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USING PIEZOELECTRIC IMPACT SENSORS FOR SEED DETECTION IN PRECISION PLANTERS

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Accurate seed placement plays a crucial role in crop establishment and yield potential in precision agriculture. Real-time seed detection allows for monitoring planter performance, identifying missed or multiple seed drops, and optimizing in-field operations. Conventional sensing technologies, such as optical and photoelectric systems, can provide high accuracy but are often affected by environmental conditions, expensive, and mechanically complex. Piezoelectric impact sensors, which convert mechanical shocks from seed impacts into electrical signals, offer a low-cost, durable, and sensitive alternative suitable for harsh farming environments. This review discusses the principles, benefits, and limitations of piezoelectric impact sensors for monitoring and controlling seed flow in precision planters, rather than directly improving the planter's metering accuracy. It emphasizes how impact plate materials and signal processing algorithms influence detection accuracy. Recent research shows that choosing proper materials—like fiberglass for consistent signal quality—and using advanced peak detection algorithms, especially adaptive thresholding methods like VTPD-AM, can achieve detection accuracies over 97% for crops such as corn and sunflower. The review also highlights recent developments in flexible and multilayer piezoelectric materials, including PVDF and hybrid composites, which increase integration options in modern planters. Collectively, these findings—based on previous studies and experimental data—support the potential of piezoelectric impact sensors as a scalable solution for real-time seed flow monitoring and control, helping to bridge the gap between laboratory tests and field deployment in precision planting systems.

Keywords: *seeding, seed distribution uniformity, sensors, accuracy, signal quality.*

INTRODUCTION

Precise seed placement in the furrow is crucial for optimal crop development, uniform growth, and high yields. Ideally, a planter should place seeds at consistent depths and equal spacing. However, real-world planting conditions often cause deviations from the intended placement, leading to missed, multiple, or unevenly spaced seeds. Modern precision planters work to address these issues through advanced metering systems that deliver uniform seed flow and reduce variability.

One common solution involves the use of metering disks with regularly spaced holes that capture individual seeds and release them at predetermined intervals. This approach improves planting uniformity and provides benefits such as seed savings, reduced labor, enhanced planting efficiency, and increased profitability for farmers (Ding et al., 2017).

Advances in planting technology have led to the integration of monitoring systems that track seeding rate and spatial distribution. However, many of these systems estimate seed flow indirectly—by measuring hopper weight, metering speed, or cavity count—due to the lack of effective, low-cost, and real-time seed detection solutions. Developing direct and accurate seed monitoring systems is critical for identifying missed drops, enabling replanting, and optimizing planting quality during operation.

It is important to note that seed detection systems do not directly enhance the metering precision of planters; instead, they provide operators with real-time information to monitor and control seed flow, allowing timely adjustments and evaluation of seeding performance. Uniform seed distribution improves weed suppression and enhances resource use by minimizing intra-species competition. To meet these agronomic demands, precision planters have been designed and refined for various crops (Karayel et al., 2006). Our recent research contributes to this effort by focusing on the development and improvement of seed passage detection systems, which are essential for evaluating the performance of metering mechanisms and enabling intelligent monitoring systems.

The ISO 7256-1 standard defines test methods and performance indicators for precision planters, including the indices for missed seeds (M), multiple seeds (D), acceptable seeds (A), and the coefficient of variation (CV). According to these criteria, drops with spacing less than 50% of the reference are categorized as multiple, and those exceeding 150% are considered missed. Acceptable drops fall within these thresholds.

Numerous researchers have developed tools to evaluate seed spacing, such as high-speed imaging (Karayel et al., 2006; Bourges et al., 2011, 2012), photoelectric sensors (Liu et al., 2021), acoustic-electric systems (Karimi et al., 2015), and fiber-optic sensors (Ding et al., 2014, 2015, 2016). While some systems offer high accuracy, they often require costly hardware and are sensitive to dust, residue, or environmental noise, limiting their use in field conditions (Cay et al., 2017; Gierz et al., 2022; Bo et al., 2020).

Piezoelectric impact sensors, which convert mechanical impacts into electrical signals, provide an alternative due to their simplicity, high sensitivity, and resilience to harsh environments. Despite these advantages, their use in seed detection systems remains limited, primarily due to challenges in signal interpretation and physical system design. Most existing applications focus on blockage detection rather than real-time seed flow monitoring.

Bourges et al. (2016) proposed a laboratory test bench using a piezoelectric sensor mounted on an impact plate to evaluate a pneumatic seed meter. The system inferred seed spacing from the time intervals between impacts. This method simplified evaluation compared to sticky belt systems and allowed for extended testing durations. Furthermore, piezoelectric microphones can be directly attached to a plate and connected to audio interfaces without additional circuitry. However, the complex signal waveforms require specialized processing techniques to ensure accurate detection. In this context, this review paper serves two main objectives: (1) to assess the feasibility, benefits, and limitations of using piezoelectric impact sensors for seed flow monitoring and control in precision planters, and (2) to present and evaluate our previously published studies, which investigate ways to enhance detection performance through signal processing and impact plate material optimization.

In our first study, Rossi et al. (2023a), we addressed the challenge of interpreting sensor signals by testing four signal processing algorithms for detecting seed impacts on an instrumented plate. A novel algorithm was proposed using simple operations such as additions, multiplications, and conditional statements—making it suitable for microcontroller-based systems. This method avoids loops and complex computations, enabling efficient real-time operation. The algorithm was validated using a high-speed camera system, and the results showed a marked improvement in detection accuracy compared to existing approaches.

Our second study, Rossi et al. (2023b), investigated the effect of plate material on signal quality and detection reliability. Various materials—including steel (thin and thick), acrylic, MDF, fiberglass (two variants), Autoclaved Aerated Concrete (AAC), and a composite of acrylic bonded to AAC—were tested for their impact characteristics. Using the same piezoelectric sensor setup, we evaluated seed detection using ISO performance indices and validated results with high-speed imaging. The findings confirmed that material selection significantly influences signal quality, and that material choice should be tailored to the seed type and application context.

Together, these studies provide practical insights into both the mechanical and algorithmic aspects of piezoelectric seed detection systems. The results —drawn from previously published studies and experimental reports— highlight the potential for integrating piezoelectric sensors into precision planters as a low-cost, high-performance solution for real-time seed monitoring, and this review synthesizes those findings to provide guidance for future research and application.

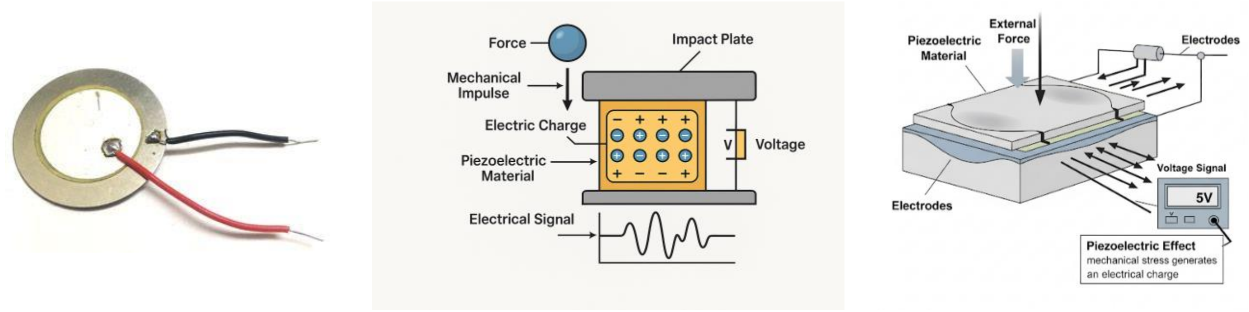
PIEZOELECTRIC SENSORS: PRINCIPLES AND APPLICATIONS IN SEED DETECTION

Piezoelectric sensors operate based on the piezoelectric effect — a phenomenon in which certain materials generate an electric charge when subjected to mechanical stress. First discovered in quartz crystals, this property has been harnessed in various synthetic and natural materials to create sensors that convert mechanical pressure, vibration, or impact into an electrical signal. These sensors have found applications across a wide range of industries, including structural monitoring, medical devices, automotive systems, and, more recently, agricultural machinery.

Working Principle of Piezoelectric Sensors

When a piezoelectric material is deformed by an external force—such as pressure, vibration, or impact—its internal dipole moments shift, causing a separation of electric charge within the material. This results in a voltage across the material's surfaces, which is proportional to the magnitude of the applied mechanical force. In seed detection applications, each seed striking a surface imparts a mechanical impulse that the piezoelectric sensor converts into a measurable electrical signal (Figure 1).

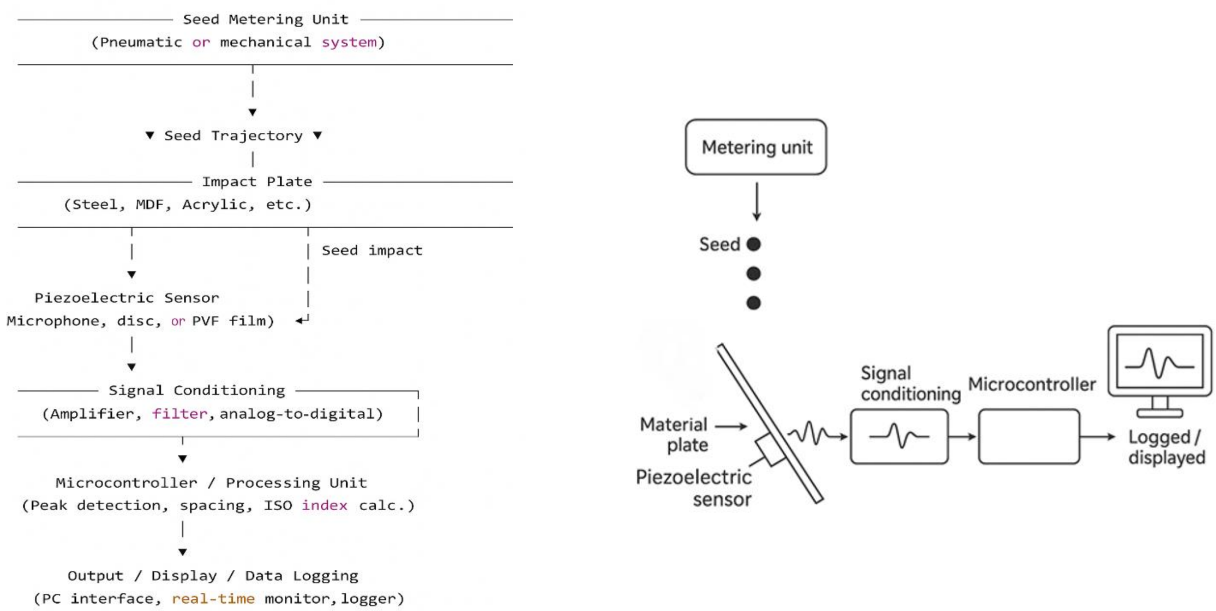
The resulting signal is typically a high-frequency transient waveform characterized by a sharp rise and decay. To extract useful information, this raw signal often requires filtering and signal processing. In typical implementations, the piezoelectric sensor is mounted on or behind an impact plate, which focuses the mechanical energy from seed impacts onto the sensor, thereby ensuring consistent signal transmission.



(a) (b) (c)

Figure 1. Working principle of a piezoelectric sensor: mechanical impact from a seed generates an electric charge within the piezoelectric material, producing a voltage and a corresponding electrical signal. (a) shows a photograph of a piezoelectric sensor, while (b, c) illustrate diagrams of a mechanical impact that generates an electric charge within the piezoelectric sensor.

A schematic representation of such a sensor system used for seed detection in precision planters is shown in Figure 2. As illustrated, seeds released from the metering unit strike an impact plate, generating a mechanical impulse. This impulse is sensed by the piezoelectric element, which produces an electrical signal. The signal is then conditioned, processed by a microcontroller, and either logged or displayed for real-time monitoring of planter performance.



(a) (b)

Figure 2. Schematic diagrams of a piezoelectric impact sensor system for seed detection in precision planters. (a): operational schematic, and (b): graphical illustration of the process. Seeds released from the metering unit strike a material plate, generating a mechanical impulse. A piezoelectric sensor mounted on or behind the plate converts this impulse into an electrical signal. The signal is conditioned, processed by a microcontroller, and logged or displayed for monitoring planter performance.

Common Piezoelectric Materials and Configurations

Piezoelectric sensors are commonly used in precision agriculture for impact detection because of their quick response, durability, and affordability. The selection of both the piezoelectric material and the mechanical setup, especially the impact plate material, greatly influences detection performance.

Piezoelectric Materials

Piezoelectric materials used in agricultural sensing can be grouped into three main categories:

- Natural materials (e.g., quartz): These offer excellent thermal stability and consistent performance but are brittle and expensive.
- Synthetic ceramics (e.g., Lead Zirconate Titanate, PZT): The most common type used in seed detection, PZT offers high piezoelectric coefficients, wide bandwidth, and cost-effective manufacturing.
- Polymeric materials (e.g., PVDF – Polyvinylidene fluoride): Flexible and lightweight, PVDF films are suitable for curved or non-rigid surfaces but typically have lower sensitivity and signal strength compared to ceramics.

Sensor Configurations

Sensor configurations vary depending on application needs and mechanical design. Common implementations include:

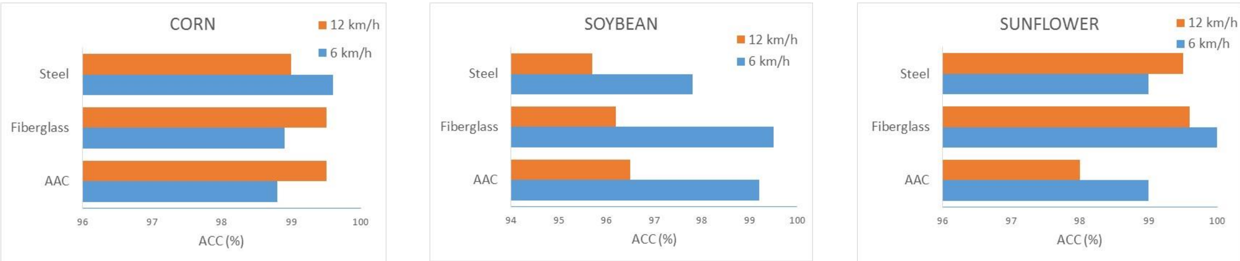
- Piezoelectric microphones: Easily mountable, these sensors are commonly adhered to an external surface of the impact plate. They are compact and suitable for cost-effective retrofitting.
- Piezoelectric discs and patches: Often bonded to or embedded within rigid materials, these provide high sensitivity and robustness, ideal for detecting small or rapid impacts.

Role of Plate Materials

While sensor type determines the electrical response, the impact plate material directly affects signal quality by influencing the amplitude, decay rate, and noise of the impact signal. Rossi et al. (2023b) conducted a comprehensive study to evaluate how different plate materials influence seed detection performance using a piezoelectric system. They tested several materials—including fiberglass, steel, and autoclaved aerated concrete (AAC)—with corn, soybean, and sunflower seeds at forward speeds of 6 and 12 km/h.

The study found that fiberglass plates consistently outperformed other materials, achieving detection accuracy exceeding 95% across all seed types and speeds. In contrast, steel, though structurally robust, showed increased detection errors at higher speeds, especially for soybeans, due to prolonged vibration decay that interferes with subsequent impacts. AAC, a lightweight and porous material, exhibited poor performance for sunflower detection due to its low peak-to-noise ratio (PNR), making it more susceptible to signal loss and environmental noise.

These results underscore the importance of matching plate material properties to seed characteristics and operational conditions. Figure 3 summarizes the detection accuracy across all tested materials, speeds, and seed types.



(a) Corn (b) Soybean (c) Sunflower

AAC: autoclaved aerated concrete

Figure 3. Detection accuracy (ACC, %) for different plate materials grouped by seed type (corn, soybean, sunflower) and forward speeds (6 and 12 km/h). Fiberglass consistently yielded the highest accuracy across all test conditions (Rossi et al., 2023b).

The findings support the conclusion that sensor-plate interaction is a critical design factor. Selection of appropriate materials—both for the sensing element and the impact interface—is essential for optimizing performance, especially in real-time microcontroller-based systems where computational simplicity and signal clarity are vital.

Signal Processing Algorithms

Piezoelectric impact sensors generate complex transient signals whose amplitude, duration, and shape depend on seed size, geometry, mass, velocity, impact angle, and plate material properties. Unlike optical or magnetic sensing systems, these signals are not inherently binary; instead, they contain overlapping vibrations, background noise, and, in some cases, multiple peaks from a single seed impact due to rebounds or irregular seed shapes. Consequently, accurate seed detection requires robust signal processing algorithms capable of distinguishing true impacts from noise and spurious events.

Signal processing plays a decisive role in the overall performance of piezoelectric seed detection systems. Poorly tuned or overly simplistic detection methods can lead to two main types of errors:

- Missed impacts, where genuine seed strikes are not detected, causing underestimation of seed delivery;
- Extra detections, where noise or multiple bounces are misinterpreted as separate seeds, inflate the multiple seed index (D) and reduce system reliability.

Algorithms must therefore balance **sensitivity** (to detect low-amplitude impacts, such as those from small or lightweight seeds) with **specificity** (to avoid false positives), while maintaining computational simplicity for real-time, microcontroller-based implementations.

In our study *"Improving the Seed Detection Accuracy of Piezoelectric Impact Sensors for Precision Seeders. Part I: A Comparative Study of Signal Processing Algorithms"* (Rossi et al., 2023a), four different peak detection methods were evaluated:

1. **PALSHIKAR** – a simple, low-complexity peak detection algorithm,
2. **SCHOLKMANN** – designed for periodic or quasi-periodic signals (ultimately unsuitable for our non-periodic impact data),
3. **OZBEK** – a Shannon entropy-based approach used previously in fruit bruise detection, and
4. **VTPD-AM** – a novel Variable Threshold Peak Detection algorithm with Automatic Minimum threshold calculation, developed in our work.

The algorithms were tested using corn, sunflower, and soybean seeds at simulated forward speeds of 6 and 12 km/h. Ground truth was established by synchronizing piezoelectric sensor signals with high-speed camera recordings.

Key findings from the study include:

- The **SCHOLKMANN** method was not effective for non-periodic seed impact signals and was excluded from detailed error analysis.
- The proposed **VTPD-AM algorithm** and the **OZBEK method** achieved the highest detection accuracy, exceeding **97 %** for corn and sunflower across all speeds.
- The **VTPD-AM algorithm** demonstrated superior adaptability by automatically setting its detection threshold based on signal noise at the start of each test, improving sensitivity for low-amplitude impacts (notably beneficial for sunflower seeds).
- For soybean seeds—tested at higher flow rates (up to 66.7 seeds/s)—detection errors increased for all algorithms, confirming that high seed throughput remains a limiting factor for piezoelectric detection systems.
- Multiple-impact filtering effectively reduced false positives from rebounds, but inevitably removed some genuine closely spaced impacts, slightly affecting the ISO indices for multiples (D) and acceptables (A).
- Compared to previously reported piezoelectric systems (e.g., Gierz et al., 2022), the VTPD-AM approach achieved lower missed detection rates (<2%) and better overall accuracy.

As shown in Figure 4, the VTPD-AM algorithm consistently outperformed the other tested methods, particularly for sunflower and soybean, while maintaining accuracy above 97 % for corn and sunflower at both speeds. These results underline that the signal processing stage is as critical as the mechanical design of the sensing system. Even with an optimal sensor and plate configuration, inadequate processing can degrade accuracy to unacceptable levels. Conversely, well-designed algorithms—particularly those with adaptive thresholding like VTPD-AM—can make piezoelectric impact sensors a competitive option for real-time seed monitoring in precision planters, combining high accuracy with low hardware complexity.

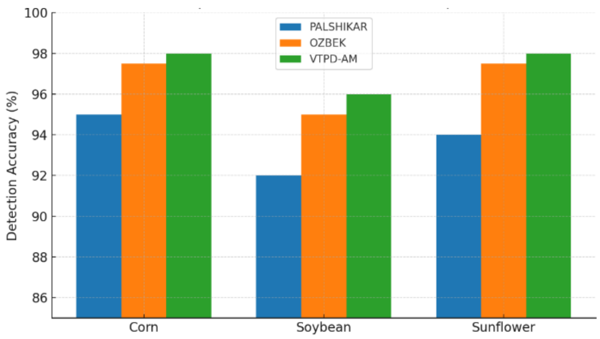


Figure 4. Detection accuracy (%) of three peak detection algorithms—PALSHIKAR, OZBEK, and VTPD-AM—for corn, soybean, and sunflower seeds at simulated forward speeds of 6 and 12 km/h. Data adapted from Rossi et al. (2023a).

ADVANTAGES OF PIEZOELECTRIC SENSORS IN PLANTERS

Piezoelectric sensors provide several advantages that make them highly effective for seed detection in precision planting systems (Figure 5). Their unique material properties and operating principles offer multiple benefits that meet the technical needs of real-time agricultural monitoring.

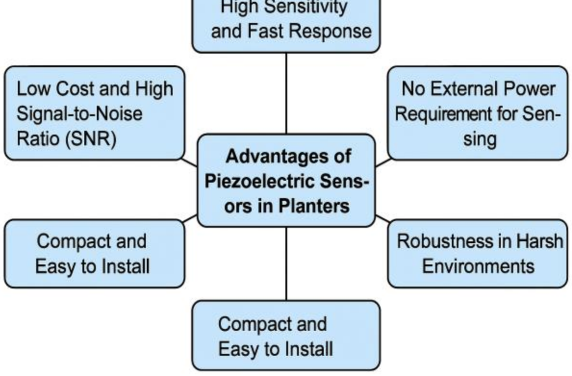


Figure 5. Overview of key advantages of piezoelectric impact sensors in precision planters.

A primary advantage is their high sensitivity and rapid response time, which makes piezoelectric sensors especially effective in detecting rapid and transient mechanical events such as seed impacts. These characteristics enable accurate, real-time monitoring of seed flow during planting, even under high-speed operation. According to Chen et al. (2019), piezoelectric materials generate an electrical charge instantaneously in response to mechanical stress, making them ideal for precision agriculture applications that require immediate feedback.

Additionally, piezoelectric sensors operate without the need for an external power source for sensing, as they inherently convert mechanical energy into electrical signals. Power is only required for the associated signal processing electronics, which simplifies system design and reduces energy consumption. This makes them particularly advantageous in field environments where power supply may be limited or inconsistent.

Another significant benefit is their robustness in harsh agricultural environments. Unlike optical or infrared sensors, which can be affected by dust accumulation, vibrations, or variable lighting conditions, piezoelectric devices are not directly influenced by light-blocking dust layers. Instead, they respond only to the mechanical impact of the seed on the plate. While excessive dust accumulation on the impact plate could potentially alter the quality of the impact signal, this effect is generally mitigated by the continuous cleaning action of seeds striking the plate and by appropriate choice of plate material and surface finish. As a result, piezoelectric systems remain more resistant to dust-related interference than optical sensing methods. Their durability under conditions of dust, shock, and temperature fluctuation ensures consistent performance throughout planting operations.

The compact size and ease of installation of piezoelectric sensors further contribute to their suitability for integration into precision planters. For instance, piezoelectric microphones can be mounted on various plate materials with minimal structural modifications. This facilitates straightforward retrofitting into existing planting machinery without the need for extensive mechanical redesign.

From an economic perspective, piezoelectric sensors offer low cost and a high signal-to-noise ratio (SNR), enabling scalable deployment with relatively simple hardware. The high SNR ensures clear signal acquisition, which is essential for reliable seed detection, especially under field conditions where ambient noise may otherwise interfere with sensor outputs.

Performance studies have confirmed the efficacy of piezoelectric sensors in this domain. Gierz et al. (2022) reported that piezoelectric-based systems demonstrated seed detection error rates as low as 10%, even under minimal tilt angles. This level of accuracy is comparable to traditional sensors such as photoelectric and infrared detectors and underscores the reliability of piezoelectric technology for precision planting applications.

Beyond simple detection, piezoelectric sensors also contribute to the development of advanced automated planting systems, where sensor feedback can be used to dynamically adjust parameters such as seeding rate and spacing. Ongoing innovations in piezoelectric materials, including relaxor-$PbTiO_3$ single crystals, are enhancing sensor sensitivity and response characteristics. Jiang et al. (2014) highlighted the potential of these advanced materials to further improve performance in agricultural sensing technologies.

It should also be noted that the characteristics of the impact signal are influenced not only by the sensor and plate material, but also by geometric and operational parameters such as the angle of the impact plate, its size, and the height from which the seed falls. These factors can affect the magnitude and shape of the mechanical impulse transferred to the sensor, potentially influencing detection sensitivity and accuracy. While the present review does not include experimental evaluation of these parameters, previous studies in impact mechanics suggest that optimizing plate geometry and seed drop conditions could further enhance signal quality. This represents an important direction for future research, complementing ongoing efforts in material selection and signal processing (Karimi et al., 2015; Gierz et al., 2022).

In summary, the integration of piezoelectric sensors in precision planters provides multiple technical and practical advantages: high sensitivity, fast response, self-powered operation, environmental robustness, compact design, economic feasibility, and high detection accuracy. These attributes not only ensure reliable seed monitoring but also support the broader goals of automation and optimization in precision agriculture.

LIMITATIONS AND SIGNAL PROCESSING NEEDS

Although piezoelectric impact sensors offer many advantages, their use in high-speed, real-time seed detection systems faces specific challenges (Figure 6). These challenges, mainly related to signal complexity, material interactions, and processing needs, must be carefully managed to ensure optimal performance in precision agriculture.

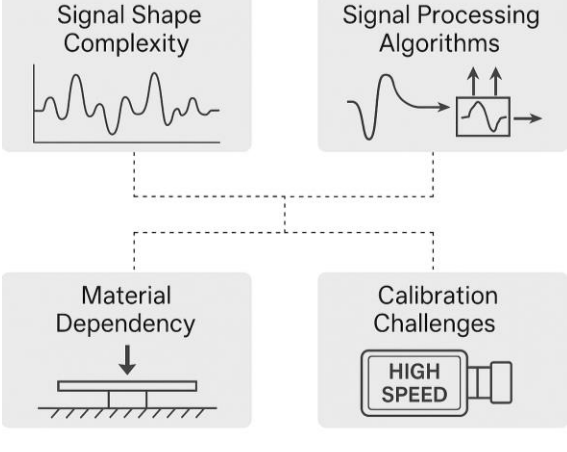


Figure 6. Illustration of major limitations and signal processing requirements for piezoelectric impact sensors in seed detection. Key challenges include signal complexity, calibration demands, material dependency, and the need for advanced filtering and peak detection algorithms.

A key challenge is the complexity of signal output**.** Unlike photoelectric systems that yield clean, binary signals upon seed passage, piezoelectric sensors generate irregular, analog waveforms. These signal variations are strongly influenced by factors such as seed mass, velocity, impact angle, and surface material. As a result, detecting and interpreting seed impact events require sophisticated signal analysis techniques to reliably differentiate meaningful data from background noise.

Another major limitation lies in the material dependency of sensor performance. The characteristics of the impact surface—such as hardness, elasticity, and structural damping—affect the amplitude and shape of the generated signal. For example, overly rigid or highly elastic surfaces may dampen or distort the impact response, complicating signal interpretation and reducing detection accuracy. This necessitates careful selection and optimization of the impact plate material, often involving empirical calibration and adjustment to balance sensitivity and robustness.

Variability in seed size, shape, and impact energy introduces inconsistencies in signal response, which can hinder the development of universally applicable detection thresholds. Accurate calibration typically requires reference measurements—such as high-speed video analysis—to validate the correlation between sensor outputs and actual seed events.

The intrinsic electrical characteristics of piezoelectric materials further contribute to performance limitations. For instance, certain polymers like polyvinylidene fluoride (PVDF) are commonly used due to their flexibility but tend to produce weaker signals under low-impact conditions. Wang et al. (2018) noted that this low-force responsiveness may reduce signal reliability when detecting small or lightweight seeds, potentially compromising system efficiency.

To overcome these limitations**,** advanced signal processing techniques are essential. Customized algorithms for peak detection, thresholding, and noise filtering are needed to accurately extract seed impact events from raw data. Techniques such as impedance analysis can be employed to characterize the frequency-dependent behavior of sensors and optimize their sensitivity (Ersman et al., 2022). Additionally, digital filtering and time-domain signal enhancement methods have been shown to improve signal-to-noise ratios, enabling clearer identification of relevant features (Daraji et al., 2022; Choi et al., 2020).

Further improvements may involve the use of sensor networks and synchronized data acquisition. By integrating multiple sensors and employing data fusion algorithms, detection reliability can be enhanced—especially in complex planting scenarios where signal clarity is affected by mechanical or environmental noise. Qiu et al. (2018) demonstrated that synchronizing input from a distributed sensor array could significantly improve seed localization and reduce false detection rates.

Material innovation also plays a critical role. Advances in microfabrication and the incorporation of functional fillers into piezoelectric composites have enabled the development of sensors with enhanced sensitivity and flexibility (Martinez & Artemev, 2010; Nivedhitha & Jeyanthi, 2022). However, as Zhang et al. (2024) cautioned, increasing material elasticity may alter signal characteristics in unintended ways, necessitating a careful balance between mechanical adaptability and electrical performance.

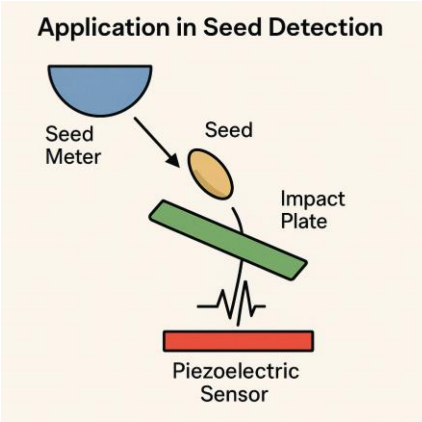
In summary, while piezoelectric impact sensors offer promising capabilities for seed detection in precision planters, their full potential can only be realized by addressing key limitations related to signal variability, material interaction, and processing demands. Continued research into both sensor design and real-time signal processing algorithms is essential to ensure reliable, scalable, and efficient operation in diverse agricultural environments.

APPLICATION IN SEED DETECTION

In the context of precision planting, piezoelectric sensors are increasingly being adopted for real-time seed detection due to their compact design, high sensitivity, and adaptability. Typically, these sensors are mounted on an impact plate positioned beneath the seed path. As each seed is ejected from the seed metering mechanism, it strikes the plate, generating a voltage pulse through the piezoelectric effect. These pulses can be processed to:

- Count individual seeds in real time,
- Determine the time interval between consecutive drops, which correlates with in-row seed spacing,
- Identify missed or multiple seed deliveries using standard ISO performance indices.

The seed detection mechanism using piezoelectric impact sensors involves the conversion of mechanical energy into an electrical signal upon seed impact, as illustrated in Figure 7. It should be noted that Figure 7 depicts the laboratory setup used in this study, in which the impact plate and sensor were positioned outside the seed tube (beneath the outlet), rather than installed inside the seed tube of a planter.



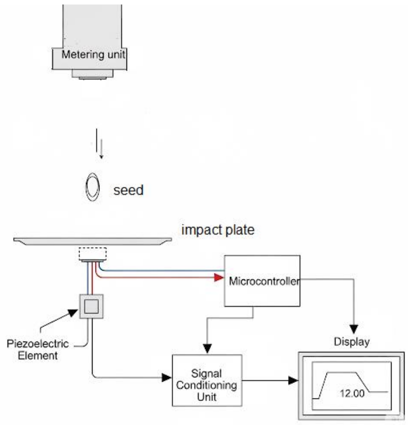


Figure 7. Schematic representation of seed detection using a piezoelectric impact sensor. As the seed is released from the seed meter, it strikes the impact plate, generating a voltage signal through the piezoelectric sensor located beneath the plate.

This method provides a cost-effective and mechanically simple alternative to optical or imaging-based systems, making it especially well-suited for laboratory test benches. While there are examples of its application under field conditions, its use remains limited due to changes in the seed flow trajectory after the seed impacts the plate. As shown by Rossi et al. (2023a, 2023b), the effectiveness of these systems depends not only on sensor selection but also on the development of tailored signal processing algorithms and the careful choice of impact plate materials to ensure detection accuracy and repeatability.

Recent advances in flexible piezoelectric materials, particularly polyvinylidene fluoride (PVDF), have significantly expanded the usability of piezoelectric sensors in agricultural machinery. PVDF exhibits excellent piezoelectric properties combined with mechanical flexibility, allowing the sensors to conform to a variety of surfaces within complex planting equipment (Liu et al., 2020; Lu et al., 2018; Lee et al., 2015). Notably, the electrospinning technique used in the fabrication of PVDF enhances its piezoelectric performance while enabling flexible form factors adaptable to irregular or curved surfaces (Lu et al., 2018; Li et al., 2024).

The core principle behind these sensors—the piezoelectric effect—enables the conversion of mechanical stress, caused by seed impact, into an electrical signal. This response forms the basis for detecting seed movement and interaction with soil. Sensors based on PVDF and similar materials offer low power consumption and high electrical sensitivity, characteristics that are essential for embedded agricultural applications where power availability and data resolution are critical (Ersman et al., 2022; Zhang, 2005; Zhou et al., 2025).

Further improvements have been demonstrated through the development of multilayer piezoelectric systems, which enhance both energy harvesting efficiency and signal strength. These multilayer configurations increase the surface area for stress detection, allowing for greater responsiveness and reliability under variable operational conditions (Guo et al., 2020). Such systems are particularly beneficial for modern precision planters, where accurate seed detection supports optimized planting density, reduced seed waste, and improved crop yield potential (Sousa et al., 2017).

Emerging research also highlights the integration of advanced functional materials, such as hybrid perovskite ferroelectrics, which have shown promise in boosting piezoelectric performance beyond traditional polymer-based systems (Shi et al., 2020; Chen et al., 2023). These materials offer enhanced sensitivity, environmental stability, and performance under a wide range of field conditions—attributes that are highly desirable for next-generation agricultural sensing platforms.

In conclusion, the application of piezoelectric impact sensors in seed detection represents a significant advancement in precision planter technology. Through continued innovations in material science—particularly with flexible polymers like PVDF and advanced multilayer or hybrid composites—these sensors are enabling more accurate, efficient, and scalable monitoring of seed delivery. Their integration into planting systems is a key step toward data-driven, high-efficiency agricultural practices.

CONCLUSIONS

Piezoelectric impact sensors offer a promising way to achieve accurate, affordable, and reliable seed detection in precision planters. Their inherent benefits—high sensitivity, quick response, and resistance to dust, vibration, and temperature changes—overcome several limitations of traditional optical or imaging-based detection systems. However, optimal performance relies on two main factors: the design of the mechanical interface, especially the impact plate material, and customized signal processing capable of interpreting complex transient waveforms. Experimental results show that materials like fiberglass deliver better signal-to-noise ratios across various seed types and speeds, while adaptive algorithms such as VTPD-AM enhance detection stability under changing conditions. Although signal complexity, calibration, and high-throughput operation pose challenges, ongoing improvements in piezoelectric materials—particularly flexible PVDF-based films and multilayer composites—are broadening their use in both laboratory and field settings. Integrating these advancements into planter monitoring systems enables piezoelectric sensors to support improved planting accuracy, less seed waste, and higher yield potential—advancing the goals of precision agriculture.

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