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Assessing Fire Risks in Agricultural Balers: A Comprehensive Study

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Abstract: Agricultural machinery, particularly balers, plays a crucial role in forage management. These machines are prone to fire incidents caused by mechanical friction, heat buildup, and the accumulation of crop residues, among other contributing factors. Despite their operational importance, fire risks associated with balers remain largely understudied. This research aims to identify critical fire risk factors in large square balers through a combined analysis of survey data, temperature monitoring, and residue characterization. A questionnaire survey was conducted among 144 large square baler users to assess fire incidence and potential risk factors. Contingency table analysis and binary logistic regression were applied to identify variables significantly associated with the fire risk. Additionally, temperature data were recorded in six balers during two harvesting seasons, and residue samples were collected and analyzed to assess their ignition potential. Using a rake for windrowing was the only variable significantly associated with increased fire risk, making balers 3.4 times more likely to experience a fire (p = 0.034). Temperature analysis showed that the feeder fork brake (190.6 °C) and hydraulic pump (128.7 °C) were the hottest components, but none of the recorded temperatures exceeded the 250 °C ignition threshold of fine agricultural residues. Residue analysis showed that particles smaller than 250 µm accounted for 39% of the total material, underscoring their potential to contribute to fire propagation. This study highlights the critical influence of raking equipment on fire risk in balers and emphasizes the importance of preventive measures such as enhanced cleaning, real-time temperature monitoring, and improved mechanical design. These findings provide actionable insights for reducing fire hazards in agricultural operations and optimizing baler safety.

Keywords: prismatic bales; straw residues; temperature sensor; fork brake; baling residues

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1. Introduction

Wildfires pose a significant and multifaceted threat, generating far-reaching environmental, economic, and human consequences. While their origins are not solely tied to agricultural machinery operations, there are documented instances where such activities have contributed to the ignition of fires [1]. A high density of agricultural machinery may increase ignitions caused by machinery operation [2]. These incidents can lead to severe consequences, including the devastation of natural ecosystems, significant financial losses, and reduced land productivity. According to data from the Ministry for Ecological Transition and Demographic Challenge [3], Spain has experienced, between 2014 and 2023, an annual average of 6299 fire starts (<1 ha) and 3071 significant wildfires (>1 ha). In relation to the cause of fires, according to data from the Government of Aragón (Spain), between 2014 and 2023, 46.9% were attributed to negligence and accidents, of which 20.7% corresponded to machines and engines. This indicates that 9.7% of all fires were attributed to machinery and engines [4].

Fires in agricultural machinery can result from a combination of factors, including heat generated during operation, friction, electrical faults, hydraulic drives, and crop residue accumulation [5]. It should also be noted that field conditions can facilitate or hinder the process of fire spread. The main influence is exerted by four main factors: relative humidity, ambient temperature, wind speed, and type and condition of the crop [6]. Several studies [7,8] show that most fires coincide with the hours of highest temperature (2:00 p.m.–4:00 p.m.).

Specific types of agricultural machinery are particularly vulnerable to fire incidents due to their operational characteristics and the timing of their activities. Two such machines significantly impacted by these risks are combined harvesters and balers. For combine harvesters, Quick [9] identified a range of potential fire-prone areas, including the engine and exhaust system, transmissions, bearings, brakes, electrical circuits, and other components. The introduction of foreign objects into the machinery can further exacerbate fire hazards.

Regarding combine harvesters, Val-Aguasca et al. [10] concluded that the accumulation of harvested material significantly influences the statistical likelihood of fire and that this likelihood increases with the number of hectares harvested by the machine, this increase being significant in combines with 6000 hectares harvested. In their on-site experiments, these authors recorded temperatures of up to 300 °C in the engine zone, particularly in the exhaust manifold. Meanwhile, the cutting bar, subject to friction, reached temperatures exceeding 400 °C. These high temperatures, coupled with the accumulation of agricultural residues from cereal harvesting, pose a substantial risk of ignition. The study also involved collecting straw residues from various machine parts, characterizing their size, and establishing ignition temperatures for various fractions, both in wheat and barley.

In the United States, researchers led by Shutske [11,12] investigated over 4000 combine harvester and tractor fires, conducting in-depth examinations of 265 fire-damaged machines. From the data gathered, they deduced that 74% of fires originated in the engine area, due to the contact of residues with high-temperature elements. Crop residues were the most frequent ignition source, surpassing fuel and oil residues.

Regarding forage balers, there are three types of balers on the market [13] depending on the characteristics (geometry and density) of the bale produced: small rectangular bales; big round bales and big square bales. There exists limited research on fire risk in balers, perhaps due to their non-self-propelled nature, lacking internal combustion engines. However, balers have many moving parts [14] (drive systems, pickup, pressing and binding mechanisms) that, due to poor operation or maintenance, can become hot and constitute ignition points for the crop residues present in the machine. In a study by Mickan [15], valuable insights into fire risk in balers are available, considering various factors. Among these, Mickan emphasized the significance of bearing maintenance and the risk of bale combustion upon ejection from the compression channel, where they are abruptly exposed to increased oxygen levels compared to their interior environment.

Regrettably, there is a paucity of studies providing detailed analyses of critical fire ignition points. A study to determine the causes of fire in balers [1], based on direct consultation with the tractor drivers, proposed a methodology according to which the risk of fire can be assessed based on three factors: the machine, the human behavior, and the work system environment. According to this research, the risk of fire in balers was low, with the main cause of the fire being the high ambient temperature.

Regarding the fire safety of balers in Europe, baler manufacturers must comply with Regulation (EU) 2023/1230 of the European Parliament and of the Council of 14 June 2023 on machinery. According to this regulation: "Depending on the hazards anticipated by the manufacturer, machinery shall when its size permits: (a) either allow easily accessible fire extinguishers to be fitted, or (b) be provided with built-in extinguishing systems". In addition, the ISO 4254-11:2011/A1:2020 [16] baler safety standard emphasizes "the importance of regular maintenance of the baler and regular clearing of wrapped crop or tying material to reduce the possibility of fire".

In recent years, the risk of fire and operational failures in agricultural machinery has become a growing concern, particularly under real field conditions involving aging equipment, limited maintenance, and increased workloads. Although most existing studies focus on combining harvesters, recent research has addressed broader safety issues in agricultural machinery. Pilarczyk and Ulewicz [17] highlighted that improper maintenance, lack of safety protections, and outdated machines are key contributors to accident and fire risk, especially in small and medium-sized farms. Furthermore, they emphasized the relevance of structured analysis methods such as Failure Mode and Effects Analysis (FMEA) for improving risk management in the agricultural sector [18]. These perspectives align with recent developments in predictive maintenance, where temperature and vibration data are used to detect early signs of mechanical failure. For instance, Radicioni et al. [19] demonstrated that combined monitoring of thermal and vibrational behavior can effectively identify wear in conveyor systems, while Barač et al. [20] applied machine learning models to predict vibration levels in tractors. Tamboli and Sambhaji [21] also proposed an IoT-based protection system for chaff cutters, offering real-time detection and intervention capabilities. Together, these studies support the integration of sensor-based diagnostics into fire prevention strategies. Despite these advances, quantitative fire risk assessment in balers remains scarce, justifying the present study's focus on ignition conditions and risk factors in large square balers under real-world operating conditions.

Given the preceding information, this study seeks to monitor various components of large square balers, aiming to identify behavioral patterns and critical ignition points that can serve as a foundation for the implementation of effective preventive measures to minimize the risk of fire.

2. Materials and Methods

2.1. Questionnaire Data Analysis of Baler Users and Owners

A questionnaire was conducted among 144 users of big square balers with the aim of gathering experiential information, identifying critical points in the machinery, and characterizing the profile of machines with a higher risk of fire incidents. The questionnaire was primarily distributed in the Aragón region (Spain), facilitated through the Young Farmers' Agrarian Association (ASAJA) and the Aragon Association of Conservation Agriculture (AGRACON), targeting both association members and unaffiliated users. Approximately 80% of the respondents were based in Aragón, with the remaining participants coming from neighboring regions, reflecting the focus of the study on this high-density machinery area. The region of Aragón was selected as the focus of the survey due to its significant representation in terms of baler density. According to the Official Registry of Agricultural Machinery (ROMA), corresponding to the year the study began (2019), Aragón accounted for approximately 8% of all registered balers in Spain, with a total of 2725 units, including

834 large square balers. This relatively high machinery density, particularly in the province of Huesca, supports the suitability of the region as a representative area for assessing fire risks in balers.

The structure of the survey was predominantly divided into two sections: (1) Technical Characteristics of Balers: within this section, data was compiled concerning the manufacturers of the balers, the power of tractors driving the balers, the age of the balers, the quantity of bales produced, the utilization of rake equipment for windrowing, and other pertinent technical details. The questionnaire included targeted questions on maintenance practices, such as the frequency of machine cleaning, the method used (compressed air, water), whether the operator performed seasonal technical checks, and whether any repairs had been carried out during the campaign. Fire prevention systems were assessed through questions about the presence of fire extinguishers or other fire-suppression devices on the baler, availability of auxiliary tools (e.g., water tank, shovel), and use of other preventive actions during field operations. (2) Characteristics of Fire Incidents in Balers (if applicable): this section focused on information related to fire incidents involving balers, encompassing the age of the baler at the time of the fire incident, the specific area of the machinery where the fire originated, the time frame of the occurrence, the type of material being baled, and other relevant incident-related details.

The data obtained were analyzed from two perspectives: (1) a descriptive analysis to characterize the sample and extract information regarding the technical specifications of the balers, the frequency of fire incidents, and the critical ignition points, and (2) a statistical analysis aimed at assessing the influence of different variables on the fire risk. Contingency tables were constructed to evaluate the association between various factors and the occurrence of fires in balers. The chi-square test of independence was applied to determine whether statistically significant relationships existed between fire occurrence and variables such as baler age, annual bale production, the presence of raking equipment, and maintenance practices.

Based on prior studies, such as that of Martínez et al. [2], which employed predictive models to assess fire risk in agricultural contexts, a logistic regression model was developed to estimate the probability of a baler experiencing a fire incident (with a binary dependent variable: 0 = no fire; 1 = fire). The initial model included multiple explanatory variables: ownership type, business type, baler age, annual bale production, use of a rake, manufacturer, maintenance level, component replacement, and fire prevention system. A backward stepwise selection method was applied to identify the most relevant predictors, sequentially removing variables with p-values greater than 0.05. However, the results indicated a poor model fit, with only one variable showing a statistically significant association with fire risk. Consequently, while the logistic regression results are presented, no validation of the model was performed, as its predictive capability was deemed insufficient. Instead, the model is included solely to confirm the effect of the identified significant factor on fire risk.

All statistical analyses were conducted using SPSS v.26 (IBM, Chigago, IL, USA) and R v.4.3.2. (R Core Team, Vienna, Austria).

2.2. Temperature Records Under Working Conditions

Temperature records were obtained from six different big square balers over two seasons of barley and wheat straw baling (five balers in the first season and three balers in the second one, with two of them being repeated). Type K thermocouple temperature probes (TC Direct, Madrid, Spain) were installed in various zones of each machine. This type of probe was selected for temperature monitoring due to its high durability, wide operational range (−200 °C to +1260 °C), and suitability for industrial applications. The sensors used comply with IEC 60584-1, Class 1, with an accuracy of ±1.5 °C or ±0.4% of the measured temperature. Their response time ranges between 1 and 5 s depending on probe design, which was appropriate for monitoring gradual heating patterns in metallic components under real operating conditions. Prior to installation, all temperature sensors were calibrated against standard reference thermocouples under controlled conditions. This process confirmed a measurement accuracy of ±0.5 °C, ensuring reliability in field data acquisition. In addition, an external temperature/humidity sensor, the HOBO Pro v2 Ext Temp/RH model (Onset Computer Corp., Bourne, MA, USA), was installed. These measurements allowed us to contextualize internal temperature readings and operational conditions. Although wind speed and direction were not recorded in real time, in the event of a hazardous temperature condition, regional meteorological data from nearby weather stations could have been consulted to assess fire spread risk. Four probes connected to a portable data logger (Data Logger THERMOMETER SE-520; TC-Direct, Madrid, Spain) were installed in each machine. In order to investigate a heterogeneous group of machines, balers with different manufacturing designs, work methodologies (individual users, service companies), and technical specifications (age, annual bale production, and accumulated bales) were monitored. This approach allowed for the examination of a variety of balers and their operating conditions, enabling a comprehensive analysis of temperature patterns and risk factors.

Table 1 highlights key technical specifications, including manufacturer details, baler design, operational methodology (individual users or service companies), as well as diverse technical characteristics such as machine age, annual bale production, and cumulative bale quantities. The selected machines represent a heterogeneous group of balers, allowing for a robust examination of temperature patterns and the identification of risk factors. The selection of monitored balers was based firstly on the representativeness of the machine based on the market share of the commercial brand and secondly on the willingness of the users to participate in the field tests. In this way, a preliminary analysis of the Aragón machinery fleet using data from the Official Registry of Agricultural Machinery (ROMA) was carried out. This analysis included over 2700 balers, of which 834 were large square balers—the focus of this study. The distribution of brands, particularly the predominance of manufacturer nº 3 units (58%), was considered to ensure that the selected machines reflected the most representative models and conditions within the region.

Table 1. Characteristics of the monitored balers in the 2020 and 2021 agricultural campaigns.

Baler ID	Manufacturer ID	Rake Equipment	Initial Number of Bales	Final Number of Bales	Monitoring Period
#1	1	Yes	40	18.020	02/07/20–04/08/20
#2	2	Yes	8.100	19.000	09/07/20–22/09/20
#3	3	No	8.900	17.000	06/07/20–27/07/20
#4	3	Yes	84.970	87.954	22/07/20–18/08/20
#5	3	Yes	5.033	8.580	29/07/20–02/09/20
#6	1	Yes	146.000	157.898	23/06/21–07/09/21
#2	2	Yes	26.200	40.950	21/06/21–08/10/21
#5	3	Yes	11.000	18.200	23/06/21–16/09/21

Temperature probes were installed in risk areas identified through the initial questionnaire conducted among various baler users with the goal of gathering experiential information, identifying critical machinery points, and characterizing the profile of machines with a higher fire risk [22]. Probe placement was also contingent on the feasibility of installation, which was determined by the chassis type of the different models. Table 2 provides details of the selected probe points on each machine.

Table 2. Location of temperature probes in the records conducted on the balers.

Probe Location	**2020**				**2021**			
	Baler ID							
	#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#2**	**#5**
(1) Compression chamber	X	X	X		X		X	
(2) Pick-up force bearing assembly	X	X	X	X		X		
(3) Hydraulic pump	X	X	X			X	X	
(4) Fan shaft bearings	X			X				
(5) Feeder fork brake for compression chamber		X	X	X	X	X		X
(6) Baling mechanism group	X				X			X
(7) Cardan shaft bearing for mechanism group transmission				X				
(8) Baling wheel drum brake					X		X	X
(9) Left side bearing of pick-up feeding shaft						X		
(10) Transmission shaft power take-off multiplier								X
(11) Pick-up force transmission	X						X	

All probes were synchronized to record data every 5 min. Subsequently, data preprocessing was performed, which involved eliminating temperature data obtained during times when the machine was not in operation. Statistical analysis was conducted to assess temperature differences among components or mechanisms in the balers with the aim of determining variations between manufacturers. Furthermore, temperatures were recorded for baler components from the same manufacturer but with different release years to study differences between newer models and/or those with fewer accumulated bales. The oldest baler was Baler #6, with 146,000 accumulated bales. Baler #1, from the same manufacturer as #6, was introduced during the campaign in which the probes were installed. From the second manufacturer, Baler #4 was the oldest, with 84,970 accumulated bales. The most recent balers, also from the second manufacturer, were Baler #3 (8900 accumulated bales) and Baler #5 (5033 accumulated bales). Baler #2 represents a third manufacturer, and it had produced 8100 bales at the beginning of the data collection period.

After confirming that the data did not meet the normality criteria, temperature differences were analyzed using the Kruskal–Wallis ANOVA, employing SPSS software v.26 (IBM, Chicago, IL, USA).

2.3. Analysis of Residues Generated in the Balers

Manual samples of residue were collected from various areas of three balers where a prior temperature study had been conducted (#1, #3, and #4). Samples were gathered from various areas of the baler, such as the hydraulic pump, pick-up transmission, feeder fork brake, and cardan transmission joints. The aim was to determine residue size based on the baler's location, given that the ignition temperature is influenced by this parameter. These three balers represented diverse operational profiles. Baler #1 was a newly introduced unit from Manufacturer 1, with minimal accumulated bale count and higher working capacity. Baler #3, from Manufacturer 2, had processed 8900 bales. In contrast, Baler #4, also from Manufacturer 2, had accumulated over 84,000 bales, reflecting long-term use and mechanical wear. This variability in service history and usage intensity reinforces the representativeness of the collected residue samples. In order to determine the size of the particles composing the residue for classification purposes, a laboratory sieving process was conducted using mesh sieves. Five sieves with mesh openings of 250 µm, 500 µm, 1 mm, 2 mm, and 4 mm were employed. To assess the combustibility of the obtained particle sizes, the results from the ignition test conducted by Val-Aguasca et al. [10] were utilized. This test was carried out in accordance with the ISO/IEC 80079-20-2:2016 [23].

3. Results and Discussion

3.1. Questionnaire Results: Fire Incidence and Risk Factors

Table 3 summarizes the questionnaire results, including the number of machines, reported fire incidents, and ignition points. A total of 144 responses were collected, corresponding to 140 balers, as some respondents owned or operated multiple machines. The results indicate that 40 balers (28.6%) had experienced at least one fire incident, while the remaining 100 balers (71.4%) had no reported fire occurrences. Among the balers affected by fire, the majority experienced a single incident (36 cases, 90%), whereas four balers (10%) suffered multiple events. The most frequently identified ignition points included bearings (32%), the clutch (25%), and the pick-up system (22.5%), while other sources such as the transmission and miscellaneous components accounted for the remaining cases.

Table 3. Results of the questionnaire to baler users.

Number of responded questionnaires	Baler owners	105
	Baler users	39
	Total	144
Number of balers	1	53
	2	11
	3	8
	>3	10
	Total	144
Fire incidents	Yes	40
	No	104
Number of fires per user/owner	1	9
	2	9
	3	3
	>3	1
Number of fires per machine	1	36
	2	3
	3	1
Fire origin areas	Bearings	13
	Pick-up	9
	Clutch	10
	Transmission	4
	Others	4
Fire incidents and notation of packed cereal	Barley	9
	Wheat	29
Balers with fire prevention systems	Fire extinguisher	100
	Water tank	25
	Both	12
	Others	3
	Total	140

Regarding the type of crop being baled at the time of fire incidents, wheat was the most commonly reported material (72.5%), followed by barley (22.5%). In terms of fire prevention measures, 100% of surveyed users reported having at least one prevention system installed on their balers; 75.4% had a fire extinguisher, while 17.8% had a water tank, and 8.6% employed both fire extinguishers and water tanks.

In addition to the statistical associations found through the questionnaire, it is worth noting that the regional context of Aragón may influence the fire incidence observed. Although a direct correlation between machinery density and fire incidence could not be robustly established with the available data, the context highlights the potential role of regional machinery concentration in fire risk and suggests a direction for future spatial analyses.

3.2. Influence of Variables on Fire Risk

The chi-square test results are summarized in Table 4, which displays the association between fire incidents and factors such as ownership type, baler age, annual bale production, use of a rake, manufacturer, maintenance level, replacement of components, and implemented fire prevention systems.

Among the analyzed factors, the use of a rake for windrowing was the only variable that showed a statistically significant association with fire occurrence ($\chi^2 = 6.837$, df = 1, $p = 0.009$). Balers using a rake exhibited a higher proportion of fire incidents than those without it. Other variables, such as baler age, number of bales per year, and maintenance practices, did not show a statistically significant relationship with the fire occurrence ($p > 0.05$). Although the manufacturer of the baler initially appeared to be associated with the fire risk ($\chi^2 = 24.240$, $p = 0.007$), the reliability of this result is compromised due to 68.2% of the expected frequencies being below 5, which violates the assumptions of the chi-square test. Therefore, the associations observed through this analysis should be interpreted as exploratory and not confirmatory.

The final logistic regression model retained only the use of a rake, as the other explanatory variables were excluded due to their lack of statistical significance in the selection process. The overall model fit was limited, as indicated by the likelihood-ratio chi-square test ($\chi^2 = 19.398$, df = 14, $p = 0.150$), suggesting that the independent variables do not provide a strong predictive capability. However, the analysis confirmed that the use of a rake was the only variable with a statistically significant effect on fire occurrence (Wald $\chi^2 = 4.504$, $p = 0.034$). The odds ratio for the use of a rake (Exp(B) = 3.408) indicated that balers equipped with a rake were 3.4 times more likely to experience a fire than those without one.

Given that only one variable was retained and the overall predictive power of the model was low, no validation process was conducted, as the model lacks robustness for fire risk prediction. This finding should be interpreted as an exploratory association rather than a conclusive causal link, due to the constraints of the dataset. The binary nature of the variables and the limited sample size likely contributed to the poor model fit. Nevertheless, this result is consistent with field experience and may warrant further investigation in future studies with more comprehensive datasets. Instead, the regression analysis served to confirm the previously observed relationship between rake usage and increased fire risk, highlighting the need for targeted preventive measures in balers using this equipment. The mechanisms behind this correlation remain to be fully understood. One plausible explanation is that raking prior to baling leads to denser windrows and increased biomass intake. The higher material flow could increase mechanical load, generating elevated temperatures in moving parts. Future studies should focus on characterizing these potential pathways in controlled conditions, combining residue mapping and thermal profiling during baling operations with and without raking.

Table 4. Results of chi-square tests and fire occurrence levels for the explanatory variables.

Variable	Variable Level	Fire (N)	No Fire (N)	% Fire Cases	χ^2 Value	df	*p*-Value
Ownership Type	Owner	29	76	27.6	0.005	1	0.944
	User	11	28	28.2			
Business Type	Company	3	10	23.1	0.253	2	0.881
	Multiservice	20	48	29.4			
	Private	17	46	27.0			
Baler Age (years)	≤3	19	36	34.5	6.488	7	0.484
	4–8	12	37	24.5			
	9–13	4	15	21.1			
	≥14	5	16	23.8			
Annual Bale Production	≤4500	12	33	26.7	5.827	6	0.443
	4501–7500	12	20	37.5			
	7501–10,500	5	19	20.8			
	≥10,501	11	32	25.6			
Use of Rake	No	10	51	16.4	6.837	1	0.009
	Yes	30	53	36.1			
Manufacturer	1	8	13	38.1	24.240	10	0.007
	2	8	3	72.7			
	3	1	5	16.7			
	4	0	1	0.0			
	5	2	1	66.7			
	6	5	7	41.7			
	7	15	52	22.4			
	Others	1	6	14.3			
Maintenance Level	No	2	2	50.0	2.610	2	0.271
	Yes	2	13	13.3			
	Daily	36	89	28.8			
Component Replacement	Original	6	8	42.9	1.758	1	0.185
	Nonoriginal	34	96	26.2			
Fire prevention system	Fire Extinguisher	24	78	23.5	3.376	2	0.185
	Water Tank	10	25	28.6			
	Fire Extinguisher + Water Tank	6	12	33.3			

Although all surveyed users reported having at least one fire prevention system onboard, the presence of these systems was not significantly associated with reduced fire risk in the logistic regression model. This result may be attributed to the binary nature of the variable (presence/absence), which does not capture differences in equipment quality, proper maintenance, or actual use. Additionally, the lack of variability in the dataset (100%

affirmative responses) reduces the statistical power of the model to detect associations. These findings highlight the need for future studies to assess fire prevention systems in terms of functionality, activation history, and maintenance records, rather than mere presence. While this study focused on the Aragón region due to its high concentration of balers and fire incidents, the geographical scope represents a limitation. Future research should aim to validate these findings in diverse agricultural settings to ensure broader applicability across different agroclimatic and operational contexts.

3.3. Temperature Records

Figure 1 displays the average temperatures recorded in the various mechanisms grouped for each of the balers under study.

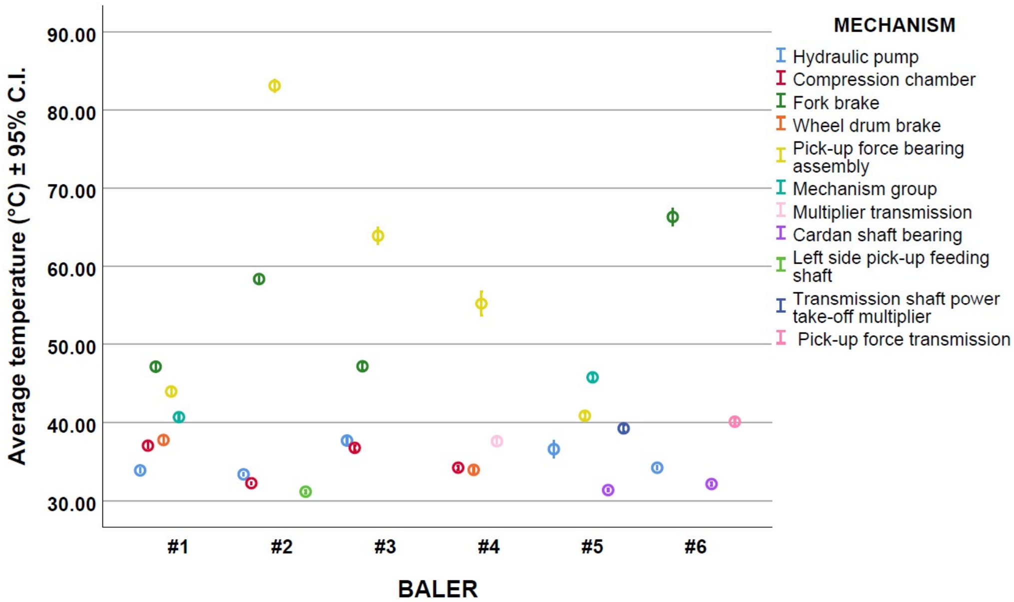


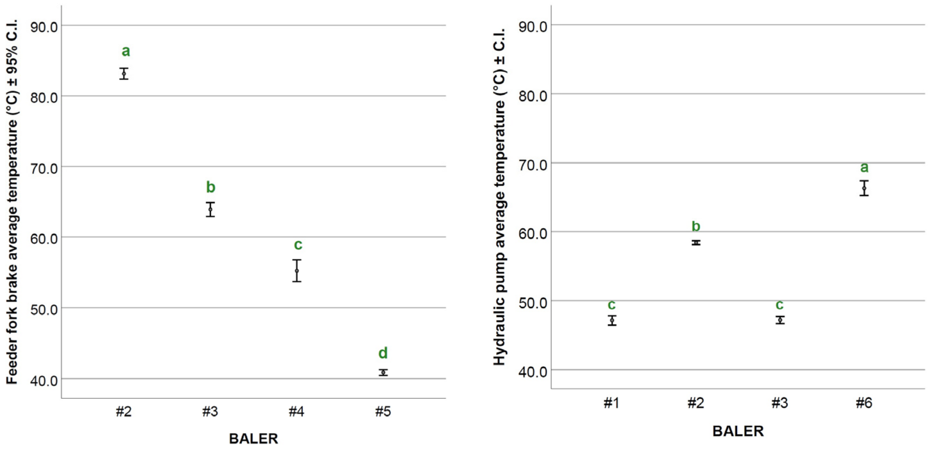
Figure 1. Average temperature (°C) ± 95% Confidence Interval of different mechanisms recorded in each of the monitored balers.

The highest temperature was recorded in the feeder fork brake, reaching 190.6 °C. This mechanism, along with the hydraulic pump, represents the hottest points of the balers, with a higher risk of fire. Concerning the effect of the baler model on the temperature observed in common mechanisms shared by multiple balers, the analyzed mechanisms included the compression chamber, the pick-up force shaft bearing, the hydraulic pump, the feeder fork brake, and the power transmission to the pick-up assembly.

Figure 2 illustrates the detected temperature differences in the feeder fork brake and the hydraulic pump, respectively, based on the baler model.

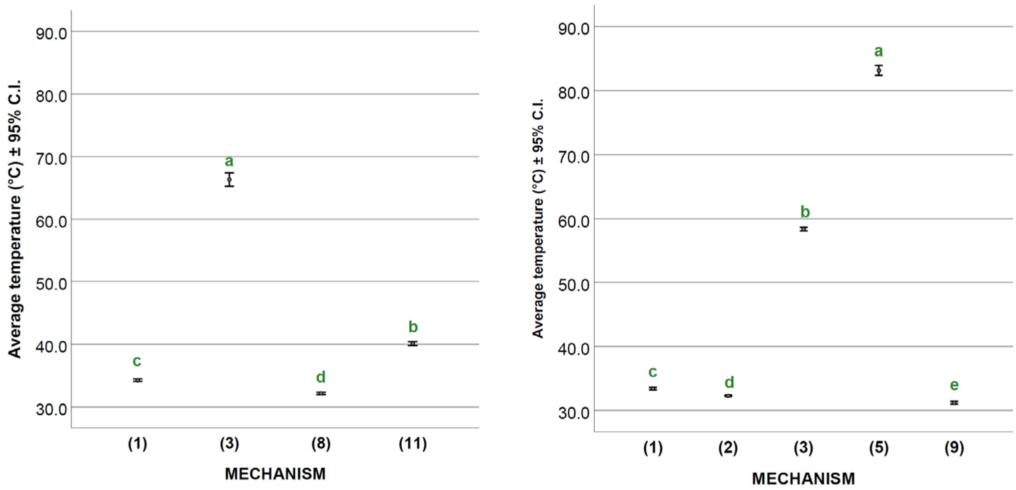
The hydraulic pump was monitored in four balers. Among the balers of Manufacturer 1, the hydraulic pump was the mechanism that exhibited the greatest difference, with Baler #6 recording the highest temperature among all the machines (66.3 °C). In contrast, Baler #1 recorded an average temperature of 47.1 °C. This latter baler and Baler #3 did not exhibit statistically significant differences between them.

The feeder fork brake of the baler was monitored in four balers, all of which displayed statistically significant differences ($p < 0.0001$). Baler #2 registered the highest value (83.1 °C). Figure 3 depicts the observed temperature differences in the components of these balers.



(**a**) (**b**)

Figure 2. Average temperature (°C) and 95% Confidence Interval recorded in (**a**) feeder fork brake and (**b**) hydraulic pump of the monitored baler models. Different letters indicate significant temperature differences ($p < 0.05$; Kruskal–Wallis ANOVA).



(**a**) (**b**)

Figure 3. Average temperature (°C) and 95% Confidence Interval recorded in the mechanisms of Baler (**a**) #6 and (**b**) #2. Different letters indicate significant temperature differences ($p < 0.05$; Kruskal–Wallis ANOVA).

Within the balers manufactured by Company 2, the feeder fork brake exhibited significant variations in temperature. Baler #3 stood out with an average temperature of 62 °C, which was notably higher compared to Baler #4 (49.6 °C) and Baler #5 (41.3 °C). These disparities did not appear to correlate with the balers' age or the number of accumulated bales. It is possible that these distinctions could be attributed to the mechanism's adjustment. Baler #3 appeared to have a tighter setting, resulting in increased friction and elevated temperatures. Conversely, Baler #1 and Baler #3 did not exhibit statistically significant temperature differences between them.

Both the feeder fork brake and the hydraulic pump displayed varying temperatures depending on the baler model. Moreover, temperature differences were also observed among identical models. These variations could be influenced by multiple factors, including environmental conditions in the geographical area where the baler was operating and general maintenance status. Additionally, user-reported working practices, such as the use of raking equipment, cleaning routines, or adjustments to bale compression, may also play a role. Although these operational aspects were identified through the questionnaire and field visits, they were not directly correlated with the recorded temperature data, and thus their influence remains qualitative and exploratory in this study. Nevertheless, specific conditions, such as prolonged use without breaks, inadequate cleaning, high ambient temperatures, or improper machine adjustment, could theoretically lead to localized overheating and warrant further investigation. The compression chamber was monitored in five balers, with those from Company 2 recording the highest temperatures (37.7 °C and 36.7 °C). The baler with the most accumulated bales, Baler #3, exhibited the highest average temperature. Statistically, there were significant temperature disparities ($p < 0.05$) among all balers, except for Balers #1 and #6 ($p = 0.292$). The temperatures in the compression chamber for these balers were almost identical, with the average temperature difference ranging from 34.25 °C to 33.93 °C in the most recent baler (#1), showing a variation of less than half a degree.

The bearing of the force shaft in the pick-up assembly was monitored across four balers, revealing statistically significant differences among them ($p < 0.0001$). Baler #1 and Baler #3 exhibited the highest temperatures, registering closely aligned mean values of 37.1 °C and 36.8 °C, respectively. Within balers from the same manufacturer (Manufacturer 2), the more modern Baler #3 recorded temperatures 2.5 °C higher, reaching 36.8 °C, in contrast to the 34.3 °C observed in Baler #4.

The power transmission to the pick-up assembly was exclusively tracked in balers from the first manufacturer. This manufacturer employs a cardan transmission system for power delivery to the pick-up assembly. The warmest temperatures were noted in the most recent baler (#1), with an average of 44.0 °C, whereas the oldest baler (#6) recorded 40.1 °C. This temperature differential may be attributed to the higher power requirements of Baler #1, which has an increased working capacity. Nevertheless, these temperature variations were minimal.

It is crucial to emphasize that fire risk escalates during adverse weather conditions [7,12]. In concordance with these findings, the highest temperatures observed in the machinery coincided with elevated ambient temperatures and reduced relative humidity levels. These peak temperatures are especially relevant when assessing fire risk, as they reflect the most extreme thermal conditions experienced by the monitored components. The highest recorded temperature was 190.6 °C in the fork brake of the compression chamber feeder, followed by 128.7 °C in the hydraulic pump. Although none of these values reached the ignition temperature of the most combustible residues (<250 μm), they approached thresholds that warrant attention. It is plausible that under specific operational conditions, temperatures within the balers could approach ignition thresholds. This value is approaching critical thresholds established in international safety standards. For example, ISO/IEC 80079-36 [24] and ATEX guidelines [25] classify equipment surface temperatures above 200 °C as a potential risk in dust-laden environments. Therefore, although ignition did not occur, these temperatures warrant attention in the context of fire prevention and justify the application of thermal monitoring strategies as part of predictive safety protocols. These findings align with the research conducted by Val-Aguasca et al. [10], which pertains to the residues collected and characterized in the machines under study. A comprehensive report detailing these results is available [22].

These findings can be interpreted in the context of predictive maintenance strategies, which are increasingly used across industrial sectors to anticipate equipment failure and reduce operational risks. Traditional predictive techniques (such as vibration analysis, oil analysis, and infrared thermography) have proven effective for early anomaly detection. The use of thermocouples to monitor surface temperature in risk-prone areas of agricultural balers offers a simplified yet informative method that aligns with this preventive philosophy. Although not as technologically advanced as real-time vibration sensors, the approach of this study captures relevant thermal behaviors that could signal mechanical stress or improper maintenance practices. In this line, Radicioni et al. [19] demonstrated that temperature and vibration measurements can effectively detect wear in conveyor systems by correlating thermal anomalies with increased friction and material degradation. In the agricultural domain, Barač et al. [20] applied machine learning algorithms to predict vibration patterns in tractors, showing the feasibility of data-driven fault prevention using operational parameters. These works suggest that integrating thermal monitoring into broader predictive maintenance frameworks could significantly enhance safety and reliability in agricultural machinery. While our study focused on fire prevention, similar sensor-based strategies could be adapted to detect precursors of equipment failure and improve decision-making in agricultural operations. Future studies should also consider expanding temperature monitoring to include electrical systems and additional potential hotspots beyond the mechanical components analyzed here, such as wiring, battery areas, or control units. This would provide a more comprehensive thermal risk profile for baler operation. In addition, machine learning approaches could enhance fire risk modeling by allowing multiparameter optimization and the integration of sensor data, operational parameters, and environmental conditions. These methods may provide improved predictive capabilities compared to conventional statistical models.

3.4. Generated Residues

The analysis of crop residues accumulated in different areas of the balers revealed no statistically significant differences in particle size distribution among the three analyzed machines (Figure 4). However, a consistent pattern was observed, with the highest weight proportion of residues corresponding to particles smaller than 250 μm (Table 5), representing approximately 39% of the total collected material.

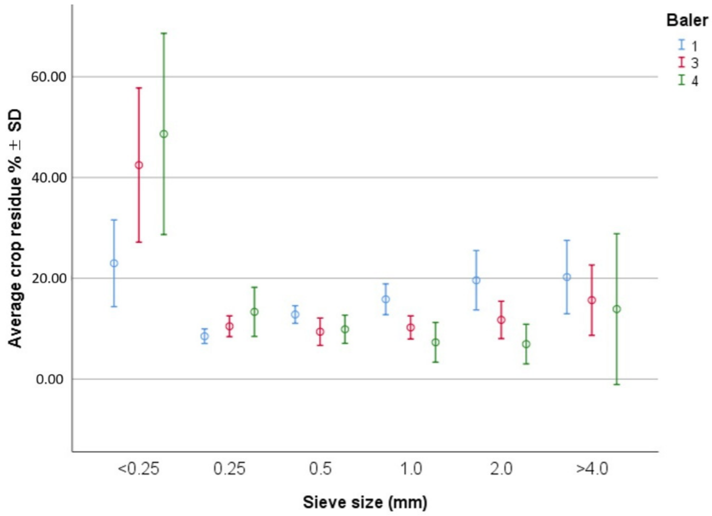


Figure 4. Average percentage ± standard deviation of crop residues (weight) for each baler (1, 3, and 4) and each sieve size.

Table 5. Average percentage of crop residues (weight) from Balers 1, 3, and 4 for each sieve size.

<250 μm	250 μm	500 μm	1 mm	2 mm	4 mm
39.09	11.03	10.61	10.74	12.18	16.32

The presence of fine particulate matter in agricultural machinery is a critical factor influencing fire risk, as smaller particles exhibit lower ignition temperatures. Previous studies have demonstrated that the ignition threshold of crop residues decreases as particle size reduces [26]. For instance, Val-Aguasca et al. [10] determined that barley residues with particle sizes below 250 μm and a layer thickness of 15 mm ignited at temperatures as low as 250 °C. Additionally, residue accumulation patterns suggest that finer, more combustible material tends to deposit in elevated regions of the machine, potentially facilitating fire spread in the event of ignition.

These findings emphasize the importance of regular cleaning and maintenance of high-risk areas within the balers, particularly in regions prone to residue accumulation and elevated temperatures. Furthermore, incorporating improved mechanical designs to reduce residue retention and developing early detection systems to monitor localized temperature increases could serve as effective fire prevention strategies. While the residue analysis provided insights into the particle size distribution in key areas of the balers, the limited number of samples and crop types restricts the generalizability of the findings. Future studies should consider increasing the sample size across different crops and regions to validate these results under broader agricultural conditions.

4. Conclusions

The findings of this study provide valuable insights into fire risk factors associated with large square balers. The results highlight that although multiple factors may contribute to fire occurrence, the use of a rake for windrowing was the only variable found to be statistically significant. The logistic regression model indicated that balers equipped with a rake were 3.4 times more likely to experience a fire compared to those without it.

The temperature analysis of key mechanical components revealed that the feeder fork brake and the hydraulic pump were the hottest areas within the balers, reaching maximum temperatures of 190.6 °C and 128.7 °C, respectively. However, none of the recorded temperatures exceeded the 250 °C ignition threshold established for fine agricultural residues of straw. This suggests that mechanical heating alone is unlikely to serve as the primary ignition source, though it may contribute to fire propagation under high ambient temperatures and low humidity.

Regarding crop residues, the study confirmed that fine particles (<250 μm) represented the largest fraction (39%) of the material collected, aligning with previous research indicating that smaller particles have lower ignition temperatures. Additionally, these fine residues tend to accumulate in elevated regions of the balers, which could increase fire spread potential in case of ignition.

In light of these findings, several fire prevention measures are recommended, including:

- Enhanced cleaning and maintenance protocols, focusing on high-risk areas prone to residue accumulation.
- Real-time temperature monitoring systems in critical baler components to detect early warning signs of excessive heating.
- Optimization of mechanical designs to reduce the retention of fine residues.
- Developing operational guidelines for baler users that emphasize the role of environmental conditions (e.g., temperature, humidity, wind speed) in fire risk.

These results contribute to a better understanding of fire hazards in agricultural balers and provide a foundation for the development of targeted safety strategies to mitigate fire risks in agricultural operations.

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