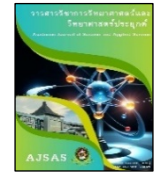




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Design and Experimental Evaluation of a Mechanical Impact-Triggered Activation System for Lightweight Aerial Platforms

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ABSTRACT

This study presents the design and experimental evaluation of a passive mechanical impact-triggering system for lightweight aerial platforms as an alternative to conventional electronic activation mechanisms, which are often associated with system complexity, external power dependence, and environmental sensitivity. The proposed system converts impact-induced kinetic energy into mechanical actuation under passive operating conditions. A hybrid material configuration consisting of high-density steel (St.37) and aluminum (Al 1100) was employed to optimize mass distribution and improve impact orientation consistency during free fall. The prototype was evaluated through controlled drop tests at heights of 5 m, 10 m, and 15 m with repeated trials. The results indicate that activation reliability generally increases with impact energy, with more consistent triggering observed at higher drop heights. Statistical analysis suggests a significant effect of drop height on activation performance ($p < 0.05$). The observed behavior is qualitatively consistent with a phenomenological energy-threshold interpretation, in which activation occurs when the available impact energy exceeds a critical threshold value. In addition, the findings suggest that front-loaded mass distribution may improve impact alignment, activation consistency, and structural stability under the investigated experimental conditions.

1. Introduction

In recent years, unmanned aerial systems (UAS) have experienced rapid development and widespread adoption across multiple sectors, including agriculture, environmental monitoring, logistics, and industrial inspection [1] The increasing functionality of these platforms has enabled the integration of auxiliary payload systems that require reliable activation mechanisms under dynamic and often uncertain operating conditions. Conventional activation mechanisms are

predominantly based on electronic systems, which offer advantages in controllability and programmability [2] However, recent studies (2023–2025) have highlighted several limitations of such systems, including high production cost, increased system complexity, and susceptibility to environmental disturbances such as vibration, humidity, and electromagnetic interference. These challenges are particularly critical for lightweight and resource-constrained platforms, where reliability and simplicity are essential design requirements [3]

In parallel, research in impact mechanics and passive mechanical systems has gained increasing attention as an alternative approach. Impact-driven mechanisms have demonstrated the ability to convert kinetic energy into mechanical actuation without requiring external power sources, offering advantages in robustness, simplicity, and energy independence [4]. Nevertheless, existing studies primarily focus on either electronic triggering systems or generalized impact mechanics without quantitatively integrating impact energy, mass distribution, and activation reliability within a unified passive mechanical framework [5]. In many cases, the role of center-of-gravity control and orientation stability in determining triggering consistency has not been systematically investigated. Furthermore, prior studies often emphasize either material selection or impact response independently, without experimentally correlating impact-energy transfer behavior with activation reliability under controlled operating conditions.

Although passive activation concepts have been reported in related impact-driven mechanical systems, limited research has specifically investigated hybrid mass-distribution strategies for lightweight aerial platforms operating under constrained and uncertain environments. In particular, there remains a lack of studies that investigate the combined influence of impact energy, orientation stability, and activation behavior within a unified experimental framework. These limitations restrict the ability to interpret threshold-transition behavior and to evaluate the contribution of mass distribution to activation consistency in passive triggering systems [6].

To address these gaps, this study proposes a passive mechanical impact-triggering system based on the conversion of impact energy into mechanical actuation. The proposed system integrates hybrid material-based mass distribution to shift the center of gravity toward the frontal section, thereby improving impact orientation consistency and energy-transfer efficiency during free fall. A prototype system was developed and experimentally evaluated through controlled drop-test conditions at varying impact energies, with activation behavior analyzed using statistical and phenomenological energy-threshold interpretations.

The novelty of this study lies in: (1) integrating hybrid mass distribution with passive impact-triggering mechanics, (2) experimentally correlating impact energy with activation reliability, and (3) proposing a phenomenological energy-threshold interpretation for passive activation behavior in lightweight aerial systems. The findings provide a preliminary engineering basis for understanding the interaction between impact energy, orientation stability, and triggering consistency in passive impact-driven mechanisms operating under constrained environmental conditions.

Previous studies on activation systems for lightweight aerial platforms have predominantly focused on electronic-based mechanisms, which generally provide high controllability and programmability but often exhibit limitations in terms of environmental robustness, energy dependence, and system complexity [2–3]. In contrast, research in general impact mechanics has explored mechanical impact-response behavior and kinetic energy transfer; however, these studies typically emphasize fundamental mechanical phenomena without incorporating mass-distribution considerations or systematic reliability evaluation within practical activation systems [4–5]. Recent investigations into passive mechanical and energy-harvesting systems have demonstrated the feasibility of converting impact energy into mechanical actuation under energy-independent conditions [6]. Nevertheless, such studies generally provide limited discussion regarding center-of-gravity control, impact orientation stability, and probabilistic activation behavior under varying impact-energy conditions.

Compared with prior studies, the proposed system attempts to integrate passive impact-triggering mechanics with hybrid mass-distribution design within a unified experimental framework. In particular, the present study incorporates front-loaded center-of-gravity optimization, phenomenological energy-threshold interpretation, and statistical evaluation of activation reliability under controlled drop-test conditions. This integrated approach provides preliminary insight into the relationship between impact energy, orientation stability, and triggering consistency under the investigated experimental conditions in passive mechanical activation systems for lightweight aerial platforms [7].

2. Methodology

2.1 Research Framework

This study adopts an experimental research approach focusing on the design, fabrication, and evaluation of a mechanical impact-triggering system. The research framework consists of four main stages: (1) conceptual design, (2) material selection and prototype fabrication, (3) experimental testing, and (4) performance evaluation and statistical analysis.

The methodology is structured to ensure repeatability and reliability of results while maintaining engineering relevance for lightweight aerial platform applications.

2.2 System Design and Theoretical Framework

The proposed system operates on the principle of converting impact-induced kinetic energy into mechanical actuation under passive conditions [8]. To establish a physics-based relationship between operating conditions and activation behavior, the free-fall impact process is interpreted using fundamental mechanics within a phenomenological energy-threshold framework.

For a prototype released from rest at a drop height (h), the velocity immediately prior to impact is (1):

$$V = \sqrt{2gh} \quad (1)$$

where (g) is the gravitational acceleration (9.81 m/s²).

The corresponding kinetic energy at impact is given by (2):

$$E = \frac{1}{2} mv^2 \quad (2)$$

Substituting the velocity expression yields (3):

$$E_k = mgh \quad (3)$$

where (m) is the mass of the prototype (kg), (g) is gravitational acceleration (9.81 m/s²), and (h) is the drop height (m).

This relationship indicates that the impact energy is directly proportional to drop height, allowing (h) to be used as a controllable experimental parameter governing the energy delivered to the triggering mechanism. For the present study, with a prototype mass of 2.3 kg, the corresponding impact energies are 112.82 J, 225.63 J, and 338.45 J for drop heights of 5 m, 10 m, and 15 m, respectively.

To interpret activation behavior, an energy-threshold criterion is adopted. The triggering mechanism is assumed to activate when the available impact energy exceeds a critical threshold value, as expressed in Equation (4):

$$E_k \geq E_{crit} \quad (4)$$

where (E_{crit}) represents the minimum energy required to overcome internal mechanical resistance, including frictional dissipation, spring resistance, geometric constraints, and localized deformation effects within the triggering mechanism.

Based on the experimental observations, the results suggest that the critical activation energy lies between the energy levels corresponding to drop heights of 10 m and 15 m. Within this transition region, activation behavior changes from partially probabilistic to consistently reliable triggering. This threshold interpretation provides a phenomenological framework for describing the observed relationship between impact energy and activation consistency and is schematically illustrated in Figure 1.

The present model is intended as a phenomenological framework describing the relationship between impact energy and activation behavior rather than a fully predictive mechanical model. Internal mechanical parameters such as frictional dissipation, spring stiffness, transient deformation, and dynamic contact interactions were not explicitly modeled and therefore limit predictive capability. Consequently, the framework should be interpreted as a simplified energy-based representation of system behavior within the scope of the current experimental conditions [9]

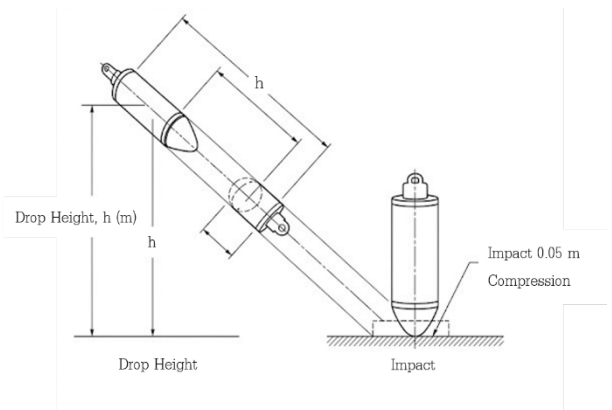


Figure 1 Conceptual diagram of the mechanical impact-triggering system illustrating energy-to-actuation conversion.

2.3 Material Selection

Material selection was conducted based on key engineering criteria, including strength-to-weight ratio, manufacturability, and impact resistance [10]. In the proposed design, St.37 steel was selected for the frontal section to enhance impact momentum due to its relatively high density and sufficient mechanical strength. In contrast, Aluminum 1100 (Al 1100) was used for the rear section to reduce the overall system weight while maintaining adequate structural integrity [11].

This hybrid material configuration enables optimized mass distribution by shifting the center of gravity toward the front section, thereby improving impact orientation consistency and enhancing the efficiency of energy transfer during impact [12].

To provide a comparative baseline for evaluating the effectiveness of the proposed hybrid mass distribution, the study conceptually considers alternative configurations, including a uniform material distribution and a non-front-loaded configuration. In a uniform configuration, the center of gravity would remain near the geometric center of the structure, potentially reducing orientation stability during free fall and decreasing the consistency of impact alignment. Similarly, a non-front-loaded configuration may increase the likelihood of off-axis impact and inefficient energy transfer to the triggering mechanism [13].

Although full experimental evaluation of these baseline configurations was beyond the scope of the present study, their expected behavior can be qualitatively interpreted based on principles of impact orientation stability and momentum transfer. The comparison framework provides a conceptual basis for isolating the contribution of the proposed hybrid mass distribution strategy and highlights the importance of center-of-gravity control in passive impact-triggered systems.

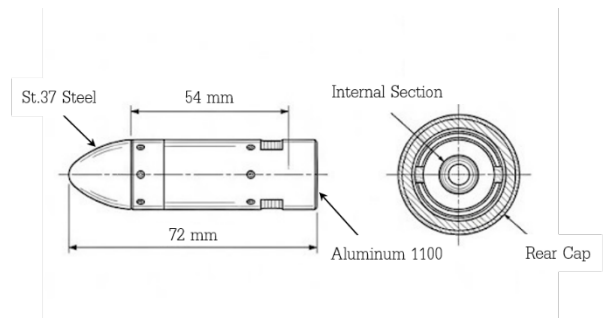


Figure 2 Fabricated prototype showing hybrid material configuration and front-loaded mass distribution.

2.4 Prototype Fabrication

The prototype was fabricated using conventional machining processes, including turning, drilling, and assembly. Dimensional tolerances were controlled to ensure proper alignment of internal components and smooth mechanical interaction.

All components were assembled into a compact structure with a total mass not exceeding the operational constraint of lightweight aerial platforms. The design ensured that the center of gravity was positioned toward the front section to enhance impact effectiveness [14]. The fabricated prototype is shown in Figure 2, illustrating the hybrid material configuration and overall structural design.

2.5 Experimental Setup

Experimental testing was conducted using a controlled drop-test method to simulate impact conditions. The prototype was released from predetermined heights of 5 m, 10 m, and 15 m under vertical free-fall conditions. Each test condition was repeated ten times to ensure statistical reliability and to capture variability in system performance [15].

During each trial, key parameters were systematically recorded, including the activation outcome (success or failure), impact orientation, and the structural condition of the prototype after impact. The testing environment was carefully controlled to minimize external disturbances such as wind effects and surface irregularities, thereby ensuring consistency across all experiments. The experimental setup used for drop testing is illustrated in Figure 3.

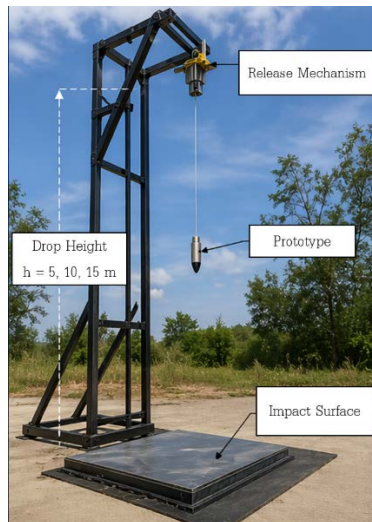


Figure 3 Experimental drop-test setup including controlled release mechanism, vertical guide system, and impact surface

Although the system was designed to promote stable nose-down orientation through front-shifted mass distribution, minor orientation deviations during free fall could not be completely eliminated. Therefore, impact orientation represents a potential uncontrolled variable affecting activation consistency. This limitation is particularly relevant under lower impact-energy conditions, where small variations in orientation may influence the effective transfer of kinetic energy to the triggering mechanism [16]

2.5.1 Orientation Stability Consideration

The orientation stability of the prototype during free fall is an important factor influencing activation consistency and impact energy transfer efficiency. In the proposed design, the center of gravity was intentionally shifted toward the frontal section through hybrid mass distribution using high-density steel in the front and lightweight aluminum in the rear. This front-loaded configuration was designed to promote passive aerodynamic stabilization and maintain a nose-down impact orientation during descent.

From a mechanics perspective, forward-shifted mass distribution increases the rotational stability of the system by reducing the tendency for tumbling or off-axis rotation during free fall. In contrast, symmetric or rear-loaded configurations may result in less stable orientation behavior and reduced alignment between the impact direction and the triggering axis.

To conceptually evaluate the contribution of mass distribution to orientation behavior, three representative configurations were considered: (1) front-loaded hybrid configuration, (2) symmetric mass distribution, and (3) rear-loaded configuration, as illustrated in Figure 4. The front-loaded configuration is expected to provide improved orientation consistency and more efficient impact-energy transfer, whereas non-optimized configurations may exhibit increased orientation variability and reduced triggering reliability.

Although orientation was qualitatively monitored during experimental testing, precise angular measurement and real-time motion tracking were beyond the scope of the present study. Therefore, the current analysis provides a qualitative interpretation of orientation stability rather than a fully quantified aerodynamic characterization. Future work should incorporate high-speed imaging and motion-tracking techniques to quantitatively evaluate orientation dynamics and their relationship with activation performance [17]

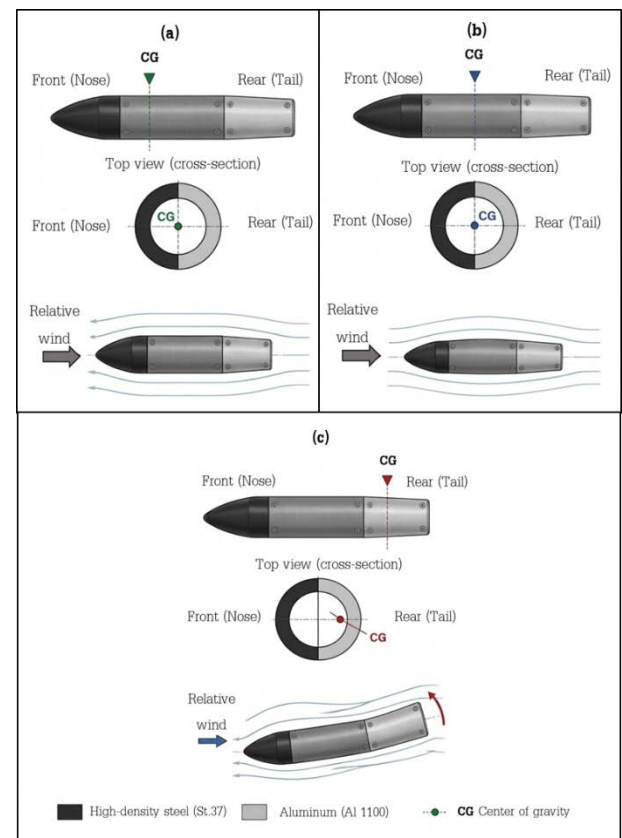


Figure 4 Comparison of baseline and hybrid mass distribution configurations illustrating expected free-fall orientation behavior: (a) front-loaded hybrid configuration, (b) symmetric mass distribution, and (c) rear-loaded configuration.

2.6 Performance Evaluation Metrics

System performance was evaluated using multiple criteria that capture both functional effectiveness and mechanical robustness. Activation reliability was defined as the ratio of successful activations to the total number of trials, providing a quantitative measure of system functionality. Repeatability was assessed based on the consistency of outcomes under identical test conditions, reflecting the stability of the triggering mechanism. Structural integrity was evaluated through post-impact inspection to ensure the absence of critical damage, while operational stability was determined by the system's ability to maintain the correct orientation during descent [15,17]

Together, these metrics provide a comprehensive evaluation framework for assessing both the functional performance and mechanical reliability of the proposed system.

2.7 Uncertainty and Error Analysis

To ensure the reliability and reproducibility of experimental results, potential sources of uncertainty were considered and controlled during the testing process.

1) Measurement Uncertainty

Variations in drop height were minimized by using a calibrated release mechanism. However, minor deviations (± 0.1 – 0.2 m) may occur due to manual setup and positioning. These variations can influence the calculated impact energy, particularly at lower drop heights.

2) Orientation Deviation

Although the system was designed with a forward-shifted center of gravity to promote stable descent, slight variations in orientation during free fall may occur. These deviations can affect the effective impact angle and reduce the efficiency of energy transfer to the triggering mechanism.

3) Surface Interaction Variability

The impact surface was controlled to ensure consistency; however, small variations in surface properties (e.g., micro-roughness) may introduce additional variability in impact response.

4) Repeatability Control

Each experimental condition was repeated 10 times to account for stochastic variations and to improve statistical reliability. The use of repeated trials allows for the estimation

of variability through standard deviation and supports subsequent statistical analysis.

Overall, these uncertainties were minimized through controlled experimental design and are not expected to significantly affect the validity of the observed trends.

2.8 Data Analysis

Collected data were analyzed using descriptive statistics and inferential statistical methods. For each experimental condition, the activation success rate, mean value, standard deviation (SD), and 95% confidence interval (95% CI) were calculated to evaluate central tendency, variability, and statistical uncertainty associated with repeated trials.

To examine the relationship between impact conditions and activation behavior, regression-based trend analysis was additionally employed to evaluate the correlation between drop height, impact energy, and activation probability. The activation response was interpreted using a probabilistic energy-threshold framework to describe the transition from partial to consistent triggering behavior as impact energy increased [18]

A one-way analysis of variance (ANOVA) was conducted to determine whether drop height has a statistically significant effect on activation performance. The significance level was set at $\alpha = 0.05$. In addition, effect size analysis using eta squared (η^2) was performed to evaluate the magnitude of the observed effect independently of statistical significance.

Although repeated trials were conducted to improve statistical reliability, the relatively limited sample size ($n = 10$ per condition) may constrain statistical power and limit the generalizability of the results. Therefore, the statistical findings should be interpreted within the scope of the present experimental framework.

2.9 Safety and Ethical Considerations

This research focuses on mechanical system design and impact behavior analysis. All experimental procedures were conducted under controlled conditions with appropriate safety measures [19]

The study emphasizes engineering principles and avoids operational or application-specific details that may pose safety

risks. The objective is to contribute to mechanical design knowledge rather than practical deployment in hazardous scenarios.

3. Results and Discussion

3.1 Activation Performance and Model-Based Analysis

The experimental results demonstrate a clear dependence of activation reliability on drop height, as summarized in Table 1.

Table 1 Activation performance of the mechanical impact-triggering system at different drop heights (mean $\pm$ standard deviation and 95% confidence interval).

Drop Height (m)	Number of Trials (n)	Successful Activations (mean $\pm$ SD)	Success Rate (mean $\pm$ SD)	95% CI of Success Rate
5	10	7.0 $\pm$ 1.52	0.70 $\pm$ 0.48	0.40–1.00
10	10	9.0 $\pm$ 0.99	0.90 $\pm$ 0.32	0.70–1.00
15	10	10.0 $\pm$ 0.00	1.00 $\pm$ 0.00	1.00–1.00

The activation response exhibits probabilistic transition behavior characteristic of threshold-driven mechanical systems. At lower impact energies, activation occurs inconsistently due to insufficient energy transfer to fully overcome internal mechanical resistance. As the impact energy approaches the critical activation threshold, the probability of successful triggering increases progressively, eventually approaching fully deterministic behavior at higher energy levels. This probabilistic transition is qualitatively consistent with the sigmoid-type activation model proposed in Equation (5).

The decreasing standard deviation and narrowing variability at higher drop heights further suggest improved activation stability and reduced sensitivity to stochastic variations in impact conditions. As illustrated in Figure 5, the activation response progressively transitions from probabilistic to more deterministic behavior as the available

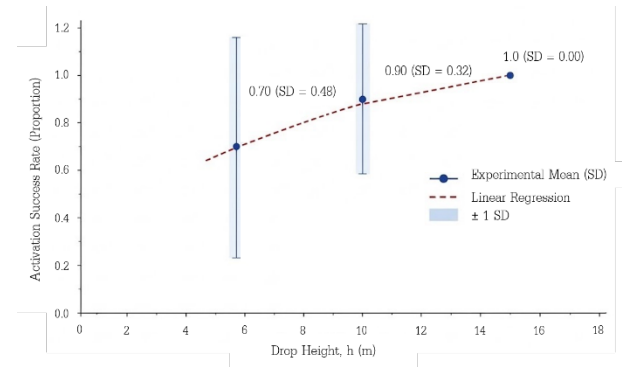


Figure 5 Drop height versus activation success rate with standard deviation error bars, regression trend, and probabilistic transition behavior ($n = 10$).

impact energy exceeds the critical threshold region. These observations suggest that activation reliability may be influenced by an energy-threshold mechanism rather than purely random variation.

Although repeated trials improve reliability estimation and reduce random variability, the relatively small sample size ($n = 10$ per condition) limits statistical power and may constrain the generalizability of the observed activation trends. Therefore, the regression-based interpretation and probabilistic transition behavior should be considered preliminary within the investigated experimental range [20].

From a mechanics perspective, the system behavior can be explained based on impact energy. The kinetic energy at impact is given by:

$$E_k = mgh$$

This relationship indicates that the available impact energy increases linearly with drop height. At lower heights (5 m), the available energy may be insufficient to consistently overcome internal mechanical resistance, resulting in occasional activation failure. In contrast, at higher heights (15 m), the available energy exceeds the required activation threshold, leading to fully consistent triggering behavior.

To further interpret the transition between partial and consistent activation, the activation behavior can be represented using a semi-analytical probabilistic framework based on a sigmoid-type response function:

$$P_{act} = \frac{1}{1 + e^{-k(E_k - E_c)}} \quad (4)$$

Where (P_{act}) represents the probability of successful activation, E_k is the impact kinetic energy, E_c is the critical activation energy threshold, and k is a fitting parameter governing the sharpness of the transition region.

This formulation describes the activation response as a threshold-transition process in which the probability of activation gradually increases as the available impact energy approaches and exceeds the critical threshold energy. At low impact energies, the activation probability remains relatively low due to insufficient energy transfer to overcome internal resistance mechanisms. Near the threshold region, activation behavior becomes probabilistic and sensitive to small variations in impact conditions and orientation. Once the available energy significantly exceeds the critical threshold, the activation probability approaches unity, resulting in deterministic triggering behavior [21]

The proposed sigmoid-type relationship is consistent with threshold phenomena commonly observed in impact-driven mechanical systems and provides a phenomenological interpretation of the experimentally observed transition from partial to fully reliable activation. However, the present framework is intended as a semi-analytical representation rather than a fully predictive model, since internal dynamic parameters such as transient deformation, frictional dissipation, and contact interactions were not explicitly quantified.

The experimental observations are generally consistent with the proposed energy-threshold interpretation, as depicted in Figure 6, where sufficient impact energy must be delivered to initiate reliable mechanical actuation.

Based on the prototype mass of 2.3 kg, the corresponding impact energies at drop heights of 5 m, 10 m, and 15 m are 112.82 J, 225.63 J, and 338.45 J, respectively. The experimental results indicate partial activation at 112.82 J, high activation reliability at 225.63 J, and fully consistent activation at 338.45 J. Therefore, the critical activation energy is estimated to lie within the range:

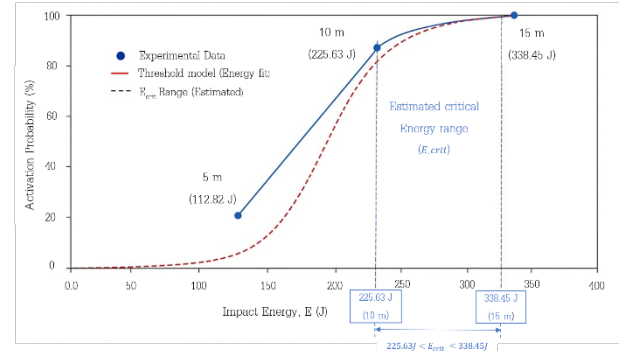


Figure 6 Impact energy vs activation probability showing threshold behavior with (E_{crit}) between 225.63–338.45 J.

$$225.63 \text{ J} < E_{crit} \leq 338.45 \text{ J}$$

This range defines the transition region from probabilistic to deterministic activation behavior and supports the proposed phenomenological energy-threshold interpretation.

3.1.1 Regression-Based Analysis

To further evaluate the relationship between drop height and activation performance, a regression-based analysis was conducted using activation success rate as the dependent variable and drop height as the independent variable. The regression trend shown in Figure 5 indicates a positive correlation between drop height and activation reliability, suggesting that increased impact energy contributes to improved triggering consistency.

A linear regression model was used as an initial approximation to characterize the overall trend within the investigated experimental range. The regression analysis yielded a high coefficient of determination (R^2), indicating that a substantial proportion of the variation in activation performance can be associated with changes in drop height and corresponding impact energy [22]

However, the observed activation behavior also suggests the presence of non-linear threshold characteristics, particularly near the transition region between partial and fully reliable activation. Consequently, the activation response was additionally interpreted using a sigmoid-type probabilistic framework, as described in Equation (5), to represent the gradual transition from probabilistic to deterministic triggering behavior.

From a statistical perspective, the sigmoid response is consistent with logistic-type activation phenomena commonly observed in threshold-governed mechanical systems. At low impact energies, activation probability remains relatively limited due to insufficient energy transfer. As the available impact energy approaches the critical threshold region, activation probability increases rapidly, eventually approaching unity at sufficiently high energy levels [23]

Although the present regression analysis provides useful insight into the relationship between impact energy and activation performance, the relatively limited number of experimental conditions restricts the development of a fully validated predictive model. Therefore, the current analysis should be interpreted as a preliminary statistical characterization of activation behavior within the investigated operating range.

3.2 Threshold Behavior of the Triggering Mechanism

A key finding of this study is the presence of a threshold-type activation behavior. The results indicate that activation reliability is not linearly proportional to drop height but instead follows a transition zone between partial and full activation.

The observed threshold-transition behavior can be interpreted based on the balance between available impact kinetic energy and internal mechanical resistance within the triggering mechanism. At lower impact energies, a portion of the energy is dissipated through frictional contact, transient deformation, and non-ideal impact alignment, reducing the effective energy available for mechanical actuation. As the impact energy increases, the mechanism becomes progressively more capable of overcoming these internal resistance forces, resulting in improved activation consistency [24]

Specifically, the experimental data indicate the existence of a critical impact energy threshold between drop heights of 10 m and 15 m. Below this threshold (5 m), the system exhibits inconsistent activation due to insufficient energy transfer. Near the threshold (10 m), the system approaches reliable activation but still shows minor variability. Above the threshold (15 m), activation becomes fully deterministic.

This behavior appears consistent with threshold-type responses reported in mechanical systems, where activation occurs only when the input energy exceeds a critical value

required to overcome internal constraints such as friction, spring resistance, or geometric locking. This interpretation is consistent with the energy-based relationship shown in Figure 5. The critical activation energy is estimated to lie between the energy levels corresponding to drop heights of 10 m and 15 m, indicating a transition region from partial to fully reliable activation [25]

From a quantitative perspective, the critical activation energy can be estimated by correlating the observed activation behavior with the corresponding impact energy levels. The results indicate that partial activation occurs at 5 m, near-complete activation at 10 m, and fully consistent activation at 15 m. This suggests that the critical activation energy (E_{crit}) lies between the energy levels corresponding to 10 m and 15 m,

$$10\text{ mg} < E_{crit} \leq 15\text{mg}$$

This range suggests a transition zone from probabilistic to more deterministic activation behavior and supports the interpretation that system performance is influenced primarily by an energy-threshold mechanism rather than purely random variation.

Similar threshold-type activation behavior has been reported in impact-driven mechanical systems and energy-activated metamaterials, where mechanical response transitions from probabilistic to deterministic behavior once the input energy exceeds a critical threshold value [8] The present observations are qualitatively consistent with these previously reported impact-energy transition phenomena.

3.3 Enhanced Visualization of Experimental Results

To further analyze the relationship between drop height and activation reliability, the results are presented in Figure 5 using an enhanced statistical representation. Unlike conventional engineering plots, the visualization incorporates error bars to represent variability across repeated trials and includes a regression line to illustrate the relationship between drop height and activation success rate.

From a statistical perspective, the regression trend suggests that activation probability increases monotonically with impact energy, supporting the proposed phenomenological energy-threshold framework. The reduction in error-bar magnitude at higher drop heights further indicates decreasing sensitivity to

stochastic variations in orientation and impact alignment as the available energy becomes sufficiently greater than the critical activation threshold [26]

The regression analysis suggests a positive relationship between drop height and activation probability within the investigated experimental range. In addition, the decreasing magnitude of the error bars with increasing height suggests improved repeatability and reduced variability at higher impact energy levels.

This enhanced graphical representation may provide improved insight of both the overall trend and the associated uncertainty in system behavior, which is essential for rigorous scientific interpretation and reproducibility [27]

Similar reductions in variability near deterministic operating regions have been reported in probabilistic mechanical activation systems and impact-response studies involving threshold-governed behavior [26,27]

3.4 Statistical Analysis with Effect Size and Post-hoc Comparison

A one-way analysis of variance (ANOVA) was conducted to evaluate the effect of drop height on activation performance [28], and the results are summarized in Table 2. The analysis indicates a statistically significant difference among the groups ($F = 3.86$, $p = 0.0336$, $p < 0.05$). To further quantify the magnitude of this effect, the effect size was calculated using eta squared (η^2), indicating a moderate to large effect.

A Bonferroni correction was applied for post-hoc pairwise comparisons to control the family-wise Type I error rate under multiple testing conditions. The Bonferroni method was selected due to its conservative nature and suitability for a limited number of comparisons, ensuring robust statistical inference.

Mechanistically, the statistically significant difference observed between low- and high-impact-energy conditions suggests that the triggering response may be influenced by a non-linear energy-transfer process rather than solely by random activation variability. The moderate-to-large effect size ($\eta^2=0.22$) further indicates that impact-energy variation contributes substantially to the observed changes in activation reliability [29]

The post-hoc results show that the difference between 5 m and 15 m is statistically significant, while the comparison between 10 m and 15 m suggests a transition toward fully reliable activation. These findings are generally consistent with the proposed energy-threshold interpretation, where activation behavior becomes more reliable as the available impact energy exceeds a critical threshold value.

Nevertheless, the relatively limited number of experimental conditions and sample size may constrain statistical power and restrict the development of a fully generalized predictive model. Future studies should incorporate additional impact-energy levels and larger experimental datasets to improve probabilistic modeling accuracy and threshold estimation reliability.

3.5 Effect of Mass Distribution on Impact Efficiency

The hybrid material configuration plays a critical role in system performance. By positioning high-density steel

(St.37) in the frontal section and lightweight aluminum (Al 1100) in the rear, the center of gravity is shifted forward.

This forward-biased mass distribution enhances aerodynamic stability and promotes a more consistent nose-down orientation during descent. As a result, the impact force is more effectively aligned with the intended activation axis, thereby improving impact-energy transfer efficiency and increasing activation consistency.

Table 2 Results of one-way ANOVA and effect size (η^2) for activation performance across different drop heights.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value	Effect Size (η^2)
Between Groups	0.466	2	0.233	3.86	0.0336	0.22
Within Groups	1.629	27	0.060	—	—	—
Total	2.095	29	—	—	—	—

The observed improvement in triggering consistency may be associated with enhanced alignment between the impact vector and the activation axis. By shifting the center of gravity toward the frontal section, rotational instability during free fall is reduced, thereby minimizing off-axis impact conditions and improving effective momentum transfer to the triggering mechanism [30].

From a mechanics perspective, the forward-shifted center of gravity reduces the tendency for tumbling and off-axis rotation during free fall. In contrast, non-optimized configurations with symmetric or rear-loaded mass distribution may exhibit greater orientation variability, potentially leading to inefficient impact alignment and reduced triggering reliability. These observations suggest that mass distribution may function as an important parameter influencing orientation stability and activation behavior in passive impact-driven systems.

Similar relationships between center-of-gravity positioning, orientation stability, and energy-transfer efficiency have been reported in free-fall dynamic systems and impact-controlled mechanical devices [14]

The conceptual comparison between front-loaded and non-optimized configurations further supports the interpretation that orientation stability may contribute to improved activation consistency. However, the present study primarily provides a qualitative assessment of orientation behavior, and precise angular measurements during free fall were not conducted. Therefore, the relationship between mass distribution, orientation dynamics, and triggering efficiency should be interpreted cautiously within the scope of the current experimental framework.

Future studies should experimentally compare multiple mass distribution configurations to quantitatively isolate the contribution of front-loaded hybrid design on impact orientation stability and triggering efficiency. In addition, high-speed imaging and motion-tracking techniques may

provide more detailed characterization of free-fall dynamics and impact alignment behavior.

3.6 Structural Integrity and Repeatability

Post-impact inspections suggest that the prototype maintains structural integrity under the investigated experimental conditions. The steel component effectively absorbs and transmits impact forces, while the aluminum structure contributes to weight reduction without compromising stability.

From a structural mechanics perspective, the steel frontal section likely contributes to localized impact-force transmission and resistance to permanent deformation, while the aluminum rear structure reduces inertial loading without significantly compromising overall structural stability. This hybrid configuration may therefore improve the balance between impact resistance and lightweight performance under repeated loading conditions [31]

The system also suggests high repeatability, with consistent activation outcomes and no evidence of mechanical failure or misalignment. This suggests that the selected design tolerances and material configuration may be suitable for the investigated dynamic loading conditions.

Although no visible structural failure or misalignment was observed during the present experiments, long-term fatigue behavior and cumulative impact degradation were not quantitatively investigated. Future work should include repeated cyclic impact testing and material degradation analysis to further evaluate structural durability under extended operational conditions.

3.7 Comparative Analysis with Electronic Activation Systems

A comparative analysis was conducted between the proposed passive mechanical impact-triggering system and previously reported electronic and impact-driven activation approaches. The comparison considers key engineering characteristics, including power requirement, activation reliability, environmental sensitivity, structural complexity, and energy-threshold behavior, in order to evaluate the relative advantages and limitations of different activation mechanisms for lightweight aerial platforms.

The comparison indicates that conventional electronic activation systems generally provide high controllability and programmability; however, they often depend on external power sources and may exhibit increased sensitivity to vibration, humidity, and electromagnetic interference under harsh operating conditions [2–3]. In contrast, passive impact-driven systems offer improved robustness and energy independence but frequently lack systematic integration of mass-distribution optimization, orientation stability analysis, and activation reliability evaluation [4–6].

The potentially improved robustness of passive mechanical systems under environmentally disturbed conditions can be mechanistically attributed to the absence of electronic sensing, signal transmission, and external power dependence. Consequently, the proposed system may exhibit reduced susceptibility to vibration-induced malfunction, electromagnetic interference, and humidity-related operational instability compared with conventional electronic activation systems [2–3].

Compared with these prior approaches, the proposed system attempts to integrate hybrid mass distribution, passive impact-triggering mechanics, and phenomenological energy-threshold interpretation within a unified experimental framework. The front-loaded configuration is intended to improve orientation consistency and impact-energy transfer efficiency, while the statistical evaluation provides preliminary insight into the probabilistic transition behavior associated with threshold-governed activation.

Nevertheless, the present comparison should be interpreted within the scope of the investigated experimental conditions. Although the proposed passive system exhibited promising reliability under the investigated experimental conditions under controlled free-fall conditions, it does not provide the programmability and adaptive control capability available in electronic systems. Therefore, the selection of activation mechanisms remains application-dependent and should consider trade-offs among reliability, environmental robustness, system complexity, and operational flexibility [32].

However, the present comparison remains semi-quantitative and should be interpreted cautiously due to differences in experimental conditions, system architectures, and performance metrics reported across prior studies.

3.8 Engineering Implications

The findings of this study provide preliminary engineering insights into the behavior and design of impact-driven activation systems. The results demonstrate that activation performance is fundamentally influenced by impact energy, which is directly related to drop height. In this context, reliable triggering appears more likely when the input energy exceeds a critical threshold required to initiate mechanical actuation. Furthermore, the results suggest that mass distribution may play an important role in determining impact orientation and the efficiency of energy transfer within the system. The use of a forward-shifted center of gravity enhances stability during descent and promotes consistent activation outcomes [33].

From an engineering-design perspective, the observed threshold-transition behavior suggests that passive activation systems may benefit from designs in which the expected operational impact energy consistently exceeds the critical activation threshold with an appropriate safety margin. This consideration is particularly important for lightweight aerial platforms operating under variable environmental and deployment conditions.

In addition, the study highlights that passive mechanical systems can achieve high levels of reliability without dependence on electronic components, making them particularly suitable for applications operating under constrained or uncertain environmental conditions. Collectively, these insights may provide a preliminary basis for the design of more robust and cost-effective activation systems for lightweight engineering applications and provide a foundation for further optimization and modeling efforts [34].

The present findings are generally consistent with recent developments in passive energy-transfer systems, impact-responsive mechanisms, and low-power autonomous engineering devices reported in the recent literature [4,34].

However, further integration of numerical simulation, transient dynamic modeling, and orientation-tracking analysis would be necessary to improve predictive capability and broaden practical applicability.

4. Conclusion

This study presented the design, development, and experimental evaluation of a passive mechanical impact-triggering system for lightweight aerial platforms, offering a potential alternative to conventional electronic activation mechanisms. The results indicate that activation reliability appears to be influenced by impact energy, which is directly related to drop height, with system performance transitioning from partial to more consistent activation as impact energy increases.

Statistical analysis suggests a significant effect of drop height on activation performance ($p < 0.05$), indicating that activation behavior is associated with the amount of energy delivered to the mechanism during impact. The observed system behavior is generally consistent with a phenomenological energy-threshold interpretation, in which activation occurs when the available impact energy exceeds a critical threshold value. Within the scope of the present experimental conditions, this framework provides a basis for interpreting impact-driven activation behavior in passive mechanical systems.

In addition, the results suggest that the results suggest that mass distribution may contribute to improved impact orientation consistency in improving impact orientation consistency and energy-transfer efficiency. The hybrid material configuration shifts the center of gravity toward the frontal section, which may contribute to enhanced aerodynamic stability and more reliable triggering behavior during free fall. However, the present analysis of orientation behavior remains primarily qualitative, and further quantitative investigation is required to isolate the specific contribution of mass distribution to activation performance.

The findings also indicate that passive mechanical systems may achieve reliable operation without dependence on electronic components, making them potentially suitable for applications operating under constrained or uncertain environmental conditions. From an engineering perspective, this work provides a preliminary framework for the design and interpretation of impact-driven activation mechanisms for lightweight systems. The present findings should therefore be

interpreted as preliminary observations within a controlled experimental framework.

Future research should expand the experimental parameter space, incorporate comparative baseline configurations, and apply quantitative motion-tracking methods to better characterize orientation dynamics and activation behavior. In addition, numerical modeling approaches such as finite element analysis and transient impact simulation may further improve the predictive capability and physical interpretation of the proposed system.

Reference

- [1] Sapkota R, Roumeliotis KI, Karkee M. UAVs meet agentic AI: A multidomain survey of autonomous aerial intelligence and agentic UAVs. *arXiv [Preprint]*. 2025. Available from: <https://doi.org/10.48550/arXiv.2506.08045>
- [2] Hashim HA. Advances in UAV avionics systems architecture, classification and integration: A comprehensive review and future perspectives. *Results Eng.* 2025; 25:103786. Available from: <https://doi.org/10.1016/j.rineng.2024.103786>
- [3] Han S, Wan P, Lian Z, Wang M, Li D, Fan C. Research on the construction and resource optimization of a UAV command information system based on large language models. *Drones.* 2025;9(9):639. Available from: <https://doi.org/10.3390/drones9090639>
- [4] Adhikari R, Jackson N. Passive frequency tuning of kinetic energy harvesters using distributed liquid-filled mass. *Actuators.* 2025;14(2):78. Available from: <https://doi.org/10.3390/act14020078>
- [5] Chen C, He Y, Chen Y, Lu G, Lu MH, Li X. Impact dynamics of mechanical metamaterials: A short review and perspective. *Forces Mech.* 2025;100335. Available from: <https://doi.org/10.1016/j.finmec.2025.100335>
- [6] Hui T, Rucareanu S, Zamora E, D'Angelo S, Liu H, Fumagalli M. Dynamic Center-of-Mass Displacement in Aerial Manipulation: An Innovative Platform Design. *arXiv preprint arXiv:2404.01110*. 2024 Apr 1. <https://doi.org/10.48550/arXiv.2404.01110>

- [7] Dimino I, Diodati G, Di Caprio F, Ciminello M, Menichino A, Inverno M, Belardo M, Di Palma L. Numerical and experimental studies of free-fall drop impact tests using strain gauge, piezoceramic, and fiber optic sensors. *Applied Mechanics*. 2022 Mar 18;3(1):313-38. <https://doi.org/10.3390/applmech3010020>
- [8] Fancher R, Frankel I, Chin KCH, Abi Ghanem M, MacNider B, Shannahan LS, et al. Dependence of the kinetic energy absorption capacity of bistable mechanical metamaterials on impactor mass and velocity. *Extreme Mech Lett*. 2023; 63:102044. Available from: <https://doi.org/10.48550/arXiv.2301.09149>
- [9] Arricca M, Inverardi N, Pandini S, Toselli M, Messori M, Auricchio F, Scalet G. Phenomenological modeling of the stress-free two-way shape-memory effect in semi-crystalline networks: formulation, numerical simulation, and experimental validation. *European Journal of Mechanics-A/Solids*. 2024 May 1; 105:105245. <https://doi.org/10.1016/j.euromechsol.2024.105245>
- [10] Chanraksmeay L, Zhao W, Han Y, Chen Y, Ghita O, Chen B. Recent advances in additive manufacturing of impact-resistant structures with high-performance polymers and their composites. *Addit Manuf Front*. 2025:200276. Available from: <https://doi.org/10.1016/j.amf.2025.200276>
- [11] Zhao Y, Lu Q, Wang Q, Li D, Li F, Luo Y. Corrosion behavior of homogenized and extruded 1100 aluminum alloy in acidic salt spray. *Materials (Basel)*. 2024;17(6):1279. Available from: <https://doi.org/10.3390/ma17061279>
- [12] Nwoye E, Floyd K, Batteas J, Felts J. Experimental quantification of impact force and energy for mechanical activation in vibratory ball mills. *RSC Mechanochem*. 2025;2(6):911-22. Available from: <https://doi.org/10.1039/d5mr00059a>
- [13] Ahmed A, Tong G, Xu J. Research on Dynamic Center-of-Mass Reconfiguration for Enhancement of UAV Performances Based on Simulations and Experiment. *Drones*. 2025 Dec 12;9(12):854. <https://doi.org/10.3390/drones9120854>
- [14] Ahmed A, Guangjin T, Jing X. Dynamic center-of-mass reconfiguration for enhanced UAV free-fall stability, structural protection, and energy efficiency. *Drones*. 2025;9(12):854. Available from: <https://doi.org/10.3390/drones9120854>
- [15] Mokkink LB, de Vet HCW, Diemeer S, Eekhout I. Sample size recommendations for studies on reliability and measurement error: An online application based on simulation studies. *Health Serv Outcomes Res Methodol*. 2023;23(3):241-65. Available from: <https://doi.org/10.1007/s10742-022-00293-9>
- [16] Celik HK, Cinar R, Rennie AE. Simulation-based assessment of the structural impact response of the Cura Baglama: a drop test approach for wooden stringed musical instruments. *European Journal of Wood and Wood Products*. 2025 Aug;83(4):133. <https://doi.org/10.1007/s00107-025-02281-5>
- [17] Takahashi TT, Griffin JA, Grandhi RV. High-speed aircraft stability and control metrics. *Aerospace*. 2024 Dec 29;12(1):12. <https://doi.org/10.3390/aerospace12010012>
- [18] Wang Z, Xue G, Song Y, Liu R, Chang G, Wu P, Zhang K. Single-Step Allowable Action Threshold Determination of Renewable Energy Automatic Generation Control Using Model-Based and Data-Driven Method. *Applied Sciences*. 2025 Nov 22;15(23):12408. <https://doi.org/10.3390/app152312408>
- [19] Giallanza A, La Scalia G, Micale R, La Fata CM. Occupational health and safety issues in human-robot collaboration: State of the art and open challenges. *Safety science*. 2024 Jan 1; 169:106313. <https://doi.org/10.1016/j.ssci.2023.106313>
- [20] Kitchenham B, Madeyski L. Recommendations for analysing and meta-analysing small sample size software engineering experiments. *Empirical Software Engineering*. 2024 Nov;29(6):137. <https://doi.org/10.1007/s10664-024-10504-1>
- [21] Parra J, Navarro-Arenas J, Sanchis P. Sub-milliwatt threshold power and tunable-bias all-optical nonlinear activation function using vanadium dioxide for wavelength-division multiplexing photonic neural networks. *Scientific Reports*. 2025 Feb 15;15(1):5608. <https://doi.org/10.1038/s41598-025-90350-3>
- [22] Lorincz J, KusaČić M, Čusto E, Blažević Z. A Comprehensive Multiple Linear Regression Modeling and

- Analysis of LoRa User Device Energy Consumption. *Journal of Sensor and Actuator Networks*. 2025 Dec 29;15(1):5. <https://doi.org/10.3390/jsan15010005>
- [23] Kononov E, Klyuev A, Tashkinov M. Prediction of technical state of mechanical systems based on interpretive neural network model. *Sensors*. 2023 Feb 8;23(4):1892. <https://doi.org/10.3390/s23041892>
- [24] Ruderman M, De Rito F. Study of Frictional and Impact Transients in Active-Passive Mechanical Pair. In 2025 IEEE International Conference on Mechatronics (ICM) 2025 Feb 28 (pp. 1-4). IEEE. <https://doi.org/10.48550/arXiv.2501.03653>
- [25] Wolf J, Bandaru NK, Dienwiebel M, Möhring HC. A novel grey-box based friction model for a wide range of machining conditions. *Wear*. 2025 Aug 16:206295. <https://doi.org/10.1016/j.wear.2025.206295>
- [26] Meyer PP, Mohr D. From deterministic physics-based to probabilistic data-driven modeling: Diffusion-based prediction of strain fields in deep drawing processes. *J Mech Phys Solids*. 2025; 203:106251. Available from: <https://doi.org/10.1016/j.jmps.2025.106251>
- [27] Pouchard L, Reyes KG, Alexander FJ, Yoon BJ. A rigorous uncertainty-aware quantification framework is essential for reproducible and replicable machine learning workflows. *Digit Discov*. 2023;2(5):1251–8. Available from: <https://doi.org/10.48550/arXiv.2301.0576>
- [28] Sutrisno U, Wulandari Y, Arifin S, Manurung MM, Faisal M. Trends, contributions and prospects: Bibliometric analysis of ANOVA research in 2022–2023. *Indones J Appl Math Stat*. 2024;1(1):27–38. Available from: <https://doi.org/10.71385/idjams.v1i1.7>
- [29] Chen Y, Chen N, Ying M. Research on Target Energy Transfer and Energy Dissipation of Coupled Fractional-Order Inerter-Based Nonlinear Energy Sinks Vibration System. *Fractal and Fractional*. 2026 Feb 2;10(2):104. <https://doi.org/10.3390/fractalfract10020104>
- [30] Agrusa HF, Gkolias I, Tsiganis K, Richardson DC, Meyer AJ, Scheeres DJ, Ćuk M, Jacobson SA, Michel P, Karatekin Ö, Cheng AF. The excited spin state of Dimorphos resulting from the DART impact. *Icarus*. 2021 Dec 1; 370:114624. <https://doi.org/10.1016/j.icarus.2021.114624>
- [31] Zhang Z, Guo H, Lan Y, Zhao L. Impact resistance study of fiber-metal hybrid composite laminate structures: experiment and simulation. *Materials*. 2025 Jun 19;18(12):2906. <https://doi.org/10.3390/ma18122906>
- [32] Jamwal A, Patidar A, Gupta S, Giallanza A. Intelligent PID-based control systems for adaptive and sustainable manufacturing. *International Journal of System Assurance Engineering and Management*. 2026 May 19:1–21. <https://doi.org/10.1007/s13198-026-03315-8>
- [33] Qu X, Jiang S, Qi X, Zhou D. Orientation and reciprocation motion significantly impact the charging performance of thermal energy storage capsule in a fluidized bed system. *Case Stud Therm Eng*. 2025:107616. Available from: <https://doi.org/10.1016/j.csite.2025.107616>
- [34] Ullah Q, Rauta T, Keskikuru J, Haverinen J, Ruuskanen P. Innovations in energy harvesting: A survey of low-power technologies and their potential. *Energy Rep*. 2025; 14:671–92. Available from: <https://doi.org/10.1016/j.egy.2025.06.019>