

## **Integrated System toward Sustainable Recycling of Pharmaceutical Waste Blister Packages**

**Amr Khamis Mahmoud**

R&D Department at the Industry Service Complex (ISC)  
Arab Academy for Science, Technology and Maritime Transport (AASTMT)  
Alexandria, Egypt  
[Amr.khamis@aast.edu](mailto:Amr.khamis@aast.edu)

**Mohamed A. Etman**

Pharmaceutics Department  
Pharos University  
Alexandria, Egypt  
[vpse@pua.edu.eg](mailto:vpse@pua.edu.eg)

**Dina M. Mahdy and Mostafa S. Hamad**

Pharmaceutics Department; Research and Innovation Center  
Arab Academy for Science, Technology and Maritime Transport (AASTMT)  
Alamein, Egypt  
[dr.dinamahdy@aast.edu](mailto:dr.dinamahdy@aast.edu); [mostafahamad@aast.edu](mailto:mostafahamad@aast.edu)

**Noha Galal, Lina Ismail and Khaled S. El-Kilany**

Department of Industrial and Management Engineering  
Arab Academy for Science, Technology and Maritime Transport (AASTMT)  
Alexandria, Egypt  
[noha.galal@aast.edu](mailto:noha.galal@aast.edu); [linaelsherif@aast.edu](mailto:linaelsherif@aast.edu); [kkilany@aast.edu](mailto:kkilany@aast.edu)

### **Abstract**

Pharmaceutical Blister Packages, consisting primarily of aluminum and plastics, hold significant potential for recycling. During pharmaceutical production, finished strips that do not meet specifications must be de-blistered, either manually or using automated machines. To facilitate the recycling process of the blisters, aluminum and plastic are separated adequately. This work presents the design of an integrated system for recycling pharmaceutical waste blister packaging. The integrated system includes de-blistering the strips, shredding the aluminum and plastic strips, separating the adhesive material that bonds the plastic and aluminum parts, and finally using electrostatic methods to separate the aluminum from the plastics. The research methodology is primarily based on reverse engineering, which involves collecting field data and extracting design specifications through the functional analysis of a used de-blistering machine and published specifications of the other three machines. This work develops the preliminary mechanical design and electrical control design of the integrated automated machines. A prototype was developed, and finite element analysis was used to analyze the stress and factor of safety. The system is projected to have a positive economic and environmental impact, promoting material recycling and ensuring sustainability within the pharmaceutical industry. In addition, developing such an integrated system is essential for reworking/reprocessing of pharmaceutical products in case of failure to meet product specifications.

## **Keywords**

Deblistering, pharmaceutical packaging waste, recycling, sustainability, waste management

## **1. Introduction**

The global pharmaceutical packaging market is expected to reach \$149.3 billion by 2026 (Shukla, Chernyaev, and Lundström 2024). Blister packaging for solid pharmaceutical products, including capsules and tablets, has become extremely popular since 1960 (Nieminen et al. 2020). Compared to traditional packaging methods such as glass or plastic bottles, the blister packs showed superior sealing performance, especially from moisture that may occur due to shelf storage. Pharmaceutical blister packs usually consist of aluminum foil lidding bonded to plastic forming films polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) to seal pills individually. Aluminum is usually used as it provides an excellent barrier with the ability to push the pills through it, recyclability, low specific weight, and low cost. Recycling pharmaceutical blister packaging has gained significant attention due to the negative environmental effects caused by landfilling (K. Hansch and Kinkel 1995). Particularly, recycling defective blister packaging is crucial for minimizing material loss, reducing production cost, and promoting sustainable manufacturing as it aligns with circular economy goals. However, recycling of materials used in pharmaceutical blister packaging is challenging due to the layered composite-like structure of the packaging (Yaren Çapkın and Gökelman 2023). This directed some studies to recycle just one material of the blister waste; however, the blister is a mixture of recyclable metal and non-metal fractions. Considerable effort has been devoted to proposing and developing methods for separating aluminum and plastic components from pharmaceutical blister packaging (Agarwal et al. 2020; Zhang et al. 2014).

This work proposes an integrated system to address the challenges of recycling waste pharmaceutical blister packs, thereby reducing pharmaceutical waste, decreasing landfill volume, lowering production costs, and mitigating environmental degradation. The proposed methodology aims to design and develop a four-phase integrated system composed of four machines with potential for real-life industry implementation. These sequential machines are compatible with any shape of medicine strips and are designed to recover various blister materials for recycling. The machines perform four key processes: de-blistering medicine strips, shredding, chemically separating plastic and aluminum materials, and finally, electrostatically separating plastic and aluminum. The recovered materials from this process can be reworked or reprocessed at a later stage; however, this is beyond the scope of the current study.

The contribution and novelty of the proposed system are twofold: 1) Recovery of materials from blister waste has traditionally focused on a single type of material; however, this work aims to separate and recover the various materials found in blister packaging. To the authors' knowledge, no previous work has attempted to recover all types of blister materials for recycling purposes. 2) Despite growing attention to the recycling of pharmaceutical blister packaging waste, there remains a lack of fully integrated systems encompassing all stages of the process, as presented in this work. Previous studies have focused solely on isolated techniques such as de-blistering, shredding, chemical separation, and electrostatic separation. The remainder of the paper is structured as follows: Section 2 reviews the different methods and machines used for recycling pharmaceutical waste blister packages. Section 3 presents the conceptual design. Section 4 presents the preliminary machine design. Section 5 provides Finite Element Simulation and Results. Finally, the conclusions and future works are presented in Section 6.

## **2. Literature Review**

The review of literature briefly describes the existing technologies and machines used for recycling waste pharmaceutical blisters packs. The following sub-sections will cover the types of each machine, limitations and insights for development.

### **2.1 De-blistering Machine**

De-blistering machine plays a critical role in the recycling process of pharmaceutical waste as it separates tablets or capsules from defective or expired blister packaging. In general, the main components of a de-blistering machine are:

1. **Feeding System:** blister packs are fed into the machine.
2. **Blister Pack Sorting:** are used to sort the blister packs to ensure correct alignment for the de-blistering process.
3. **De-blistering Station:** this is the core component where tablets or capsules are extracted from the blister packs. The mechanism is designed to carefully separate the tablets or capsules from the blister packaging without creating any damage to the medication.

4. **Product Separation:** where the separated tablets or capsules are collected in a designated tray, while the empty blister packs are discarded or recycled.
5. **Control System:** this is used to manage and monitor the entire process, ensuring smooth and efficient operation.

De-blistering machines are of three types: manual, semi-automatic, and automatic machines. Manual de-blistering machines offer a simple and cost-effective way to remove products from small batches of blister packs. Blister packs are manually fed through a set of rollers by turning a handle. Tablets are simultaneously removed from the blister pack and separated from the waste packaging. Alternatively, semi-automatic de-blistering machines generate higher throughput compared to manual machines. Although, the mechanical system is driven by a motor; packs still need to be placed in the machine by hand. Whilst, feeding the packs automatically speeds up the process. Semi-automated machines offer affordable solutions that can handle most blister pack types including thermo-formed and alu-alu packs. Finally, automatic de-blistering machines have an integrated magazine feed that enables blister packs to be fed automatically. As a much larger amount of blister packs are fed unassisted, the operator has more freedom to walk away from the machine focusing on other tasks that are required at the line. Automatic machines either work on the roller principle, where the packs are fed through a roller to be pushed out or use advanced cutting technology. Beedle (2016) addressed the importance of de-blistering and the importance of automating this process and affirmed that automated de-blistering machines offer an increase in quality, yield, speed and efficiency over the traditional hand de-blistering method, specifically when the volume of rework/reprocessing of blisters is large.

### **Environmental and Economic Impact of De-blistering Machines**

The reuse of de-blistered products for repackaging, reworking or reprocessing, as well as reusing or recycling of waste packaging materials which in turn is reflected positively on the environment and economic aspects. The recycling of waste packaging allows the recovery of aluminum and plastics which contributes to waste minimization and supporting circular economy. Economically, automated de-blistering machines reduce time associated with manual separation of tablets and capsules from blister packs, thereby improving production and material recovery efficiency.

### **Key Challenges in Designing and Manufacturing De-blistering Machines**

Manufacturing de-blistering machines faces several challenges, including:

- High precision in the design and manufacturing process to ensure machine accuracy and consistency in removing products from blister packs without damaging them.
- Enclosed de-blistering systems to collect dust and prevent it from spreading into the environment. Integrating dust extraction units or vacuum systems within the machine to effectively remove dust generated during the de-blistering process.
- Different blister pack materials (e.g., plastic, aluminum) require different handling techniques. The machine must be versatile enough to handle various materials without compromising efficiency.
- Developing fully automated systems that can integrate seamlessly into existing production lines can be complex. This involves sophisticated software and hardware engineering.
- De-blistering machines in the pharmaceutical industry must meet strict regulatory standards to ensure the safety and integrity of extracted products.
- The process of de-blistering can sometimes cause minimal, hardly identifiable damage to the products, which can affect their functionality, especially in the case of pharmaceuticals.
- Balancing the cost of manufacturing with the need for scalability and efficiency is a constant challenge. Researchers must find ways to produce machines that are both cost-effective and capable of handling large volumes.

### **Plastic Shredding Machine**

The process of shredding the pharmaceutical blister packs is crucial before separating the blister packs materials which include (aluminum and PVC/PET). Since these materials are strongly bonded with adhesive materials, making it difficult to separate without shredding (Kremser et al. 2023); shredding, as a pretreatment process, can increase the efficiency of recycling procedures (Kheirabadi and Sheikhi 2022), as it helps in reducing the size of the blister before separation (Flizikowski, Kruszelnicka, and Macko 2021). Miękoś et al. (2023) designed the process of granulating waste pharmaceutical blisters and proposed a density liquid separation method that is composed of seven steps to recover aluminum and PVC separately from waste pharmaceutical blisters. Ayo et al. (2017) proposed a design for a shredding machine that includes a feeding unit, shredding unit, power transmission, and the machine frame. Other work focused on the conceptual design of the shaft and blades such as (Wong et al. 2022). This confirms that this step is an essential preparatory step for separation of blister packs materials.

### Chemical Separation Machine

A chemical separation process is used to separate aluminum foil from the plastic pharmaceutical blister. Zhang et al. (2023) reviewed the separation of plastic for pharmaceutical blisters recovery and Yaren Capkin and Göknelma (2023) reviewed hydrometallurgical, thermal processes, and electro hydrophilic fragmentation for separating plastic and aluminum. The hydrometallurgical technique involves either focusing on a single layer to extract aluminum in solution or only dissolving the adhesive between the layers to separate them. Thermal degradation techniques mainly break down the plastic component and isolate it from the aluminum by creating composite materials. Finally, the electrohydraulic fragmentation method separates aluminum from plastic while also reducing energy use.

Wang et al. (2015) implemented the hydrometallurgical techniques and achieved a complete separation of aluminum under optimal conditions using the hydrometallurgical method. Yousef et al. (2018) developed a technology based on ultrasonic treatment to speed up the breakage rate of adhesive bonds and the molecular forces between the layers of composite packaging and achieved a complete separation of all the materials. Nieminen et al. (2020) found an environmentally friendly method of separation using the deep eutectic solvent along with lactic acid for separating aluminum and plastic from blister packaging. Shukla et al. (2022) succeeded in recovering 100% of the aluminum from waste pharmaceutical blisters by a delamination technique using organic solvents at low temperatures. The use of bio-hydrometallurgy for dissolution of aluminum demonstrated that plastic material can be reprocessed, rendering this method both an economical and environmentally sustainable treatment option (Kremser et al. 2023). Miękoś et al. (2023) proposed a design for a tank constructed from chemically resistant polypropylene, featuring a welded metal rack and a specially designed agitator to enhance aluminum and PVC separation of waste pharmaceutical blisters without disturbing the PVC layer. Göknelma et al. (2024) categorized waste pharmaceutical blisters into plastic-rich and aluminum-rich blisters and investigated their degradation mechanisms and their thermal behavior. Agarwal (2020) demonstrated that under ideal conditions electrohydraulic fragmentation of aluminum and polymer can result in extracting up to 88% of aluminum (with a purity of  $\geq 99.4\%$ ) and polymers from the examined waste blister samples. Although all these methods were reported in literature as being successful in separating plastic and aluminum; yet, it was unclear whether it has been applied to large volumes of blisters or not.

### Electrostatic Separation

Electrostatic separation is used for separating plastic fragments from the aluminum fragments. Tribo-electrostatic separation of granular plastic waste is investigated in (Wu, Li, and Xu 2013). Mechanical recycling is advised for plastic waste to preserve its virgin quality. Tribo-electrostatic separation leverages the differences in surface properties of various materials to create opposing charges, allowing them to be diverted within an electric field and collected separately. This method offers benefits such as high efficiency, low costs, no issues with water disposal or secondary pollution, and it can handle a relatively broad range of particle sizes.

## 3. Integrated System Conceptual Design

The conceptual design of the proposed integrated system is presented in Figure 1. The system comprises four interconnected machines: de-blistering, plastic shredding, chemical separation, and electrostatic separation machine. Each machine is detailed in the following sub-sections.

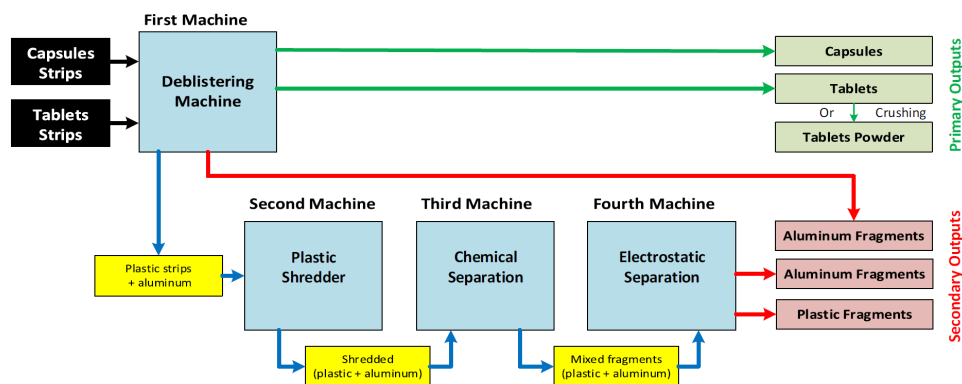


Figure 1. Schematic representation of the proposed integrated system

**a. Stage 1 - Designing a Novel Mechanism for a De-blistering Machine**

An automatic de-blistering machine is designed with a novel mechanism that allows to de-blister different layouts and sizes of blisters of medicine strips. The machine is designed with the ability to be adjusted for most layouts of tablet strips, accommodating various strip configurations, and for different tablet heights, ensuring versatility across diverse pharmaceutical packaging formats.

The de-blistering machine block diagram (shown in Figure 2a), illustrates the system's architecture, integrating essential components including power sources, sensors, actuators, user interface, and alarm system, all managed by a central CPU. The machine integrates a well-structured system comprising a dual voltage power source (1) with overload protection (2) safeguarding electrical components during high-load operations (3), multiple proximity sensors (4) for real-time monitoring (including strip feeder, de-blistering drum, tablet container, plastic strip container, and current sensors (5) to ensure operational efficiency), and actuators such as the strip feeder motor (10) and deblistering drum motor (12) for precise mechanical actions. A user-friendly interface includes an LCD touch screen (7), manual controls (8), and an emergency stop switch (9) to prioritize usability and safety. The alarm system (6) provides visual and audio alerts for operational issues, while the CPU (14) acts as the intelligent core, processing inputs, coordinating outputs, and ensuring seamless interaction between all components, resulting in a robust, automated, and efficient de-blistering process.

The conceptual mechanical design of the de-blistering Machine is shown in (Figure 2b), which highlights the key components and functionality, ensuring efficient separation of tablets from blister packaging. The system utilizes a continuous strip feeder (19), which guides blister strips into the machine for processing. The continuous strips feeder can be adjusted automatically to any blister shape, which has not been previously developed. Adjustable rollers (20) and pressing drums (16) are core to the mechanism, exerting controlled pressure to release tablets from the packaging without damaging their integrity. To meet medical-grade standards, the machine is designed to be fabricated using stainless-steel 316, a material known for its corrosion resistance, hygiene, and durability in pharmaceutical applications. The design also includes clear separation pathways (22) for the extracted tablets and the discarded plastic strips, directing them into dedicated collection containers. This structured design prioritizes precision, adaptability, versatility across diverse pharmaceutical packaging formats, ease of maintenance, and compliance with medical-grade material requirements, making it reliable and efficient for industrial use.

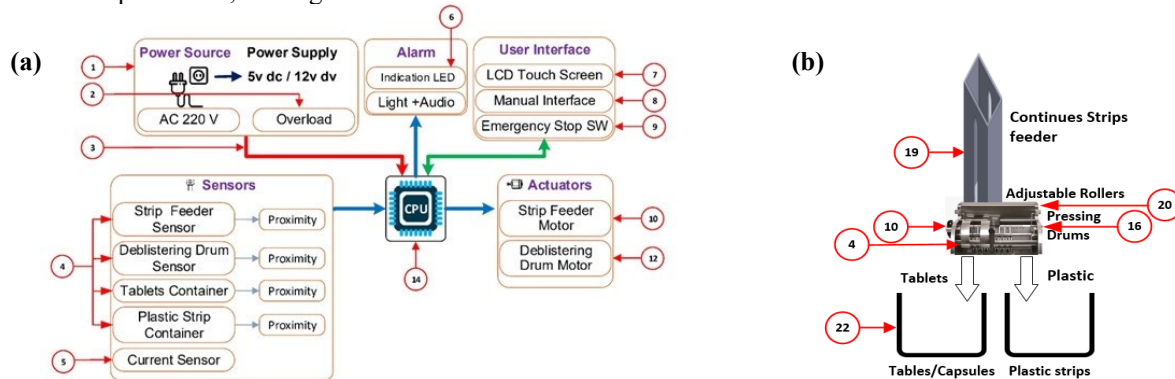


Figure 2. (a) De-blistering Machine Block Diagram (b) De-blistering Machine Mechanical Conceptual Design

**b. Stage 2 - Designing a Plastic Shredder Machine**

The plastic shredder machine (Figure 3) is the second machine of the system. It is mainly used to cut the discarded blister released from the de-blistering process into small fragments of mixed plastic and aluminum. The shredding process is crucial to facilitate the separation performance in the next stage, as the small pieces of strips will be subjected to more solvents than the non-shredded medicine strips. The machine is designed to efficiently process blister packaging by shredding its plastic strips covered with AL foil into smaller fragments for subsequent separation. The block diagram (Figure 3a) shows the integration of a reliable power source (1, 2), sensors (4, 5, 6), actuators (11), a central control system (12), and user-friendly interface, ensuring a seamless and efficient shredding process. The machine operates using a power supply of 5V DC and 12V DC, derived from a 220V AC input (1), with an overload protection system (2) safeguarding electrical components during high-load operations (3). This robust power

configuration ensures reliable and uninterrupted performance during continuous operation. The machine incorporates advanced sensors for precise monitoring and safety. Proximity sensors (4) are strategically placed, with a safety sensor ensuring the machine halts operations when conditions are unsafe and a crushing tank sensor detecting the presence of material in the shredding chamber. A limit switch (5) monitors access points to maintain operational integrity, while a current sensor (6) tracks power consumption to optimize efficiency and identify potential issues like stuck shredded particles inside the moving parts of the machine. These sensors provide real-time feedback, ensuring smooth and secure machine operation. At the middle of the shredding process is the shredder motor (11), the primary actuator responsible for delivering the torque and speed required for effective shredding (Shredding Speed will be determined as soon as starting the tests). This motor is controlled by the CPU (12), which acts as the system's central hub, processing data from sensors and coordinating actuator responses. The user interface enhances operational control with an LCD touch screen (8) for seamless interaction, a manual interface (9) for fine-tuning, and an emergency stop switch (10) for immediate action in case of emergencies. An alarm system (7) with visual and audio alerts keeps operators informed about the system's status or any potential issues.

The conceptual mechanical design of the machine is illustrated in (Figure 3b). The design integrates essential components into a compact system, ensuring effective shredding of blister packaging materials into smaller fragments for downstream separation processes. At the top of the machine is the hopper (18), which serves as the entry point for blister strip materials, guiding them into the shredding chamber (20) for processing. The shredding chamber is equipped with high-precision stainless steel blades that ensure efficient and uniform cutting of materials, reducing them into smaller fragments suitable for separation. The motor (11), located at the base of the system, provides the necessary power to drive the entire shredding operation, ensuring consistent performance even under varying loads. To collect the shredded material, the machine is equipped with a crushing tank (21), placed beneath the shredding chamber. This tank ensures clean and organized material collection, preventing scatter and facilitating easy transfer to subsequent processing stages. The system's design prioritizes safety, precision, and user convenience.

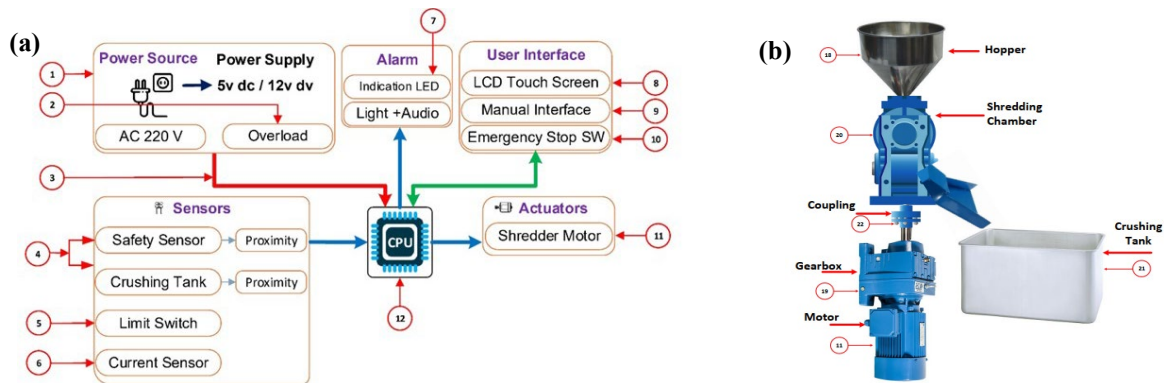


Figure 3. (a) Plastic Shredder machine block diagram (b) Plastic Shredder machine Conceptual Design

### c. Stage 3 - Designing a Chemical Separation Machine

The chemical separation machine is the third machine of the system (Figure 4). The separation process is a crucial part of the recycling system, designed to separate the adhesive bonds between aluminum foil and plastic in blister packaging using chemical solvents.

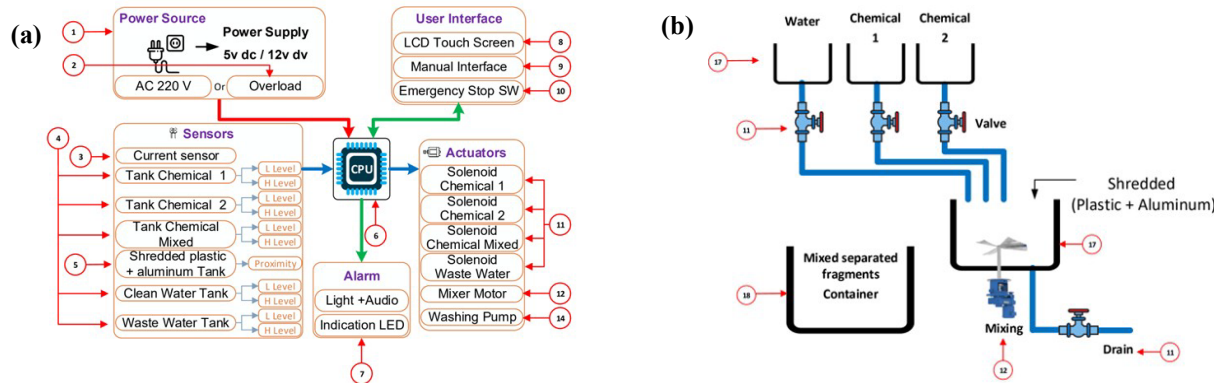


Figure 4. (a) Chemical Separation Machine Block Diagram, (b) Chemical Separation Machine Mechanical Conceptual Design

The block diagram in (Figure 4a) illustrates the different integrated components of the chemical separation machine. The machine operates using a 5V/12V DC power supply derived from a 220V AC input (1), with an overload protection system (2) to prevent damage during high-demand operations. Real-time monitoring is achieved through an array of sensors. A current sensor (3) monitors electrical load, adding another layer of safety and operational efficiency. Tanks level sensors (4) monitors liquids level in tanks and ensures proper handling of liquids throughout the process. Tanks include chemical tanks (Chemical 1, Chemical 2, and Mixed), shredded plastic and aluminum tank, clean water tank, and wastewater tank. The control system is powered by a CPU (6) that integrates all inputs from the sensors and manages outputs to actuators. The actuators include solenoid valves (11) for controlling the flow of chemicals, mixed substances, and wastewater; a mixer motor (12) for thorough blending of chemicals and materials; and a washing pump (14) to facilitate rinsing processes. These actuators ensure precision in the chemical separation process while maintaining a high level of automation. User interaction is facilitated through an intuitive interface comprising an LCD touch screen (8), manual operation controls (9), and an emergency stop switch (10) for immediate intervention in case of unexpected issues. The system is equipped with an alarm unit (7) that provides both visual and audio signals to alert operators of system states or potential malfunctions.

The conceptual mechanical design shown in (Figure 4b) includes three tanks (17) at the top for water, Chemical 1, and Chemical 2, each equipped with valves (11) to control the flow of liquids into the mixing chamber. The control of these valves ensures precise and correct proportions of chemicals and water being used during the separation process. The shredded plastic and aluminum fragments are introduced into the mixing chamber (17), where a mixer (12) blends the fragments with the chemical solutions. Mechanical mixing ensures thorough breakdown of adhesion between aluminum and plastic. Once the process is complete, the separated materials are directed to a mixed separated fragments container (18) for collection and further processing. The design also incorporates a drain valve (11) for removing excess or waste liquid, ensuring proper handling and cleanliness.

#### d. Stage 4 - Designing an Electrostatic Separation Machine

The fourth and final stage of the proposed system is the electrostatic separation machine, which is designed to separate aluminum and plastic fragments using an electrostatic approach. The electrostatic separation machine utilizes high-voltage electrostatic forces to effectively separate plastic and aluminum fragments from shredded blister packaging. Figure 5a is the machine block diagram that highlights the system architecture integrating its different components of power, sensors, actuators, and control systems to ensure precision and safety in the electrostatic separation process. The machine operates on a 5V/12V DC power supply derived from a 220V AC input (1), with overload protection (2) to safeguard the system during high-load conditions. Real-time monitoring is achieved through a suite of sensors, including proximity sensors (3) for the plastic and aluminum tanks, a current sensor (4) for monitoring electrical performance, and an interlock door safety sensor (5) for secure operation. Additionally, specialized sensors like the electrostatic intensity sensor (6) and spark sensor (7) ensure accurate control and safe handling of the high-voltage electrostatic circuit. The central processing unit (CPU, 9) serves as the machine's control hub, managing inputs from the sensors and directing outputs to various actuators. These actuators include a drum motor (12) for rotating materials, an electrostatic circuit (14) to generate the required separation voltage, a shaker motor (15) to ensure consistent material flow, and a heater (17) to optimize operating conditions. The machine also incorporates potentiometers (18) for fine-tuning key parameters such as speed control, electrostatic intensity, and vibration control. This feature allows

operators to adjust settings based on material properties, ensuring high separation efficiency. The user interface includes manual operation controls (10), an emergency stop switch (11) for safety and complemented by an alarm system (8) with LED indicators and audio signals to notify operators of system status or potential issues.

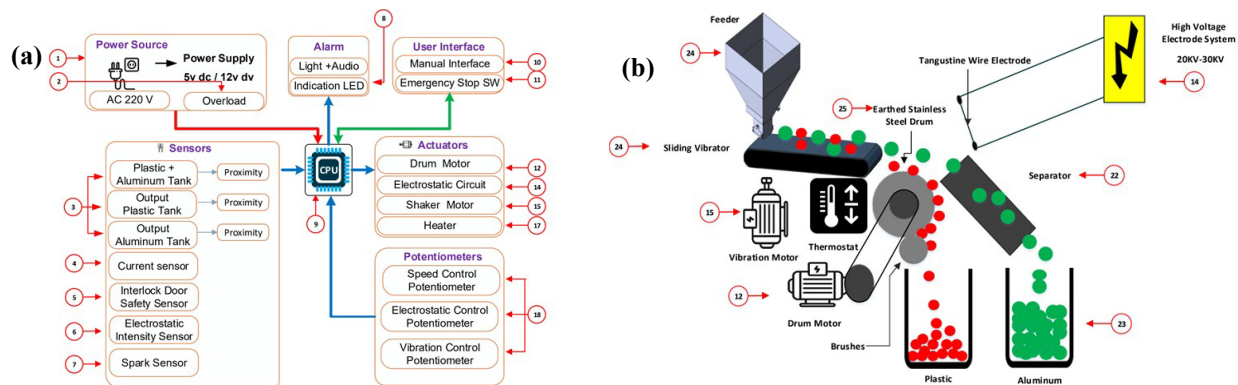


Figure 5. (a) Electrostatic Separation Machine Block Diagram, (b) Electrostatic Separation Machine Mechanical Conceptual Design

The conceptual mechanical design demonstrates the integration of feeding, separation, and collection processes, ensuring precision and efficiency. As illustrated in (Figure 5b), the process begins with the feeder (24), which introduces shredded plastic and aluminum fragments into the system. The materials are evenly distributed onto a sliding vibrator (24), powered by a vibration motor (15), ensuring consistent and controlled material flow into the separation stage. This vibration action eliminates clumping and spreads the fragments uniformly for optimal separation. The fragments are directed onto an earthed stainless-steel drum (25), which rotates under the action of the drum motor (12). The drum serves as the conductive surface for the electrostatic separation process. Above the drum, a tungsten wire electrode system (14) generates adjustable high-voltage electrostatic field (20 kV–30 kV). This field induces opposite charges on the aluminum and plastic fragments as they pass through, exploiting the difference in their electrical conductivity properties. As the fragments leave the drum, the charged aluminum pieces are attracted to the separator (22), which guides them into the designated aluminum collection bin (23). Simultaneously, the plastic fragments, which are less conductive, follow their natural trajectory into a separate plastic collection bin (23). Brushes attached to the drum ensure that any residual fragments are cleared off, maintaining continuous operation and preventing buildup. The process is enhanced by a thermostat, which maintains optimal operating conditions for the drum and electrode system with minimum humidity, ensuring consistent separation performance.

#### 4. Preliminary Mechanical Design

This section provides detailed blueprints and 3D models developed using SolidWorks for each machine in the integrated system (Figure 6). These models will facilitate the CNC fabrication of several parts of the machines including feeders, shredding chambers, mixing tanks, and separation drums. It is important to note that this design represents a preliminary version, focusing on feasibility and integration of functional requirements.



Figure 6. 3D models for each machine in the integrated system (a) de-blistering, (b) shredder, (c) chemical separation, and (d) electrostatic separation

#### **a. De-Blistering Machine**

The preliminary mechanical design model of the de-blistering machine, shown in Figure 6a, serves as the foundation for visualizing the spatial arrangement of components, assessing functionality, and preparing for manufacturing and further assembly. The machine's key components are:

- **Blisters Tower:** Positioned at the top, it guides blister strips into the processing chamber for separation.
- **Blister Pusher Mechanism:** A DC motor is used to push the blister strips one by one from the blister tower into the separation chamber. This ensures controlled and consistent feeding of the strips into the rollers.
- **Roller Mechanism:** Located centrally, the rollers apply controlled pressure to extract tablets or capsules from the blister packaging. The rollers are adjustable to accommodate blister strips of varying sizes and tablet heights. This mechanism is actuated via an AC motor.
- **Separation Pathways:** The processed tablets or capsules are directed into a designated collection container, while the plastic strips are funneled into a separate disposal bin outside the machine.
- **Motor and Gear Assembly:** Located within the base housing, the motor provides the necessary torque for the roller mechanism, transmitted through a gear system.
- **Emergency Stop Button and Control Panel:** Positioned on the top surface for accessibility, ensuring safety during operation.
- **Mobility Features:** The machine is equipped with caster wheels for easy relocation, enhancing its operational flexibility.

#### **b. Plastic Shredder Machine**

The shredder machine model (Figure 6b) provides a comprehensive visualization of its functional components and spatial arrangement, ensuring its feasibility for manufacturing and operation. The machine consists of the following key components:

- **Shredding Pot:** Centrally positioned, it houses the blades that shred the input material into smaller fragments for downstream separation.
- **Control Box:** Mounted on the back side of the body frame, the control box provides access to the power controls and safety features, including an emergency stop button.
- **Body Frame:** Constructed from a sturdy SS316 material, the frame supports the shredding pot, motor, and control box, ensuring stability during operation.
- **Motor:** Located at the base, the motor (Single Phase, 1 hp, 3000 rpm) drives the shredding blades through a robust transmission mechanism, providing the required torque for shredding.
- **Mobility Features:** The machine is equipped with wheels to allow easy relocation and operational flexibility.

#### **c. Chemical Separation Machine Preliminary Design**

The SolidWorks model for the chemical separation machine, shown in (Figure 6c), provides an in-depth visualization of its mechanical design, focusing on ease of operation, efficiency, and manufacturability. The machine incorporates the following key components:

- **Mixing Chamber:** Positioned centrally, this chamber is equipped with a blade for uniform mixing of chemicals and waste, ensuring effective separation.
- **Chemical Tanks:** Located on either side of the machine, the tanks store and deliver chemicals to the mixing chamber with precision control.
- **Drainage and Collection System:** Allows for the controlled removal of separated chemical waste into designated collection bins.
- **Control Panel:** Ergonomically positioned at the front of the machine, the panel includes switches, indicators, and a display for operational control.
- **Structural Frame:** Constructed from SS316 stainless steel, the frame supports the entire assembly, ensuring stability and durability during operation.
- **Wheels and Base:** The base includes caster wheels, facilitating easy mobility and positioning of the machine in various operational environments

#### d. Electrostatic Separation Machine Preliminary Design

The SolidWorks model for the Electrostatic Separation Machine shown in (Figure 6d) provides a detailed visualization of its mechanical structure, focusing on functional efficiency and manufacturability. The machine consists of the following primary components:

- **Electrostatic Drum:** Positioned centrally, the drum applies to a high-voltage field to achieve efficient separation of plastic and aluminum fragments based on their electrostatic properties.
- **High-Voltage Electrode System:** Configured to create the necessary electric field intensity for effective material separation.
- **Hopper:** Located at the top of the machine, it serves as the input point for mixed materials, guiding them into the electrostatic drum.
- **Collection Bins:** Strategically placed at the output end, the bins segregate plastic and aluminum fragments post-separation.
- **Control Box:** Mounted on the frame, the control box provides operational control, including high-voltage settings and emergency stop functionality.
- **Structural Frame:** Fabricated from robust materials, the frame supports all components and ensures stability during operation.

### 5. Simulation Using Finite Element Analysis

Finite Element Analysis (FEA) was used to simulate, validate, and optimize the design of components for the integrated systems to obtain more efficient, safer, and innovative design. Stress analysis and calculations for factors of safety (FOS) were conducted for the de-blistering and the electrostatic separation machine.

#### a. Finite Element Analysis Results for De-Blistering Machine

FEA simulation result for the FOS de-blistering machine is shown in (Figure 7a), demonstrating the structural integrity and reliability under operational loads. The FOS analysis indicates that the frame can safely withstand applied loads, with FOS values ranging from 1.4 to 5.0. The stress distribution analysis, conducted under a 500N load, reveals a maximum von Mises stress of  $1.27 \times 10^8$  N/m<sup>2</sup>, which is well below the material's yield strength of  $1.723 \times 10^8$  N/m<sup>2</sup> as shown in (Figure 7b). This confirms that the structure can endure the applied forces without permanent deformation or failure. Overall, the design is robust and efficient, validating the preliminary mechanical design and ensuring its suitability for further development in the next project phase.

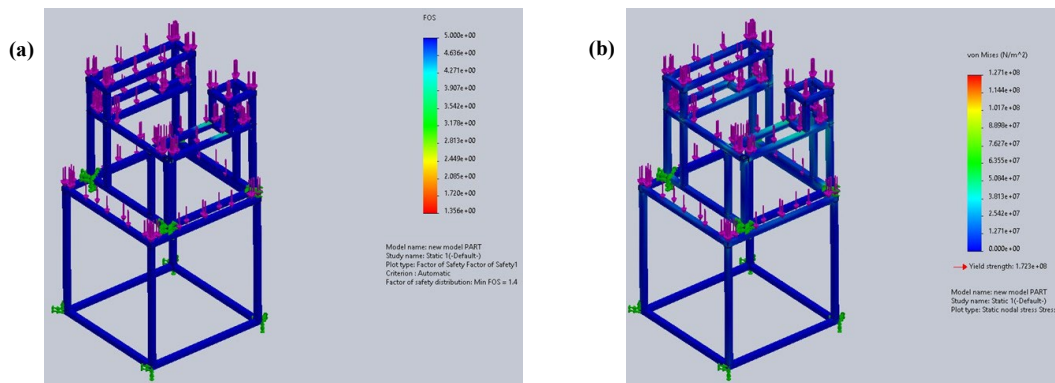


Figure 7. (a) De-blistering Machine Factor of Safety Simulation results, (b) Deblistering Machine - Stress Analysis simulation results

#### b. Finite Element Analysis Results for Electrostatic Separation Machine

FEA simulation result for the FOS for the Electrostatic Separation Machine under operational load is shown in (Figure 8a). The results showed a minimum FOS value of 10, demonstrating a highly robust and over-engineered design capable of handling expected stress without failure. The displacement analysis in (Figure 8b) revealed a maximum

deflection of approximately 9.98  $\mu\text{m}$ , primarily occurring in the upper section of the frame, which is negligible and ensures no compromise to the machine's structural integrity or alignment. The high safety factor and minimal deformation validate the machine's reliability and durability for the intended application.

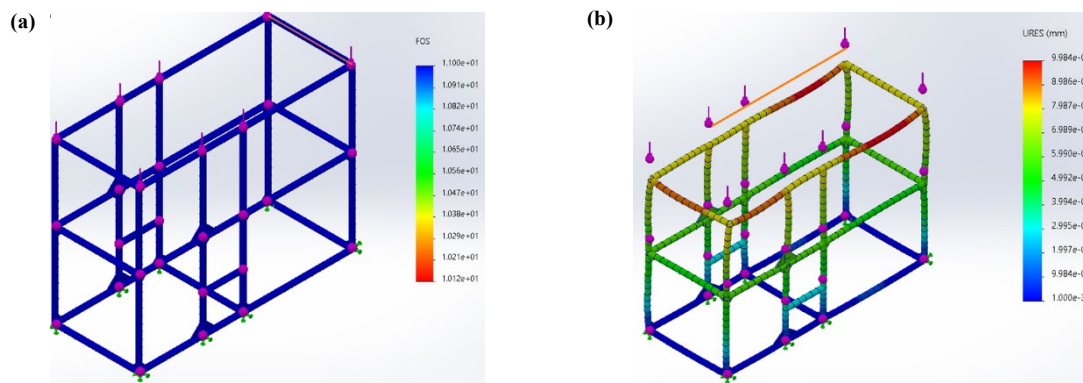


Figure 8. (a) Electrostatic Separation Machine Factor of Safety Simulation results, (b) Electrostatic Separation Machine - Stress Analysis

## 6. Conclusions

This paper addresses the recycling of defective blister packaging in the pharmaceutical industry. A review of the literature reveals fragmented efforts, with prior research primarily focused on recovering plastic and aluminum from tablet blister strips. This highlights the importance of addressing blister recycling and underscores the need for an integrated, automated system capable of deblistering these packs, shredding the materials, and effectively achieving complete separation of aluminum and plastic. A conceptual framework for the deblistering system was developed, emphasizing efficiency, modularity, and scalability. The integrated system comprises four interconnected machines: deblistering, plastic shredding, chemical separation, and electrostatic separation. The modular design ensures compatibility with various blister shapes and configurations while maintaining ease of maintenance and adaptability. Finite element simulations were conducted to evaluate the factor of safety and perform stress analyses for both the deblistering and electrostatic separation machines.

Successfully implementing such a system in an industrial setting would have several positive implications. First, from a production standpoint, the automated reworking and reprocessing of defective tablet blisters would effectively increase production rates and improve demand fulfillment. Second, from an economic perspective, recovering plastic and aluminum would help reduce raw material costs and losses while promoting material valorization. Finally, from an environmental perspective, diverting plastic waste from defective blisters away from landfills toward reworking and reprocessing would support the principles of a circular economy and promote sustainability.

The next step is to develop prototypes for each phase of the system, followed by fabrication, assembly, testing, and experimentation. Finally, the system can be implemented on an industrial scale. At this stage, the reliability of the developed system and its economic viability can be assessed under continuous operating conditions. Furthermore, conducting a comprehensive life cycle assessment to evaluate the system's environmental impact would help demonstrate its significance from a sustainability perspective.

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## **Biographies**

**Amr Khamis Mahmoud** is the Head of the Research and Development Department at the Industry Service Complex, AASTMT. He has over 18 years of experience in mechatronics, robotics, embedded systems, and renewable energy applications. Eng. Khamis has led and contributed to several nationally funded projects, including the Campus Smart Recycling System, Mobile Mechanical Ventilator, and Atmospheric Water Generator, securing more than 7 million EGP in research funding. He has published on topics related to machine intelligence, energy-efficient systems, and robotic design. He is currently pursuing his PhD in Electronics and Communication Engineering at AASTMT, focusing on multi-modal sensing and deep learning for adaptive, energy-aware control in collaborative robotics.

**Mohamed A. Etman** is a Professor of Pharmaceutics since 2000. The Vice President of Pharos University for CSED. Former head of dept. of Pharmaceutics, Acting Dean of OAPI (Oman), Vice dean of College of Pharmacy (AASTMT) and the Faculty of Pharmacy, Pharos Univ. Has more than 60 Journal and conference publications and is a reviewer of STDF and 9 national and international journals. Supervised about 15 PhD and Master theses and 5 projects. He is a member of FIP (Switzerland) and AAPS (USA). He was both a member and reviewer for National Professorship Promotion Committee (2010 - 2019). He participated in more than 25 conferences and is the winner of FIP – BPP prize, Portugal (2010). An experienced scientific consultant for many pharmaceutical companies in and outside Egypt (2002 -2016).

**Dina M. Mahdy** is a lecturer of Pharmaceutics, Acting director for central lab for pharmaceutical analysis, Alamein branch, AASTMT, and Head of quality Assurance unit. She received her Ph.D. in Pharmaceutics from faculty of Pharmacy, Alexandria University in 2019. Her primary emphasis is on the in-vitro evaluation of pharmaceutical dosage forms with respect to their dissolution behavior, quantifying their degradation upon storage using compendial techniques and procedures and possible interactions with food supplements. Her post-doctoral research focuses on formulation and biological evaluation of nanocarrier systems.

**Mostafa S. Hamad** obtained the PhD degree in Electrical Engineering from Strathclyde University, UK, in 2009 and the BSc and the MSc degree from Alexandria University, Egypt, in 1999 and 2003, respectively. Currently he is the Director of Research and Innovation Center, AASTMT, and professor power electronics applications and electric drive systems at Electrical and Control Engineering Department, College of Engineering, AASTMT. He is a certified energy manager by the Association of Energy Engineers (AEE) – USA since 2017 and a certified Consultant of New and Renewable Energy Systems since 2019. His research interests include electric machines and drives, power electronics applications in power quality, electric vehicles, smart grid, and renewable energy.

**Noha M. Galal** is a Professor of Industrial and Management Engineering, AASTMT. She holds a PhD. degree in production engineering from Alexandria University, Egypt. Her research interests include modeling and optimization of closed-loop supply chains, sustainable manufacturing, sustainable production planning, life cycle engineering, and economic assessment of renewable energy technology applications. She is a senior member of the IISE.

**Lina Ismail** is an Assistant Professor at the Department of Industrial and Management Engineering, Arab Academy for Science, Technology, and Maritime Transport. Dr. Ismail holds a Ph.D. degree in Industrial Engineering from University of Central Florida, USA (2021). Her research interests include Neuroergonomic, human centered design, cognitive ergonomics, sustainability, and six sigma. She is a member of the Human Factors and ergonomics society.

**Khaled S. El-Kilany** is a Professor of Industrial Engineering and Dean of the Industry Service Complex at AASTMT, Egypt. He holds a Ph.D. from Dublin City University, Ireland, conducted in collaboration with Intel. His research focuses on sustainable manufacturing, process optimization, and green supply chains, with numerous publications in agri-food, pharmaceuticals, and intelligent production systems. Beyond research, he has led major academic quality initiatives at AASTMT and is a senior member of the IISE.