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Abstract

Agricultural machinery is constantly exposed to repeated loads under diverse operating conditions, making fatigue life evaluation essential for ensuring structural durability. This review provides a systematic review of the literature from the last decade (2015-2025), focusing key methodologies and recent advanced in fatigue life evaluation for agricultural machinery. Relevant literature was analyzed with a focus on stress and strain data acquisition, signal preprocessing techniques, repeated load classification, mean stress correction, damage accumulation models, and FEA-MBD and DEM-MBD integrated simulation approaches. This review highlights the accuracy of in-field stress and strain measurements, the appropriateness of fatigue evaluation methods under variable mean stress, the quality of load characterization, and the feasibility of simulation-coupled fatigue analysis. Furthermore, the review presents a comparison of the applicability and effectiveness of each method based on case studies. Several limitations in current research are also identified, such as inconsistency in evaluation standards, discrepancies between experimental and simulation results, and challenges in reproducing complex operating conditions. Ultimately, this comprehensive review establishes a systematic foundation for improving structural durability evaluation, early-stage design safety, and maintenance planning for agricultural machinery.

Keywords: agricultural machinery; evaluation method; fatigue life; review, structural durability.

Introduction

Agricultural machinery plays a crucial role in enhancing productivity and addressing labor shortages in rural areas, and the scope and frequency of its use have constantly increased (Ma *et al*., 2023). Accordingly, the performance and durability standards required of agricultural machinery have also increased, and in particular, ensuring durability against repeated mechanical loads and impacts over long periods has become a critical design and maintenance challenge (Wang *et al*., 2023). Various types of agricultural machinery are employed for diverse purposes, and each type is exposed to irregular loads in a variety of working environments and conditions. These environmental characteristics lead to a higher risk of fatigue failure in machine parts, resulting in reduced work efficiency, economic losses, and employee safety issues (Fajri *et al*., 2021). Furthermore, work delays and interruptions from agricultural machinery breakdowns and damage add to the economic burden on farmers and have direct and indirect impacts on national food security (Jena and Tanti, 2023). In particular, the economic consequences of such failures are significant. Research indicates that repair and maintenance costs can account for up to 15% of the total lifetime operating costs of agricultural machinery, while unexpected downtime during critical farming seasons can lead to substantial lost opportunity costs (ASAE EP496, 2006, Hunt, 2008). The recent shrinking labor force and aging rural population have increased the dependence on agricultural machinery, and the agricultural environment has become harsher due to global climate change (Singh and Jitendra, 2022, Nelson *et al*., 2024). Accordingly, ensuring the reliability and durability of agricultural machinery has become crucial in its design and development.

Fatigue failure is a physical phenomenon in which cyclic loading causes micro-cracks to develop and progressively grow inside a material, leading to structural failure when a critical limit is exceeded (Boardman, 1990). In particular, agricultural machinery is continuously exposed to complex loads such as shock and vibration in poor working environments and during operation. These loads are not simple repetitive cycles but have non-linear traits with irregular variations in magnitude and direction, interacting with environmental factors to cause compound fatigue damage (Yuan *et al*., 2015, Chen *et al*., 2023a). Therefore, simple static load-based design or conventional fatigue life evaluation techniques are insufficient to reliably ensure the durability of agricultural machinery (Zhunisbekov, 1987). Furthermore, diverse factors affect fatigue failure, including material properties, micro-defects during the manufacturing process, and wear and corrosion during usage, which lower the accuracy of fatigue life evaluation (Popovych *et al.*, 2020).

Recent studies on the fatigue life evaluation of agricultural machinery have focused on enhancing the durability of these machines through the optimization of structural design, improvement of material properties, and refinement of manufacturing processes (Kanayev *et al.*, 2024). Advances in sensor technology have enabled the measurement of loads during agricultural operations in real time, allowing for improved data processing and statistical analysis techniques that enhance the accuracy of fatigue life evaluation (Chen *et al.*, 2023b). Furthermore, there are studies that evaluated fatigue life by using finite element analysis (FEA) and multibody dynamics simulation (MBD) techniques, and reflecting the complex structure and dynamic loading conditions of agricultural machinery. However, it is still difficult to fully reflect the various loading conditions encountered in actual agricultural operation environments, and there is a lack of standardized evaluation criteria and methods (Song *et al.*, 2024). Most studies rely on limited laboratory environments and simplified simulation conditions, which limit the consistency of results and their applicability in the field. In particular, discrepancies between field and laboratory data, uncertainty and signal noise in load data, and simplification of material and structural 3D modeling have been indicated as the main contributors to the lower accuracy of fatigue life evaluation (Franco *et al.*, 2018, Zhu *et al.*, 2024). Therefore, it is required to create a systematic fatigue life evaluation system that effectively integrates experimental and field data and combines advanced simulation and data analysis techniques. While previous studies have often addressed specific stages of durability assessment, this study provides a unique contribution by presenting the first comprehensive review that synthesize the entire process of fatigue life evaluation for agricultural machinery. This includes full process from in-field load acquisition and signal processing and simulation methodologies such as FEA-MBD and DEM-MBD.

In this study, we analyzed recent major studies related to fatigue life evaluation of agricultural machinery from the perspectives of load measurement, data processing, life prediction techniques, and simulation analysis, and discussed the characteristics and limitations of each elementary technique. Based on the analysis and discussion, this study aims to suggest future research directions for improving the durability of agricultural machinery.

Methods

In this study, we utilized major academic databases such as Web of Science, Scopus, and ScienceDirect to systematically analyze recent research trends in fatigue life evaluation of agricultural machinery. Based on such search keywords as “agricultural machinery”, “fatigue life”, “fatigue analysis”, “fatigue damage”, and ”fatigue simulation” in combination, we found related research papers. The research period was set to the last decade (2015-2025) to reflect the latest technology trends and research performance. To ensure the academic rigor and reliability of the review, specific inclusion and exclusion criteria were applied during the selection process. We exclusively included peer-reviewed original research articles indexed in SCI/SCIE-indexed journals. Consequently, non-peer-reviewed materials, such as conference proceedings, gray literature, theses, and technical reports, were excluded from the final analysis. While no specific citation threshold was applied in order to ensure a comprehensive representation of recent technical developments, priority was given to studies that provided clear experimental validation or advanced simulation methodologies. The selected papers were systematically categorized and compared based on various key aspects, including load data acquisition and processing, fatigue life evaluation methods, simulation techniques, and result validation. In the analysis process, we comprehensively reviewed the purpose, methodology, data processing techniques, main results, and limitations of each study.

Recent research trend in fatigue life evaluation of agricultural machinery

Fatigue life evaluation of agricultural machinery is a complex field that involves various factors such as load data acquisition and processing, fatigue life evaluation method, and simulation method. This section analyzed recent research trends in each of these key elements, reviewed the current status and direction of research. Figure 1 illustrates the entire structure of the fatigue life evaluation process.

Load data acquisition and processing method

The reliability of a fatigue life evaluation of agricultural machinery depends on how accurately it can reflect the cyclic loading applied to the structure in a real working environment (Tyutrin, 2020). Therefore, the crucial first step is to accurately measure the stresses encountered during agricultural machinery operation and driving. In agricultural work, the stresses generated vary irregularly depending on the ground conditions, the working method, and the type of machinery equipped, and the cumulative fatigue damage to the structure is highly complex (Ceylan *et al.*, 2015).

Load measurement method

A highly reliable load measurement method is essential to accurately analyze the load characteristics applied to agricultural machinery. Strain gauges, accelerometers, displacement sensors, and torque meters are currently employed as the main means of measuring loads in the agricultural machinery field. Among them, the strain gauge is the most common method because it can be directly attached to the area where stress concentration is expected and measure the strain in the structure in real time.

For example, Kim *et al.* (2024) attached strain gauges to 34 stress concentration sites of an agricultural front-end loader derived through multibody dynamics analysis, and utilized a CAN communication-based DAQ system to collect strain data and convert it into stress, which was used for fatigue life evaluation. Furthermore, Hwang *et al.* (2024) attached a rosette-type 3-axial strain gauge to the structural joints of an electric multi-purpose tractor to measure strain under various working conditions and converted it into von Mises stress for fatigue life evaluation. As such, strain gauge-based strain measurement techniques have been applied in numerous studies and are used as a key technology for analyzing stresses in agricultural machinery (Koyuncu *et al.*, 2012, Cardei *et al.*, 2023, Kim *et al.*, 2022).

On the other hand, when torsional loads applied to rotating members or dynamic characterization is required, torque meters or rotational speed sensors are used. Kim *et al.* (2021) measured the torque and speed generated during operation in real time through a torque meter and a rotational speed sensor equipped with the rear drive system of a 78 kW tractor. This was used to derive the load acting on the spiral bevel gear by considering the gear ratio and gear efficiency, and used to set the accelerated life test conditions. There are also a number of studies that applied a measurement system that combined multiple sensors to analyze load variations under different operating conditions. Paraforos *et al.* (2014) combined a total of 28 strain gauges, two IMUs, and an RTK-GNSS receiver on a 4-rotor swather, to collect real-time strain and load data in various driving situations, including road driving, machine operation, and turning. In this study, the IMUs were used to measure dynamic loads in the vertical direction and the load distribution was analyzed according to the position information collected by RTK-GNSS. Zhang *et al*. (2024) developed a measurement system consisting of various sensors such as strain gauge, accelerometer, tension sensor, angle sensor, hydraulic pressure sensor, and GNSS receiver on the tractor and mounted plow structure, in order to collect load data under plowing working conditions. The developed measurement system can collect data such as working depth, driving speed, draft, and stress, and especially analyze load distribution using an NI-based DAQ module and remote monitoring function using LabView.

In recent years, CAN-Bus-based real-time measurement systems have been commercialized, and they simultaneously collect various operating status data such as engine speed, hydraulic operation status, and steering angle from the electronic control unit (ECU) inside the tractor and machine. These measurement systems can analyze the correlation between different working conditions and the loads applied to the structure and can identify load variations as operating conditions change. Matteti *et al*. (2017) integrated CAN-Bus operation status data, and Wheel Force Transducer (WFT), measured the vertical load of four wheels of a tractor in real time, and suggested a fatigue life evaluation method that can more accurately reflect the fatigue behavior of the structure under actual operating conditions. These various measurement systems have been employed to accurately measure loads on agricultural machinery, as shown in various studies.

Data preprocessing method

The measured load data is typically stored as a continuous time series signal in the form of a load time history, which contains various signal distortion factors such as disturbances, high-frequency vibrations, and sensor noise (Moon *et al*., 2011, Khan *et al*., 2025). In particular, as vibration, shock, and external interference occur frequently in the operating environment of agricultural machinery, the reliability of fatigue life evaluation can be deteriorated if the raw data is used without refinement. Therefore, the measured load data must be preprocessed before analysis.

The most commonly used preprocessing technique is a low-pass filter, of which the

Butterworth filter is effective in maintaining the quality of the measured signal due to its stable phase and constant frequency response (Piskorowski, 2006). He *et al*. (2024) attached a strain gauge to a tractor PTO gearbox to measure strain, which was then converted to stress. A Butterworth filter was then applied to the converted stress time history data to remove high-frequency components, and a combination of detrending and outlier removal techniques was applied to improve the data quality for fatigue life evaluation. Wen *et al*. (2021) measured strain in real time by attaching a strain gauge to the housing structure of the tractor power transmission system. The measured strains were converted to stresses, and a Butterworth filter was applied to remove high frequencies. This approach minimized the distortion of the stress time history signal and ensured stable data quality suitable for fatigue life evaluation. In other fields, various techniques such as resampling, interpolation, and moving average are applied for data preprocessing, but these techniques are rarely applied in agricultural machinery (Zhou *et al*., 2020, Minda *et al*., 2020, Marshall *et al*., 2016). The limited application of these techniques in agricultural machinery may be attributed to concern that smoothing and resampling could inadvertently suppress transient impact loads and high-frequency peaks that are often critical for fatigue damage in harsh off-road environments. However, the selective application of these methods offers significant potential for enhancing data reliability. For example, interpolation can be effectively used to reconstruct missing data points caused by sensor dropouts during rigorous field operations (Lepot *et al*., 2017). Similarly, moving averages can assist in trend analysis by isolating low-frequency global load variations from localized stochastic noise (Carbone and Kiyono, 2016). Implementing these data processing methods would allow for a more nuanced analysis of the complex, non-linear load time histories typical of agricultural machinery, ultimately leading to more robust fatigue life evaluation.

Load cycle counting method

The noise of the preprocessed load data is removed, the signal quality is secured, and the data is refined into a time series history for fatigue life evaluation. Stress time history is then derived from a comprehensive consideration of the structure geometry, material properties, and load data. The stress time history is categorized into repeated stress cycles by applying the cycle counting method, and for each cycle, the stress amplitude, mean stress, and iteration number are derived (Amzallag *et al*., 1994). Stress cycles directly affect the reliability of fatigue life evaluation results, and accurate cycle counting is pivotal for the fatigue analysis process.

The rainflow counting method is applied in most studies on fatigue life evaluation of agricultural machinery for cycle counting (Figure 3). The rainflow counting method involves a sequential extraction of local peaks and valleys from a time series of stress time histories and then analysis of the correlations between the extreme points to identify repeated stress cycles (Glinka and Kam, 1987). The entire stress time history is decomposed into repetitive cycles, and each identified cycle is organized based on its mean stress and amplitude. Since this process can be reliably applied in environments with complex and irregularly changing loading conditions, such as agricultural operations, it is utilized in fatigue analysis, such as cumulative damage rate calculations and life prediction. On the other hand, the rainflow counting method has the advantage of accurately classifying repetitive cycles, but it has the limitation that it does not reflect the temporal sequence of the load time history or the overall time series structure (Dowling, 1971). Auxiliary cycle counting methods, such as level crossing counting, peak counting, and simple range counting, are often employed to analyze the characteristics of loads that are compensated for these limitations. These methods are useful for analyzing the periodicity, amplitude distribution, and frequency of occurrence of loads, but they have limitations compared to rainflow counting methods for fatigue life evaluation, such as load sequence and cumulative damage (Rychlik, 1987). Therefore, the rainflow counting method is still the dominant method for fatigue life evaluation of agricultural machinery.

Paraforos *et al*. (2014), which was mentioned earlier in this study, measured the loads acting on a 4-rotor swather, converted them into stresses, and applied rainflow counting methods to analyze the amplitude distribution of repetitive cycles per operation condition. Paraforos *et al*. (2016), which is the follow-up study, further extended the measurement points compared to the previous study and performed rainflow counting based on stress-time history collected under different operation conditions, in order to classify the repetitive cycles and utilize them for damage calculations. In this process, low-amplitude cycle removal and matrix extrapolation techniques were simultaneously applied, and the predictability of life under accelerated durability test conditions was presented. Lee *et al*. (2015) applied the rainflow counting method to the measured PTO load time history during rotary and baler operation of a tractor, classified the amplitude and mean stress of the cyclic loading, and analyzed the load distribution according to the working conditions. In the process, the characteristics of the repetitive cycles were compared and analyzed in line with a PTO rotation velocity and travel speed, effectively presenting the differences in load time history under different operation conditions.

Kim *et al*. (2019) applied the rainflow counting method based on the PTO torque time history generated during the rotary tiller operation of a multi-purpose cultivator, and decomposed the irregularly fluctuating loads into repetitive cycles. They organized the distribution of amplitude and iteration number per working condition and identified the changes in load characteristics. Markumningsih *et al*. (2022a, 2022b) derived stresses based on measured load data to analyze the load applied to the hopper structure of a semiautomatic transplanter, and applied the rainflow counting method to the stress time history. From the stress time history derived for 4-bar link and cam-type transplanters, respectively, the amplitude and mean stress of the repetitive cycles were categorized, and the load characteristics of each structure type were compared. In Markumningsih *et al*. (2023), the follow-up study, the drive structures of the two transplanters (4-bar link and cam type) were directly compared, and the same technique was applied to analyze the differences in cyclic loading characteristics based on the drive method. By comparing the distribution of the cyclic loading acting on the different transplanter structures, they derived the differences in load distribution according to the machine types. The wavelet transform method has been recently applied to fatigue life evaluation, which can simultaneously consider the temporal and frequency features of the signal. This method can only extract the main load components, and it has been proposed to apply the rainflow counting method simultaneously. Sun *et al*. (2023) applied the wavelet transform method to the vibration load acting on the mounting bracket of a hybrid tractor exhaust system to subdivide the load signal, and applied the rainflow counting method to the separated significant load components to improve the accuracy of cyclic loading classification.

Fatigue life evaluation method

After the measurement and preprocessing of load data, it is necessary to evaluate the fatigue life under the actual conditions of use, where the structure is subjected to repeated loads. Since the magnitude and frequency of cyclic loading vary depending on the working conditions and operating environment of agricultural machinery, it is difficult to accurately evaluate the actual fatigue life based on the static load design method alone. Therefore, it is essential to apply fatigue life evaluation techniques to evaluate the degree of damage accumulated by cyclic loading based on actual measured load time history and to predict the time of structural damage.

Stress-life curve

The stress-life curve (S-N curve) is the most utilized fatigue life evaluation technique under high-cycle fatigue conditions and represents the correlation between the iteration numbers until a material reaches failure under a constant repetitive stress amplitude (σ_a) (Murakami *et al.*, 2021, Kun *et al.*, 2008). It is usually expressed in the form of a straight line on a log-log scale and is effective in evaluating the fatigue properties of materials (Burhan and Kim *et al.*, 2019). S-N curves are mainly constructed under completely reserved stress conditions, where the mean stress (σ_m) is zero, and are constructed by converting repeated life tests or field load data into stresses (Kumbhar and Tayade, 2014, Tridello *et al.*, 2021). In the agricultural machinery field, it is commonly used to estimate fatigue damage by categorizing load data obtained under actual working conditions into load cycles through the rainflow counting method, converting them into stress amplitudes, and accumulating the iteration numbers corresponding to each stress level. However, in actual agricultural machinery structures, it is necessary to convert the actual loading condition with mean stress to a condition with zero mean stress. The equivalent completely reserved stress (σ_{eq}) is the calculated value. The equivalent completely reserved stress refers to the repetitive stress amplitude corrected for the effect of the mean stress, which enables more accurate fatigue life predictions under real-world conditions (Zhu *et al.*, 2017, Papuga *et al.*, 2018, Böhm *et al.*, 2020). The mean stress is corrected through the equations of Goodman, Gerber, and Soderberg; the application of the calibrated equivalent completely reserved stress to the existing S-N curve makes it possible to predict fatigue life under real-world conditions (Figure 4).

The Goodman equation linearly corrects for the stress-life relationship and is the most frequently used. The Gerber equation reflects the effect of mean stress in a parabolic form, which provides a high degree of accuracy in life prediction, but can be complicated to analyze. The Soderberg equation provides the most conservative lifetime prediction by limiting the upper bound of the mean stress to the yield strength (Sendeckyj, 2001, Böhm and Głowacka, 2020, Henriques *et al.*, 2021). The respective correction equations can be found in Eq. 1 - 3.

Goodman: $\sigma_{eq} = \frac{S_u \cdot \sigma_a}{S_u - \sigma_m}$ (Eq. 1)

Gerber: $\sigma_{eq} = \frac{S^2{}_u \cdot \sigma_a}{S^2{}_u - \sigma_m}$ (Eq. 2)

Soderberg: $\sigma_{eq} = \frac{S_y \cdot \sigma_a}{S_y - \sigma_m}$ (Eq. 3)

where:

σ_{eq}= Equivalent completely reserved stress (MPa)

σ_a= Stress amplitude (MPa)

σ_m= Mean stress (MPa)

S_u= Ultimate tensile strength (MPa)

S_y= Yield Strength (MPa)

These correction equations have been practically applied in fatigue life analysis of agricultural machinery, and various studies have reported their applications. Kim *et al.* (2023) targeted the fastening device, which is a vulnerable part of an agricultural by-product collector, and measured the stresses on the device under various driving and working conditions. Based on the measured stress data, the mean stress was calculated and the Goodman equation was applied to derive an equivalent completely reserved stress reflecting the mean stress. The calibrated stress was then applied to the S-N curve to predict the fatigue life. Hwang *et al.* (2025) measured the stresses applied to the structure under actual operating conditions for a machine that simultaneously performs mulching and covering. Based on this, the mean stress was calculated, and the equivalent completely reserved stress reflecting the mean stress was derived by applying the Goodman equation. This was applied to the calibrated S-N curve and utilized for life prediction. Abrahám *et al.* (2022) evaluated the fatigue life of the tractor wheel spike segment and applied the Gerber equation for the mean stress correction. The calibrated equivalent completely reserved stress was applied to the S-N curve to predict the life, and the structural safety was analyzed for different design variables. Bankapur *et al.* (2015) applied Goodman, Gerber, and Soderberg equations to a tractor-trailer chassis to analyze and compare fatigue life under cyclic loading conditions. In particular, the Soderberg equation acted as a conservative evaluation criterion and predicted the shortest life, and it was confirmed that the choice of equation significantly changed the life prediction results. Zhao *et al.* (2022) compared the Goodman, Gerber, and FKM equations to correct for the effect of mean stress in the fatigue life evaluation of a forage crusher rotor. As a result of comparing the life predicted by each equation with the actual cracking patterns, it was found that the Gerber equation showed the highest accuracy and could accurately reflect the nonlinear relationship between mean stress and life.

A number of studies have also been conducted using the Smith-Watson-Topper (SWT) equation as a mean stress correction technique. SWT equation is originally strain-life (ε–N) based, but in experimental settings where strain measurements are difficult or impossible, it is modified to a stress-based approximate expression utilizing peak stress and stress amplitude (Dowling, 2009, Łagoda *et al.*, 2022). The form of the SWT equation can be found in Eq. 4.

$$\text{Smith-Watson-Topper: } \sigma_{eq} = \sqrt{(\sigma_m + \sigma_a) \cdot \sigma_a} \qquad \text{(Eq. 4)}$$

There have been studies that applied the SWT equation to evaluate fatigue life. Lee *et al.* (2015) measured torque data under actual working conditions for the PTO drive gear of a 75 kW agricultural tractor. The measured loads were converted to equivalent completely repeated torque calibrated for mean torque by applying the SWT equation, which was then applied to the S-N curve to predict the cycling life. Kim *et al.* (2020) measured the torque acting on a spiral bevel gear of a tractor and analyzed the fatigue life according to the operating conditions. Based on the measured data, the SWT equation was applied to calculate the equivalent completely repeated torque reflecting the mean torque, which was applied to the S-N curve to evaluate the fatigue life. In addition, fatigue analysis considering the effect of mean stress was performed to compare durability differences per operating condition, and evaluate factors that reduce the life of the gear structure. As such, mean stress correction is pivotal for improving the accuracy of S-N-based fatigue life analysis, and various equations have been selectively applied according to the actual measurement conditions and characteristics of the mechanical structure. The selection of a mean stress correction equation primarily depends on the material properties and the required reliability level. For general agricultural machinery structures, such as frames and implements made of steel alloys, the Goodman equation is the most widely adopted because it provides a balanced compromise between predictive accuracy and design efficiency (Shigley *et al*., 1985). The Soderberg equation is preferred for safety-critical components where even minor deformation must be avoided, as it offers the most conservative life estimates and ensures a high safety margin (Badr and Ishak, 2021). The Gerber equation can provide higher prediction accuracy under tensile mean stress conditions. However, caution is required under compressive loads, as it may overpredict fatigue life (Joun *et al*., 2022). For components subjected to complex loading conditions and severe torque variations, such as transmission gears, the SWT equation is often applied to capture nonlinear fatigue characteristics more effectively (Łagoda *et al*., 2022). Ultimately, although the final selection depends on specific component and loading characteristics, the Goodman equation is commonly used as a general guideline for structural fatigue evaluation in agricultural machinery.

Cumulative damage method

Fatigue life is a concept that predicts the cumulative damage of a structure under cyclic loading, and the cumulative damage method is utilized to evaluate the effect of various magnitudes of cyclic loading on fatigue life (Miner, 1945, Fatemi and Yang, 1998). In particular, for agricultural machinery, where irregular stress fluctuations occur under various working methods and environmental conditions, fatigue life evaluation based on a single stress condition cannot accurately predict the actual time to failure. Therefore, cumulative damage methods that can analyze repetitive stress cycles and evaluate fatigue life are important for fatigue life evaluation of agricultural machinery. The most commonly used cumulative damage method is the Palmgren-Miner rule (Hectors and Waele, 2021). The Palmgren-Miner rule calculates the overall cumulative damage by independently summing the damage caused to the material by repetitive stress cycles at different stress levels to calculate the overall cumulative damage, which is expressed as in Eq. 5.

$$\text{Palmgrn-Miner: } D = \sum_{i=1}^{k} \frac{n_i}{N_i} \qquad \text{(Eq. 5)}$$

where:

D= Total damage sum

n_i= Number of acyally applied cycles for i_{th} stress

N_i= Life cycles for i_{th} stress

k= Total number of stress level

The Palmgren-Miner rule is one of the most widely utilized fatigue life evaluation techniques in industry fields due to its simplicity of calculation and ease of connection with S-N curves (Sun *et al*., 2014). In particular, because the iteration number per stress level is accumulated and converted into a damage ratio, it can be applied not only to a single stress condition, but also to environments with repetitive stresses of varying amplitudes (Zuo *et al*., 2014). In the field of agricultural machinery, the Palmgren-Miner rule is also employed as a standard analysis technique to predict the fatigue life of structures and has become an effective means to evaluate the cumulative damage caused by stress cycles under various operating conditions. Tyutrin (2020) evaluated the fatigue life of a spring strut, a part of a cultivator, by measuring the load applied to it and applying the Palmgren-Miner rule to the derived stress time history. After categorizing the derived stress data based on stress levels, the cumulative damage was calculated by comparing the iteration number and allowable life for each level, and the equivalent completely reserved stress was calculated to evaluate the durability of the structure. Islam *et al*. (2021) applied the load duration distribution (LDD) technique to construct the cyclic loading distribution based on the experimentally measured torque data of the picking device gear of the automatic paprika transplanter, and evaluated the fatigue life through the Palmgren-Minor rule. As a result, the maximum fatigue life of 4635.97 hours was estimated for SCM 420H steel materials and 5 mm face width, which is more than 18 times longer than the existing fatigue life (255 hours). Siddique *et al*. (2022) measured the hydraulic pressure applied to a hydraulic pump of 78 kW tractor and applied the Palmgren-Miner rule to derive the cumulative damage and evaluate the fatigue life based on it. The measured pressure data were categorized by pressure level, and the damage accumulation was calculated by comparing the iteration number and the allowable life to analyze the durability and fatigue life of the hydraulic pump.

In the field of agricultural machinery, nonlinear cumulative damage methods have also been reported in some cases. Unlike linear methods, nonlinear cumulative damage models do not assumed linear damage accumulation. Instead, these models account for the sequence of cyclic loading, amplitude variations, and load interactions, enabling a more accurate representation of fatigue failure behavior (Huang *et al.*, 2019). However, a clear trade-off exists in their practical application. While nonlinear cumulative damage models offer superior predictive accuracy, they require more complex material parameter identification and greater computational effort. In contrast, the Palmgren-Miner rule is widely used for durability assessment because it requires minimal parameter identification and offers high computational efficiency and ease of implementation. Nevertheless, nonlinear models are often preferred for critical components where higher prediction accuracy is required. For example, Yan *et al.* (2025) proposed a fatigue life prediction technique that reflects load sequence effects by applying the Lemaitre model, a nonlinear cumulative damage technique, and the block-jumping technique together to analyze the repeated torque load on a PTO shaft of the tractor. The Lemaitre model defines the damage variable based on the energy dissipation inside the material and is based on the theory of Continuum Damage Mechanics (CDM) (Lemaitre, 1985). The block-jumping technique is utilized by dividing the irregular load time history into operating sections, and accumulating the damage in each section to calculate the overall damage (Sun and Xu, 2021). These examples exhibit that, considering the characteristics of agricultural machinery structures with complex and fluctuating cyclic loading conditions, nonlinear damage accumulation models can be an alternative for more accurate life prediction.

Simulation-based fatigue life evaluation

The fatigue life of agricultural machinery has been generally evaluated with field/survey data. In cycling life testing or in-situ measurements, cyclic loading acts on the components, the time of damage occurrence is identified, and their life is predicted. However, these physical tests are time-consuming and costly, and have the limitation that it is difficult to fully reproduce the working conditions (Nakhaei *et al.*, 2023). Furthermore, they require the construction of separate test environments each time for repeated testing under different conditions or for comparing life under different design settings (Okenyi *et al.*, 2024, Solazzi and Mazzoni, 2023). Recent studies have utilized simulation-based fatigue life evaluation techniques to overcome these limitations. Simulation can numerically implement various operating conditions and load time history, which can be reflected in the analysis model to predict stress generation and damage accumulation under cyclic loading (Huang *et al*., 2021, Hao *et al*., 2023). It is also advantageous for design optimization and structural improvement because it can freely apply extreme conditions or complex operating conditions that are difficult to implement via tests, and it can perform repeated analysis on the same model (Xian *et al*., 2024). In recent research, simulation-based fatigue life evaluation methods have been utilized not only for life prediction in the early stages of design, but also as a reliable life prediction method based on surveyed data.

Among simulation-based fatigue life evaluation methods, FEA is the most widely applied because it can analyze the stress distribution and fatigue damage under cyclic loading of agricultural machinery structures. Based on a case of cyclic loading failure in a bell crank assembly of a tractor hydraulic system, Dhangar *et al*. (2017) utilized measured load data from actual working conditions to construct a cyclic loading specification (RWUP) and performed simulations based on FEA. The simulation results indicated that the stress concentration area was consistent with the actual failure location, and the maximum stress at that location was reduced by about 67% through design changes. The correlation coefficient between the simulation analysis results and the test results was 0.975, showing a high degree of agreement. Jahanbakhshi and Heidarbeigi (2019) performed static analysis, vibration characterization, and fatigue analysis simulation by using FEA on the lower link arm of a tractor. The highest probability of fatigue failure was found at the chain fixing device, where cyclic loading was concentrated, and a fatigue safety factor had a minimum value of 1.51 at high-stress regions. Rezaei *et al*. (2023) performed static and dynamic simulations using FEA on the rear axle of combine harvester based on measured actual loads under paved and unpaved roads, and agricultural driving conditions, and evaluated fatigue life and fatigue safety factor. The lowest fatigue safety factor was found under the maximum load condition measured during driving on unpaved roads; structural optimization improved the stress concentration distribution and led to an eightfold safety factor increase.

Although FEA is effective in analyzing static and dynamic stresses at the structural level, it has limitations in reflecting the kinematic characteristics of the entire mechanical system (Vlase *et al*., 2022). On the other hand, since agricultural machinery has complex mechanical characteristics such as rotation, repetitive motion, nonlinear contact, and multi-joint connection, Multi-Body Dynamics (MBD)-based analysis techniques are utilized to implement cyclic loading and analyze structural response. MBD has strengths in simulating temporal changes in kinematic conditions and contact loads, but it is limited in analyzing local stresses. Therefore, it is typically used in conjunction with FEA or Discrete Element Method (DEM). FEM-MBD coupled simulation is utilized to evaluate stress distributions and fatigue life in a part unit under repetitive conditions. Furthermore, DEM-MBD coupled simulation can numerically show the interaction between the nonlinear reaction of soil particles and mechanical motion, which is effectively applied to soil-mechanical system analysis. As a representative example of FEM-MBD coupled simulation, Yin *et al*. (2024) performed MBD simulation on the rope clamping drive mechanism of a D-type knotter in a square baler, and modeled the worm shaft as a flexible body to analyze the loads generated during repeated operation. The fatigue life was then evaluated by coupling FEA with fatigue analysis, and the results were found to be consistent with the repeated test results of the prototype. An example of DEM-MBD coupling can be found in Xie *et al*. (2025), which targeted a rotary tiller blade with a vibration mechanism. In this study, soil reaction was calculated from the DEM and coupled with the MBD model to analyze the torque and stresses under vibration conditions. The fatigue vulnerable areas were then predicted through finite element-based structural analysis, and the optimal design was applied; the results showed that the maximum strain and equivalent stress were reduced by 52.6% and 46.8%, respectively, and the mean torque was reduced by 12.9% compared to the previous design. As such, the fatigue life evaluation of agricultural machinery requires co-simulation that can integrate the dynamic behavior of the machine and external environmental conditions than a single analysis method, and the combined analysis method based on FEA-MBD and DEM-MBD is expected to play an important role in establishing a consistent analysis system from the early design stage to life prediction in the future.

Limitations and future work

Recent research on fatigue life evaluation of agricultural machinery has made technological advances through the application of load measurement techniques and simulation-based analysis methods. In particular, the introduction of strain gauge-based sensor systems, application of mean stress correction formulas, and FEA-MBD coupled analysis play a pivotal role in predicting the life of agricultural machinery structures exposed to cyclic loading. However, these techniques still have limitations in being fully reflected in the real-world agricultural operation environment. The cyclic loading applied to structures during real-world agricultural operation is irregularly varied due to various factors such as working methods and ground/terrain conditions. However, most existing studies have collected load data under limited operating conditions or only a single working method, and have not fully reflected the characteristics of the actual working environment, such as the load occurrence sequence, complex working conditions, and amplitude variations. This can lead to inconsistencies between test and analytical results and reduce the reliability of fatigue life evaluation. In addition, the mean stress correction equation and the Palmgren-Miner rule have the advantages of simple calculation and clear applicability, but they have limitations in accurately reflecting the complex and irregular load time history applied to agricultural machinery. For instance, the Goodman, Gerber, and Soderberg correction equations are valid under constant stress conditions, but can be inaccurate under conditions where the stress amplitude frequently varies. Since the Palmgren-Miner rule also simplifies the actual damage behavior, and linearly aggregates the damage accumulation, it cannot fully describe the fatigue failure mechanism of real materials.

Future research should apply non-linear cumulative damage methods that can fully reflect the load time history to enable reliable life predictions under different operating conditions. In addition, since simulation-based analysis techniques are applicable to the prediction of the stress distribution and fatigue life of structures under cyclic loading conditions, there should be more studies on fatigue life evaluation utilizing FEA-MBD and DEM-MBD coupled analysis techniques. In this case, the practical applicability should be increased by applying actual measured loads as analysis inputs and comparing and verifying the analysis results with experimental values. Furthermore, consistent application of analysis methods and evaluation criteria is necessary to increase the reliability and utilization of fatigue life evaluation analysis. There should be research that can standardize key elements such as the definition of cyclic loading, mean stress correction, and damage accumulation calculation method, and expand them into a universal evaluation technique applicable to various agricultural machinery structures.

Conclusions

The fatigue life evaluation of agricultural machinery has evolved from a simple durability analysis to a key field for ensuring the safety and reliability of structures. Therefore, this review summarizes recent research trends and analyzes the current research state and major limitations, by focusing on the main technical elements utilized in fatigue analysis of agricultural machinery (e.g., load measurement, data processing, life prediction techniques, and simulation-based analysis). Real-time sensor-based load measurement systems provide the foundation for the analysis of cyclic loading characteristics, while the mean stress correction equations and the linear cumulative damage method are mainly employed for life prediction under high-cycle fatigue conditions. Simulation-based analysis techniques with FEA-MBD and DEM-MBD coupled analysis are also utilized to analyze the behavior under cyclic loading at the system level beyond the component level. However, challenges remain to accurately reflect the irregular load characteristics of actual agricultural operation conditions and to ensure the reliability of the analysis results. In particular, the comparison of results between analysis methods, validation of analysis based on actual measurement data, and standardization of evaluation criteria have not yet been sufficiently established. In future research, the following are suggested as main challenges: the application of the nonlinear cumulative damage method, establishment of a simulation verification system based on actual measured loads, advancement of mean stress and load time history reflection techniques, and standardization of evaluation procedures. Furthermore, the integration of emerging technologies such as machine learning-based predictive maintenance and digital twin frameworks is expected to significantly advance fatigue life evaluation. These technologies can enable real-time structural monitoring and more accurate life-cycle simulation by continuously incorporating field operation data. This review attempted to summarize the current technical state in fatigue life evaluation of agricultural machinery, and suggest research directions to ensure structural reliability, and increase the effectiveness of life prediction. Ultimately, This review is expected to make practical contributions to optimizing the design of agricultural machinery, improving maintenance efficiency, equipment life cycle management, and creating a sustainable agricultural technology system.

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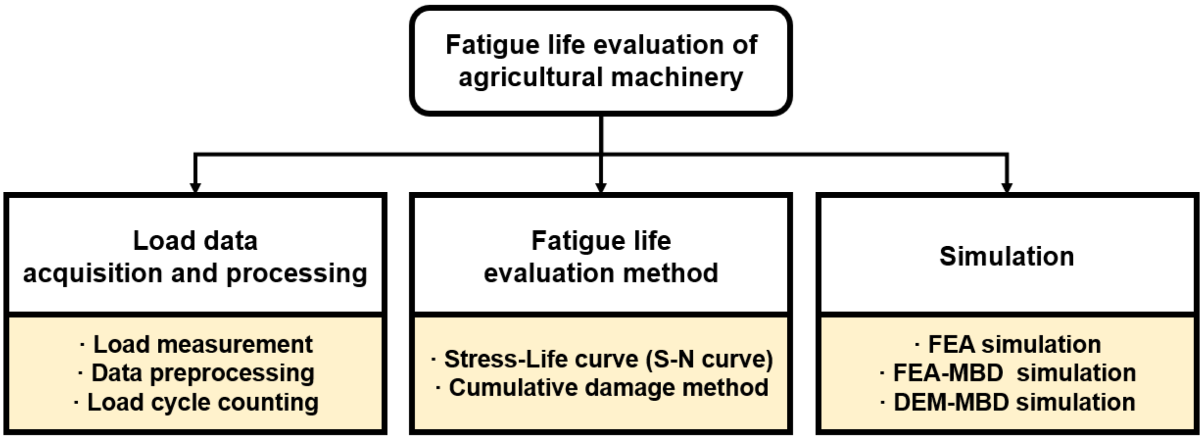

Figure 1. Framework in fatigue life evaluation of agricultural machinery.

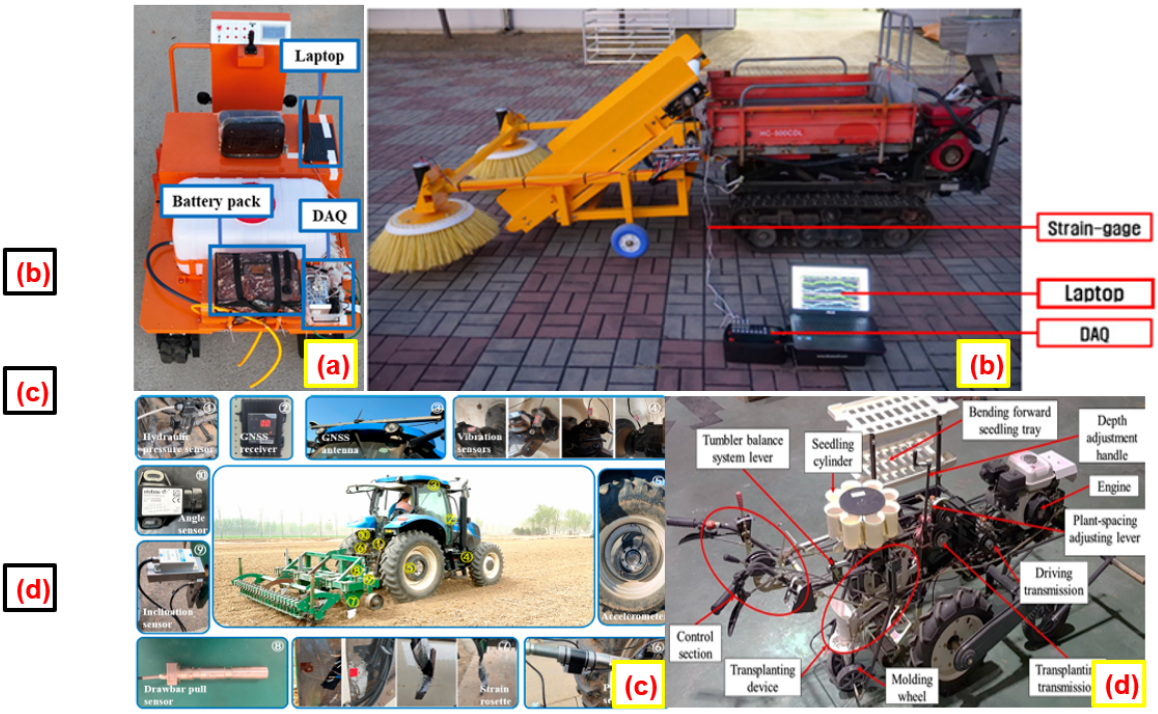

Figure 2. Example of load measurement systems applied in agricultural machinery. a) Retrieved from: Hwang *et al*. Agriculture 2024;14:416; with permission. b) Retrieved from: Kim *et al*. Agriculture 2022;12:1071; with permission. c) Retrieved from: Zhang *et al*., Agriculture 2024;14:1604; with permission. d) Retrieved from: Markumningsih *et al.* Agriculture 2023;3:588; with permission.

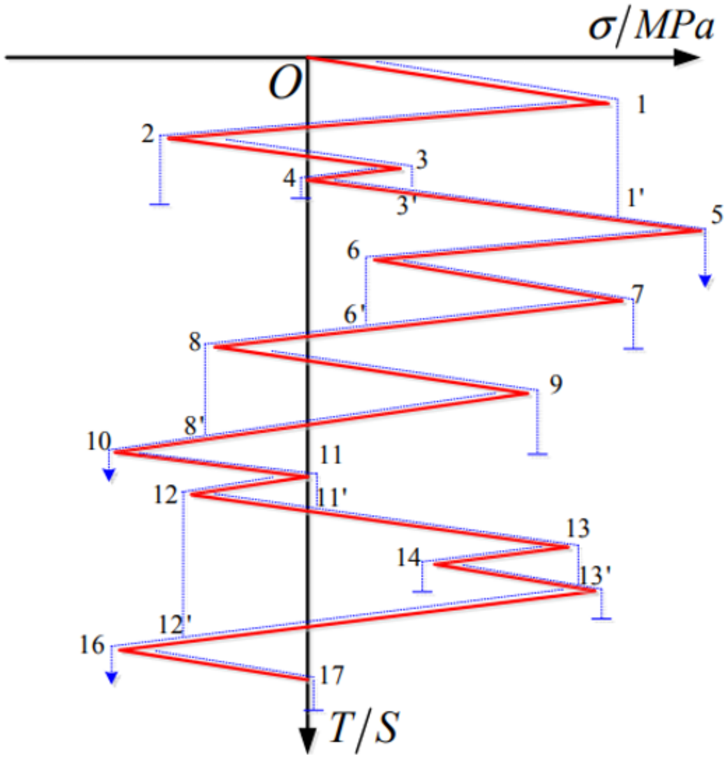

Figure 3. Operation of rainflow counting method. Retrieved from: Chen *et al*. Sens Transducers 2014;171:78-85; with permission.

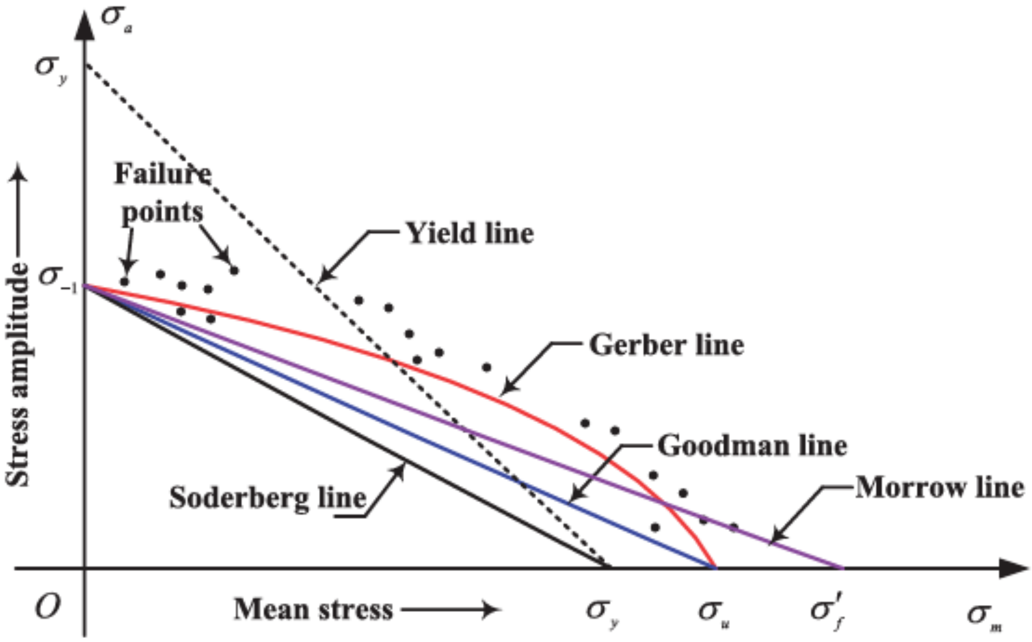

Figure 4. Mean stress correction equations for fatigue life evaluation. Retrieved from: Zhu *et al*. Int J Damage Mech 2017;26:1219-1241; with permission.

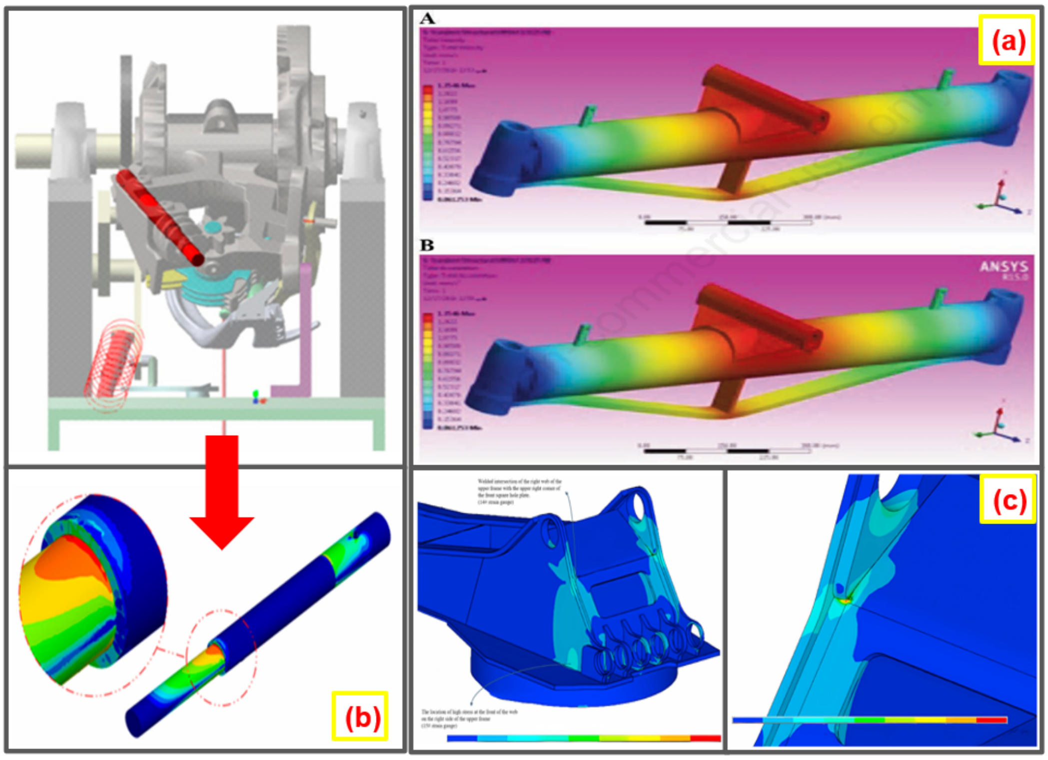

Figure 5. Example of simulation techniques applied to agricultural machinery. a) Retrieved from: Rezaei *et al*. J Agric Eng 2023;54:1448; with permission. b) Retrieved from: Yin *et al.* Agriculture 2024;14:947; with permission. c) Retrieved from: Xian *et al*. Heliyon 2024;10:e33126; with permission.

Table 1. Recent application of sensor-based load measurement in agricultural machinery fatigue life evaluation.

Reference	Target	Sensor used	Measured variable
Kim *et al*. (2024)	Front-end loader structure	Strain gauge	Critical stress points identified *via* MBD; strain measured and converted to stress using CAN-based DAQ system.
Hwang *et al*. (2024)	Structural joints of an electric multi-purpose tractor	Rosette-type 3-axial strain gauge	Multi-condition strain measurements converted to von Mises stress for fatigue evaluation.
Koyuncu *et al*. (2012)	Front axle support of agricultural tractor	Rosette-type 3-axial strain gauge	Principal strain measured under dynamic loading equivalent to three times gravitational acceleration; converted to stress for structural analysis.
Cardei *et al*. (2023)	Modular cultivator with linear supports	Strain gauge	Forces on supports of working bodies, processed as random vibration data sequences.
Kim *et al*. (2022)	Fastening device of an agricultural by-product collector	Strain gauge	Strain at the point of maximum stress (17.5 cm from frame); converted to stress using elastic modulus.
Han *et al*. (2022)	Rear drive system of 78 kW tractor	Torque meter, RPM sensor	Real-time acquisition of torque and rotational speed; used for spiral bevel gear load estimation and accelerated life testing.
Kim *et al*. (2021)	4-rotor swather	Strain gauges, IMU, RTK-GNSS	Real-time acquisition under transport, operation, and turning modes; combined strain, acceleration, and position tracking.
Paraforos *et al*. (2014)	Tractor and mounted plow	Strain gauge, accelerometer, tension sensor, angle sensor, hydraulic pressure sensor, GNSS	Sensor-integrated DAQ system with LabView-based remote monitoring; analyzed working depth, speed, draft, and stress.
Zhang *et al*. (2024)	All four tractor wheels	CAN-Bus, WFT	Combined CAN-based operating data and wheel force signals; vertical load measured in real time for fatigue behavior analysis.

Table 2. Recent application of rainflow counting in agricultural machinery fatigue life research.

Reference	Target	Load type	Cycle counting method	Application summary
Paraforos *et al*. (2014)	4-rotor swather	Stress	Rainflow counting	Analyzed stress amplitude distribution by operating mode based on field-measured data.
Paraforos *et al*. (2016)	4-rotor swather	Stress	Rainflow counting	Extended measurement range; applied matrix extrapolation for accelerated durability testing.
Lee *et al*. (2015)	Tractor PTO	Torque	Rainflow counting	Evaluated changes in torque cycles depending on PTO speed and driving conditions.
Kim *et al*. (2019)	Rotary tiller	Torque	Rainflow counting	Decomposed variable torque loads into repeatable cycles; evaluated cycle frequency and amplitude per task.
Markumningsih *et al*. (2022a)	Transplanter (4-bar link type)	Stress	Rainflow counting	Extracted cycle characteristics from structural stress; focused on 4-bar link mechanism.
Markumningsih *et al*. (2022b)	Transplanter (cam type)	Stress	Rainflow counting	Extracted cycle characteristics from structural stress; focused on cam mechanism.
Markumningsih *et al*. (2023)	Transplanter 4-bar link type and cam type)	Stress	Rainflow counting	Conducted comparative fatigue analysis across different mechanical configurations(4-bar link and cam type).
Sun *et al*. (2023)	Hybrid tractor bracket	Vibration load	Rainflow counting + Wavelet	Enhanced cycle extraction accuracy by combining the wavelet transform with the rainflow method.

Table 3. Recent application of mean stress correction equations in agricultural machinery fatigue life evaluation.

Reference	Target	Correction equation	Application summary
Kim *et al*. (2023)	Fastening device of an agricultural by-product collector	Goodman	Mean stress was corrected using the Goodman equation, and fatigue life was evaluated *via* S–N curve.
Hwang *et al*. (2025)	Mulching and covering machine	Goodman	Goodman correction was applied to field-measured stress to predict fatigue life under working conditions.
Abrahám *et al*. (2022)	Tractor wheel spike segment	Gerber	The Gerber equation was used to correct mean stress, enabling fatigue life evaluation under varying loads.
Bankapur *et al*. (2015)	Tractor trailer chassis	Goodman / Gerber / Soderberg	Fatigue life was compared using three correction models; Soderberg gave the most conservative prediction.
Zhao *et al*. (2022)	forage crusher rotor	Goodman / Gerber / FKM	Fatigue life was evaluated under each correction model; Gerber provided the closest match to observed cracks.
Lee *et al*. (2015)	PTO gear (75 kW tractor)	SWT	SWT equation was applied to corrected torque amplitude for fatigue analysis via S–N curve.
Kim *et al*. (2020)	Tractor Spiral Bevel Gear	SWT	SWT-based correction was used to account for mean torque effects under variable load cycles.

Table 4. Recent application of cumulative damage models in agricultural machinery fatigue life evaluation.

Reference	Target	Damage model applied	Application summary
Tyutrin (2020)	Spring strut of cultivator	Palmgren–Miner (linear)	Damage summed across stress levels; equivalent stress used for durability.
Islam *et al*. (2021)	Gear of automatic paprika transplanter	Palmgren–Miner (linear) + LDD	Estimated fatigue life of 4635.97 hours, which is approximately 18 times longer than the existing fatigue life.
Siddique *et al*. (2022)	Hydraulic pump of 78 kW tractor	Palmgren–Miner (linear)	Pressure cycles analyzed; durability evaluated using damage accumulation.
Yan *et al*. (2025)	PTO shaft of the tractor	Lemaitre (nonlinear) + block-jumping	Load sequence effects modeled; damage evolution predicted more accurately.

Table 5. Recent simulation-based fatigue life evaluation studies on agricultural machinery.

Reference	Target component	Simulation method	Application summary
Dhangar *et al*. (2017)	Bell crank of hydraulic system	FEA	Critical fatigue location identified; redesign reduced maximum stress by approximately 67%.
Jahanbakhshi and Heidarbeigi (2019)	Lower link arm of tractor	FEA	Fatigue safety factor quantitatively evaluated; minimum value calculated as 1.51 at high-stress regions.
Rezaei *et al*. (2023)	Rear axle of combine harvester	FEA	Fatigue life and safety factor evaluated under various terrains; optimization led to an eightfold safety factor increase.
Yin *et al*. (2024)	Knotter drive in square baler	MBD + FEA	Dynamic loads derived *via* MBD; FEA-based fatigue results validated through repeated experimental trials.
Xie *et al*. (2025)	Rotary tiller blade with vibration mechanism	DEM + MBD + FEA	Coupled soil–machine dynamics modeled; structural improvements reduced strain by 52.6% and torque by 12.9%.