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From degradation to growth: intercropping insights

Od degradacji do wzrostu: spostrzeżenia dotyczące współrzędnych upraw

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Soil nutrients in areas degraded by mines may be depleted, which can negatively affect the health and growth of poultry and livestock. Intercropping offers greater benefits in soil quality in areas degraded by mines compared to sole cropping. Intercropping soybeans with corn can increase carbon (C) sequestration in the soil, soil oxygen (O_2) levels, magnesium (Mg) levels, silicon (Si) levels, and titanium (Ti) distribution, providing a sustainable option for farmers. It also increases potassium (K) levels in the soil, improves nutrient utilization, and alleviates aluminum (Al) toxicity for plant growth. Intercropping can reduce iron (Fe) accumulation in the soil, potentially supporting plant growth and nutrient uptake. Complementary nutrient uptake patterns by the two crops in the intercropping system contribute to these benefits. This method can increase yields and support plant health in mixed cropping systems.

Keywords: soil quality, corn, soybeans, crop coordination

Składniki odżywcze gleby na terenach zdegradowanych przez kopalnie mogą się wyczerpać, co może mieć negatywny wpływ na zdrowie i wzrost drobiu i zwierząt gospodarskich. Uprawa współrzędna oferuje większe korzyści w zakresie jakości gleby na terenach zdegradowanych przez kopalnie w porównaniu z uprawą wyłączną. Uprawa współrzędna soi z kukurydzą może zwiększyć sekwestrację węgla (C) w glebie, poziom tlenu w glebie (O_2), poziom magnezu (Mg), poziom krzemu (Si) i dystrybucję tytanu (Ti), zapewniając zrównoważoną opcję dla rolników. Zwiększa również poziom potasu (K) w glebie, poprawia wykorzystanie składników odżywczych i łagodzi toksyczność glinu (Al) dla wzrostu roślin. Uprawa współrzędna może zmniejszyć gromadzenie się żelaza (Fe) w glebie, potencjalnie wspierając wzrost roślin i wchłanianie składników odżywczych. Uzupełniające się wzorce pobierania składników odżywczych przez dwie uprawy w systemie uprawy współrzędnej przyczyniają się do tych zalet. Ta metoda może zwiększyć plony i wspierać zdrowie roślin w systemach upraw mieszanych.

Słowa kluczowe: jakość gleby, kukurydza, soja, współrzędne uprawy

Introduction

Following the introduction of a free market economy and liberalization of construction laws in Poland after 1990, urban development accelerated, particularly in suburban areas (McNeill and Winiwarter, 2004, Pepliński, 2019). This expansion caused a 17.2% decrease in agricultural land. The urban sprawl and conversion of agricultural land for urban purposes near major cities led to a shift towards extensive agricultural production, resulting in reduced interest among farmers in agricultural production in Poland (Pepliński, 2019). The process that can potentially return the trends for agricultural production is the restructuring of industry and the liquidation of some industrial plants and mines (Chmiela et al. 2024, Ouda et al. 2007). However, it should be remembered that post-mining and post-industrial areas are usually contaminated by mining or industrial activities. Hard coal mining in Poland emits about 26 million Mg of waste rock to the surface per year, of which about 7 million Mg per year is located on dumps (Magdziarczyk et al. 2024b). Several hundred years of mining have left thousands of hectares of dumps and areas that could be returned to society after reclamation. A form of reclamation could be their development for agricultural activities. Underground mining is associated with water hazards and even the oldest mines were provided with various solutions to reduce this hazard (Gawęda et al. 2025). Water flowing into the mine poses a threat to people working underground and to the existence of the mine (Magdziarczyk et al. 2024a). The mine pumping station system discharges over 200 million m3 of mine waters of varying mineralization to local watercourses annually (Chmiela et al. 2024). Part of the discharged mine waters directly from the pumping stations, and another part, after minor treatment, could irrigate agricultural

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crops, especially those produced for industrial needs. Additionally, human activities such as fossil fuel combustion, aggressive industrialization, and deforestation are the main contributors to produce high levels of greenhouse gas emissions (GGE), particularly CO_2, which trap heat and cause the Earth's temperature to rise. More energy is absorbed by methane than by CO_2, making it the second most important GGE (Kataria, 2015).

By implementing proper soil management practices, degraded mine lands can be rejuvenated, replenishing essential nutrients for sustainable agriculture. Issayeva et al. (2024) demonstrated that post-mining land in areas where mineral extraction has taken place can account for a substantial portion of land utilized for different purposes. This land acts as a substrate for the formation of anthropogenic soils, which may have unfavorable physicochemical properties. Iron (Fe), along with aluminum (Al), is a common element that can hinder plant growth in acidic soils. According to Nazir et al. (2024), soil carbon (C) is a crucial component of the C cycle, playing a vital role in storing C and reducing GGE. Cuetos et al. (2017) showed that C aids poultry by supporting healthy digestion and reducing the likelihood of digestive issues. According to Zhou et al. (2021), increasing soil C can reduce methane emissions from ruminant livestock by providing a more stable environment for the microbes in their digestive systems, resulting in lower methane production. Moreover, higher soil C levels can enhance forage quality, which in turn can help decrease methane emissions from ruminants.

Regarding soil oxygen (O_2), Manghwar et al. (2024) demonstrated the importance of soil O_2 for the well-being of plant roots. Adequate soil O_2 is crucial for proper respiration and nutrient absorption in plants. Insufficient levels of soil O_2 can lead to stunted growth and make plants more vulnerable to diseases. For plants to grow and develop, soil magnesium (Mg) is a necessary ingredient that is crucial for photosynthesis and enzyme activity (Ahmed et al., 2023).

On the other hand, soil Al is recognized for its detrimental impact on plant growth, as it can impede root development and nutrient absorption (Ofoe et al., 2023). With respect to soil silicon (Si), it is a naturally occurring element that is essential for plant health and growth (Khan, 2025).

With respect to soil potassium (K), Hasanuzzaman et al. (2018) highlighted its significance in enhancing water absorption and overall plant health. In 2019, Thor demonstrated the importance of soil calcium (Ca) for plant growth, as it plays a crucial role in cell wall structure and enzyme activation. A lack of Ca can result in stunted growth and inadequate yield development in plants.

Soil titanium (Ti) is recognized for its ability to improve soil structure and increase water retention, making it ideal for agricultural use (Lyu et al., 2017). According to Rai et al. (2020), Fe in the soil is essential for plant growth as it helps activate enzymes and synthesize chlorophyll. However, an excess of Fe in the soil can be toxic to plants, causing nutrient imbalances and stunted growth.

Polish researchers have uncovered a notable decrease in agricultural land, which is impacting feed production and animal populations (Busko and Szafranska, 2018). Poland's agricultural sector plays a crucial role in both European and international markets by supplying a wide range of agricultural, horticultural, and animal-based products. According to Niwińska et al. (2020) and Król-Badziak et al. (2024), approximately 50% of Poland's land area, totalling 15.4 million hectares, is dedicated to agriculture. Historically, the Polish economy has heavily relied on agriculture, with crops covering 14.413 million hectares, orchards spanning 265 thousand hectares, and meadows and pastures occupying around 4,048,500 hectares in 1989. The cultivation of grain maize (*Zea mays* L.) in Poland has seen significant growth, with the area planted increasing from 152,000 hectares in 2000 to 1,196,000 hectares in 2022. The average yield has also risen from 5.6 to 7.0 tons per hectare over the past 24 years. Soybeans (*Glycine max* L.) are grown primarily for their high protein (40%) and oil (20%) content, with the majority used in the feed industry to produce protein-rich soybean meal for livestock and poultry consumption. Poland's reliance on imported genetically modified soybean meal for cattle feed has increased, with 65% of protein needs for cattle feeding being met by imports in 2016 (Niwińska et al., 2020). Additionally, the production of cattle, milk, and slaughter animals contributes significantly to Poland's agricultural output, accounting for 26% of total production. In 2023, Poland, Spain, Germany, France, and Italy were the main poultry meat producers in the EU, with Italy experiencing a significant increase in production, accounting for 10.0% of total production (The Poultry site, 2024). To enhance crop diversity and maximize land use efficiency, intercropping soybeans with maize has become an advantageous practice in Poland. This approach not only helps maintain soil fertility but also promotes a more sustainable and profitable agricultural system, reducing the need for imported protein feed and enhancing the sector's self-sufficiency.

The aim of this paper is to present the results of several years of research conducted in Egypt on the impact of intercropping on soil quality and soybean and corn yields. Intercropping can be used anywhere, but the topic of its use in post-industrial areas may be of interest to Polish readers. Considering geographic, economic, and climatic constraints, the research findings could be piloted in Poland. The following hypotheses are put forward in the article:

- H1. Soybeans and maize can be successfully grown together, increasing their yield.
- H2. Intercropping contributes to improved soil health, significantly increases the levels of key nutrients in the soil.
- H3. Intercropping reduces reliance on chemicals.

Materials and Methods

A two-year study was during the summer seasons of 2021 and 2022. The study aimed to investigate soil nutrient dynamics in different cropping systems to enhance agricultural productivity and sustainability in the region, with the goal of improving soil quality in mining lands. The research was carried out at the Agricultural Research Center, located at Latitude 30°00′30″ N, Longitude 31°12′43″ E, and an elevation of 26 meters above sea level. In order to achieve 100% plant density of soybean and maize under intercropping, two rows of soybean seeds were drilled in the center of the raised beds, while maize plants were grown on both sides of the raised beds (140 cm wide). Two rows of sole soybeans were planted in a 70 cm wide ridge, with two plants per hill spaced 20 cm apart. One plant of sole maize per hill, spaced 30 cm apart, was planted in a 70 cm wide ridge. The Water, Soil, and Environment Research Institute at ARC utilized techniques outlined by Chapman and Pratt (1961) and Jackson (1965) to analyze the chemical properties of the rhizosphere in all treatments at a depth of 0-30 cm. The SEM Model Quanta 250 FEG (Field Emission Gun) at the Egyptian Mineral Resources Authority Central Laboratories Sector was employed to examine the superficial soil structure. The soil texture was identified as clay loam, with wheat being the previous winter crop in both seasons. A total of 476 kg of calcium superphosphate (15.5% P_2O_5) per hectare was applied to the soil during both summer seasons. *Bradyrhizobium japonicum* was introduced into soybean seeds using Arabic gum were used as a binding agent. Soybean seeds of cultivar Giza 111 were planted on May 25th and 22nd in 2019 and 2020, respectively, while maize variety T.W.C. 321 was planted 15 days later. Mineral N fertilizer was applied to maize at a rate of 285.6 kg N per hectare as ammonium nitrate (33.5% N) in two equal doses before the first and second irrigation in both intercropping and sole plantings. For soybean, mineral N fertilizer was applied at a rate of 35.7 kg N per hectare as ammonium nitrate (33.5% N) before the first irrigation in both intercropping and sole plantings. At harvest, chemical analysis of a soil sample provides valuable information such as weight percentage, atomic percentage, k-ratio (which indicates the proportion of different elements or compounds in the soil sample), atomic mass, and fluorescence intensity of various elements (Figs. 3 -11). This data is essential for understanding soil composition, identifying pollutants, assessing fertility, and predicting plant growth potential. It helps in making informed decisions about agricultural practices and environmental management. At harvest, maize grain and soybean seed yields per hectare (kg) were determined from weight of each plot and converted to kg per hectare. LER defines the ratio of area needed under sole cropping to one of intercropping at the same management level to produce an equivalent yield (Mead and Willey, 1980). It is calculated as follows: LER = (Yab / Yaa) + (Yba / Ybb), Where Yaa = Pure stand yield of crop a (maize), Ybb = Pure stand yield of crop b (soybean), Yab = Intercrop yield of crop a (maize) and Yba = Intercrop yield of crop b (soybean). An analysis of variance was conducted on the findings collected for each season. Following the completion of the error mean squares homogeneity test, a combined analysis of the two experimental seasons was performed. ANOVA was performed on the observed variables using the MSTAT-C statistical program (Freed, 1991). According to Gomez and Gomez (1984), mean comparisons were conducted at the 5% level of probability using the least significant differences (L.S.D.) technique.

Results and Discussion

Field tests were conducted during the summers of 2012, 2014, 2015, 2019, 2020, and 2024 at various agricultural research stations in Egypt (Abdel-Galil et al., 2014, Metwally et al., 2019a; 2019b, 2021; Abdel-Wahab and Abdel-Wahab, 2020 and Abdel-Wahab et al., 2019, 2024). The soybean yield ranged from 1110 $kg \cdot ha^{-1}$ to 2720 $kg \cdot ha^{-1}$, while the maize yield ranged from 4830 $kg \cdot ha^{-1}$ to 8380 $kg \cdot ha^{-1}$ under mixed intercropping (Fig. 1). Field tests have demonstrated the potential for increased yields through mixed intercropping practices at Egyptian agricultural research stations. The results indicate that soybean and maize can be successfully grown together to enhance productivity.

LER ranged from 1.25 to 1.68 in the mixed intercropping system, indicating a moderate to high level of LER (Fig. 2). This suggests that the combined yield of crops in the intercropping system exceeded the yield of crops grown separately. The successful implementation of the mixed intercropping system maximized land use efficiency and overall productivity. These results highlight the advantages of incorporating intercropping techniques in agricultural practices.

Intercropping not only boosts yields but also contributes to soil health improvement and reduces the reliance on chemical inputs, making it a sustainable practice for Egyptian farmers (Figs. 3-11). In the rhizosphere of sole maize, soil C content was 78.49% higher compared to sole soybean, and 53.23% higher in intercropping. Sole maize had a higher atomic percentage of C in the soil by 67.95% compared to sole soybean, while intercropping showed a 48.16% increase (Fig. 3).

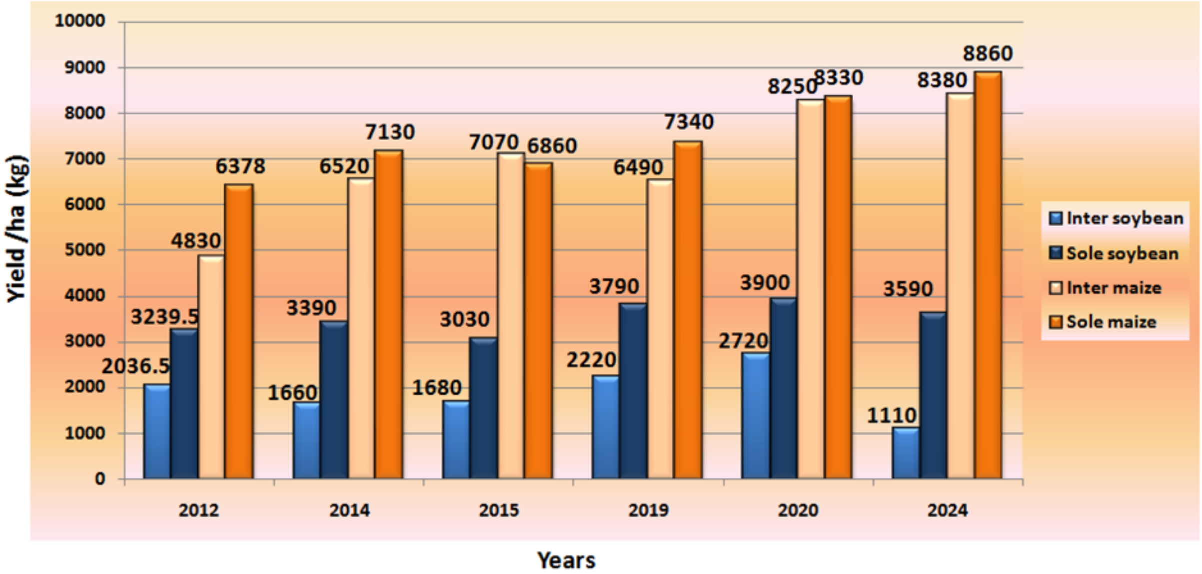

Fig. 1. Yield of soybean and maize under intercropping and sole cropping.
Rys. 1. Plon soi i kukurydzy w uprawie współrzędnej i wyłącznej.

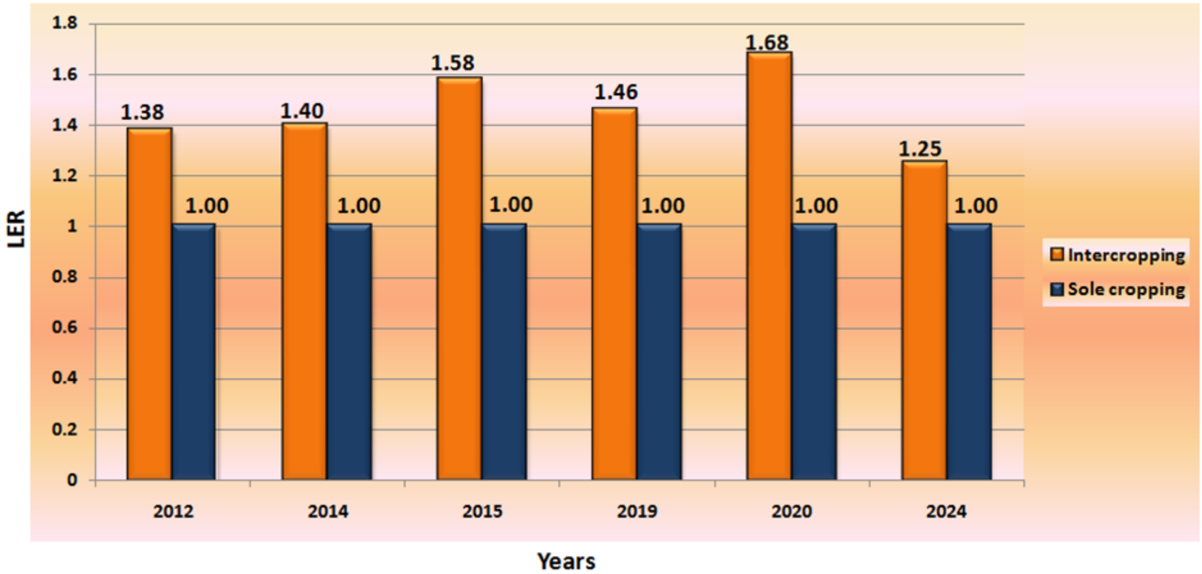

Fig. 2. LER of intercropping soybean with maize and sole cropping of both species.
Rys. 2. LER uprawy współrzędnej soi z kukurydzą i uprawy wyłącznej obu gatunków.

The proportion of C in the soil sample was significantly higher in sole maize (82.00%) compared to sole soybean (82.00%) and intercropping (54.23%). There were no significant differences between sole soybean and intercropping, but the atomic mass of C in the soil was 2.45% higher in the rhizosphere of sole maize compared to sole soybean and intercropping. Fluorescence intensity of C in the soil did not differ significantly between intercropping, sole maize, and sole soybean. The significance of plant-microbe interactions in soil C dynamics is underscored by these findings, potentially influenced by variations in microbial activity and root exudates across different cropping systems. C is essential for maintaining soil health and fertility, making it a key factor in sustainable agriculture practices (Nazir et al., 2024). This suggests that growing maize could result in more soil C sequestration. Intercropping soybean with maize can enhance soil C levels compared to sole soybean, offering a more sustainable option for farmers to improve soil health and C sequestration. It is important to consider crop selection when implementing agricultural practices to improve soil sustainability and health.

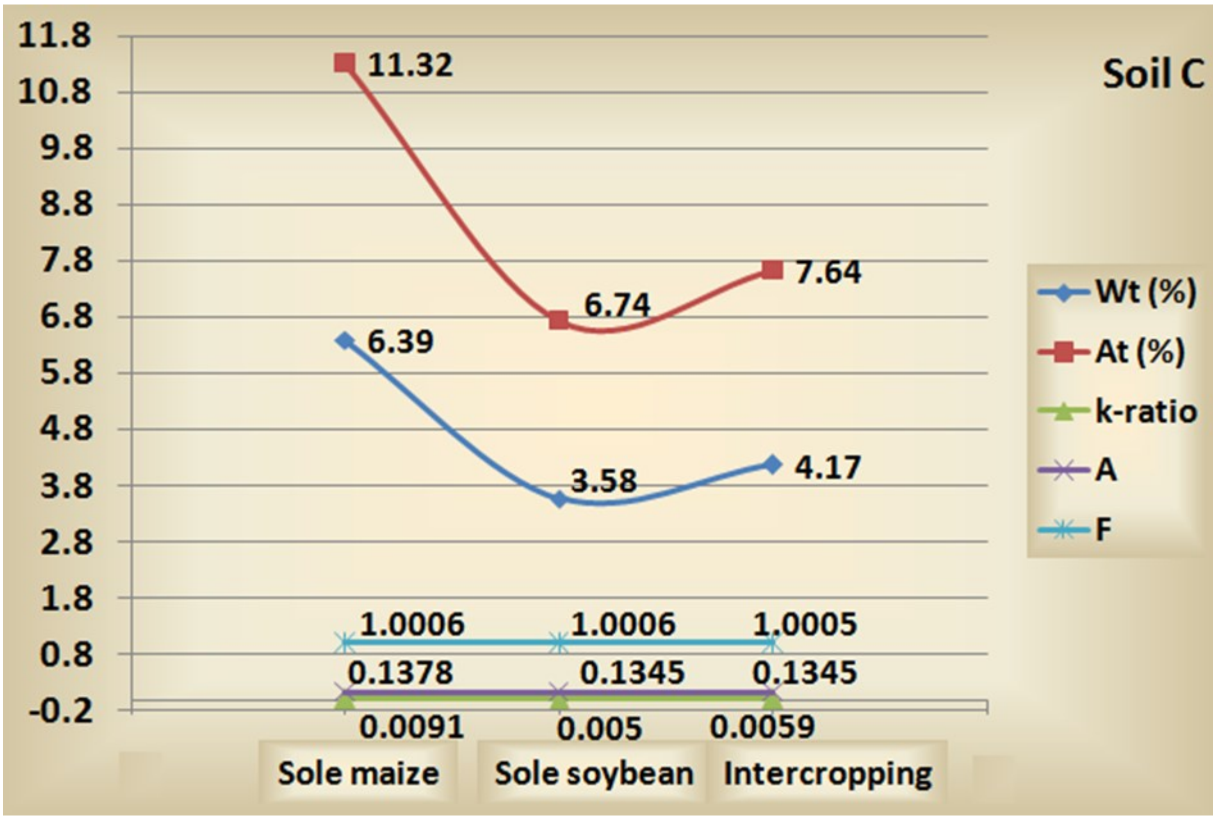

Fig. 3. Soil C in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.078), At (0.206), k-Ratio (0.0011), A (0.0026), F (ns).

Rys. 3. Zawartość C w glebie ryzosfery mieszanej uprawy międzyplonowej soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,078), At (0,206), K-Ratio (0,0011), A (0,0026), F (ns).

In the rhizosphere of sole maize, sole soybean, and intercropping, there were no significant differences in soil O_2 levels based on weight, atomic percentage, or fluorescence intensity (Fig. 4). The presence of different plant species did not have a notable effect on soil O_2 content, suggesting that other factors may be more influential. Root exudates or microbial activity could be contributing to maintaining consistent O_2 levels across plant species. Sole maize had a higher percentage of O_2 in the soil sample (12.76%) compared to sole soybeans, while intercropping had a higher percentage of 5.46%. Sole soybean had a slightly higher atomic percentage of O_2 compared to sole maize by 0.06% and intercropping by 0.04%. Sole maize had a higher atomic mass of O_2 compared to sole soybean by 3.66% and intercropping by 2.83%. These results could be attributed to variations in root morphology and exudation patterns between maize and soybean plants, potentially affecting soil O_2 levels. Adequate soil O_2 is crucial for proper respiration and nutrient absorption in plants (Manghwar et al. 2024). These findings suggest that intercropping can positively impact soil O_2 levels compared to sole maize or soybean.

There were no significant differences between sole maize and sole soybean, but intercropping soybean with maize resulted in higher soil Mg content in the rhizosphere compared to sole soybean (11.34% vs. 8.60%) (Fig. 5). The atomic percentage of Mg in the soil was also higher in the rhizosphere of intercropped soybean with maize compared to sole soybean (7.11%) and sole maize (15.31%). These results could be attributed to the synergistic nutrient uptake between maize and soybean in intercropping systems, resulting in a more effective utilization of soil nutrients. Furthermore, the root exudates from both crops may have played a role in the increased Mg content in the rhizosphere of intercropped soybean with maize. Additionally, the rhizosphere of sole soybean had a slightly higher atomic percentage of Mg compared to sole maize (0.06%) and intercropping (0.04%). On the other hand, the rhizosphere of sole maize had a higher atomic mass of Mg compared to sole soybean (5.96%) and intercropping (1.32%). Fluorescence intensity of Mg in the soil did not show significant differences between intercropping, sole maize, and sole soybean. These results could be attributed to variations in the root exudates released by different plant species, which can affect the availability and absorption of Mg in the rhizosphere. For the best plant health and yield, it's critical to periodically check the Mg levels in the soil and add more as necessary (Ahmed et al., 2023). Overall, these results suggest that intercropping can enhance soil Mg levels compared to sole cropping methods.

The weight, percentage, and fluorescence intensity of soil Al in the rhizosphere of sole maize

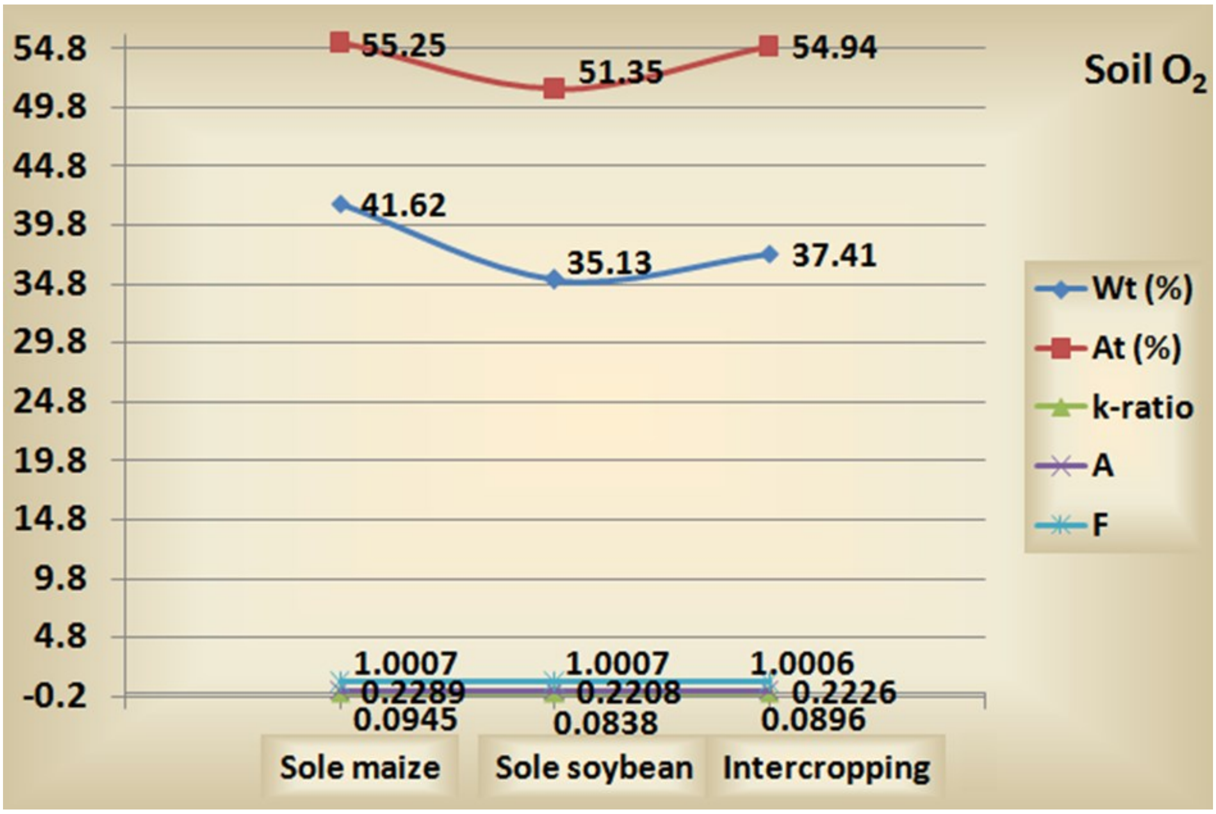

Fig. 4. Soil O_2 in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (ns), At (ns), k-Ratio (0.0098), A (0.0006), F (ns).

Rys. 4. Zawartość tlenu w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (ns), At (ns), K-Ratio (0,0098), A (0,0006), F (ns).

were higher than those of intercropping and sole soybean (Fig. 6). Sole soybean had a greater atomic percentage of Al in the soil compared to sole maize and intercropping. Intercropping had a larger atomic mass of Al in the soil compared to sole soybean and sole maize. Maize roots secrete more Al into the soil compared to soybean roots. This is because maize roots release organic acids that can dissolve Al in the soil, making it more accessible for absorption. Schmitt et al. (2015) found that soil Al is known for its negative effects on plant growth. The varying root exudates between maize and soybeans can influence the levels of Al toxicity in different plant species. Intercropping soybeans with maize can potentially alleviate the adverse impacts of Al toxicity on plant growth. The soybean roots can aid in decreasing the Al content in the soil through their exudates. Furthermore, competitive interactions between maize and soybean in intercropping systems may also influence the distribution of Al in the soil. This practice can enhance crop yields and promote plant health in mixed cropping systems.

In the rhizosphere of intercropped plants, the Si content in the soil was higher compared to sole maize and sole soybean in terms of weight, atomic percentage, and proportion (Fig. 7). Sole maize had a greater atomic mass of Si in the soil compared to sole soybean and intercropping. Soil Si strengthens plant cell walls, enhances resistance to pests and diseases, and improves nutrient absorption (Khan, 2025). There was no significant difference in the fluorescence intensity of Si in the soil between intercropping, sole maize, and sole soybean. These results may be attributed to the varying abilities of maize and soybean to absorb and store Si in their tissues, resulting in differences in Si distribution in the rhizosphere. The cropping system employed had an impact on the Si content in the soil. Intercropping can have a unique influence on the soil's nutritional composition, as evidenced by the observed variations in Si concentration. Compared to sole soybean and sole maize, the soil sample from the rhizosphere of intercropped plants showed higher levels of K in terms of weight, atomic percentage, and proportion (Fig. 8). Additionally, the rhizosphere of sole maize exhibited greater fluorescence intensity of K compared to sole soybean and intercropping. In contrast, the rhizosphere of sole soybean had a higher atomic mass of K compared to sole maize and intercropping. These results may be attributed to the complementary relationship between soybean and maize roots, which enhances nutrient uptake efficiency and improves soil nutrient availability. K is a crucial nutrient for plant growth as it plays a vital role in promoting photosynthesis, protein synthesis, and enzyme activation (Hasanuzzaman et al., 2018).

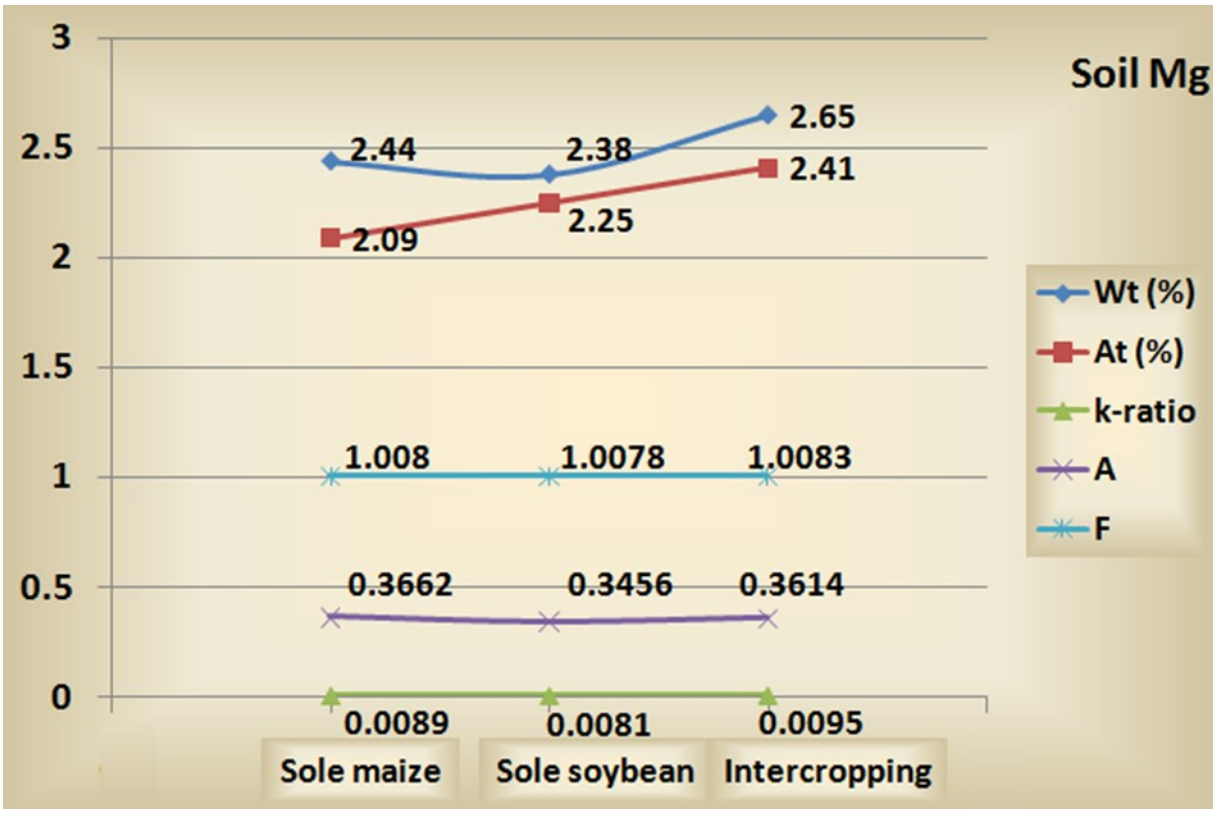

Fig. 5. Soil Mg in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.078), At (0.080), k-Ratio (0.0006), A (0.0007), F (ns).

Rys. 5. Zawartość magnezu w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,078), At (0,080), K-Ratio (0,0006), A (0,0007), F (ns).

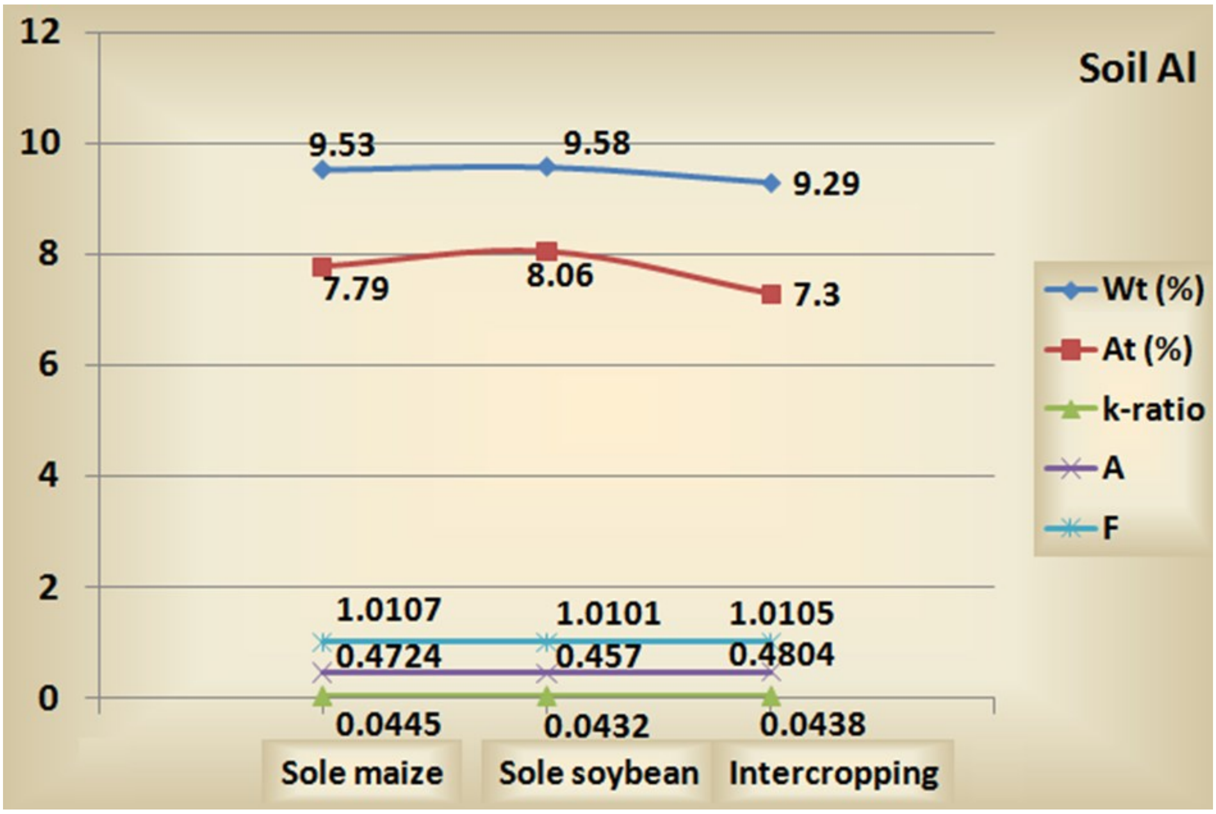

Fig. 6. Soil Al in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.053), At (0.097), k-Ratio (0.0009), A (0.0006), F (0.0005).

Rys. 6. Glebowy Al w ryzosferze mieszanej międzyplonu soi z kukurydzą i jedyną uprawą obu gatunków. L.S.D. 0,05 Wt (0,053), At (0,097), K-Ratio (0,0009), A (0,0006), F (0,0005).

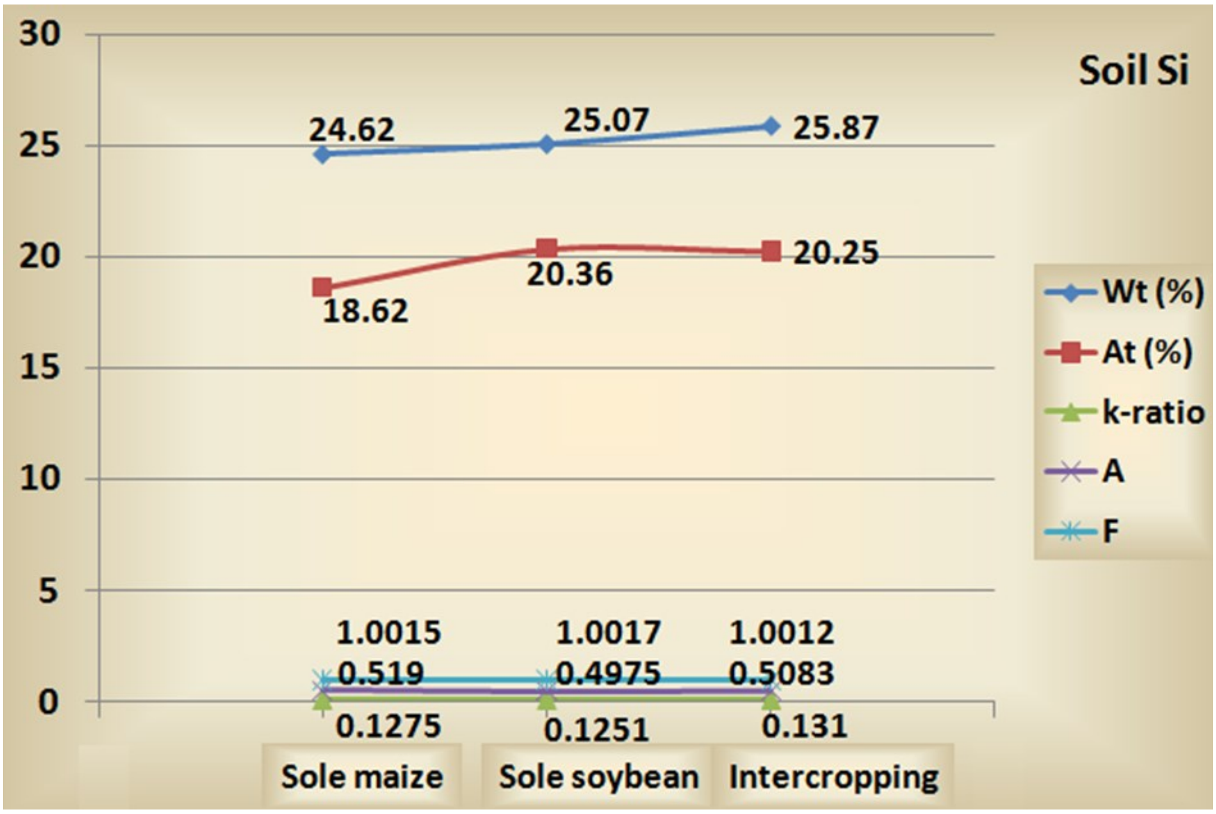

Fig. 7. Soil Si in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.081), At (0.119), k-Ratio (0.0009), A (0.001), F (ns).

Rys. 7. Zawartość krzemu w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,081), At (0,119), K-Ratio (0,0009), A (0,001), F (ns).

Overall, these results suggest that intercropping enhances soil K levels compared to sole cropping practices. The synergistic N uptake patterns of the two crops in an intercropping system can contribute to this improvement. Intercropping promotes efficient utilization of soil nutrients, resulting in increased K levels in the soil. This highlights the potential of intercropping as a sustainable agricultural approach to boost soil fertility and crop productivity.

In the rhizosphere of intercropped plants, the soil had higher Ca levels compared to sole soybean and sole maize, as evidenced by weight, atomic percentage, proportion, and fluorescence intensity of Ca (Fig. 9). Sole maize exhibited the highest Ca atomic mass in the soil. These results may be due to the complementary root systems of intercropped plants may improve nutrient uptake and cycling in the soil. Furthermore, the proximity of multiple plant species could stimulate microbial activity, resulting in increased Ca availability in the rhizosphere. A lack of Ca can result in stunted growth and inadequate yield development in plants (Thor, 2019). These results suggest that intercropping could enhance Ca availability in the soil, potentially promoting plant growth and development. Intercropping can also improve overall nutrient availability, leading to healthier and more productive plants. These findings underscore the potential advantages of incorporating intercropping into sustainable agricultural practices.

The soil in the rhizosphere of intercropped plants had higher levels of Ti compared to sole maize and sole soybean, based on factors such as weight, atomic percentage, proportion, and fluorescence intensity (Fig. 10). The highest atomic mass of Ti was found in the soil of sole maize. These results may be due to the complementary nutrient uptake of the two plants in the intercropping system, leading to increased Ti accumulation in the rhizosphere. Ti provides essential nutrients and promotes root development, leading to enhanced plant growth (Lyu et al., 2017). These results suggest that intercropping can change the distribution of Ti in the soil compared to sole cropping methods. This change in Ti distribution may impact the availability and uptake of Ti by plants, potentially affecting plant growth and nutrient absorption. The soil in the sole maize rhizosphere contained higher amounts of Fe based on weight, atomic percentage, proportion, and fluorescence intensity compared to the soil in sole soybean and intercropped plants. However, the soil of intercropped plants had the highest atomic mass of Fe (Fig. 11). These differences could be attributed to variations in root exudates released by maize plants compared to soybean plants, influencing Fe availability and uptake in the rhizosphere.

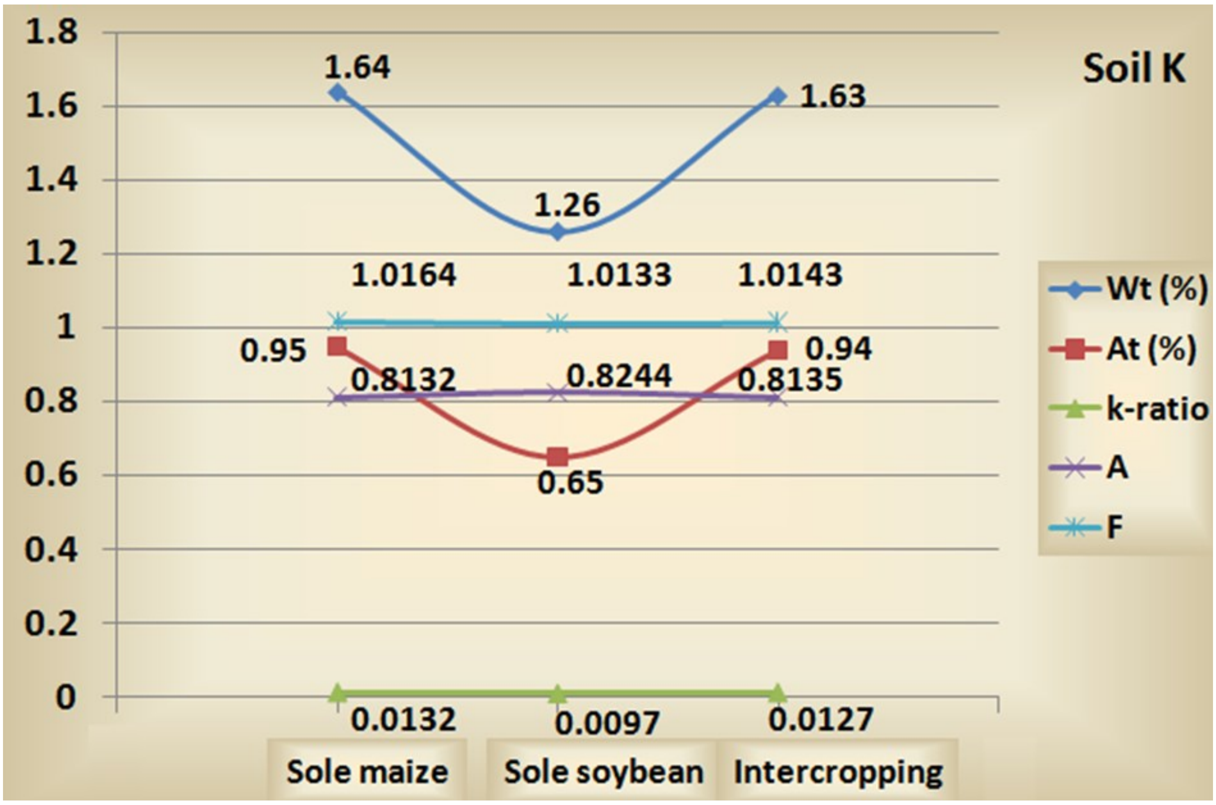

Fig. 8. Soil K in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.176), At (0.067), k-Ratio (0.0007), A (0.001), F (0.0008).

Rys. 8. Zawartość potasu w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,176), At (0,067), K-Ratio (0,0007), A (0,001), F (0,0008).

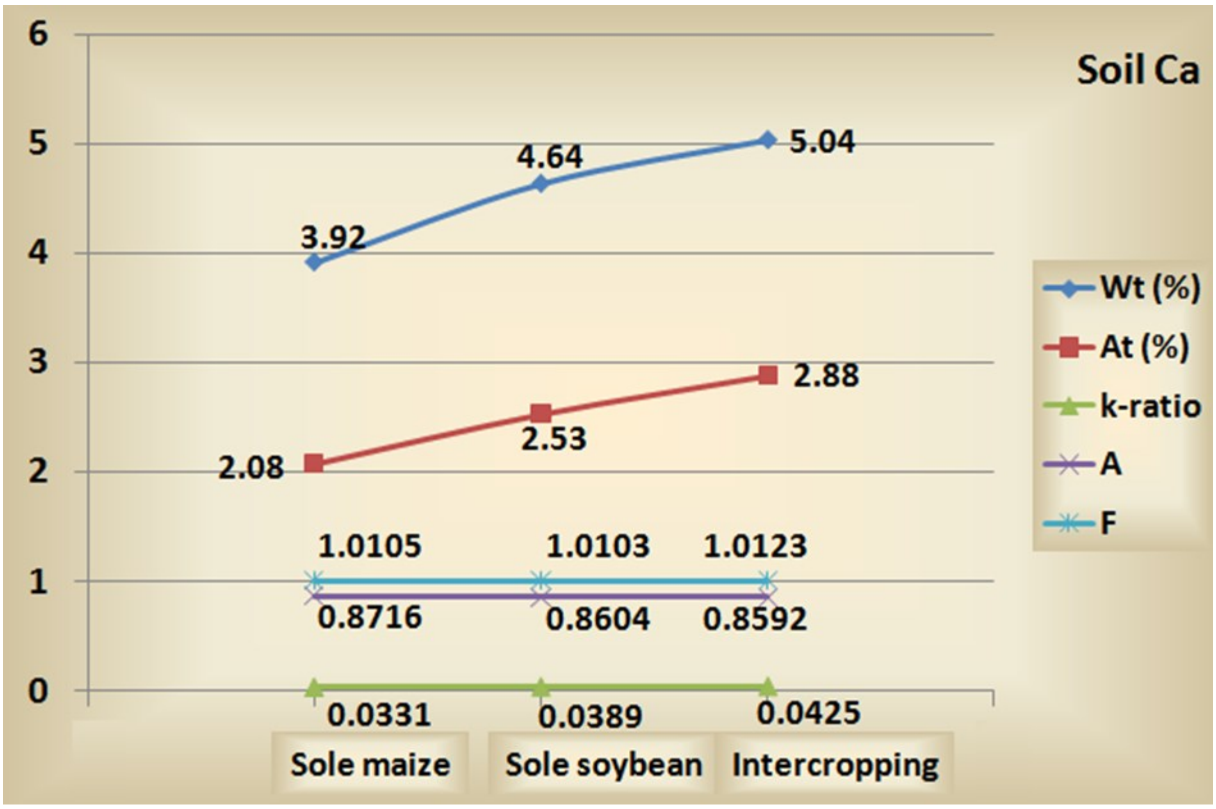

Fig. 9. Soil Ca in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.138), At (0.108), k-Ratio (0.001), A (0.0006), F (0.0006).

Rys. 9. Zawartość Ca w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,138), At (0,108), K-Ratio (0,001), A (0,0006), F (0,0006).

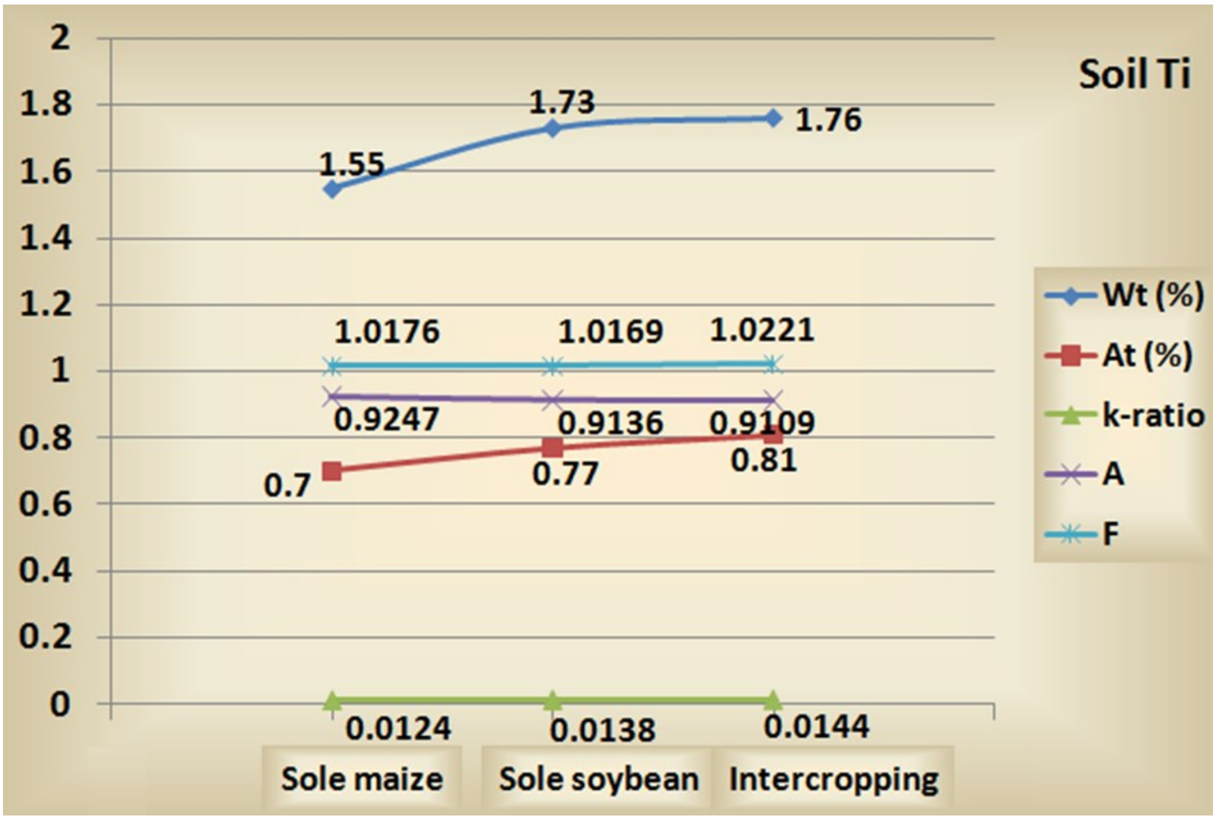

Fig. 10. Soil Ti in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.079), At (0.098), k-Ratio (0.001), A (0.0006), F (0.0008).

Rys. 10. Zawartość Ti w glebie w ryzosferze mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,079), At (0,098), K-Ratio (0,001), A (0,0006), F (0,0008).

Additionally, differences in soil pH and microbial activity among the plant systems may also contribute to the observed variations in Fe content. Abdel-Wahab et al. (2024) reported that intercropping soybean with maize resulted in lower soil Fe compared to sole cropping of both crops. Sole maize plants may have a greater ability to mobilize and absorb Fe from the soil compared to soybeans, resulting in higher Fe content in the rhizosphere. These findings highlight the significant impact of plant species and their interactions on the availability and distribution of Fe in the soil.

Conclusion

Studies have shown that intercropping soybeans and maize has numerous benefits over sole cropping, both in terms of improving soil quality and increasing yields. Intercropping significantly increases levels of key soil nutrients, such as carbon, oxygen, magnesium, silicon, and titanium. These nutrients play a vital role in improving soil structure, increasing water retention capacity, and supporting microbial activity. Higher levels of these nutrients contribute to better plant growth and health. One key finding is that intercropping reduces aluminum toxicity and iron accumulation in the soil. Excess aluminum and iron can be harmful to plants, hindering their growth and nutrient uptake. Reducing these toxic elements supports healthy plant growth and improves their ability to efficiently use available resources. Studies have also shown that intercropping increases soybean and maize yields. This is especially important in areas degraded by mining, where soils are often poor in nutrients and have low productivity. Intercropping allows for more efficient use of available resources and space, which translates into higher yields and greater profitability for farmers. In conclusion, intercropping soybeans with maize is an effective method for improving soil quality and increasing yields in areas degraded by mining. It is a sustainable and profitable agricultural practice that supports the health of soil and plants. These findings underscore the importance of implementing intercropping practices in agriculture, especially in regions affected by land degradation.

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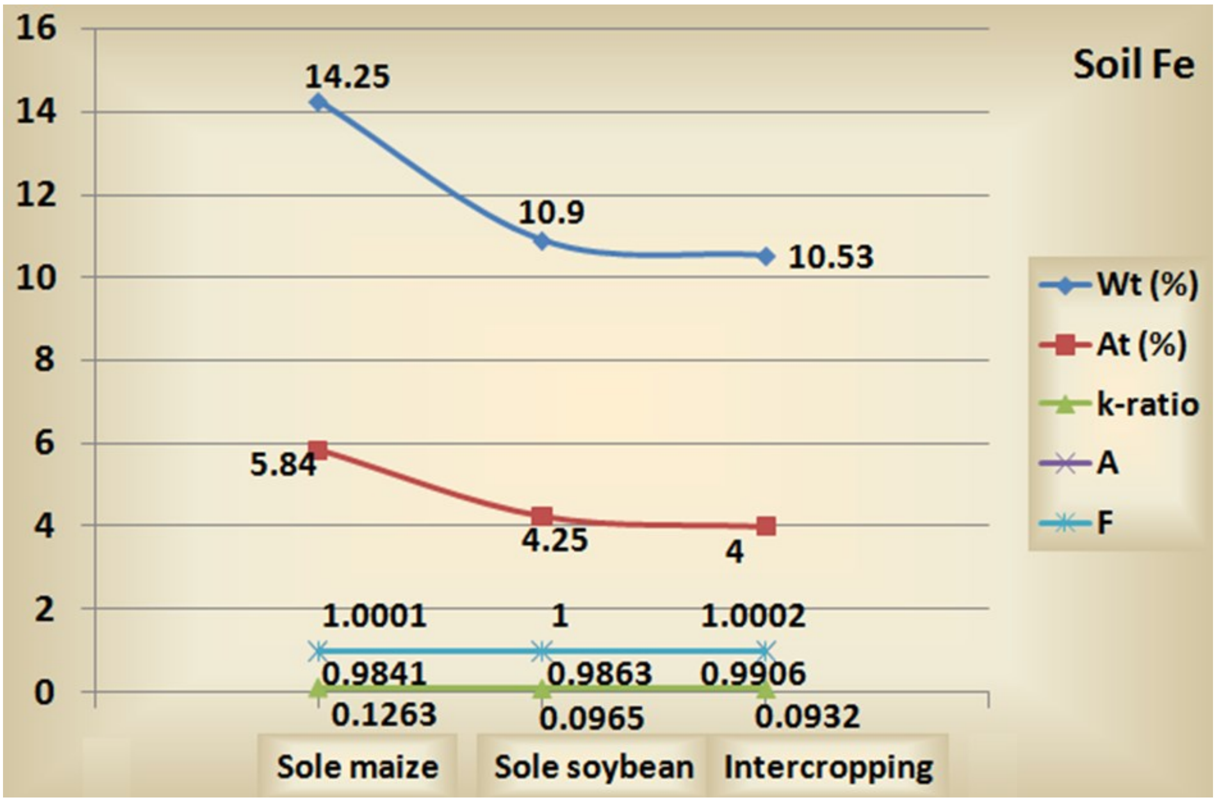

Fig. 11. Soil Fe in rhizosphere of mixed intercropping soybean with maize and sole cropping of both species. L.S.D. 0.05 Wt (0.133), At (0.147), k-Ratio (0.0009), A (0.0007), F (ns).
Rys. 11. Zawartość Fe w glebie ryzosfery mieszanej uprawy soi z kukurydzą i samodzielnej uprawy obu gatunków. L.S.D. 0,05 Wt (0,133), At (0,147), K-Ratio (0,0009), A (0,0007), F (ns).

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In conclusion, intercropping soybeans with corn is an effective method for improving soil quality and increasing yields in areas degraded by mining. It is a sustainable and profitable agricultural practice that supports the health of soil and plants. These findings underscore the importance of implementing intercropping practices in agriculture, especially in regions affected by land degradation.

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