NECIS (Needle Crusher Integrated System): Portable Syringe Destroyer Featuring a Rotary Shredder, Magnetic Segregation, and Real-Time IoT Based Web Monitoring for Healthcare Facilities

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Abstract

The management of used syringe waste in healthcare facilities can pose risks during storage, handling, and disposal. This study presents NECIS (Needle Crusher Integrated System), a portable prototype designed to process used syringe needles and plastic barrels directly at the point of care. This study used a prototype development and experimental testing method. The prototype was developed through needs identification, mechanical and electrical design, fabrication, assembly, and IoT dashboard development. The prototype was then tested through functional, microbiological, magnetic segregation, and field tests. NECIS combines a high-torque rotary shredder, UV-C treatment, magnetic segregation, and Internet of Things (IoT)-based monitoring in a closed, battery-powered unit. The rotary shredder processed metal needles and plastic syringe barrels into fragments of up to 5 mm without stalling. However, the processing time was approximately 30 s, which was longer than the initial target of 8–10 s. UV-C treatment reduced microorganisms by 89.25% after 60 s of exposure. Magnetic segregation collected 1,000 g of needles from a 1,087 g sample, resulting in an efficiency of 91.99%. The IoT system showed the operating status and enabled real-time monitoring and control through a web dashboard. The prototype was tested at three healthcare facilities and received positive user feedback. The users also suggested improvements in operational safety, UV-C testing, operating information, and adaptation to user needs.

Keywords: *Magnetic segregation; Medical waste; NECIS; Rotary shredder; UV-C*

1. Introduction

Healthcare systems generate large quantities of used syringe waste that require controlled handling because sharps can cause occupational exposure and may carry blood-borne pathogens. Globally, the medical sector uses approximately 16 billion syringes annually, and this waste is categorized as infectious hazardous and toxic material requiring specific management [1], [3]. In Indonesia, healthcare hazardous-waste generation has been reported at approximately 296.86 tons per day, while third-party treatment capacity is around 151.6 tons per day. This gap can increase healthcare facilities' dependence on external waste-treatment services and potentially extend the storage period of waste at service points [2].

Improper management of sharps is also associated with Needle Stick Injury (NSI). A reported prevalence of needle-stick injury among healthcare workers in Indonesia is 38% [4], while exposure to used needles can provide a transmission route for blood-borne pathogens such as HIV, Hepatitis B, and Hepatitis C [1]. At healthcare facilities, sharps management continues to involve challenges in storage, transfer, and destruction. Safety boxes provide containment, but they do not change the physical characteristics of needles into non-sharps material; therefore, exposure potential remains during subsequent handling. An approach that changes the physical form of sharps as early as possible at the point of care is consequently needed to minimize direct contact between healthcare workers and used needles [6], [7].

Existing needle-destruction technologies have limitations. Needle burners use combustion or high-temperature heating to destroy the needle, whereas needle cutters separate or cut the needle from the syringe body. These approaches generally do not integrate the treatment of metal and plastic syringe components within a single process [5], [8]. Based on this need, NECIS was developed as a portable device integrating mechanical shredding, UV-C decontamination, magnetic material separation, and IoT monitoring. The integration of several previously separated stages into one workflow constitutes the principal technological novelty.

Previously developed syringe-waste treatment technologies have largely focused on individual processing or sorting functions, such as needle destruction or automated medical-waste sorting [7], [10]. Decontamination and device-condition monitoring have also commonly been addressed as separate functions. Recent studies have demonstrated the use of IoT for real-time monitoring and data management in medical-waste systems [12], [13]. This gap indicates the need for a device capable of combining shredding, decontamination treatment, material separation, and monitoring in a closed and portable system.

The principal novelty of NECIS is therefore the integration of rotary shredding, UV-C treatment, magnetic segregation, and IoT-based monitoring and control in a single enclosed, battery-powered unit. The system also processes the needle and plastic syringe barrel simultaneously. The present development should subsequently be strengthened through quantitative comparisons with previous devices or studies, particularly in capacity, processing time, separation efficiency, energy consumption, and safety performance.

The objective of NECIS is to produce a syringe-waste treatment prototype capable of simultaneously shredding needles and plastic syringe barrels, applying UV-C treatment to the resulting residue, separating metal and plastic fractions, and providing monitoring and control through an IoT dashboard. The relevance of the development lies in the need for a more integrated, portable, and point-of-care technology for the initial treatment of infectious sharps.

1.1. The Table and Figure Related Tecnology and System Architecture

Needle-waste destruction technologies can employ thermal or mechanical approaches. Previous studies have investigated automatic needle destruction and melting-based treatment for syringe needles [9], [13]. NECIS adopts a rotary-shredder approach without a thermal destruction stage and combines it with subsequent treatment functions in the same device.

The NECIS shredding subsystem uses an RS-775 high-torque DC motor controlled by a BTS7960 motor driver. The motor provides the cutting torque required to process metal and plastic materials, while speed regulation is performed using pulse-width modulation (PWM). After shredding, the residue is directed to a magnetic segregation mechanism using neodymium magnets to attract metal fragments from the plastic fraction. Magnetic separation is based on differences in magnetic response between materials and has been applied in various resource-utilization and environmental-treatment processes [11], [16].

For monitoring and control, an ESP32 DevKit V1 functions as the main computing and communication unit. An infrared sensor provides feedback for object detection or counting, while a voltage sensor monitors battery condition. Operational data are transmitted through Wi-Fi to Firebase Realtime Database and presented through a web dashboard. Similar IoT-based approaches have been developed for medical-waste monitoring, including real-time monitoring, data transmission, cloud-based management, and notification functions [12], [13]. This architecture enables real-time information access and reduces dependence on manual recording [13].

Bio-safety is supported by UV-C treatment of the shredded residue. UV-C exposure has been investigated as a non-contact decontamination approach for medical devices and has demonstrated potential for reducing bacterial contamination [17]. In NECIS, the effectiveness of the treatment is evaluated through different exposure durations and measurement of microorganism colony counts [14], [15] as shown in Figure 1.

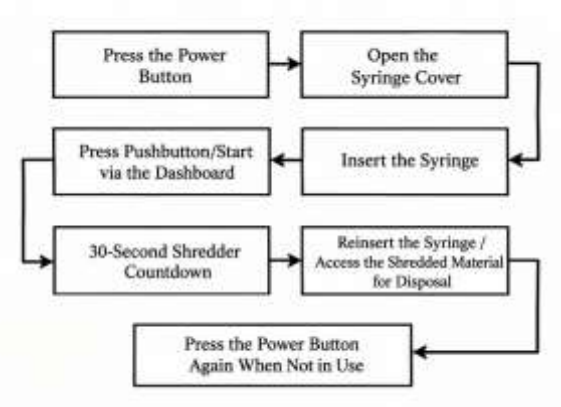


Figure 1. ~~Development~~ flowchart of the development of NECIS prototype

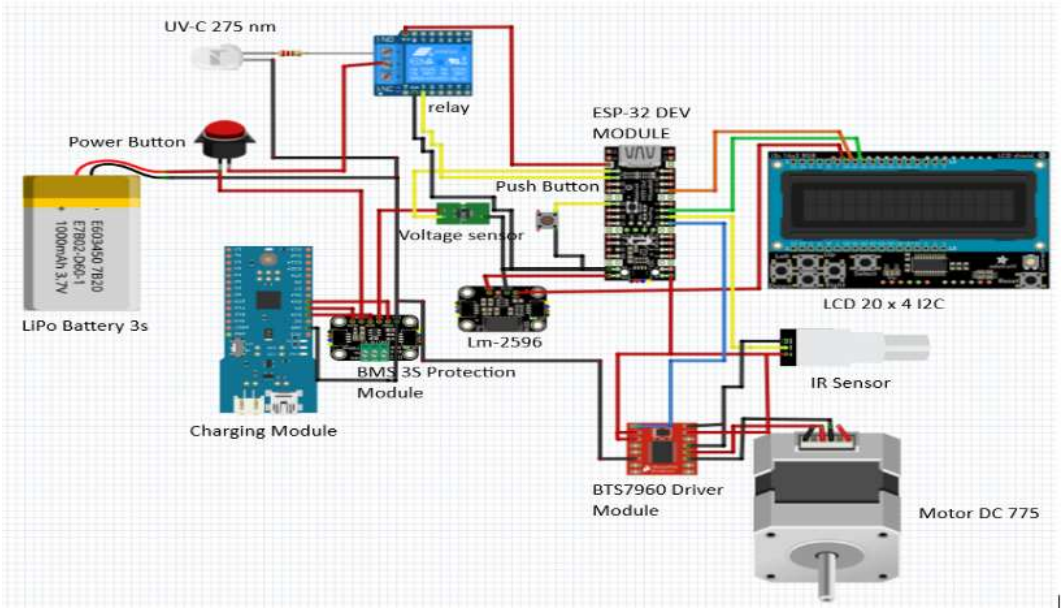


Figure 2. Wiring diagram of the NECIS system.

2. Method

NECIS was developed through a sequence of needs identification, technical design, product fabrication and assembly, IoT dashboard development, reliability testing, and field evaluation. Needs identification was conducted through observation and interviews at healthcare facilities to map problems in the storage, transfer, and destruction of used needles. The identified requirements were translated into a closed shredding chamber, simultaneous processing capability for metal and plastic, residue-separation mechanism, decontamination treatment, and monitoring and control functions.

Mechanical design covered the rotary-shredder configuration, shredding chamber, enclosure, collection system, and residue outlet. The frame used 20 × 20 mm aluminum T-slot profiles, while the casing formed a closed operating space. The shredder was driven by a DC motor through a pulley-belt transmission. Electronic components were physically separated from the shredding chamber to improve operational safety.

Electrical design placed the ESP32 as the central controller, integrated with the motor driver, infrared sensor, voltage sensor, LCD, relay, Battery Management System (BMS), and power modules. Battery power was selected to support portability. For segregation, neodymium magnets and a small DC fan were used to assist in directing metal and plastic residues into different paths.

The NECIS dashboard was developed using HTML, CSS, and JavaScript and connected to Firebase Realtime Database. Information was organized into sensor, command, alert, and status groups. The dashboard displays motor status, device connectivity, battery capacity, cumulative needle count, shredding timer, and UV-C status, while also providing monitoring and control functions.

Testing covered the mechanical, electrical, and sensor subsystems; IoT communication; magnetic segregation; UV-C effectiveness; and field demonstration. The development and testing flow is presented in Figure 1, while the electrical interconnection is shown in Figure 2. Because the work involved microbiological testing and field demonstrations, bio-safety and operational safety considerations were incorporated into the evaluation.

3. Results and Discussion

The development produced a functional NECIS prototype in which the major subsystems were realized and integrated. The prototype contains a closed shredding chamber, rotary-shredder system, UV-C module, magnetic-segregation mechanism, ESP32-based control system, and IoT dashboard. The configuration enables waste handling through a single sequence, from syringe insertion to residue separation and operational monitoring.

From the mechanical perspective, the rotary shredder successfully processed needles and plastic syringe barrels simultaneously into fragments with a maximum size of 5 mm without stalling. However, the measured operating time was approximately 30 s, which did not meet the initial target of 8–10 s. This result indicates that the fundamental shredding function was achieved, but torque, transmission, blade geometry, and operating parameters still require optimization to increase throughput.

Microbiological testing was conducted at the Biology Education Laboratory of Universitas Muhammadiyah Surakarta using UV-C exposure durations of 15, 30, 45, and 60 s. The corresponding reductions in microorganisms were 36.56%, 52.87%, 72.22%, and 89.25%, respectively. The highest reduction was obtained at 60 s. This value falls within the development target of 80–90%; however, further validation remains necessary before the UV-C subsystem can be used as the sole basis for a full sterilization claim.

Magnetic-segregation testing showed that the system attracted 1,000 g from a total needle-sample mass of 1,087 g. The resulting attraction percentage was 91.99%. The result confirms that the separation mechanism was functional, although a residual fraction was not attracted. Optimization of magnet position, residue trajectory, and airflow interaction could therefore improve separation efficiency.

The IoT integration operated according to the intended design. Operational data and device status could be monitored in real time through the web dashboard, while users could issue commands and control the shredding process through the interface. The system also provided an overload notification. This implementation strengthens NECIS as not only a mechanical device but also a digitally monitored waste-treatment system.

Operational demonstrations were conducted at Rumah Sakit UMS A.R. Fachrudin, Muhammadiyah Medical Center (MMC), and Rumah Sakit Umum Pusat (RSUP) Surakarta. User responses to the function and operating concept were positive. The feedback included requests for improved operational safety, additional information during operation, further validation of the UV-C module, and adaptation of the device to healthcare-facility needs. These inputs provide a basis for subsequent development.

The results provide clear quantitative indicators, but overall system efficiency cannot be concluded from a single parameter. The current prototype demonstrates the basic functions of shredding, decontamination, material separation, and digital monitoring. A more comprehensive evaluation should consider the relationship among processing capacity, processing time, energy consumption, separation efficiency, and operational requirements. Further comparison with previous studies should also be supported by statistical analysis and quantitative performance indicators where comparable data are available, as shown in Table 1.

Table 1. Summary of NECIS targets and main achievements.

Parameter	Target	Test result / achievement
Shredding	5 mm; 8-10 s; no stalling	5 mm; approximately 30 s per shredding cycle; no stalling
UV-C	80-90% microorganism reduction	89.25% microorganism reduction at 60 s
Magnetic segregation	Separate metal residue	1,000 g from 1,087 g; 91.99% attracted
IoT	Real-time monitoring and control	Integrated dashboard operating in real time
Portability	Compact, fully enclosed, battery-powered	Realized and usable at point of care

The specifications and test results for the NECIS prototype are based on five key performance parameters: shredding, UV-C treatment, magnetic separation, IoT integration, and portability. Shredding tests yielded a maximum fragment size of 5 mm without jamming, demonstrating the prototype's capability to process composite components consisting of metal needles and plastic syringes. However, the shredding cycle took approximately 30 seconds exceeding the initial target of 8-10 seconds indicating a need for further optimization of the overall cutting mechanism. UV-C testing showed an 89.25% reduction in microorganisms after 60 seconds of exposure, indicating that the applied UV-C level contributed to lowering the microbial load under the tested conditions. Magnetic separation achieved a recovery rate of 91.99%, with 1,000 g of material successfully extracted from an initial mass of 1,087 g. The IoT system was successfully integrated into a dashboard for real-time monitoring and operation, while the portability target was met through the development of a compact, fully enclosed, battery-powered prototype suitable for point-of-care use.

The 91.99% magnetic attraction rate indicates that most of the tested needle mass was captured by the magnetic segregation subsystem. The remaining fraction suggests that separation is affected by the position of the magnet, the path followed by the shredded material, and airflow. These parameters should be investigated systematically in subsequent testing.

The three-facility demonstration provides an initial indication of practical acceptance, but it is not sufficient to establish long-term reliability or general performance across healthcare settings. Future evaluation should include capacity, energy consumption, operational cost, user safety, bio-safety validation, repeated-cycle reliability, and longer-duration operation. These measurements would also enable stronger quantitative comparison with previous technologies, as shown in Figure 3.



Figure 3. Front physical view of the NECIS prototype.



Figure 4. NECIS web-dashboard interface.

4. Conclusion

NECIS was successfully realized as a portable initial-treatment prototype for syringe waste at the point of care by integrating a rotary shredder, UV-C treatment, magnetic segregation, and IoT monitoring in one enclosed, battery-powered device. The rotary shredder simultaneously processed needles and plastic syringe barrels into fragments with a maximum size of 5 mm without stalling, although the approximately 30 s processing time remains above the initial 8–10 s target. UV-C treatment produced an 89.25% reduction in microorganisms after 60 s of exposure, while magnetic segregation attracted 1,000 g of a 1,087 g needle sample, corresponding to 91.99%. The IoT subsystem provided real-time monitoring and control through a web dashboard. From an application perspective, NECIS provides an integrated approach for initial syringe-waste treatment at the point of care and has the potential to reduce direct handling of sharps while providing real-time process information. Demonstration at three healthcare facilities produced positive initial responses and identified requirements concerning safety, operating information, UV-C validation, and design adaptation. Broader implementation impacts still require evidence from capacity, energy consumption, operational cost, user safety, bio-safety validation, and long-term reliability testing. Subsequent development should prioritize shredding-speed optimization, residue-separation improvement, bio-safety validation, and refinement of the monitoring system.

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