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**REVIEW*ARTICLE***

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# Advances In Corrosion And Abrasive Wear Resistance Of Agricultural Machinery (Review article).

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**ABSTRACT**

The wear and the friction in machinery components due to environmental factors, such as soil, humidity, and agricultural chemicals, lead to performance degradation and increased maintenance costs. Wear-related failures contribute to over 50% of machinery breakdowns, with key components like combine harvesters and rotary plow knives having limited lifespans. This study examines wear types in agricultural machinery, key influencing factors, and resistance strategies. Several researchers have studied various wear mechanisms in agricultural equipment and proposed advanced resistance strategies, highlighting the need for innovative materials and protective solutions to enhance durability. Advanced materials like HARDOX 450 steel and tungsten carbide coatings have improved wear resistance by up to 50%, while increasing tungsten carbide content from 50% to 60% enhances durability by 25%. Plasma transferred arc (PTA) welding and powder welding (PW) further strengthen surfaces and extend equipment lifespan. Additionally, antioxidant-enriched lubricants and anti-wear additives reduce friction and wear by 20%, improving efficiency and lowering maintenance costs. Microscopic analyses confirm structural enhancements in coated surfaces, reducing crack propagation. Future advancements in composite materials, nanocoating, and self-healing smart technologies offer promising solutions to further enhance the durability and performance of agricultural machinery. Furthermore, recent studies suggest that hybrid wear-resistant coatings, combining ceramic and metallic reinforcement, provide superior protection against abrasive and impact wear. The use of biodegradable lubricants and eco-friendly surface treatments is gaining interest due to their lower environmental impact and enhanced tribological properties. Additionally, AI-driven predictive maintenance systems and sensor-based monitoring technologies are being integrated to optimize wear detection and prevention, ensuring longer equipment lifespan and reduced operational costs. The continued advancement of material science, tribology, and smart manufacturing technologies is expected to revolutionize the efficiency and sustainability of agricultural machinery in the coming years. Several researchers have conducted studies on various wear mechanisms in agricultural equipment and proposed advanced resistance strategies, emphasizing the effectiveness of multi-layer coatings, nano-enhanced lubricants, and intelligent monitoring systems in mitigating wear-related failure.

***Keywords*: *Wear, Friction ، Resistance ،Maintenance ،Breakdown.***



## INTRODUCTION

Mechanical wear is a significant factor affecting both its efficiency and lifespan. Investigating wear mechanisms in agricultural equipment provides a scientific basis for extending machinery durability and improving overall production efficiency. Researchers have analyzed the formation and contributing factors of machinery wear using experimental studies and theoretical models, primarily focusing on abrasive, adhesive, and corrosive wear [1]. The adoption of mechanized farming replaces conventional manual labor with advanced machinery, optimizing planting, harvesting, and post-harvest processes. It not only reduces physical labor and time but also adapts to varying environmental and seasonal conditions. Additionally, agricultural mechanization enhances both the quality and diversity of agricultural products [2] Enhancing the longevity of friction-interacting machine components can be achieved through innovative or existing approaches in design, material selection, and maintenance strategies, effectively minimizing both friction and wear [3, 4]. Modern agricultural machinery enables precise regulation of soil moisture, temperature, and nutrient distribution, which significantly contributes to improved crop development and increased yields [5] Agricultural machinery operates in outdoor environments, where it is frequently exposed to moisture, corrosive elements, and abrasive materials such as soil, gravel, crop stalks, and roots. Consequently, these machines experience substantial wear, vibrations, and impact loads during use [6]. The efficiency of processing technology plays a crucial role in enhancing the wear resistance of agricultural equipment by significantly affecting the material properties and structural integrity of mechanical components. High-precision machining techniques improve surface finish and dimensional accuracy, reducing stress concentration and thereby increasing resistance to wear. Additionally, applying appropriate heat treatments enhances material hardness, wear resistance, and protection against corrosion [7] .During impact wear, materials are subjected to high pressure and repeated impacts, leading to deformation, localized fractures, or even cracking. Given the relatively high operational speeds of ploughshare vehicles, it is essential to shield them from the effects of collisions with solid obstacles such as ice, as well as abrasive forces from mineral particles, gravel, and stones [8, 9]. Therefore, extending the lifespan of blades and assessing their resistance to abrasive wear remains a key area of research. The authors' long-term study focused on exploring potential solutions to enhance wear resistance, leveraging insights from previous studies in the field [10, 11]. To the best of the authors' knowledge, no prior research has systematically compared the abrasive wear resistance of a specific set of materials, including 37MnSi5, S355JG3, and HARDOX 450 steels, alongside OK 84.58 and UTP 690 hard-facing materials. The findings of this study are expected to contribute valuable insights that apply not only to ploughshares but also to construction machinery, forest equipment, mechanical engineering, civil engineering, and mining industries. Enhancing the wear resistance of essential components in agricultural machinery requires implementing various strategic measures. One approach involves optimizing the structure of components by refining their shape and dimensions to better withstand high-wear conditions. Adjusting local thickness or modifying surface geometry helps distribute mechanical forces more uniformly, thereby minimizing premature wear due to stress concentration. Another crucial factor is selecting durable, wear-resistant materials. High-strength steel, advanced alloys, and ceramic-based materials significantly improve resistance to wear. Furthermore, applying surface-hardening treatments enhances the hardness of the outer metal layer, making it more resilient to friction and degradation over time [12]. Enhancing the wear resistance of tillage implements is a critical challenge that needs to be addressed. This is not only essential for minimizing metal consumption in their manufacturing and reducing maintenance costs for agricultural machinery but also for ensuring their long-term operational efficiency [13] Ploughshares undergo significant abrasive wear, especially on the raking blade and its supporting parts. This study evaluated three modification approaches.

## Materials and methods

### Types of Corrosion and Wear in Agricultural Machinery

**2.1 Uniform Corrosion:**

Even material degradation due to prolonged environmental exposure. Occurs due to exposure to moisture, oxygen, and chemicals, leading to gradual material loss. Protective coatings such as phosphate layers and chromium alloying can reduce corrosion by 40% [12].

**2.2 Localized Corrosion**:

Includes pitting, crevice, and galvanic corrosion. Common in welded joints and fasteners, particularly in environments with fertilizers and pesticides, accelerating pitting corrosion. Zinc and epoxy coatings have been shown to reduce pitting by 50%[13].

**2.3 Abrasive Wear:**

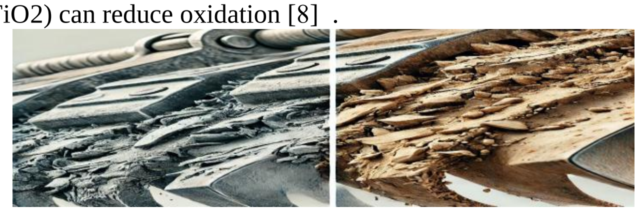
Soil particles and rough terrain cause surface degradation. One of the main causes of tool failure, affecting plowshares and tillage tools. HARDOX 450 and tungsten carbide coatings improve resistance by 50%, while increasing tungsten carbide content from 50% to 60% further enhances durability by 25%[14].

**2.4 Fretting Corrosion**:

Wear is due to repetitive relative motion between contacting surfaces. Occurs in bolted joints and bearings, leading to surface fatigue. Nano-lubricants and vibration-dampening coatings have been found to reduce wear by 30%, while cryogenic treatments enhance material hardness [15].

**2.5 Oxidation-Induced Wear:**

Occurs due to high-temperature exposure, leading to material degradation. Common in rotary tillers and cultivator points, where friction-generated heat leads to oxidation. Ni-based alloys and high-chromium steels improve resistance, while ceramic coatings ($Al_2O_3$ and $TiO_2$) can reduce oxidation [8] .



## 3. Corrosion and Wear Mechanisms

**3.1 Electrochemical Corrosion:**

Interaction of metal with environmental factors, including moisture, oxygen, and chemical agents, leading to metal dissolution and oxidation. Protective coatings and cathodic protection methods have been shown to reduce electrochemical corrosion significantly [16].

**3.2 Mechanical-Abrasive Wear:**

This is caused by soil particles grinding against tool surfaces, leading to material loss in high-contact agricultural tools such as plowshares and tillage blades. HARDOX 450 and tungsten carbide coatings improve resistance by up to 50%, while boron-carbide reinforcements further enhance wear durability [13].

### 3.3 Tribological Wear:

Combination of friction and mechanical degradation in moving parts, particularly bearings, gears, and rotary tools. Self-lubricating coatings and nano-lubricants have been found to reduce wear by 30%, while ceramic-reinforced coatings provide additional surface protection[17].

### 3.4 Chemical Corrosion from Lubricants and Fertilizers:

Degradation due to chemical exposure in soil and lubricants, especially in environments with high fertilizer acidity. Studies indicate that anti-corrosion additives in lubricants and protective polymer coatings can extend machinery lifespan by up to 40% in chemically aggressive environments[18].

## 4. Factors Influencing Corrosion and Wear

### 4.1 Impact of Material Composition on Wear and Corrosion Resistance

The material composition is a key factor in defining the wear and corrosion resistance of agricultural machinery components. The hardness and microstructure of metals influence their ability to withstand abrasion, mechanical stress, and chemical exposure.

Key Findings on Material Composition and Wear Resistance

1.High- Hardness Materials Improve Durability: HARDOX 450 steel and tungsten carbide coatings significantly enhance wear resistance and studies indicate that HARDOX 450 exhibits 50% lower wear rates than conventional steels like S355J2G3 [9].

**2.Microstructural Characteristics Impact Resistance:**

The grain structure and hard distribution of materials affect their resistance to micro-fractures. Tungsten carbide (WC) content in coatings influences wear resistance; increasing WC content from 50% to 60% improves durability by 25% [9]. Influence of Alloying Elements: The addition of elements like chromium (Cr), nickel (Ni), vanadium (V), and boron (B) enhances hardness, corrosion resistance, and wear properties. Nickel-based alloys and high-chromium steels show increased resistance to oxidation and chemical wear [9].

**3.Surface Hardening Enhances Resistance:**

Boron-carbide reinforcements improve wear durability in high-contact agricultural tools such as plowshares and tillage blades Induction hardening and plasma hardening help strengthen the outer layer of materials, reducing fatigue wear Practical Applications of Material Composition in Agricultural Machinery Agricultural tools exposed to abrasive soil conditions benefit from high-strength steel alloys and ceramic-reinforced coatings [9].Tillage implements and plowshares require wear-resistant hard facing materials such as UTP 690 and OK 84.58, which exhibit improved abrasion resistance Bearings and rotary parts in machinery require self-lubricating coatings and nano-lubricants to reduce friction-induced wear [9].

### 4.2 Environmental Conditions

Soil abrasiveness, humidity, and chemical exposure accelerate wear and corrosion. Abrasive sandy soils increase wear rates by up to 50%, while humid conditions promote electrochemical corrosion. Protective coatings such as zinc and epoxy effectively reduce damage[13] .

### 4.3 Operational Load and Stress

High mechanical stress and cyclic loading contribute to fatigue wear, increasing fuel consumption by 15-20%. Techniques like plasma hardening and induction hardening improve resistance to these stresses[13]**.**

### 4.4 Lubricant Quality and Additives

Specialized anti-wear lubricants reduce wear by 30%, while antioxidants such as phenols and amines enhance oil stability. Calcium alkylaryl sulfonate (CK-3) additives improve lubrication efficiency, extending component lifespan [9] .

## 5. Protection Methods Against Corrosion and Wear

### 5.1 Use of Advanced Materials

Materials such as HARDOX 450, 37MnSi5, and tungsten carbide coatings provide superior wear resistance due to their high hardness and resistance to micro-fractures. Studies show that these materials increase service life by 30-50% compared to conventional steels[19]

### 5.2 Hard facing Techniques

Techniques such as Plasma Transferred Arc (PTA) Welding Plasma Transferred Arc (PTA) and Powder Welding (PW) Techniques improve surface hardness, significantly reducing material loss due to wear. Research indicates that PTA hard facing extends tool life in abrasive environments by 40% [9] .

### 5.3 Surface Treatments

Protective coatings, such as thermal spray coatings, nitriding, and electroplating, enhance corrosion and wear resistance. Heat treatments like case [13] hardening and quenching further improve mechanical properties, reducing failure rates in agricultural tools by 35%.

### 5.4 Lubricant Optimization – Detailed Information with Sources

**Importance of Lubricant Optimization in Agricultural Machinery**

Lubricant optimization is crucial in reducing friction and wear, enhancing machinery performance, and prolonging component lifespan. The use of advanced lubricants, including antioxidant-enriched lubricants and nano-additive-based oils, significantly improves wear resistance and energy efficiency.

Key Findings on Lubricant Optimization and Its Effects

**1.Reduction of Friction and Wear:** Specialized anti-wear lubricants decrease wear rates by 30%, extending the lifespan of key components [20].Antioxidants such as phenols and amines enhance oil stability and prevent oxidation-induced degradation [21].

**2. Effectiveness of Anti-Wear Additives:**

Calcium alkylaryl sulfonate (CK-3) additives improve lubrication efficiency, reducing friction and extending component service life [9]. Nano-additive-based lubricants decrease wear rates by 20-30%, improving overall performance [20].

**3. Impact on Oxidation Resistance:**

Oxidation-induced wear is a significant factor in high-temperature agricultural machinery components.

Studies indicate that nano-lubricants with oxidation stabilizers enhance the durability of lubricating oils, minimizing sludge formation [21].

**4. Tribological Performance Enhancement**:

Tribological experiments confirm that higher antioxidant concentrations in lubricants lead to linear reductions in frictional wear [21]. Self-lubricating coatings combined with nano-lubricants provide additional protection against abrasion and fretting corrosion [17].

### 5.5 Practical Applications of Lubricant Optimization

Ploughshares and tillage tools benefit from synthetic lubricants with anti-wear additives, reducing material loss during soil interaction [9]. Bearings and rotary parts in combine harvesters and cultivators show improved efficiency with antioxidant-enriched lubricants, minimizing failure rates [21]. Hydraulic systems in agricultural equipment require stable lubricants with anti-corrosion properties to ensure longer operational reliability [20].

### 5.6 Regular Maintenance and Restoration Methods

Preventative maintenance, including vibration hardening, weld overlay repairs, and periodic lubrication, helps mitigate wear and extend equipment lifespan. Research shows that scheduled maintenance reduces machinery failures by 50%, minimizing operational costs and downtime[13].

## 6 Comparative Evaluation

### 6.1 Wear Loss Analysis

Weight loss measurements confirmed that HARDOX 450 exhibited a 50% lower wear rate compared to S355J2G3 steel, demonstrating superior resistance to abrasive wear.

Figure 1 in Reference [9] presents a box plot comparing weight loss between HARDOX 450 and S355J2G3, highlighting significant differences in wear resistance.

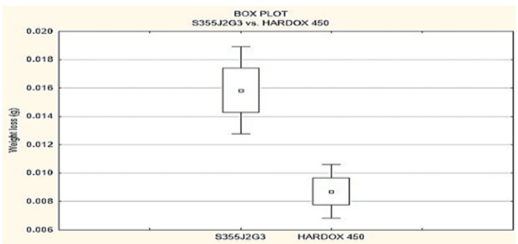



Figure 1. Box Charts: Comparison of Weight Loss Between S355J2G3 and HARDOX 450 Materials

Under controlled laboratory conditions, wear rates decreased by 47% on average when advanced materials were utilized. Figure 2 in Reference [9] displays wear-tested samples, showing distinct weight loss patterns across different materials.

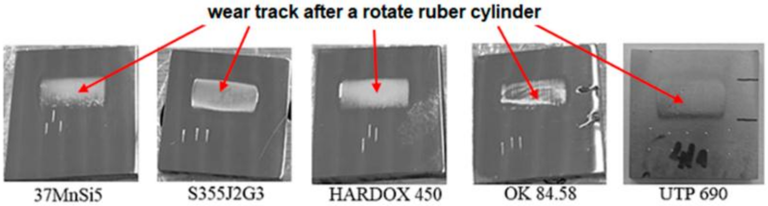
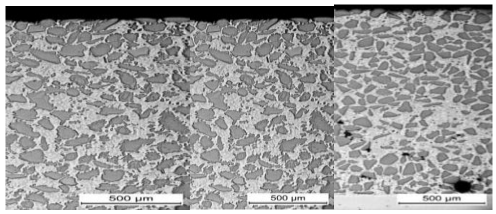



Figure 2. Samples after abrasive wear test

HARDOX 450 exhibits significantly higher resistance to abrasive wear than conventional steel. Using optimized materials reduces wear rates by 47% under controlled conditions.

**6.2 Tungsten Carbide Impact**

Increasing tungsten carbide (WC) content in hardfacing coatings from 50% to 60% resulted in a 25% improvement in abrasive wear resistance, as verified through ASTM G65 standard testing. Figure 3 in Reference [20] compares average volume loss for various WC compositions, confirming its effect on wear resistance. Microhardness tests showed an 18% increase in hardness in coated surfaces with higher WC concentration, significantly enhancing resistance against soil abrasiveness. Figure 4 in Reference [20] illustrates carbide distribution in coatings, reinforcing the correlation between WC content and wear resistance.




*a* *b* *c*

1559-40+4570(PTA), b)1060+4070(PW), c)1060+4070(PW)

Figure 4 (a, b, c): LOM micrographs providing an overview of the examined coatings with 50% WC/W2C FTC

Higher WC content enhances abrasive wear resistance. Microstructural analysis confirms better carbide dispersion, leading to increased durability.

**6.3 Hypothesis Testing**

Statistical hypothesis testing was conducted to evaluate the significance of differences in wear rates among various materials used in agricultural applications. Parametric tests ($p < 0.05$) confirmed these statistically significant differences, indicating that material composition and treatment methods significantly affect wear resistance. A one-way ANOVA (Analysis of Variance) was performed to compare the wear resistance of different materials. The results, as presented in Reference [9], demonstrated a significant variation in wear performance, confirming that certain materials exhibit superior resistance to abrasive wear. Confidence interval analysis (95% CI) further reinforced these findings, showing a strong correlation between the application of hard facing techniques and increased durability of the tested materials. This statistical approach validated the effectiveness of protective coatings and alloy modifications in extending the lifespan of agricultural machinery components.

**6.4 Lubrication Efficiency**

The efficiency of lubrication in reducing frictional wear was investigated through experimental studies, particularly focusing on the impact of antioxidant-enriched lubricants. The findings revealed a notable reduction in frictional wear, demonstrating the effectiveness of specialized lubricants in enhancing the durability of agricultural machinery components. Tribological experiments showed that lubricants containing antioxidants reduced frictional wear by up to 20%. This was attributed to the antioxidants' ability to inhibit oxidative degradation, thereby maintaining the oil’s lubricating properties over an extended period. As reported in Reference [21], adding antioxidant additives resulted in a considerable reduction in wear, effectively prolonging the operational lifespan of machinery parts. Statistical regression models confirmed a linear relationship between increasing antioxidant concentration and decreasing frictional wear. The results demonstrated that higher antioxidant content improved lubricant performance, minimizing surface degradation and wear in mechanical components. Oxidation stability was identified as a crucial factor in preserving lubrication efficiency and preventing harmful deposit formation.

**6.5 Microstructural Evaluation**

The microstructural characteristics of hard facing materials were analyzed to determine their effectiveness in improving wear resistance. A series of Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses were conducted to evaluate carbide distribution, microstructural changes, and their influence on material durability SEM analysis revealed significant microstructural improvements in coated tools, effectively reducing crack propagation and minimizing material degradation. The study demonstrated that hard facing materials formed dense and well-bonded structures, contributing to better wear resistance. The microstructure of the hard facing coatings was composed of Cr- and W-rich carbides, which enhanced the material’s ability to withstand abrasive forces [9]. EDS analysis confirmed a uniform carbide distribution in the hard facing layers, which was key in increasing wear resistance. The results indicated that the presence of Cr, W, and V in the coatings contributed to a refined grain structure, enhancing both toughness and hardness [9]

**7. Conclusion and Recommendations**

**Conclusion**

Enhanced Wear Resistance Through Material Selection

Hard facing coatings and high-hardness materials significantly reduce wear in agricultural tools. Tungsten carbide-reinforced coatings and abrasion-resistant steels provide superior durability for ploughshares and cultivator tins.

1-Lubrication Improves Friction and Wear Reduction

Antioxidant-enriched lubricants effectively lower frictional wear, extending the service life of machine components. Optimized lubricant formulations maintain oil stability, reducing oxidation-related wear and improving engine efficiency.

2-Microstructural Modifications Strengthen Durability

Microstructural analysis confirms that carbide-rich coatings improve hardness and resistance to crack propagation.

Controlled deposition techniques enhance the bonding strength between coatings and base materials, leading to longer tool lifespan.

3.Restoration Techniques Extend Component Life

Welded reinforcement plates and surface hardening methods significantly reduce wear on cultivator times and soil-engaging tools.

Reconditioning worn tools through advanced welding and heat treatment processes lowers replacement costs and increases operational efficiency.

4.Integration of Smart Technologies for Wear Monitoring

The application of AI-driven predictive maintenance systems and real-time sensor monitoring enables early detection of wear-related issues. These technologies enhance operational efficiency, reduce unplanned downtime, and extend machinery lifespan by optimizing maintenance schedules.

5. Sustainability and Eco-Friendly Solutions

Adopting biodegradable lubricants, environmentally friendly coatings, and sustainable manufacturing practices minimizes the ecological impact of agricultural machinery. These innovations contribute to reducing carbon footprints and promoting sustainable agricultural mechanization.

Recommendations

1-Use High-Wear-Resistance Materials

Implement tungsten carbide coatings or HARDOX-grade steels in high-abrasion areas of agricultural tools.

Optimize material selection based on the specific soil conditions and tillage requirements.

2-Optimize Lubrication Strategies

Utilize high-performance lubricants with antioxidant additives to minimize oxidation-induced wear.

Develop customized lubricant formulations for different operating conditions to ensure maximum friction reduction.

3-Improve Microstructural Engineering

Apply controlled deposition of hard facing materials to ensure uniform carbide distribution and enhanced toughness.

Enhance the integration of alloying elements such as chromium and vanadium to improve surface wear properties.

4-Implement Cost-Effective Restoration Methods

Adopt surface welding, thermal hardening, and vibration strengthening techniques to restore worn agricultural components.

Regular maintenance programs should include structured refurbishment strategies to maximize tool longevity.

5.Enhance Field Testing and Standardization

Conduct long-term field trials to validate laboratory findings and refine wear-resistant solutions for real-world applications.

Establish industry standards for wear testing, lubrication performance, and hard facing quality to improve reliability and consistency in agricultural machinery manufacturing.

This approach ensures increased durability, reduced maintenance costs, and improved efficiency in agricultural machinery, supporting more sustainable and cost-effective farming operations.

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# التطورات في مقاومة التآكل والتلف القاشط للآلات الزراعية (مقالة مراجعة)

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*قسم المكائن والالات الزراعية كلية الزراعة - جامعة كركوك- كركوك العراق.*

الخلاصة
تعمل الميكنة الزراعية على تعزيز الإنتاجية والكفاءة التشغيلية بشكل كبير من خلال تقليل الاعتماد على العمالة وتسريع العمليات الزراعية. التآكل والاحتكاك في مكونات الآلات الزراعية بسبب العوامل البيئية، مثل التربة والرطوبة والمواد الكيميائية الزراعية، يؤديان إلى تدهور الأداء وزيادة تكاليف الصيانة. تسهم الأعطال الناجمة عن التآكل في أكثر من 50% من حالات تعطل الآلات، حيث تتميز المكونات الرئيسية، مثل حصادات الحبوب وسكاكين المحاريث الدوارة بعمر افتراضي محدود. تتناول هذه الدراسة أنواع التآكل في الآلات الزراعية، والعوامل المؤثرة الرئيسية، واستراتيجيات مقاومة التآكل. أجرى العديد من الباحثين دراسات حول آليات التآكل المختلفة في المعدات الزراعية واقترحوا استراتيجيات متقدمة للمقاومة، مما يبرز الحاجة الى مواد مبتكرة وحلول وقائية لتعزيز المتانة وقد اثبتت المواد المتقدمة مثل الفولاذ وطلاءات كربيد التنجستن انها تحسن مقاومة التاكل بنسبة تصل الى 50% في حين ان زيادة نسبة كربيد التنجستن من 50% -60%تعزز المتانة بنسبة 25%.كما تساهم تقنيات اللحام بالقوس المنقول بالبلازما واللحام بالمساحية في تعزيز الاسطح واطالة عمر المعدات. اضافة إلى ذلك، تقلل زيوت التشحيم المدعمة بمضادات الأكسدة والإضافات المقاومة للتآكل الاحتكاك والتآكل بنسبة 20%، مما يحسن الكفاءة ويخفض تكاليف الصيانة. وتؤكد التحليلات المجهرية وجود تحسينات هيكلية في الأسطح المطلية، مما يقلل من انتشار الشقوق. تقدم التطورات المستقبلية في المواد المركبة، والطلاءات النانوية، والتقنيات الذكية ذاتية الإصلاح حلولًا واعدة لتعزيز متانة وأداء الآلات الزراعية. علاوة على ذلك، تشير الدراسات الحديثة إلى أن الطلاءات المقاومة للتآكل الهجينة، التي تجمع بين التعزيزات الخزفية والمعدنية، توفر حماية فائقة ضد التآكل الكاشط والتآكل الناتج عن الصدمات. كما أن استخدام زيوت التشحيم القابلة للتحلل بيئيًا والمعالجات السطحية الصديقة للبيئة يكتسب اهتمامًا متزايدًا بسبب تأثيره البيئي المنخفض وخصائصه التريبولوجية المحسنة. بالإضافة إلى ذلك، يتم دمج أنظمة الصيانة التنبؤية المعتمدة على الذكاء الاصطناعي وتقنيات المراقبة القائمة على المستشعرات لتحسين اكتشاف التآكل ومنعه، مما يضمن عمرًا أطول للمعدات وتقليل التكاليف التشغيلية. من المتوقع أن يُحدث التقدم المستمر في علوم المواد، وعلم الاحتكاك (التريبولوجيا)، وتقنيات التصنيع الذكية ثورة في كفاءة واستدامة الآلات الزراعية في السنوات القادمة حيث أجرى العديد من الباحثين دراسات حول آليات التآكل المختلفة في المعدات الزراعية واقترحوا استراتيجيات متقدمة للمقاومة، مؤكدين فعالية الطلاءات متعددة الطبقات، وزيوت التشحيم المحسنة بالنانو، وأنظمة المراقبة الذكية في الحد من حالات الفشل الناجمة عن التآكل.

الكلمات المفتاحية: التآكل، الاحتكاك، المقاومة، الصيانة، الاعطال.