is a material with high hardness, a high melting point, la ow friction coefficient, hydrophobic properties, and self-cleaning properties as well as high resistance against wear and corrosion [5]. In a study, a TiN coating, by the physical vapor deposition method (PVD), was deposited on tillage tools, and the experimental results showed that this coating showed a significant effect on increasing the life span of tillage tools and decreasing the draft force in comparison to conventional steel [6]. Titanium-based multilayered hard coatings were developed for the alloyed steel MDN121 using the cathodic arc evaporation technique. The microstructural mechanical properties of the titanium-based coatings were evaluated to analyze the protective properties of the coatings [7]. Coating morphology and its composition and surface topography, as well as the presence of diamond-like carbon, were investigated using methods of field emission scanning electron microscopy equipped with energy dispersive X-ray spectroscopy (EDS), scanning tunneling microscopy, glancing angle X-ray diffraction (XRD), and Raman spectroscopy. It was found that the developed coatings were defect-free, dense, homogeneous, and had a thickness range of 1–2 µm. The hardness and elastic modulus of the coatings were measured using the nano-indentation method and were 5.6 and 297.6 GPa, respectively. Figure 1 shows a sliding system to specify the external friction angle. To specify the soil–metal external friction coefficient, different normal stresses were loaded on the slider; then, the required draft force corresponding to the different normal loads was measured, and the measured shear stress was plotted against the normal stress. The coefficient of external friction was determined by specifying the slope of this line [8–10].

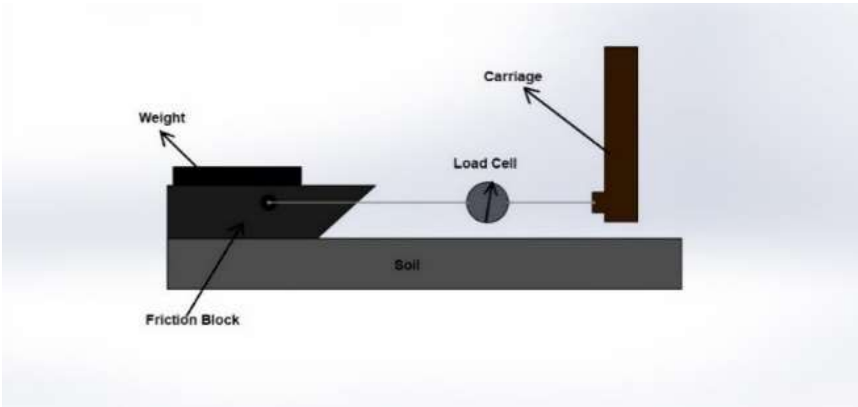

Figure 1. Sliding system to specify the soil's adhesion factor and its external friction angle [8].

The draft force increased almost linearly with increasing the soil–tool friction and adhesion. With increasing the adhesion from 0 to 20 kPa and the external friction angle from 25° to 35°, the draft force increased up to 46%. Reduction of the friction and soil–tool adhesion by modification of the tool surface showed a significant impact on the draft force reduction [11]. The coefficient of soil–tool external friction is computed by Equation (1) [12].

$$\mu' = \frac{F}{N} = \tan\delta \quad (1)$$

where μ' = the soil external friction coefficient; δ = the soil external friction angle, degrees; F = draft force, N; N = normal load, N.

Adhesion is the tendency of the soil to attach to a foreign material. It depends on the tool surface material and soil moisture content [10]. Adhesion measurement is similar to the coefficient of soil external friction. Payne [13] expressed soil adhesion as a parameter using Equation (2). This equation describes the maximum friction and adhesion between a metal surface and soil.

$$\tau_{max} = c_a + \sigma_n \tan\delta \quad (2)$$

where

τ_{max} = maximum shear stress, $N \cdot m^{-2}$;

C_a = soil adhesion, $N \cdot m^{-2}$;

σ_n = normal stress, $N \cdot m^{-2}$.

Figure 2 shows a straight line with a gentle slope can be drawn between the shear and normal stress. The point at which the line crosses the vertical axis determines the adhesion value (C_a) where the normal stress is zero. The angle of δ is determined by specifying the slope of the plotted line [8].

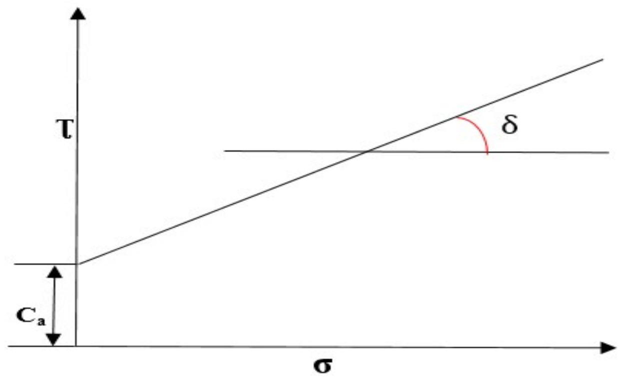

Figure 2. Shear stress versus normal stress to determine the soil adhesion and external friction angle.

Today, for many complicated problems, using the fuzzy logic method (FL) is a better solution for the realization of artificial intelligence (AI) goals than the classical mathematical models. FL is conceptually simple and flexible in concept. In fact, it is possible to organize a fuzzy system to solve a complex problem using if–then rules. Marakoglu and Carman [14] developed a model based on the FL modeling principles (max–min-mamdani) to predict the degree of soil loosening and tilling operation efficiency compared to the regression model. Their results showed that the relative average error of the measured and predicted values in the FL model was less than the regression model. In the last few years, the ANFIS method has been applied in different sciences. Using the power of training the neural networks and the linguistic advantage of fuzzy systems, these types of systems have been able to benefit from the advantages of these two models in order to analyze complex processes. ANFIS has been used to describe soil crushing in primary tillage operations using the moldboard plow, the subsoiler, and secondary tillage such as using a cultivator and disk. In engineering science, ANFIS is able to find non-linear relationships between the inputs and outputs of a problem [15]. Badiger et al. [16] used the cathodic arc evaporation method to develop a thin coated layer to reduce wear and increase lifespan. Performance of the thin solid layers were examined by machining MDN431 steel at a cutting speed of 59–118 $m \cdot min^{-1}$, feeding rate of 0.062–0.125 $mm \cdot rev^{-1}$, and cutting depth of 0.2–0.4 mm. An ANN trained model and statistical regression models were applied to predict the response parameters based on the experimental data, with minimum error. The fretting corrosion and adhesive wear resistance of Ti-based thin solid films deposited on MDN121 steel substrate were evaluated [17]. Fretting corrosion analysis showed that coating with a TiC–C monolayer decreased the coefficient of friction by 68.49% and coating with a Ti multilayer reduced it by 42.46% in comparison with the substrate.

Recent studies have shown that by modifying the surface of tillage tools with composite coatings such as TiO_2-Al_2O_3-SiO_2, wear, friction, adhesion and, thus, draft force can be reduced. Also, nano-TiN has been used in several cases of soil-involved tools, and positive effects were found [4,6,11,18]. Nanotitanium-nitride and tantalum carbide, due to their hardness, low friction, corrosion resistance, fatigue resistance, high hydrophobicity, flexibility in material design, and the ability to optimize physical and mechanical properties, can be used in specific applications, such as soil cutting tools [5,6,19]. Sahu and Raheman [20] conducted research to predict the required draft of some common tillage implements in soil bin and field conditions. Three different tools, including a plow with a cutting width of 0.1 m, a tine with a cutting width of 0.075 m, and a disc with a diameter of 0.3 m, were studied in the soil bin in sandy clay loam soil at three depths of 0.05, 0.075, and 0.1 m and velocities of 1.2, 2.2, 3.2, and 4.2 $km \cdot h^{-1}$. In the second stage, the required draft of six different scale-model implements was measured under the same conditions at a depth of 0.075 m and velocity of 3.2 $km \cdot h^{-1}$. The regression equations for the required draft of the reference tillage implements and scale-model tools were developed using orthogonal and multiple regression methods. A good relationship was found between measured and predicted draft values. This method produced valid results in predicting the draft requirement of tillage implements in different soil conditions by examining only the reference tillage tool in any soil type in reference conditions. The draft requirement of a chisel plow during tillage operations was studied [21]. Field trials were conducted at three working depths (WDs) of 10, 20, and 30 cm and three forward velocities (FVs) of 2, 4, and 6 km·h^{-1} in a clay loam soil. To predict the draft force, the ANFIS method was used. The FV and WD were considered as input variables, and the draft force as output. A comparison was accomplished between the results of the optimum ANFIS model and the mathematical model developed by the American Society of Agricultural and Biological Engineers (ASABE). To select the optimum model with the highest prediction ability, some statistical criteria, such as coefficient of determination (R^2), root mean square error (RMSE), mean relative deviation modulus (MRDM), mean of absolute value of prediction residual error (MAVPRE), and prediction error mean (PEM), were used. The results demonstrated that the optimum ANFIS model, with valid values of R^2 = 0.994, RMSE = 0.722 kN, MRDM = 3.172%, MAVPRE = 0.561 kN, and PEM = −0.071%, was more accurate than the ASABE model. Al-Dosary et al. [22] used the ANFIS method and compared it with a multiple linear regression (MLR) model to specify a disk plow's energy and draft requirements. A total of 133 data were collected by performing tests in the field and from the literature. A total of 121 data were arbitrarily used for training, and the remaining data were used for the evaluation of models. The input variables were plowing depth, plowing velocity, soil texture, soil moisture content, soil bulk density, disk diameter, disk angle, and disk tilt angle, and required draft was considered as output. Four membership functions were used with ANFIS: a triangular membership function, generalized bell-shaped membership function, trapezoidal membership function, and Gaussian curve membership function. A comparison of the outcome of the ANFIS and MLR modeling showed that the triangular membership function performance was better than the other functions. As predicted, the draft force of the optimum ANFIS model was compared to the measured values, and the average relative error was −1.97%.

Elsheikha et al. [23] evaluated the effect of using three different coating materials on the draft requirement of a chisel plow. Four chisel plow shares with the same geometric dimensions were tested. The first chisel plow share was standard iron without coating and was considered as a control; the other three were coated with copper, aluminum, and stainless steel. Experiments were conducted in a soil bin with a dynamometer attached to a 26 kW Kobota tractor to measure the required horizontal force value of each share as the required draft. The required draft for all plow shares was evaluated at different working depths of 15, 20, and 25 cm and different forward velocities of 0.58, 0.75, and 1 m·s^{-1}, with three replications and using a completely randomized design in silty clay loam soil. It was found that the stainless steel-coated share required the minimum horizontal force at all depths and almost all forward velocities. Therefore, the stainless steel-coated share was recommended due to its minimum draft and low price. Barzegar et al. [11] conducted a series of tests to reduce the draft force of furrowers by surface coating. Due to the self-scouring ability and low frictional characteristics of ultra-high molecular weight polyethylene (UHMW-PE), a narrow metal furrower was coated with plastic. Then, a steel tine similar to the plastic-coated tine in terms of shape and dimension was fabricated. Both tines were designed and built like the furrower and were tested to measure the draft in a soil bin filled with heavy clay soil. Each test was repeated three times over a depth of 20 cm at the two moisture content levels of 4% and 18% dry based and different soil bulk densities The required draft of the polythene-coated tine was significantly less than for the steel tine at both moistures.

However, many aspects related to the application of nano-TiN-TaC in soil-involved tools remain undetermined. In particular, experiments have not been performed to investigate the effects of these coatings on tillage tools in the soil bin or field. It is not clear how, and based on which effective parameters, nano-coatings decrease the draft requirement of tillage tools. This, it is necessary to evaluate nano-coated tillage tool performance in terms of the required draft and energy. Also, further research is needed to investigate their performance in comparison with conventional tools. In this research, for the first time, nano-coated blades were fabricated and tested in the soil bin using different soil textures, and the draft requirement was measured and compared with the requirement of conventional tools like St37. There is lack of knowledge on the effect of coatings, and specifically, on nanocoated tools' interaction with the soil and the effect of the coatings on soil properties, which affect tillage draft force and energy requirements.

The aim of this study was to investigate and compare the effect of five materials—St37 (SST37) plate, galvanized steel (GAS), fiberglass (Glass Fiber-Reinforced Polymer) (GFRP), and two nano-coated plates of titanium nitride and tantalum carbide (TiN-TaC) (due to high hydrophobicity and moisture excretion)—on the draft force in a soil bin and to develop a comprehensive model in order to predict the draft force based on the input variables, including rake angle, soil moisture, soil cohesion, soil–tool adhesion, the tool speed, using ANFIS.

2. Materials and Methods

2.1. Material Characteristics

Table 1 shows the percentages of sand, clay, and silt and the soil texture type, which were specified by the Hydrometer method. Different soil textures were collected from different areas of Ardabil province plain based on soil texture maps. The required amount of soil was transported to the test workshop, and all conditions were created in the soil bin.

Table 1. Percentage of sand, clay, and silt in different soil textures.

Soil Texture	Sand Percentage (%)	Clay Percentage (%)	Silt Percentage (%)
Sandy-Loamy	73	10	17
Loamy	46	24	30
Clay-Loamy	30	40	30

Five different cubic structures, 10 cm long and wide and with a thickness of 2 mm using different materials, including st37 (SST37), galvanized steel, fiberglass, and nano-coated materials of titanium nitride and steel-based tantalum carbide, were prepared. Galvanized steel is especially suitable in various weather environments due to its resistance to moisture and wetting (hydrophobicity), as well as anti-rust, anti-wear, and anti-corrosion properties. The adhesion of the soil is a function of moisture, and the tensile strength is also a linear function of adhesion. By increasing the adhesion of the soil in the blades, the tensile strength increases and the tillage quality decreases [6,11].

It is important to choose the right method for layering two samples on a substrate of st37 for proper coating. Among the different layering methods, the sputtering method was chosen due to its high coverage yield, stability, and deeper penetration. The sputtering method should create a gas plasma (usually argon gas) between the substrate and the target. The bombardment of the target material by high-energy ions causes the atoms to be removed from the surface of the target material and their deposition on the substrate, forming a thin layer. For a better understanding of the structural analysis and the depth of the layers, a cross-sectional surface of the coated samples was cut, and the average layered depth was obtained using a scanning electron microscope (SEM) with a resolution of 50,000 times (Figure 3).

Nano titanium is high-strength, low-friction coefficient and increases the stability of the coating. Also, recently, nano-titanium nitride has improved the wear weakness of this material. TiN is a ceramic material with extremely high hardness, which is usually used as an alloy coating to improve the surface properties of the material. Titanium nitride is used as a thin coating for coat drill bits and milling cutters to maintain sharp edges and prevent corrosion and wear. This coating usually increases tool life by 2 to 10 times. In this research, ion sputtering or sputtering was used to coat TiN and TaC on the surface of the samples, which is one of the methods of physical vapor deposition (PVD) in making thin layers.

After preparing and polishing the surface of the samples, and applying a vacuum inside the chamber, excess gases are removed from the source. Then nitrogen, hydrogen and argon gases of a certain amount are imported to the chamber, and by applying the potential difference, plasma is formed on the surface of the samples. Then, the gases ionize and hit the surface of the sample, which is the cathode. As a result of the collision of these particles with the surface of the sample, the pollution of the surface of the samples is removed using the sputtering method, and the temperature of the sample increases. This gas is ionized in the plasma and reacts with the nitrogen ions in the chamber; it is deposited on the surface of the sample, and as a result, the TiN layer is created. This layering method is superior to many layering methods because of its high capability in creating thin films with high purity. This process can greatly affect the structure, mechanical properties, and tribological behavior of coatings [6,24].

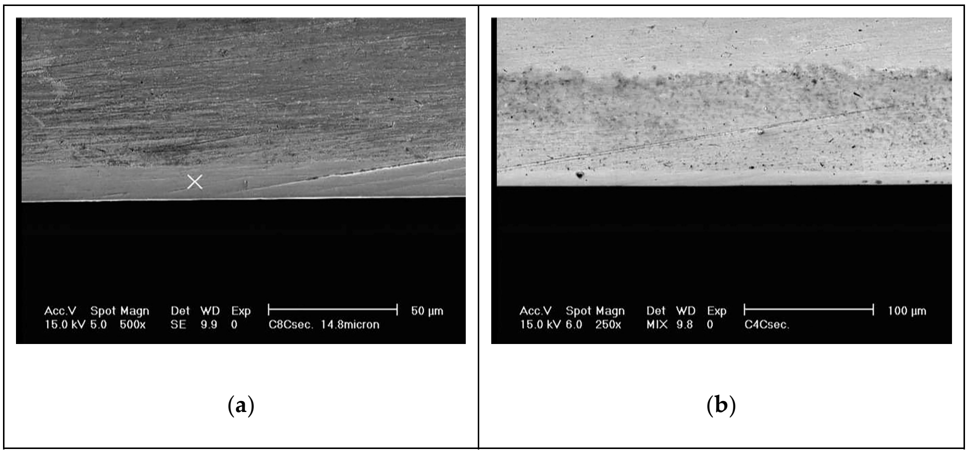

Figure 3. SEM image of the cross-section of the sample thickness. (**a**) Tantalum carbide; (**b**) titanium nitride.

The rear part of the blades was folded to facilitate the tool movement and to decrease the tool–soil friction and ultimate draft force (Figure 4). The geometric shape of all blades was similar.

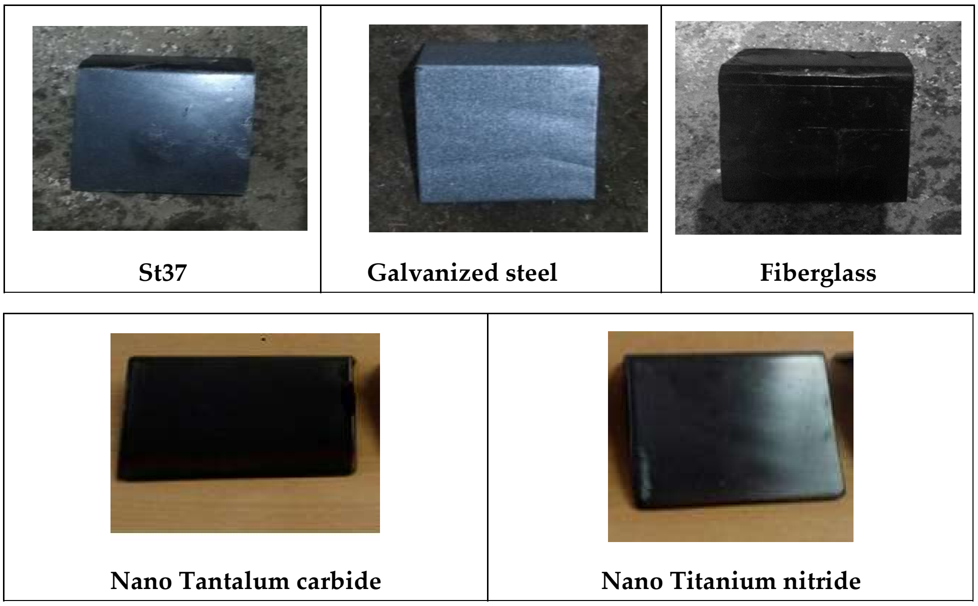

Figure 4. Blades for cutting the soil and for measurement of external friction coefficients.

2.2. Test Stand

In order to study the effect of the external soil friction and adhesion on the required draft force, a system was developed, and its components were drawn and assembled using SolidWorks 2016 (Figure 5).

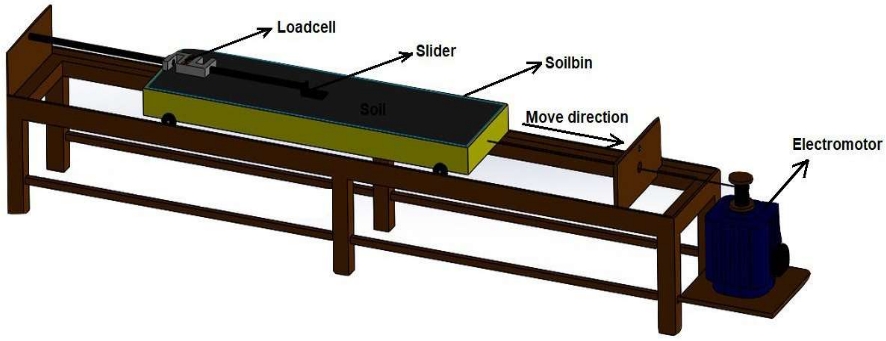

Figure 5. Schematic of developed device for measuring external soil friction coefficient and adhesion.

To measure the adhesion, soil–tool friction angle, and the draft of tillage blades under controlled conditions, a device was designed and built that was able to conduct the required tests at different conditions. In an overview (Figure 5), a device with a total length of 4 m, width of 0.3 m, and height of 0.5 m was developed. It included a chassis and a power transmission system. The soil tank, with a length of 2 m, was pulled on the rails by a tow wire connected to a 1.5 kW electric motor. To measure the draft force, an S-shaped load cell was placed in the middle of a rod; one side of the rod was fixed to the chassis, and the other side was connected to the blades engaged with the soil. The load cell was connected to a data logger (DT800, Lontek company, Glenbrook, NSW, Australia) to record the data. One of the factors that should be taken into consideration is the speed of the tank containing the soil. To provide and control of the linear speed of the soil tank, an inverter (VFD model 2 kW/220 V) was used, and by changing the frequency of the inverter, the sliding speeds of 0.1, 0.2, and 0.3 m·s^{-1} were obtained at frequencies of 140–210 and 280 Hz.

The purpose of this test was to obtain the parameters of the Columbus–Mohr equation (Equation (1)). The line slope and its distance from the origin in the y axis are the soil external friction angle (δ) and adhesion (C_a), respectively. In order to obtain these parameters, at least three tests for each material were conducted, and for each test, a different vertical load was used. Hence, the three loads of 20, 10, and 30 N were used. The maximum amount of draft force was recorded as the draft force, and the draft-normal load diagram was plotted for different soil textures (Figure 6).

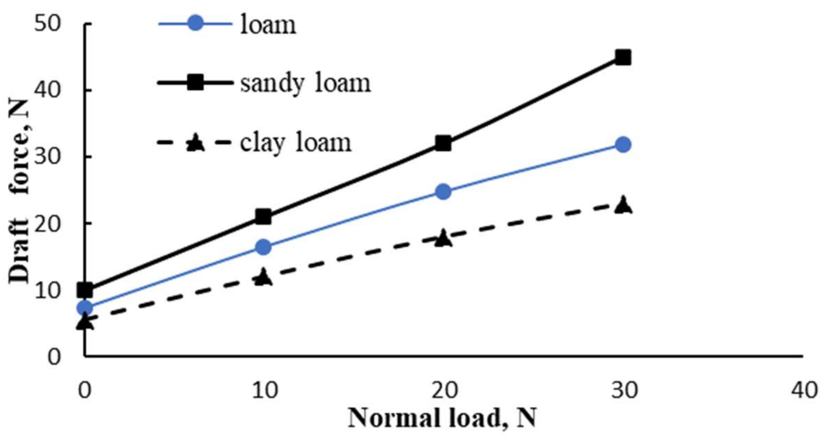

Figure 6. Variation of draft force versus vertical load.

Then the shear stress–normal stress diagram was exacted; the regression line passing through these three points is called the Columbus–Mohr equation line. For more information on adhesion tests and friction coefficients, refer to the research conducted by Marani et al. [8].

To perform the soil cutting tests, a soil bin was used. The tilling plate was attached to a fixed beam connected to a circular part, and a few holes were created. Using these holes, different rake angles were created for beam and blade (Figure 7).

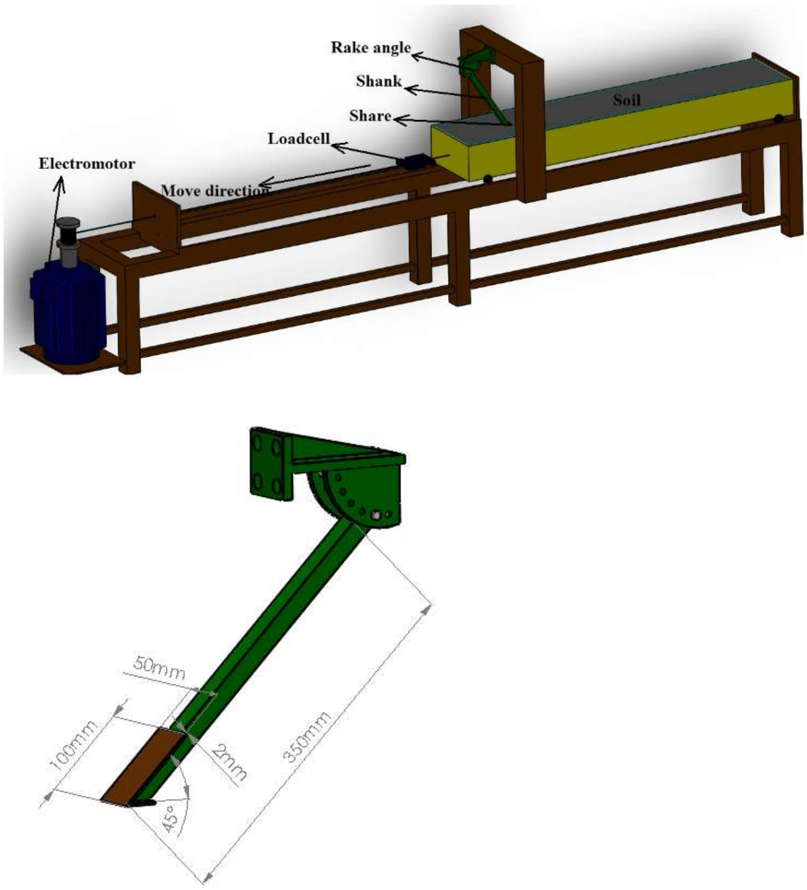

Figure 7. Laboratory soil bin used to perform soil cutting tests (**top**); geometry of coated bade on the tine (**bottom**).

The main aim was to investigate the effect of different coatings on tool performance. It was decided to also analyze other important parameters, like soil moisture, tool speed, and rake angle. Another factor for possible study was working depth; however, because of limited tool geometry, especially regarding nano-coated tools, it was considered as a constant parameter. In a tillage tool, the angle of attack determines how the blade enters the soil and determines the soil movement on the blade; changing the rake angle changes the distance and time of soil movement along the blade surface. The effect of the three rake angles of 30, 45, and 60° on the draft force requirement was investigated. All tests were conducted at an average soil density of 1.3 $g \cdot cm^{-3}$; for this, a 20 kg roller was run three times on the soil inside the soil box, and all tests were carried out at a depth of 10 cm. By adjusting the frequency of the inverter, three traveling speeds of 0.1, 0.2, and 0.3 $m \cdot s^{-1}$ were created. Tests were conducted using the five tilling tools in Figure 6 at the three different soil moistures of 10, 20, and 30% (d.b.) in the three soil textures of Table 1 at travel speeds of 0.1, 0.2, and 0.3 $m \cdot s^{-1}$ and rake angles of 30, 45, and 60°. All tests were repeated three times. To obtain the actual required draft force for soil cutting, once the soil box was moved in free mode without soil cutting, the required force was recorded. Then, this force was subtracted from the total force required for pulling the soil box during soil cutting. SPSS16 software was used to conduct variance analysis and also for regression modeling.

2.3. ANFIS Modelling

We aimed predict the draft force with all effective factors at the same time. Soil cohesion was used as representative of soil texture and soil moisture, and soil–tool adhesion as representative of the tilling tool type. Therefore, the four input factors of advance speed, rake angle, soil cohesion, and soil–tool adhesion were considered as input factors, and the required draft was considered as the output in ANFIS.

To train and obtain precise data for the target, the data were divided into three categories: training data, validation data, and test data. A total of 70% of the data used the training process to compute the gradient and optimize the variables. In the training process, the network should be prevented from becoming specialized and creating the phenomenon of overfitting in reaching the minimum error. For this purpose, 15% of the data was used for validation; these data are actually part of are training data. During the training of the network in regular intervals of the optimization process, the data obtained from the network are checked using the validation data. The training of the network continues until the optimization error related to the evaluation data starts to increase; when this error increased to a certain value or a certain number of repetitions, network training was stopped [25]. Finally, the remaining 15% of the data was used as test data, to test the performance of the network after training. The test data are not used during network training, but they are used to compare the error rate. The division of data for the above three groups was done randomly because, in this case, the data of each class were selected from different parts of the data set and included all the characteristics. Then, from 405 available data on draft force, 285 were used for training, 60 for evaluation, and 60 for testing.

The four most commonly used membership functions, Gaussmf (Gaussian membership function), Trimf (Triangular membership function), Trapmf (Trapezoidal membership function), and Gbellmf (Generalized bell-shaped membership function), are represented as input functions to represent the inputs (Figure 8).

The number of membership functions for each entry (three in number) was assumed to prevent over-regulation and system complicating. The space of all the entries was divided into three regions. Linguistic variables for speed (slow-normal-fast), for the blade rake angle (small-average-large), for soil cohesion (low-medium-high), and for soil–tool adhesion (poor-mean-rich) were used. The output membership function for this network was linear. The number of rules created by the network for the draft force model was 81. However, only a few are presented in Table 2 for better understanding of ANFIS modelling.

Table 2. Some rules of the developed ANFIS model.

	Input Variables				Linear Output Function (Draft Force), N
Rules	**Speed, m·s^{-1}**	**Rake Angle, Degrees**	**Cohesion, Pa**	**Adhesion, Pa**	
Rule1	slow	small	low	poor	D = 2.8s + 83a − 16c + 3962ad + 2.8
Rule8	slow	small	high	mean	D = 45s + 1349a − 190c + 6741ad + 45
Rule18	slow	avg	high	rich	D = 94s + 4247a − 290c + 5302ad + 94
Rule28	normal	small	low	poor	D = −3.4s − 50.7a − 16.6c + 4136ad − 1.7
Rule38	normal	avg	low	mean	D = −91s − 2061a − 235c + 5069ad − 45
Rule48	normal	big	low	rich	D = −107s − 3220a − 566c + 6359ad − 53
Rule58	fast	small	medium	poor	D = −28s − 279a − 15c + 5152ad − 9.3
Rule68	fast	avg	medium	mean	D = −277s − 4161a − 131c + 3975ad − 92
Rule78	fast	big	medium	rich	D = −867s − 1735a − 470c + 7668ad − 289
Rule81	fast	big	high	rich	D = 1155s + 2310a − 469c + 7832ad + 385

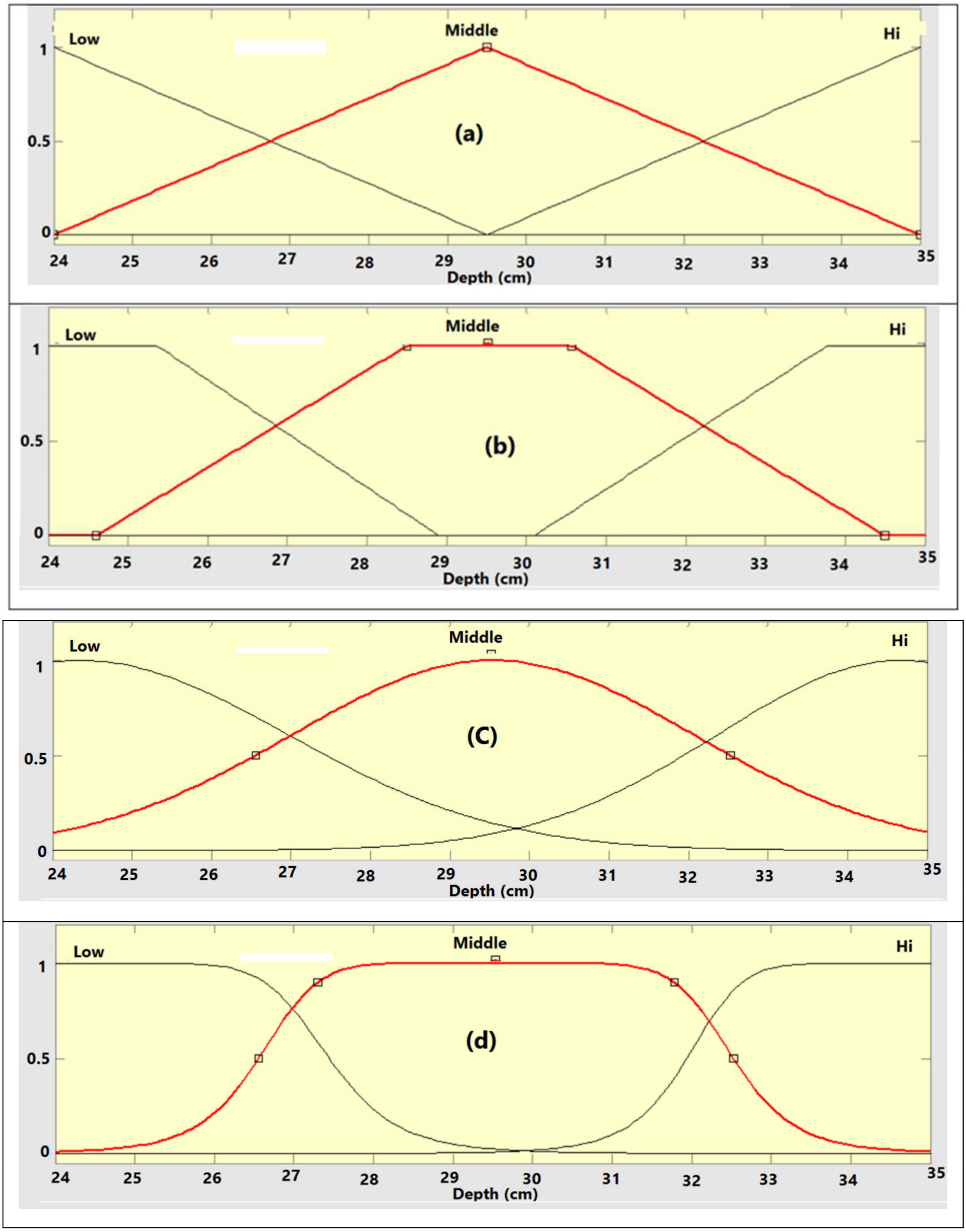

Figure 8. Different membership functions used for input variables (**a**) Triangular, (**b**) Trapezoidal, (**c**) Gaussian, (**d**) Bell-shaped.

These rules are based on the FL system of the Takagi–Sugeno–Kang or TSK type system. In this system, the if–then part comprises fuzzy rules, but the resulting part is non-fuzzy and a linear combination of input variables.

To compute the output parameter, the weight of each rule was specified. The weight was computed in such way that, in each rule, the membership degree of the input signal in the membership functions of each variable was determined, and its minimum value was considered as the weight of the rule. Figure 9 demonstrates this for a network with two inputs.

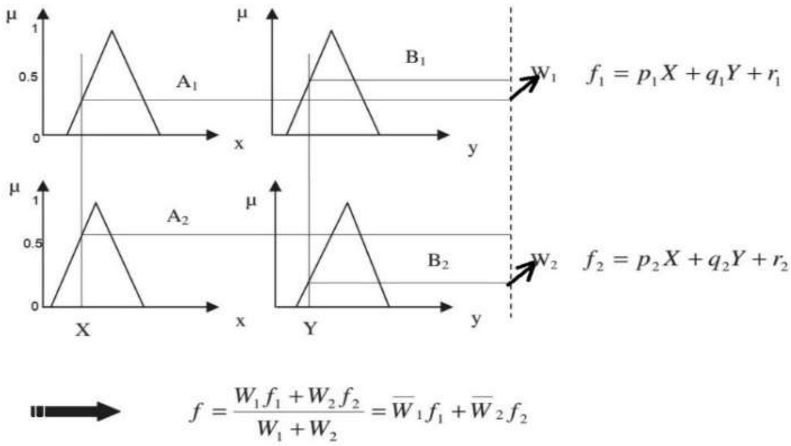

Figure 9. Schematic of fuzzy inference system: Takagi–Sugeno.

Finally, the final output of the model is computed by the Equation (3).

$$f = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \tag{3}$$

where f_1 and f_2 are linear functions for rules 1 and 2, respectively, and w_1 and w_2 are the weights of each law. To evaluate the capability of the developed models, two statistical criteria, relative error (ε) and coefficient of determination (R^2), were used, which are presented by the Equations (4) and (5) [25].

$$\varepsilon = \frac{100}{N} \sum_{i=1}^{N} \frac{Y_{measured} - Y_{predicted}}{Y_{measured}} \tag{4}$$

$$R^2 = \frac{\sum_{i=1}^{N} \left(Y_{measured} - Y_{predicted}\right)^2}{\sum_{i=1}^{N} \left(Y_{measured} - Y_{predicted}\right)^2} \tag{5}$$

where $Y_{measured}$ and $Y_{predicted}$ are measured and predicted values, respectively.

3. Results and Discussion

Table 3 shows the analysis of variance of the draft force requirement at different parameter settings. Data were analyzed in a 3 × 3 × 5 × 9 factorial design based on a randomized complete block design. The data change coefficient was 0.88%. It was found that the main effects of travel speed, rake angle, and soil adhesion and cohesion were significant on draft force at the 1% probability level. Also, the binary effect of these parameters was significant at the 1% probability level. However, triple interaction was not significant. The triple interaction effect of speed*rake angle*adhesion and speed*rake angle*cohesion was significant at the 5% level, and speed*adhesion*cohesion and rake angle*adhesion*cohesion were significant at 1%. The quadruple effect of input parameters was significant at a probability level of 5%.

The ANFIS network was developed to predict the draft force of the soil cutting blade using four different models. Table 4 presents the structural parameters of the models along with the statistical criteria for evaluating their performance.

Table 3. Analysis of variance of draft force change due to travel speed, rake angle, and soil adhesion and cohesion.

Source	DOF	Sum of Squares	Mean of Squares	F-Value	*p*-Value
Speed	2	8,431,423	4,215,711	3488.02 **	0.000
Rake angle	2	6,209,571	3,104,785	2568.85 **	0.000
Adhesion	4	41,820,740	10,455,185	8650.46 **	0.000
Cohesion	8	15,521,397	1,940,175	1605.27 **	0.000
Speed*Rake angle	4	123,109	30,777	25.46 **	0.000
Speed*Adhesion	8	630,415	78,802	65.20 **	0.000
Speed*Cohesion	16	240,828	15,052	12.45 **	0.000
Rake angle*Adhesion	8	411,298	51,412	42.54 **	0.000
Rake angle*Cohesion	16	193,016	12,064	9.98 **	0.000
Adhesion*Cohesion	32	2,230,482	69,703	57.67 **	0.000
Speed*Rake angle*Adhesion	16	22,892	1431	1.18 *	0.275
Speed*Rake angle*Cohesion	32	51,782	1618	1.34 *	0.101
Speed*Adhesion*Cohesion	64	294,870	4607	3.81 **	0.000
Rake angle*Adhesion*Cohesion	64	177,193	2769	2.29 **	0.000
Speed*Rake angle*Adhesion*Cohesion	128	191,407	1495	1.24 *	0.049
Error	810	978,988	1209		
Total	1214	77,529,410			

** Highly significant. * Significant.

Table 4. Structural features of the best developed ANFIS models.

Model	Type of MF		Number of MF		Optimization Method	Test	
	Input	Output	Input	Epoch		ε (%)	R^2
Grid Partition	Trimf	Linear	Hybrid	30	Hybrid	6.77	0.9407
Grid Partition	Gaussmf	Linear	Hybrid	30	Hybrid	6.39	0.9491
Grid Partition	Trapmf	Linear	Hybrid	30	Hybrid	6.27	0.9511
Grid Partition	Gbellmf	Linear	Hybrid	30	Hybrid	6.1	0.9568

All models have high capability ($R^2 \geq 0.94$ and $\varepsilon \leq 7\%$) in prediction. The optimum model was the model built based on the linear membership function (Gbellmf), with ($R^2 = 0.956$ and ε (%) = 6.1). Also, a model was developed based on multiple linear regression in SPSS16 software to gain more knowledge about the effect of each input variable on the draft force. Table 5 illustrates the statistical specifications of the stepwise regression model for draft force prediction.

Table 5. Comparison between the experimental and predicted values of the draft force by ANFIS and regression models.

Model	Unstandardized Coefficients		Standardized Coefficients	t	sig
	B	Std. Error	Beta		
(Constant)	−576.275	40.645		−14.178	0.000
Speed	100.032	6.596	0.325	15.167	0.000
Rake angle	5.890	0.440	0.287	13.397	0.000
Cohesion	0.025	0.01	0.372	17.295	0.000
Adhesion	0.420	0.013	0.678	31.569	0.000

The statistical criteria of the prediction model for draft force were $R^2 = 0.816$ and ε (%) = 14. According to the statistical criteria, the regression model cannot accurately control and predict the output values as well as the ANFIS model. However, regression models have significant advantages over the ANFIS model. The ANFIS model does not provide a single relation for modeling the output variable and does not provide an index for comparing the impact of each input variable on the output variable, while the regression model directly addresses the impact of each factor. According to Table 4 and the standard coefficients indicated therein, the soil–tool adhesion, soil cohesion, tool speed, and rake angle showed the greatest impact on the blade's draft requirement.

Table 6 presents the regression equation for each blade draft as a function of the soil moisture content. Based on the developed models of draft force, the conventional St37 and galvanized steel blades, with 12.7 and 8.95 coefficients, respectively, were more sensitive to moisture change. This is because the hydrophilic property of the steel surface and the water tension forces cause the moist soil to be absorbed into steel surface molecules in the contact area, which prevents the rolling of the soil particles from the tool surface. However, the surfaces of the nano-carbide and titanium nitride, with slopes of 6.7 and 7.7, showed less sensitivity to moisture increases. Nano-coatings have hydrophobic properties and prevent the establishment of such sticky layers. Also, GFRP showed acceptable performance as compared to conventional or galvanized steel. Similar results were found by other researchers testing coated-surface effects on the draft force [2,11,26–28].

Table 6. Determination coefficient of regression models to predict the draft force in terms of moisture content for different materials.

Plate Material	Regression Equation	Coefficient of Determination
ST37	y = 12.7x + 519.33	0.9941
GAS	y = 8.95x + 790.67	0.8936
GFRP	y = 10x + 511.67	0.8698
N-TiN	y = 7.7x + 365.33	0.9973
N_TaC	y = 6.7x + 320.33	0.9166

Figure 10 indicates that the blade coated with nano-material required less draft force than any other tool. The draft force increased directly with increasing moisture content for all materials.

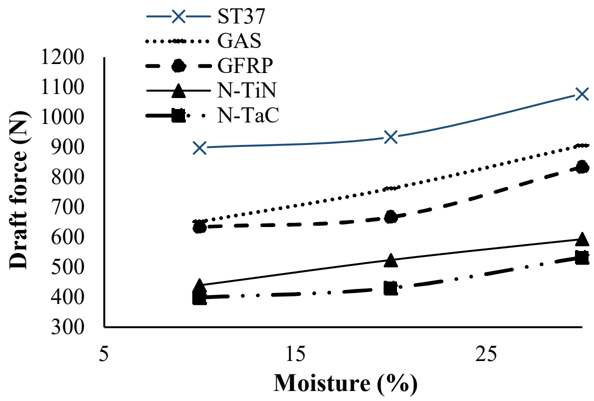

Figure 10. The effect of moisture and tool material type on draft force.

The speed increase range was 0.1–0.3 m·s^{-1}, and the draft force increased linearly with velocity (Figure 11). Chandon and Kushwaha [29] reported the draft force of tillage equipment as a linear function of velocity. Söhne [30] found that the required draft was a function of soil acceleration and that acceleration is proportional to the square of velocity. On the other hand, different relations have been presented for draft force versus velocity; the difference can be related to the different field conditions and the type of tillage tool used in the studies. Owen [31] found that the draft force increases quadratically with velocity increase; however, Summers et al. [32] reported a linear function between them. The draft requirement can be a linear, quadratic, parabolic, or exponential function of the tractor speed. These differences can be related to the required inertia to accelerate the soil, the effect of shear rate on shear strength and soil–metal friction, as well as soil adhesion and cohesion; all of these depend on the soil type and its condition, e.g., moisture and bulk density [33].

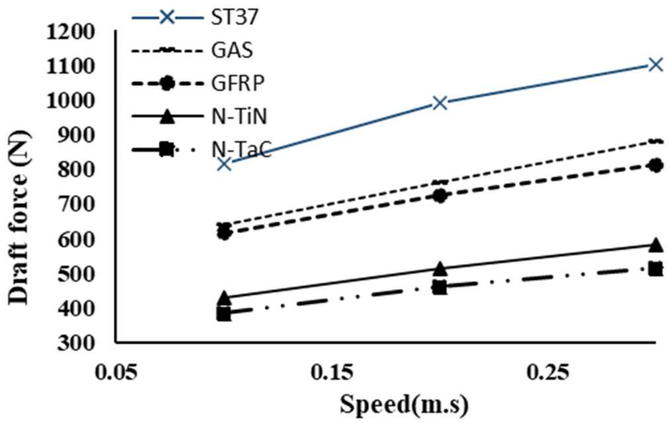

Figure 11. The effect of speed and tool material type on draft force.

In terms of the regression equations in Table 7, the slope of the draft force changes due to the velocity for st37 blade was 1425, and for the nano-TaC blade, it was 645. Then, it was found that increasing the travel speed was more significant on the draft force of the St37 blade than nano-TiN and nano-TaC blades. Therefore, it was indicated that the nano-coated blades, due to a flat surface area relative to other blades, retained their initial performance, causing a lower draft force increment [34].

Table 7. Regression equations and determination coefficients for draft force diagrams in terms of speed increase for different tool materials.

Plate Material	Regression Equation	Coefficient of Determination
ST37	y = 1425x + 684.67	0.9819
GAS	y = 1195x + 522	0.9999
GFRP	y = 980x + 521.67	0.9977
N-TiN	y = 755x + 358.33	0.9958
N_TaC	y = 645x + 325.33	0.9895

Table 8 presents the linear regression models for the effect of rake angle on the required draft. High determination factors show a good relationship between rake angle and draft force for all material types. Increasing the rake angle decreased the tendency for penetration and increased the amount of soil on the blade during cutting; hence, Figure 12 and Table 7 show that when increasing the blade rake angle from 30 to 60°, the draft force increases. Söhne [30] and Dransfield et al. [33] found that the optimum rake angle range for the minimum draft was between 20 and 30°. The draft force increases at rake angles below 20° due to the gradual increasing effect of the soil–tool interface area, which is associated with adhesive and frictional forces. Similar to previous research, it was found that a rake angle of 30° was the optimum angle in this research in terms of required draft. Considering these research findings and past research, future studies need to investigate a rake angle between 15 and 35° to find the optimum angle for tillage tools. The nano-coated blades showed the lowest draft force (Figure 12). Also, the furrow created by the coated blades compared to the metal type was symmetrical and monotonic. Therefore, it was concluded that operation with relatively low rake angles using nano-coatings and reinforcement polymers can improve tilling performance [6,11,29].

Table 8. The effect of rake angle on draft force requirement of the tools of different materials.

Plate Material	Regression Equation	Coefficient of Determination
ST37	y = 1425x + 684.67	0.9819
GAS	y = 1195x + 522	0.9999
GFRP	y = 980x + 521.67	0.9958
N-TiN	y = 755x + 358.33	0.9958
N_TaC	y = 645x + 325.33	0.9895

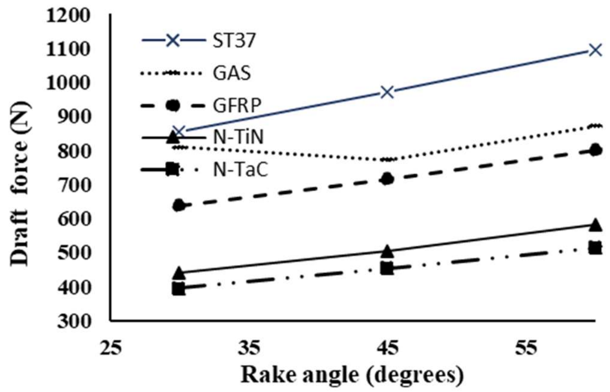

Figure 12. The effect of rake angle and tool material type on draft force.

One of the main features of nano-coatings in the discussion of tillage tools is their wear resistance. The main priority of the authors in this study was to investigate the draft requirement of nano-coated tools and to find its relationship with adhesion and friction using the ANFIS model. Also, as the traveled distances in the soil bin were short, the soil cutting under such conditions was not significant with regard to nano-coating abrasion. To investigate abrasion, intensive field trials should be conducted. For more information about the abrasion process and the lifespan of these coatings, refer to research by Sharifi Malvajerdi et al. [6].

It was concluded that the magnitude and variation trend of tillage tool performance, like the draft requirement, mostly depends on soil properties such as texture, moisture content, bulk density, soil friction angle, cohesion, soil–tool friction angle, and adhesion. To investigate operation parameters like forward velocity, tool geometry, and rake angle effect, we need to determine the mentioned parameters of soil to find and explain the relation between input and output parameters properly.

4. Conclusions

1. The ANFIS model showed better performance in predicting the draft force than the stepwise regression models.
2. It was found that soil–tool adhesion showed the greatest effect on draft force.
3. The results showed that nano-coating of blades was significant in reducing draft force, especially in sticky soils, compared to normal St37 and galvanized steel. At a moisture content of 20%, the draft requirement of St37 and nano-coated blades was 936 and 477 N, respectively, indicating a 49% and 53% draft reduction in studying the blade speed effect on the draft requirement. These high percentages of draft reduction show the importance of Nano-coating in reducing the energy requirement of tillage operations. Also, the soil furrow created by nano blades was more symmetrical and monotonic.
4. By understanding the conditions of the blades in the soil and the issues governing the tillage, the use of fiberglass through reinforced polymer fibers demonstrated acceptable performance compared to common galvanized steel against on draft reduction.

However, nano-tantalum carbide was the best coating in terms of its resistance and draft force reduction.

5. Improving the surface of the blades in the tools involved with the soil should be done in such a way as to reduce production costs and fuel consumption and increase tillage efficiency. These results can be achieved by knowing the working conditions of the blades in the soil and the tribological issues governing the tillage blades. Due to the challenges in conducting field trials as well as the high cost of coatings and coating application processes for large-scale tests, tests were conducted in the soil bin. It is hopeful that in the near future, by studying and applying the new methods of coating, problems regarding agricultural industry equipment, such as friction, wear, corrosion, erosion, etc., can be solved.

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