

GNG 5140

**Design Project User and Product Manual**

**Solar Panel Recycling Sorter - Electrostatic Separator**

Submitted by:

[Solar Deconstruction Unit - Sunset Renewables]

[Nelson Hidocos, 8265361]

[Au Zi Lam, 300386037]

[Muhammad Abdullah, 300439798]

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University of Ottawa

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# List of Acronyms and Glossary

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Table 1: Acronyms

Acronym	Definition
PV	Photovoltaic
RPM	Revolutions per minute
mL	Milliliter
g	Gram
M	Molarity
C	Celsius
V	Volts
pH	Acidity/basicity
hrs.	Hours
kWh	Kilowatt Hour
GUI	Graphic User Interface

# 1 Introduction

This **User and Product Manual** is designed to serve as a comprehensive reference guide for understanding, operating, maintaining, and improving the **Solar Panel Recycling Sorter**, developed as part of the broader initiative by **Sunset Renewables**. The system utilizes **electrostatic separation technology** to efficiently recover valuable materials from decommissioned photovoltaic (PV) modules [1] [2]. This manual is intended to ensure that users can operate the prototype safely and effectively, while also supporting documentation for testing, troubleshooting, and future development.

The system's design and development are grounded in the urgent global need to manage the growing volume of solar panel waste generated from aging PV installations [3]. As millions of solar panels near the end of their operational lifespan [4], the industry faces a major sustainability challenge: how to responsibly recycle these panels while recovering critical raw materials like **silver, copper, and aluminum** [5] [6]. Existing recycling methods such as chemical leaching or high-temperature thermal processing are costly, hazardous, and energy-intensive [7]. The Solar Panel Recycling Sorter offers a **low-cost, energy-efficient, and environmentally friendly alternative**, employing electrostatic separation to sort conductive and non-conductive particles from shredded PV panels [8].

## 1.1 Context and Assumptions

The work documented in this manual is the culmination of an extensive multi-phase prototyping process. The prototype was iteratively developed to meet both functional and sustainability goals. The following assumptions were made during the design, testing, and documentation phases:

- **Operational Environment:** The prototype is assumed to be operated in a **controlled indoor environment**, such as a university laboratory or pilot test facility, where variables like humidity and airborne particulates are minimized to maintain charge efficiency and safety.

- **User Background:** The system is intended for users who possess a **basic understanding of high-voltage equipment and material separation techniques**, such as students, lab technicians, and researchers. Minimal prior experience with electrostatic systems is acceptable, as long as this manual is followed closely.
- **Material Preparation:** It is assumed that input material has been **pre-shredded or ground to appropriate particle sizes** and is **free from moisture and volatile contaminants**, which can disrupt the electrostatic charge distribution and separation performance.
- **Safety Practices:** Users are expected to follow general **lab safety protocols**, including wearing personal protective equipment (PPE) and avoiding direct contact with high-voltage components.

These assumptions ensure a baseline for successful and safe operation and inform the design limitations and recommendations stated throughout this manual.

## 1.2 Purpose of the Document

The primary purpose of this User and Product Manual is to:

- Provide clear, structured **instructions for setup, calibration, and safe operation** of the electrostatic separator system.
- Serve as a **technical reference document** for the prototype design, subsystem interactions, and test outcomes.
- Support **troubleshooting and maintenance** through detailed guidance on component functions and failure modes.
- Act as a foundational resource for **future design iterations, upgrades, and academic replication** of the system.

The manual consolidates both operational knowledge and engineering documentation to bridge the gap between theoretical development and practical deployment of the system.

## 1.3 Document Organization

To ensure ease of use, the manual is structured as follows:

- **Section 1: Introduction**

Provides the background, assumptions, scope, intended audience, and security considerations.

- **Section 2: Overview**

Offers a breakdown of the system architecture, including the triboelectric generator, separation chamber, control electronics, and supporting structures.

- **Section 3: Getting Started**

Provides a step-by-step guide to system assembly, wiring, component calibration, and pre-start checks.

- **Section 4: Using the System**

Explains how to operate the system under normal and test conditions, including material loading, speed adjustments, and bin handling.

- **Section 5: Troubleshooting and Support**

Covers periodic maintenance tasks, common issues, and solutions based on real-world testing.

- **Section 6: Product Documentation**

Lists dimensions, material specifications, voltage ratings, subsystem details, and testing parameters. Also summarizes results from mechanical, chemical, and electrical testing, including observations from component performance and optimization.

## 1.4 Scope of Activities

The document covers all aspects of the system's **life cycle** in the current prototype phase, including:

- Design intent and functional overview of the subsystems.
- Full assembly, calibration, and testing processes.
- Analysis of chemical composition testing results for material recovery.

- System limitations, upgrade suggestions, and recommendations for scaling and sustainability.
- Guidelines for safe operation, system adjustments, and post-use shutdown.

However, this manual **does not cover**:

- Industrial automation for continuous material feed or bulk processing.
- Long-term regulatory compliance or certification for commercial deployment.
- Operation under extreme environmental conditions or at voltages exceeding current safety-tested thresholds.

## 1.5 Intended Audience

This manual is intended for the following user groups:

- **University Students and Instructors** – Especially those involved in sustainable engineering, waste recovery, materials science, or renewable energy research.
- **Prototype Testers and Lab Technicians** – Who are responsible for operating and collecting performance data from the separator system.
- **Product Developers and Engineers** – Interested in adapting the system for real-world deployment or improving system components for industrial use.
- **Research Collaborators and Project Sponsors** – Who require detailed documentation for evaluation, funding justification, or technical assessment.

The manual assumes a minimum level of technical literacy but strives to remain accessible through clear diagrams, definitions, and step-by-step instructions.

## 1.6 Security and Privacy Considerations

Although the system is a **hardware prototype** with no built-in data logging or network communication features, several safety and procedural security measures must be considered:

- **Electrical Safety**: The triboelectric generator operates at high voltages (estimated up to 7.5 kV). Users must ensure proper grounding, use of insulating materials, and physical

barriers around high-voltage regions. Only trained personnel should modify electrical connections or adjust electrode spacing.

- **Mechanical Safety:** The rotating drums and vibration mechanisms pose a **pinch and entanglement hazard**. Hair, clothing, and loose accessories must be secured. Users must never reach into the system during operation.
- **Operational Access Control:** The system should be used in **authorized environments only** (e.g., designated lab stations or monitored classrooms). Key switches or removable power supplies can be used to restrict access.
- **Material Handling and Disposal:** Separated and unseparated material samples—especially those containing metals or fine particulates—should be handled with gloves and masks. Proper disposal and containment procedures must be followed.
- **Data Privacy:** Since the system does not store or transmit data, **privacy risks are minimal**. However, if integrated with monitoring systems in the future, user access and data storage policies must be considered.

The Solar Panel Recycling Sorter represents a significant step toward the development of clean, scalable, and efficient solar panel recycling technologies. This User Manual provides the necessary operational guidance and technical background to maximize the value of the system in a variety of settings, from classrooms to early-stage research environments. Through responsible use and iterative improvement, this project can continue to drive innovation in **sustainable resource recovery** and support the transition toward a **circular solar economy**.

## 2 Overview

### 2.1 The Problem and Its Importance

With global efforts to combat climate change, solar power has emerged as a leading source of clean, renewable energy. However, as the solar industry matures, an increasing number of **photovoltaic (PV) modules are reaching the end of their operational life**, creating a new challenge: **solar panel waste management**. Millions of panels are expected to be



decommissioned in the coming years, containing valuable but potentially hazardous materials like **silver, copper, aluminum, silicon, and lead-based compounds**.

Current recycling methods often involve **high-temperature thermal processing** or **chemical leaching**, which are both energy-intensive and environmentally damaging. These approaches also lack selectivity, often leading to material cross-contamination or incomplete recovery. There is a clear need for **sustainable, selective, and low-energy recycling methods** that can recover valuable materials efficiently while minimizing environmental harm.

This project addresses that need through the development of a **low-cost, scalable electrostatic separation system** capable of separating metals and non-metals from shredded solar panel waste based on their **electrical conductivity** and **triboelectric charge** properties.

## 2.2 Fundamental Needs of the User

The intended users—students, lab operators, and early-stage recyclers—require a system that is:

- **Easy to Operate** – Minimal setup and intuitive operation for users with limited experience in electrical or mechanical systems.
- **Safe** – Built-in safety mechanisms to mitigate the risks of high voltage and moving components.
- **Modular and Accessible** – Easily disassembled and reassembled for maintenance, upgrades, or educational demonstration.
- **Efficient** – Capable of visibly and functionally separating conductive particles from non-conductive ones to demonstrate proof-of-concept material recovery.
- **Affordable and Scalable** – Low-cost design with potential to evolve into a more advanced prototype or full-scale recycling system.

## 2.3 Key aspects of Electrostatic Separator

This electrostatic separator stands out from other solar panel recycling approaches due to the following features:

- **Chemical-Free Operation:** Unlike traditional chemical-based recovery, this system uses no corrosive reagents or high-temperature furnaces, making it cleaner and safer.
- **Triboelectric Separation:** The use of triboelectric charging allows for material sorting based purely on physical and electrical properties, minimizing cross-contamination.
- **Modular and Customizable Design:** Components such as belts, rollers, and brushes can be easily swapped or adjusted, allowing users to optimize performance or repurpose the system for different feedstocks (e.g., e-waste, batteries).
- **Low Power Consumption:** Operates using a **12V power supply** with minimal energy usage, supporting both environmental sustainability and cost efficiency.
- **Designed for Education and Prototyping:** Tailored for academic, research, and demonstration settings, it supports hands-on learning and practical understanding of sustainable engineering principles.

## 2.4 Key Features and Functions

The system performs the following core functions:

- **Charges the particles** using a triboelectric generator made of rotating belts, brushes, and rollers.
- **Feeds particles** consistently through a vibrating tray that distributes material onto a grounded drum.
- **Separates conductive from non-conductive materials** using a static electric field that alters particle trajectories based on their charge.
- **Collects sorted particles** into one of three bins—front, middle, or rear—based on their conductivity.
- **Provides adjustable settings** like drum speed, belt tension, and electrode distance to fine-tune separation performance.

These functions work together to enable selective material recovery from mixed PV waste streams.

## 2.5 System Architecture, System Environment, and Special Conditions

The product architecture is **hardware-based** and entirely **offline**, making it safe for use in workshops and labs without internet connectivity or software dependencies. The system includes:

- **Triboelectric Charging Unit** – A rotating belt system coupled with Teflon rollers, a copper brush, and a DC motor that generates static electricity.
- **Separation Unit** – A grounded aluminum drum and a high-voltage electrode that influence the particle paths based on charge.
- **Vibrating Feeder** – A small motor-based tray that delivers particles evenly.
- **User Interaction Mode** – Controlled **manually** using power switches and physical adjustments (e.g., knobs and sliders for motor speed and belt tension). There is **no GUI or web-based interface** at this stage.

To operate correctly, the system requires:

- **A low-humidity environment:** Moisture in the air can significantly reduce charge buildup and interfere with separation.
- **Dry and pre-shredded material:** The feedstock must be processed into **small, dry particles** to enable consistent charging and movement.
- **Stable work surface and safety clearances:** The prototype should be placed on a flat, insulated workbench with clear surroundings to prevent accidental contact with moving or high-voltage components.
- **Protective shielding:** While the prototype includes a wooden or acrylic enclosure to minimize exposure, **users must still wear gloves, safety glasses, and avoid touching high-voltage areas during operation.**

## 2.6 Conventions

### Units and Symbols

- All measurements follow the International System of Units (SI) (e.g., mm, °C, V, g).
- Chemical symbols and formulas are written in standard notation (e.g., HNO<sub>3</sub>, AgCl, Cu<sup>2+</sup>).

- Arrows (→) indicate chemical reactions or process flows.
- All figures and tables are labeled and referred to in the text for ease of reference.

## 2.7 Cautions & Warnings

The **Solar Panel Recycling Sorter** includes high-voltage electrical components, rotating mechanical systems, and optional chemical testing procedures that may pose safety risks if not handled properly. Users must carefully review the following cautions and warnings before operating or maintaining the system.

### 2.7.1 Electrical Hazards

- The **triboelectric generator** operates at voltages up to **7.5 kV**. Direct contact with charged components, such as the **electrode roller** or **copper brush**, can result in severe electric shock.
- Always ensure that the **system is properly grounded**, and avoid touching conductive elements during operation.
- Adjustments to wiring or the electrode setup must only be performed with the **system powered off and unplugged**.
- Use **insulated tools and protective gloves** when working near the power supply or electrical connections.

### 2.7.2 Mechanical Hazards

- The system includes **fast-spinning rollers, belts, and vibrating components**. These pose a risk of **entanglement, pinch points, and abrasion** injuries.
- Keep **hands, tools, and loose clothing** away from moving parts at all times.
- Never attempt to remove blockages or adjust mechanical components while the system is running.

### 2.7.3 Material Handling Hazards

- The input material (shredded solar panels) may contain **sharp fragments**, including **glass, metal slivers, and conductive wires**. Always wear **cut-resistant gloves and eye protection** when handling material.
- Processed materials may contain **residues of heavy metals** such as **lead, cadmium, and antimony**, which can be harmful if inhaled or ingested. Use appropriate **respiratory protection and work in a ventilated area**.

#### 2.7.4 Chemical Hazards (for Chemical Testing Subsystem)

If performing chemical validation procedures using the **chemical testing subsystem**, the following precautions apply:

- **Nitric Acid (HNO<sub>3</sub>, 6M):** Highly corrosive. Causes severe skin burns and eye damage. Emits toxic fumes when heated or spilled. Always handle in a **fume hood** with **nitrile gloves, goggles, and a lab coat**.
- **Hydrochloric Acid (HCl, 3M):** Corrosive and irritant. Produces hydrogen chloride vapors that can damage respiratory tissues.
- **Sodium Hydroxide (NaOH, 3M):** Strong base that causes **chemical burns**. Avoid skin and eye contact; neutralize spills with a mild acid under supervision.
- **Silver Nitrate and Metal Salts:** May stain skin permanently and are **environmentally toxic**. Avoid disposing of into sinks; collect all chemical waste for proper hazardous waste disposal.

#### General Chemical Lab Practices:

- Perform all chemical handling procedures under a **certified fume hood**.
- Never mix chemicals without following the documented protocol.
- Label all containers clearly and store them according to chemical safety regulations.
- Dispose of all used chemicals according to your institution's **hazardous waste guidelines**.
- Have a **chemical spill kit and eyewash station** readily accessible in your lab area.

#### 2.7.5 System Environment

- Operate the system only on a **stable, non-conductive workbench** in a dry area free from flammable or conductive materials.
- Avoid operation in **high-humidity environments**, which can degrade electrostatic performance and increase the risk of discharge.
- Ensure the **working area is well-lit, ventilated**, and kept clear of unnecessary objects or people during operation.

### 2.7.6 Final Note

Failure to adhere to the above cautions and safety procedures may result in **serious injury, equipment damage, exposure to toxic substances, or institutional disciplinary action**. All users must be properly trained and supervised when operating the system and performing Chemical analysis.

## 3 Getting started

This system is designed to demonstrate the electrostatic separation process used in solar panel recycling. It separates charged particles using a friction-based triboelectric charging system followed by an electrostatic deflection field.

To start the system:

### Connect Power Supply:

- Use a variable DC power supply (12V/5A recommended).
- Connect directly to the roller motor. Use the built-in **voltage control knob** to adjust the motor speed.

### Turn On Main Components:

- Adjust the **power dial** to start the aluminum roller rotation.
- Press the **vibrating motor switch** to feed particles into the separation zone.
- Ensure the **electrode plate** is connected to the high-voltage power module.

### Input Materials:

- Pour mixed particle samples (such as shredded solar panel fragments) into the hopper at the top.
- Materials should be **dry** and relatively fine to avoid clumping.

### Observe the Separation:

- Charged particles will be deflected and collected in separate output trays based on polarity.

### Shutdown Procedure:

- Turn off all dials and switches.
- Disconnect the power supply after operation.

## 3.1 Set-up Considerations

To ensure smooth operation and replicability of the electrostatic separator system, several hardware and environmental setup factors must be carefully arranged before use. Below are the essential components and considerations:

- **Power Source:** A variable DC power supply (preferably 12V/5A) is required to run the system. This supply features a built-in voltage control knob that allows users to adjust motor speed manually. Using this method simplifies the design by removing the need for motor driver circuits such as the BTS7960.
- **Roller Motor Control:** This refers to the motor in the *separator* subsystem, which drives the **aluminum roller**. In contrast, the *generator* subsystem uses the **Teflon roller** as the driven element.
- **Arduino Uno:** The Arduino Uno microcontroller is used to control the vibration motor. Its role in this system is limited to enabling/disabling vibration, but it can be reprogrammed for more advanced automation, such as integrating sensors or timers for automated feeding.
- **Input System:** The input system uses a 3D printed funnel structure that feeds the raw material (typically shredded photovoltaic cells or similar granular material) into the roller assembly. The input funnel is 3D-printed and designed to guide shredded photovoltaic material into the roller assembly in a smooth and consistent manner. Its geometry ensures proper alignment with the roller zone and helps prevent clogging. A vibration motor is mounted underneath hooper to assist with continuous material flow when needed.
- **Output Configuration:** The system relies on gravity-based sorting. After passing through the separation zone, particles are deflected and fall into appropriately placed collection

bins. The number and positioning of these bins depend on material type and observed trajectory. The frame holding the bins should be adjustable to fine-tune separation accuracy.

- **Environmental Considerations:** It is recommended to operate the device on a level, non-conductive surface to ensure stability and reduce interference with the electric field. The 3D printed funnel should remain dry to prevent warping or interference due to static buildup. Ensure that all wiring is properly insulated and grounded, especially in the high-voltage section.

This setup configuration ensures the system is both safe and easily operable by non-technical users, while remaining open to future expansions.

### 3.2 User Access Considerations

The electrostatic separator system is designed with simplicity and safety in mind to accommodate users from both technical and non-technical backgrounds. Below are detailed user access considerations to ensure safe and effective use:

- **No Digital Authentication Required:** The system is entirely hardware-based and does not require digital login, password entry, or user account creation. All interaction occurs through physical components such as power dials, switches, and manual loading.
- **Intended Use Context:** The device is intended strictly for demonstration and academic purposes, particularly within lab environments where supervision and controlled use are expected. It is not suited for industrial-scale use or continuous operation.
- **User Types:**
  - *Primary Users:* Students or project team members who have undergone initial setup or usage training.
  - *Secondary Users:* Instructors, reviewers, or other users observing the system or interacting under direct guidance.
- **Risk Awareness:** Operators must be made aware of potential safety hazards, particularly:
  - Exposure to **high-voltage** elements (electrode plate)
  - Rotating mechanical parts (rollers and motor shafts)



- Possible static build-up around the input funnel and separation area
- **Safety Guidelines:**
  - The system should only be operated **under supervision** or by users who have reviewed safety training materials.
  - Avoid placing hands near the roller or electrode zone while the device is powered.
  - Ensure proper grounding and avoid touching exposed wires.
- **Accessibility:** The physical interface is kept minimal to support easy access. Labels or icons on switches and dials are recommended for clearer user guidance, particularly for unfamiliar users.

### 3.3 Accessing the System

Accessing the system is straightforward and does not require any software login or digital interface. The prototype is designed to be operated via manual controls and simple hardware switches.

#### Steps to Access the System:

1. **Place the System on a Flat Surface**
  - Ensure stability and insulation from static-sensitive surfaces.
2. **Connect the Power Supply**
  - Plug in the variable DC power supply to a standard AC outlet.
  - Connect the output leads to the motor terminals with proper polarity.
3. **Power On the Roller System**
  - Rotate the voltage dial on the power supply to start the roller motor.
  - Adjust speed as necessary using the same dial.
4. **Activate the Vibration Motor**
  - Use the toggle switch or push button connected to Arduino to power on the feeder vibration system.
5. **Check the Electrode System**
  - Ensure the high-voltage module is powered and that the electrode plate is securely grounded.
  - Activate as needed for separation functionality.

There is **no need for user ID, passwords, or computer interface**. All controls are physical and designed for easy operation even by non-technical users.

### 3.4 System Organization & Navigation

#### 3.4.1 System Overview

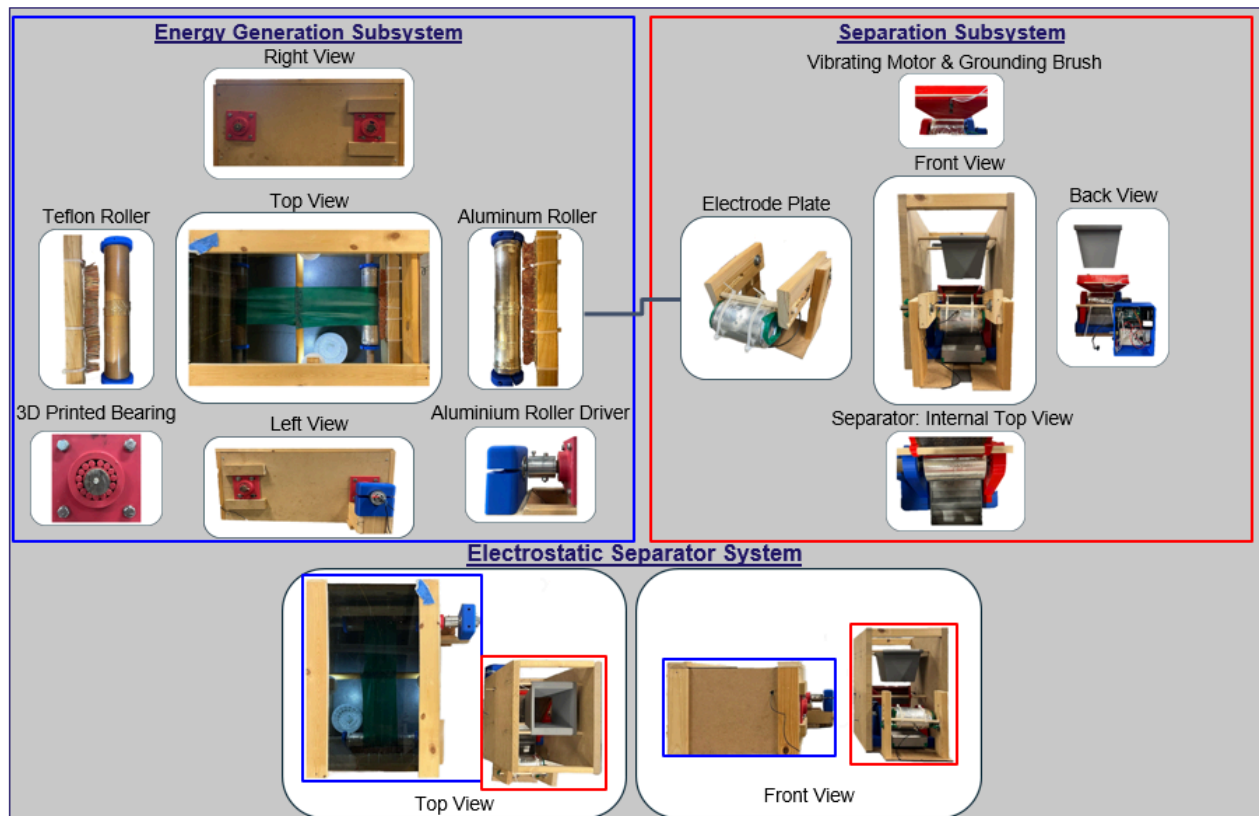


Figure 1: *Electrostatic Separator Subsystem breakdown schematic*

The **Electrostatic Separator System** consists of two primary subsystems that operate in sequence to generate electrostatic charge and separate particles based on their electrical properties:

1. **Energy Generation Subsystem**
2. **Separation Subsystem**

The integration of both subsystems enables the functional separation of mixed materials, such as those from solar panel recycling, based on triboelectric charging and electrostatic attraction or repulsion.

### 3.4.2 Energy Generation Subsystem

#### Purpose:

To generate triboelectric charge via friction between two materials (Teflon and aluminum), which imparts an electrostatic charge to the particles.

#### Main Components:



Figure 2: *Generator system*

- **Teflon Roller:** A triboelectrically negative surface used to build up negative charge through friction.
- **Aluminum Roller:** A triboelectrically positive surface that interacts with the Teflon to create a charge imbalance.

- **3D Printed Bearings:** Custom 3D-printed designed to support roller rotation while minimizing cost.
- **Aluminum Roller Driver:** Motorized mechanism that rotates the aluminum roller to drive the triboelectric process between belt and rollers.

#### **Functionality:**

- As the rollers rotate, materials passing between them experience contact-based charge transfer (triboelectric effect).
- The aluminum roller is powered by a motor, while the Teflon roller is driven.
- Charged particles then proceed to the separation subsystem for sorting.

### **3.4.3. Separation Subsystem**

#### **Purpose:**

To separate the charged particles using a high-voltage electric field and grounded surfaces.

#### **Main Components:**

- **Electrode Plate:** Applies a high-voltage field to attract or repel charged particles depending on their polarity.
- **Vibrating Motor:** Assists in distributing particles evenly and reduces clogging at the inlet.
- **Grounding Brush:** Helps neutralize unwanted or residual charge on certain surfaces.
- **Hopper (Input Feeder):** Holds and feeds the mixed particles into the system in a controlled manner.

#### **Functionality:**

- Charged particles enter the separation area through the hopper.
- The electric field generated by the electrode plate affects particle trajectories.
- Depending on their charge, particles are either attracted to or repelled from specific regions and sorted into distinct collection bins.

## **3.5 Exiting the System**

- Turn dial for generator motor driver to off position
- Press button again to turn off vibrating feeder motor
- Turn dial for rotating drum driver to off position

## 4 Using the System

This section outlines how users can operate the electrostatic separator from beginning to end. The system is designed to be intuitive and safe, even for users with a minimal technical background. Operation includes loading material, controlling the roller speed, enabling vibration, and observing the separation process.

### 4.1 Generator Operation

- Input:
  - No external material input is required. The Teflon roller, in contact with a belt or a counter-material (e.g., aluminum), builds charge through motion.
- Roller Activation:
  - Power the DC motor driving the Teflon roller using the power supply.
  - Adjust speed using the dial or a potentiometer (if present) to optimize friction and charge generation.
- Charge Collection:
  - Use a metal collection surface or Van de Graaff-style dome to observe charge accumulation.
  - High-voltage output can be verified through spark-gap tests or measured using an electrometer.
- Grounding Consideration:
  - Ensure proper grounding of non-charged components to prevent back-discharge.

#### 4.1.1 Manual Adjustments – Generator Subsystem

The generator subsystem is relatively simple and requires minimal tuning, but the following adjustments can help optimize performance:

- Adjust Roller Tension:
  - If the latex belt slips or the aluminum roller doesn't rotate smoothly, slightly reposition the motor or roller holders to increase belt tension. Avoid over-tightening.

- **Roller Speed Control:**
  - Adjust the DC motor speed using the potentiometer or the power supply dial. A moderate speed is typically sufficient for generating charge without excessive friction or instability.
- **Roller Contact Pressure:**
  - Ensure consistent physical contact between the Teflon roller and its friction surface (e.g., belt or aluminum plate). Misalignment may reduce charge generation.
- **Grounding Verification:**
  - Ensure that grounding wires for non-charged components are securely attached. Poor grounding can cause loss of charge or back-discharge.
- **Charge Detection:**
  - To verify effective charge generation, use a spark gap test or place a small metal object nearby to check for static attraction.

## **4.2 Separator Operation**

- **Input:**
  - Load dry, fine particles into the 3D-printed funnel. Ensure the material is free of moisture to avoid clogging or sticking.
- **Roller Activation:**
  - Power on the DC motor via the potentiometer connected to the Arduino. The aluminum roller rotates and imparts charge to the particles through triboelectric contact with the funnel or belt.
- **Vibration Motor Activation:**
  - Use the switch to activate the vibration motor mounted under the funnel to ensure smooth and continuous material flow.
- **Separation Process:**
  - Charged particles are influenced by the high-voltage electrode plate and attracted toward it, falling into the front part of the bin.
  - Neutral or less-charged particles fall straight down into the center of the output tray.

- Monitoring and Adjustment:
  - Throughout the operation, users should observe the particle behavior and make manual adjustments (see 4.1.1) to roller speed, tray angle, or electrode alignment to improve efficiency and separation clarity.
- Safety Monitoring:
  - Never touch the electrode or moving components while powered.
  - Ensure all grounding wires remain connected during use.

#### **4.2.1 Manual Adjustments – Separator Subsystem**

These manual adjustments are critical to fine-tuning the separation effectiveness:

- Tray Alignment and Angle:
  - Change the angle or position of the output bins if particles aren't sorting correctly. Proper alignment ensures that attracted particles fall into the front bin and others into the center bin.
- Electrode Plate Distance:
  - Vary the distance between the electrode and the particle path to adjust the electric field effect. Closer proximity increases separation strength but also risks arcing.
- Roller Speed via Potentiometer:
  - Use the potentiometer connected to Arduino to find the optimal rotation speed. Higher speeds increase throughput; slower speeds may improve charging quality.
- Anti-static Measures:
  - If particles stick to the funnel or roller, consider applying anti-static spray or improving environmental humidity. Ensure grounding wire is intact for reliable discharge.

## **5 Troubleshooting & Support**

This section provides guidance for identifying and correcting common issues that may occur during operation of the Electrostatic Separator System. Each subsection includes a description of the symptom, the likely cause, and clear, step-by-step corrective actions.

## 5.1 Roller System Issues

### Roller Not Spinning

- **Symptom:** One or both rollers are stationary while system is powered.
- **Possible Causes:**
  - Motor is not receiving power.
  - Latex belt is too tight
  - Roller bearings are jammed.
- **Corrective Actions:**
  - Check that the motor is connected to the power supply.
  - Inspect the drive belt; tighten or replace if damaged.
  - Remove rollers and inspect bearings; clean or lubricate as needed.
  - Assist motor by physically spinning roller. If roller begins to spin, and if this intervention is required for every start-up, adjust tension to reduce load on roller.

### Latex Belt Slipping

- **Symptom:** The latex belt between rollers slips during rotation.
- **Possible Causes:**
  - Belt is too loose.
  - Rollers are misaligned.
  - Low tension
- **Corrective Actions:**
  - Increase belt tension slightly by adjusting roller position.
  - Recheck alignment of rollers to ensure parallel contact surfaces.

## 5.2 Separation Issues

### Poor Particle Separation

- **Symptom:** Particles are not sorting into expected collection bins.
- **Possible Causes:**



- Insufficient charge generation in rollers.
- Electrode plate not powered.
- Vibrating motor not operating, causing poor material spread.
- **Corrective Actions:**
  - Confirm proper contact between Teflon and aluminum rollers.
  - Verify the electrode plate is connected to the high-voltage supply.
    - Can conduct spark-gap test to verify voltage accumulation on electrode.  
Should arc from at least 2mm away.
  - Check and test vibrating motor for function; reconnect or replace as needed.
  - Use multimeter to verify that drum is grounded

### **Particles Clumping or Sticking Feeder**

- **Symptom:** Material input is not flowing smoothly through vibrating feeder .
- **Possible Causes:**
  - Moisture in particles.
  - Vibrating motor not active.
  - Hopper walls causing buildup due to static.
- **Corrective Actions:**
  - Dry materials before use to reduce moisture content.
  - Check vibrating motor; replace if malfunctioning.
  - Lightly coat hopper walls with anti-static spray if buildup occurs.

## **5.3 Electrical and Power Issues**

### **System Not Powering On**

- **Symptom:** No response when system is switched on.
- **Possible Causes:**
  - Disconnected power supply.
  - Faulty power adapter.
  - Internal wiring loose or damaged.

- **Corrective Actions:**
  - Ensure all power cords are securely plugged in.
  - Test the power adapter using a multimeter.
  - Open the wiring panel and check for disconnected or frayed wires.
  - Separator: Replace 6V Battery and test again.

### **Electrode Plate Producing No Field**

- **Symptom:** Electrode plate is not generating an electric field.
- **Possible Causes:**
  - High-voltage power module is not functioning.
  - Grounding wire is disconnected.
- **Corrective Actions:**
  - Inspect high-voltage module for LED indicator or heat buildup.
  - Confirm all ground connections are securely attached to the frame.
  - Replace high-voltage module if no output is detected.

## **5.4 Mechanical Failures**

### **Roller Noise or Vibration**

- **Symptom:** Unusual noise or shaking from roller assembly.
- **Possible Causes:**
  - Roller bearings are worn or misaligned.
  - Drive shaft is bent or off-center.
- **Corrective Actions:**
  - Replace worn bearings with matching 3D printed or commercial units.
  - Inspect the shaft and replace if visibly warped.

### **Output Tray Misalignment**

- **Symptom:** Separated particles are falling into incorrect bins.
- **Possible Causes:**

- Tray is misaligned or has shifted.
- Separation angle not optimized.
- **Corrective Actions:**
  - Realign tray underneath the separator outlet.
  - Adjust the separator tilt angle to improve trajectory divergence.

## 5.5 Special Considerations

The electrostatic separator is a high-voltage system that relies on consistent charge buildup and controlled particle flow. The following considerations must be observed:

**Humidity sensitivity:** High humidity can disrupt charge accumulation. Operate the system in a dry environment to maintain effective electrostatic performance.

**Particle size distribution:** The system performs best with particles between 100 microns and 4 mm. Oversized or undersized materials can disrupt separation accuracy.

**Material pre-treatment:** Ensure that materials entering the hopper are dry and free of excess debris or oils, as these can affect charge transfer.

**High voltage safety:** Avoid direct contact with electrode plate and copper brush during operation. Ensure enclosure is secured before use. Individuals with implanted electronic medical devices, such as pacemakers or defibrillators, should not operate or remain in close proximity to the electrostatic separator system during operation. The high-voltage field generated by the system may cause electromagnetic interference that can affect device performance.

**Feed consistency:** Clumping or irregular feeding may lead to poor separation. Always sieve and pre-mix material before feeding.

## 5.6 Maintenance

Regular maintenance is essential to prevent failure and maintain efficiency:

**Daily checks:**

- Ensure all wiring and connections are intact.
- Verify the copper brush is clean and not in contact with the rotating belt.
- Inspect the belt tension and re-align rollers if needed.

**Weekly tasks:**

- Clean electrode plate using a dry cloth to prevent dust buildup.
- Inspect the enclosure for moisture or contaminants.
- Check vibration motor mountings for looseness.

**Monthly service:**

- Recalibrate feeder alignment.
- Inspect all rotating components (rollers, drums) for wear and replace if needed.
- Inspect teflon coating on rollers/vibrating feeder, replace if needed. Similarly, inspect aluminum tape on second roller.

**5.7 Support**

If technical support or emergency assistance is needed, users can contact the project support team via email:

Primary Contact: Nelson Hidocos — [nhido066@uottawa.ca](mailto:nhido066@uottawa.ca)

System Integration Lead: Au Zi-Lam (Marcos) — [zau042@uottawa.ca](mailto:zau042@uottawa.ca)

Chemical Lead: Muhammad Abdullah — [mabdu103@uottawa.ca](mailto:mabdu103@uottawa.ca)

To report a problem:

Send an email with the subject line: “Electrostatic Separator Issue – [Short Description]”.

Include the following:

- Date and time of issue

- Description of problem and observed symptoms
- Any photos or error data
- Steps attempted for resolution

Security Incident Handling:

In case of electrical fire or high-voltage hazard:

- Immediately disconnect power supply.
- Use Class C fire extinguisher.
- Report incident to supervising authority.

## **6 Product Documentation**

The electrostatic separator prototype is divided into mechanical, electrical, and software systems. Below is a breakdown of how each subsystem was developed.

### **Mechanical Design:**

- The roller assembly is composed of a Teflon-covered aluminum drum for triboelectric charge generation.
- The enclosure for both the generator and separator subsystems uses wood and acrylic for visibility, cost efficiency, and electrical insulation.
- A vibrating feeder was integrated to regulate feed distribution.
- Alternatives like pure Teflon rollers were considered but deemed cost-prohibitive.

### **Electrical Design:**

- Power system switched from 24V to 12V (5A) for stability and electrical component voltage/amperage limitations.
- Motor controller optimized using variable control knob.
- Copper brush was iteratively redesigned for optimal charge transfer without direct contact.
- Voltage output achieved up to 20–28 kV.
- Software and Control:

- Arduino Nano used to control motor speed and vibration timing.
- Simple PWM signal programming to adjust speed.
- Tinkercad simulations validated motor performance.


### Material Analysis:

- Sieve system implemented to control particle size.
- Testing verified optimal performance at 0.55 mm average particle size.
- Separation efficiency evaluated using chemical testing (nitric acid, HCl, NaOH).
- Material Substitution Notes:
- Wood frame can be replaced with a fully acrylic/transparent plastic for commercial use.
- Copper brush should maintain spacing; if replaced, must be conductive and flexible (e.g., fine gauge wire).
- Latex belt alternatives (nylon or rubberized fabric) were tested; latex provided best tension and charge response.

## 6.1 Generator Subsystem

### 6.1.1 Equipment list

Table 2: Equipment list – Generator Subsystem

Component	Image
Wooden broomstick - roller core	

Rolling Pin



Teflon Sheet



Aluminum Tape



Copper Wire Brush



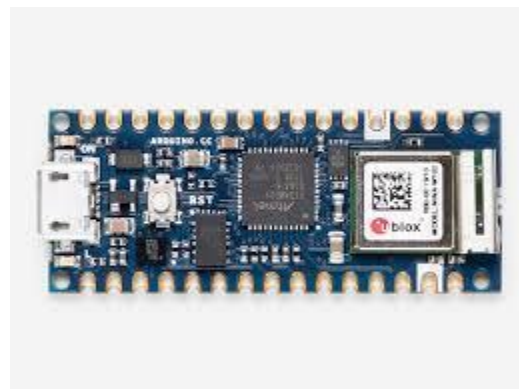
Latex Resistance Band



XD-775 DC Motor

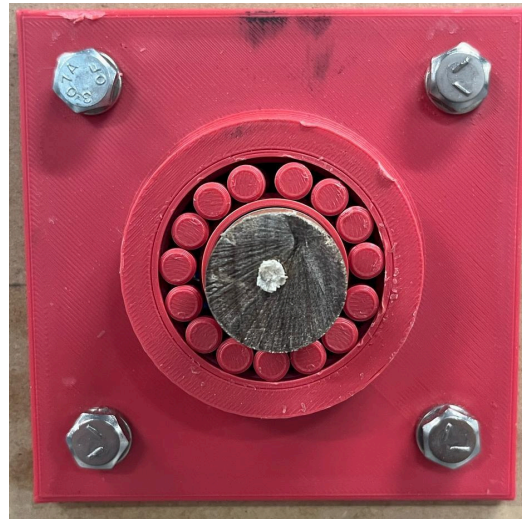


Arduino Nano

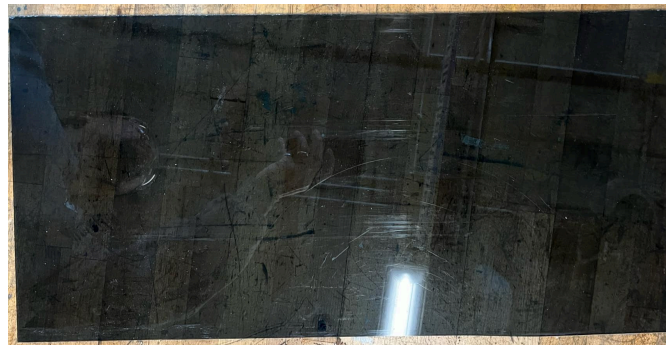




3D-printed bearing mounts



Acrylic Panel



Wooden Planks



MDF Panels



12V/5A Power Supply (With Knob)



### 6.1.2 Instructions

#### Assembly of Triboelectric Generator:

1. Print 3D Bearings
2. Cut two shafts from broomstick to desired length
3. Bore hole into wooden rolling pin to allow for broomstick shafts to fit
4. Sand external surface of broomstick and internal surface of food rollers
5. Apply wood glue to shaft and roller, insert shafter into roller, allow 24h to set.
6. Apply aluminum tape to the outer surface of one roller, latex sheet to the other.
7. Construct rectangular frame with wooden planks using wood screws
  - a. include slots for sliding MDF side panels and acrylic top panel
8. Cut MDF and acrylic panels to size, slide into slotted wood planks.
9. Mount 3D printed bearings on the outside of the side panels, secure using bolts, nuts, and split washers.
10. Insert rollers into bearings
  - a. secure shaft to bearings using adhesive
11. Machine solid aluminum cylindrical bar to include the following (use mill/lathe as appropriate):
  - a. Bore to fit motor shaft
  - b. threaded hole for set screw to secure motor shaft to aluminum roller coupler
  - c. Bore to fit roller shaft (broomstick diameter)
  - d. Through-hole to insert bolt to secure shaft to aluminum coupler.
12. Secure aluminum roller coupler to driven roller shaft from the outside of the bearing.
13. Connect XD-775 DC motor to coupler, secure using set screw.
14. Cut latex belt to size, secure loop using appropriate rubber glue.
15. Affix belt to rollers, adjust tension using slotted bearing mounts.
  - a. Include fixed wooden guide shaft if lateral belt slipping is a consistent issue.
16. Cut 18 gauge copper wire to desired brush length, sharpen one end of each cut section and solder copper bristles to copper wire.
  - a. Create two identical brushes

- i. Brush that is close to motor should have wire connected to ground terminal of motor
  - ii. Second brush will be connected to electrode plate.
17. Install copper brushes 1–2 mm from belt path
  - a. Ensure belt does not touch brush
18. Connect motor to 12V power supply.
19. Cover with acrylic top and secure enclosure.

## **6.2 Separator Subsystem**

### **6.2.1 Equipment list**

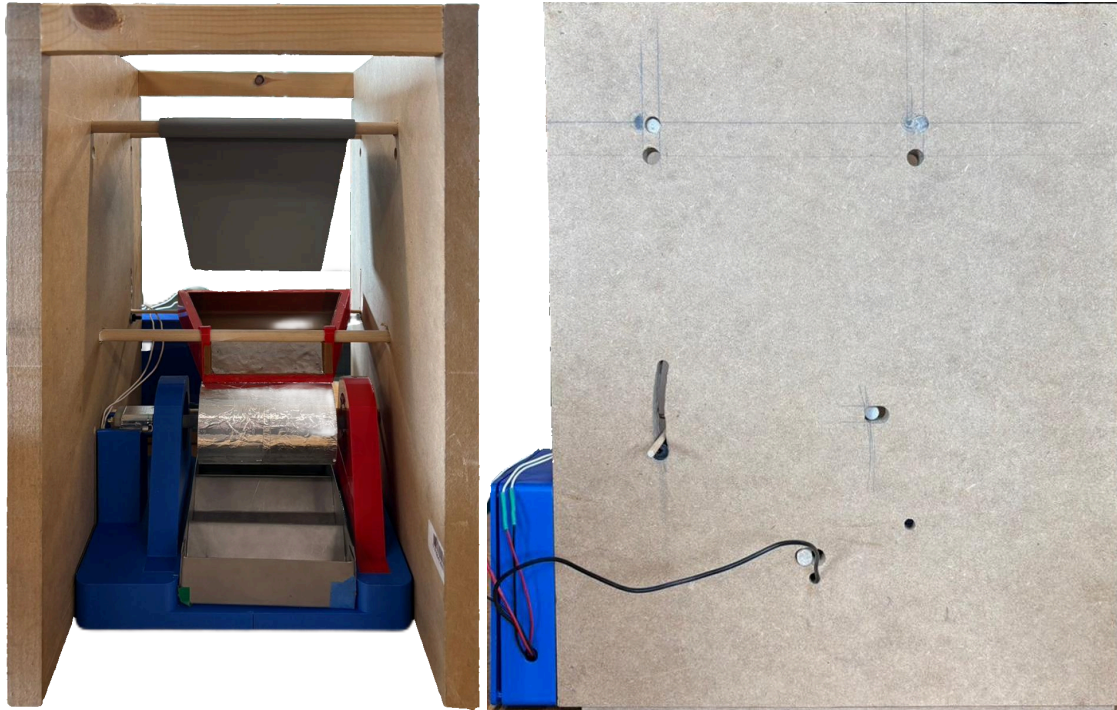
- 3D Printed Roller Holders
- DC Motor (5V)
- Arduino Uno
- Micro Vibration Motor (3V, 12,000 RPM)
- Electrode Plate (aluminum)
- 3D printed Hopper
- Output Bins (3)
- Modular Wooden Frame
- Motor Mounting Brackets
- Connecting Wires
- Potentiometer (for speed control)
- Push Button Switch (for vibration motor)

### **6.2.2 Instructions**

The following outlines the step-by-step instructions to assemble and operate the separator subsystem. This section is intended for non-technical users, including educators or future engineering teams.

#### **Step 1: Frame and Mounting**

- Construct a wooden frame to support the vibration feeder and the 3D-printed hopper.
- Mount the aluminum roller (drum) onto 3D printed holders.



**Figure 3: *Front View & Side View***

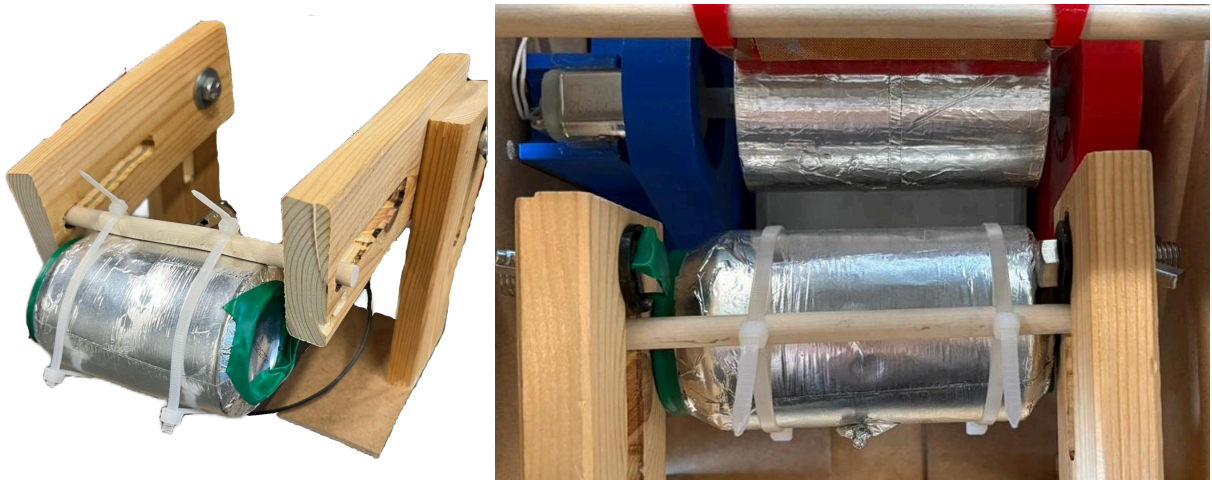
### **Step 2: Vibrating Feeder**

- Create a funnel-style hopper using 3D printed PLA.
- Mount the vibration motor under the feeder base.
- Connect the motor to a power switch (toggle or push button) via Arduino Uno.
- Ensure the feeder gently slopes toward the rotating drum.

### **Step 3: Electrode Plate Placement**

- Position the aluminum electrode roll (or plate) parallel to the drum, close enough for an electric field to influence particles.
- Connect electrode to the copper brush (from generator subsystem).
- Mount securely using adjustable brackets to allow fine-tuning of distance.

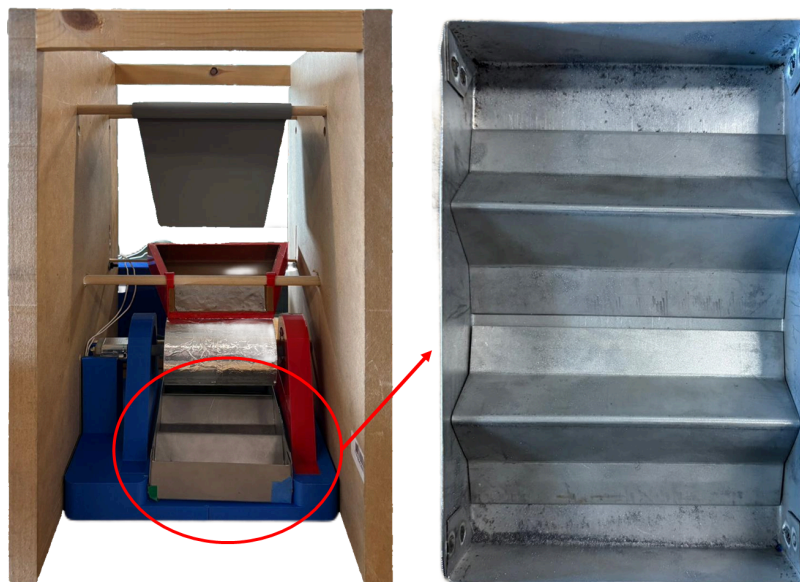




**Figure 4: Modular Roller Assembly Using Wooden Frame**

#### **Step 4: Output Bins**

- Place three bins below the drum, separated by a set of removable or slidable dividers. This setup allows for easier adjustment and more flexible separation of particle types:
  - Front bin: For deflected (highly charged conductive) particles
  - Center bin: For non-conductive or weakly charged particles
  - Rear bin: For overflow or ambiguous separation
- Frame slots can help guide particles cleanly.



**Figure 5: Modular Output Tray with Slidable Dividers for Material Sorting**

## Step 5: Wiring & Controls

- Connect DC motor to potentiometer for speed tuning.
- Connect vibration motor circuit to Arduino digital output and ground.
- Ensure all exposed wires are insulated.

## 6.3 Mechanical Testing

### 6.3.1 Voltage Output Test (Spark Gap Method)

- Place two metal probes connected to the copper brush and ground.
- Gradually increase voltage until a visible spark jumps between probes.
- Measure distance of spark; estimate voltage via Paschen's Law (approx. 3 kV/mm).



**Figure 6: *High-Voltage Discharge Verification via Spark Gap Method***

### 6.3.2 Particle Separation Trial

- Input mixed dry particles via the hopper.
- Observe particle behavior:
  - Conductive particles curve toward electrode and fall into front bin.
  - Non-conductive particles fall directly.
- Adjust tray angle or roller speed to improve sorting.

### 6.3.3 Roller Speed & Motor Control

- Use a potentiometer to test roller at various speeds.
- Observe consistency of rotation and separation effect.
- Note: Speeds around 50–100 RPM worked best for separation.

#### **6.3.4 Feeder Efficiency Test**

- Load hopper with 5g of dry shredded material.
- Activate vibration and measure time to fully dispense.
- Repeat with different angles or vibration motor power settings.

#### **6.3.5 Grounding Verification**

- Use a multimeter to verify all conductive parts (drum, electrode) are properly grounded.
- Improper grounding may result in back discharge or inefficient separation

#### **6.3.6 Modularity & Adjustability**

- Test the ability to:
  - Swap rollers (e.g., material swap test)
  - Change electrode distance
  - Reposition bins
  - Replace motors without rebuilding the frame
- These features improve maintainability and scalability.

### **6.4 B.O.M**

The table below provides a detailed breakdown of all major components used in the construction of the electrostatic separation system, including both the triboelectric generator and the separator subsystems. This Bill of Materials (BOM) outlines the mechanical, electrical, and structural elements required for full system assembly and operation.

All items were selected based on a balance between cost, availability, safety, and functional performance. Where possible, low-cost or recycled materials were used to maintain sustainability and affordability in line with the project's goals. Estimated prices are provided in Canadian Dollars (CAD), and component sources include common suppliers such as Amazon, local hardware stores, and university-provided materials.



This BOM serves not only as a procurement reference for future replication but also as a transparency tool for budget planning and sustainability evaluation.

**Table 3: Bill of Materials (BOM)**

NO	Item	Qty	Unit Price (CAD)	Tax(CAD)	Total (CAD)
1	10 PCS DC 3V 12000RPM Micro Flat Vibration	1	10.29	1.34	11.63
2	DC Stepper Motor Driver BTS7960B H-Bridge	1	16.39	2.13	18.52
3	CEMENT GLUE	2	1.25	0.16	2.66
4	Food Grade Lye Sodium Hydroxide - (1lbs or 453g)	1	21.99	2.86	24.85
5	HEQU PH Test Strips	1	8.9	1.16	10.06
6	24V 6A Power Supply Adapter	1	24.99	3.25	28.24
7	TheraBand Resistance Bands	1	14.62	1.90	16.52
8	FOIL ROLL	1	1.5	0.20	1.70
9	Duracell Coppertop 9V Alkaline Batteries - 4 Pack	1	29.99	3.90	33.89
10	Muriatic Acid 4L	1	21.99	2.86	24.85
11	Distilled Water 4L	1	2.99	0.39	3.38
12	Stainer	1	3.75	0.49	4.24
13	Stainer	1	4.25	0.55	4.80
14	Zip ties	1	2.45	0.32	2.77
					188.10

## 7 Analytical Validation of Prototype Output

To extract and quantify the amount of **silver (Ag)**, **copper (Cu)**, and **aluminum (Al)** present in shredded solar panel waste, chemical testing was done using **acid dissolution, precipitation, and gravimetric analysis techniques**.

This analysis helps evaluate the **economic viability of recycling** and the **efficiency of material separation** from electrostatic and mechanical processes.

### 7.1 Materials and Chemicals

- Solar panel feedstock (5 g, 10 g, 20 g)
- Distal feed (5 g, 10 g, 20 g)
- Middle feed (5 g, 10 g, 20 g)
- 6M Nitric Acid (HNO<sub>3</sub>)
- 3M Hydrochloric Acid (HCl)

- 3M Sodium Hydroxide (NaOH)
- Distilled Water
- Filter papers, beakers, glass rods, pH paper
- Drying oven (50–60°C)

## 7.2 Experimental Procedure

### Step 1: Acid Dissolution of Metals

- React a weighed sample of feed (**commonly 5 g or 10 g**) with **100–200 mL of 6M HNO<sub>3</sub>** in a glass beaker.
- Stir the mixture with reasonable stirring (**300-500 RPM**) and maintain it at either room temperature or **~50°C** to speed up dissolution.
- Let the reaction last for at least **2-4 hours** until a noticeable color change (typically blue for copper) and reduction in solid mass is observed.

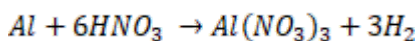
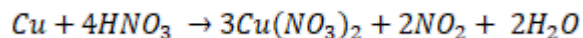
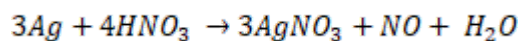


Figure 7: *Addition of Nitric Acid in feed sample.*

### Step 2: Filtration of Residue

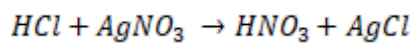
- After the reaction, filter the mixture using a filter paper.
- Collect the **residue** (unreacted solids, plastics, silicon) and **dry at 60°C for 24 hours**.



Figure 8: *Separation of filtrate and residue.*

### Step 3: Precipitation of Silver as AgCl

- Treat the **filtrate** containing dissolved metal ions with **3M HCl (100–200 mL)** to precipitate **Ag<sup>+</sup> as AgCl**.
- Stir the mixture and allow it to sit for up to 24 hours to ensure complete precipitation. The solution will turn green which is an indicator for Copper Chloride (CuCl<sub>2</sub>).
- Filter, dry, and weigh the white AgCl precipitate.





**Figure 9:** *Addition of HCl in filtrate turns it green due to Copper Chloride formation.*

**Step 4: Precipitation of Aluminum Hydroxide ( $\text{Al}(\text{OH})_3$ )**

- After AgCl filtration, **add NaOH dropwise** to the filtrate to adjust the **pH to ~5**.
- At this pH,  **$\text{Al}^{3+}$  ions will precipitate as white  $\text{Al}(\text{OH})_3$** , which can then be filtered, dried, and weighed.

**Step 5: Precipitation of Copper Hydroxide ( $\text{Cu}(\text{OH})_2$ ) and Conversion to CuO**

- After  $\text{Al}(\text{OH})_3$  is removed, add more NaOH to raise the pH to **~9–10**, precipitating  **$\text{Cu}^{2+}$  as  $\text{Cu}(\text{OH})_2$  (blue)**.
- Heating or drying the  $\text{Cu}(\text{OH})_2$  converts it to **CuO (black)**, which can then be weighed.



Figure 10: *Drying converts blue  $\text{Cu}(\text{OH})_2$  into black  $\text{CuO}$ .*

### 7.3 Chemical Selection and Process Parameters

#### 7.3.1 Use of $\text{HNO}_3$

- Nitric acid is a **strong oxidizing acid** that effectively dissolves metals like **Cu, Ag, and Al**. A concentration of **6M** ensures rapid and complete dissolution while being manageable in terms of lab safety.
- The volume (100–200 mL) is selected to **fully submerge** the feed and allow for **uniform reaction**, especially in finely powdered samples.
- Using a higher quantity will cause **Excess  $\text{NO}_3^-$  ions** to form **soluble complexes with  $\text{Ag}^+$** , preventing  $\text{AgCl}$  precipitation unless strong  $\text{HCl}$  is used. Additionally, **overly diluted metal ion concentration** makes **precipitation less efficient**, especially for  $\text{AgCl}$  (may delay or prevent full formation).

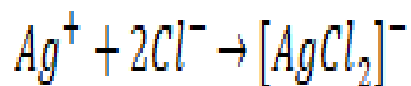
#### 7.3.2 Drying

- Drying ensures **accurate weight measurement** of the solid residue. **Moisture content can skew the data**, particularly because metal hydroxides (like  $\text{Al}(\text{OH})_3$  or  $\text{Cu}(\text{OH})_2$ ) are hygroscopic.

- Using an oven instead of letting the residue dry in open air is preferred, as some metal hydroxides may still remain in the residue and will absorb atmospheric humidity.
- Since filter papers are being used for filtration, it is best to weigh the filter paper before filtration because it is difficult to completely scrape the residue of precipitate from the filter paper. The weight of filter paper can then be subtracted to determine the exact weight of residue or precipitate.
- Do not set the oven temperature to more than 60°C as filter papers are cellulose-based and may decompose at higher temperatures.

### 7.3.3 Use of HCl

- Silver forms an **insoluble white precipitate (AgCl)** when reacted with  $\text{Cl}^-$  ions. A moderate concentration of **3M HCl** is enough to provide  $\text{Cl}^-$  ions for the reaction while avoiding excess acidity that might form soluble complexes.
- Delayed precipitation was sometimes observed due to **complexation with  $\text{NO}_3^-$  ions**, which was corrected by waiting for 24 hours or using slightly more concentrated HCl.
- **Excess  $\text{Cl}^-$  ions** can form **soluble silver complexes**, like



### 7.3.4 Importance of Precise pH Control

Maintaining accurate pH at each stage is **critical** to:

- **Ensure correct metal precipitates** form.
- **Prevent redissolution** (Al and Cu hydroxides redissolve in strong base).
- **Enable selective separation** of metals (Ag at low pH, Al at ~5, Cu at ~9).

### 7.3.5 pH 5 for $\text{Al}(\text{OH})_3$ precipitation

- $\text{Al}(\text{OH})_3$  precipitates best between **pH 4.5 and 6**. If the pH goes above **~9**,  $\text{Al}(\text{OH})_3$  **dissolves again**, forming  $[\text{Al}(\text{OH})_4]^-$  (a soluble aluminate ion), causing loss of aluminum in solution.
- If pH is increased,  $\text{Cu}(\text{OH})_2$  will be formed. Decreasing the pH by adding HCl does not cause  $\text{Cu}(\text{OH})_2$  to revert to a soluble form. Very careful monitoring of pH is required, and drop-wise addition of NaOH ensures that pH does not overshoot.

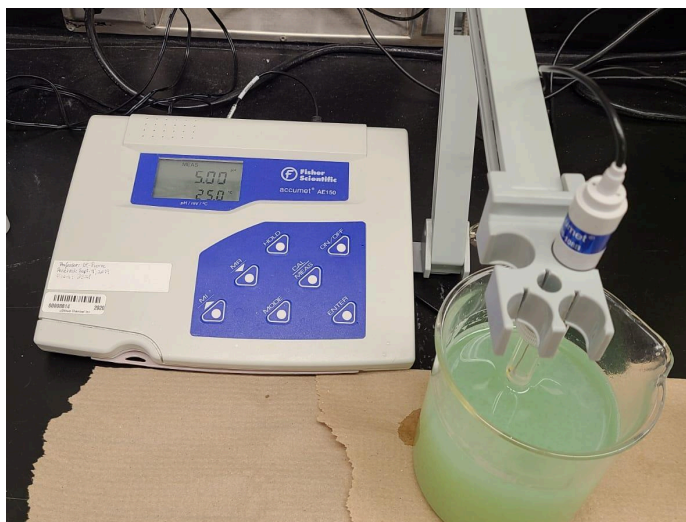


Figure 11: *Precise pH control for  $\text{Al}(\text{OH})_3$  precipitation.*

### 7.3.6 pH 9-11 for $\text{Cu}(\text{OH})_2$ precipitation

- $\text{Cu}^{2+}$  precipitates as  $\text{Cu}(\text{OH})_2$  at around pH 9–11. If pH goes too high,  $\text{Cu}(\text{OH})_2$  can form soluble  $[\text{Cu}(\text{OH})_4]^{2-}$ .
- $\text{CuO}$  is **more stable for weighing** because it doesn't retain water like  $\text{Cu}(\text{OH})_2$ , ensuring **accurate mass analysis**. However, **pH 13-14** is required for  $\text{CuO}$  formation. This high pH may cause the filter paper to decompose or degrade.
- $\text{CuO}$  does not always form at **pH 13-14**. It is preferable to precipitate Copper in  $\text{Cu}(\text{OH})_2$  form and let it dry in an oven for **2-3 days** until all  $\text{Cu}(\text{OH})_2$  is decomposed to  $\text{CuO}$ .





Figure 12: *Precise pH control for  $\text{Cu}(\text{OH})_2$  precipitation.*

### 7.3 Observations and Color Indicators

- **Blue color after  $\text{HNO}_3$  addition** → Presence of  $\text{Cu}^{2+}$
- **White cloudiness after  $\text{HCl}$**  →  $\text{AgCl}$  precipitation
- **Green color of solution after  $\text{HCl}$**  →  $\text{CuCl}_2$  formation
- **White-blue precipitate at pH 5** →  $\text{Al}(\text{OH})_3$  along with some  $\text{Cu}(\text{OH})_2$
- **Green precipitate at pH 5** →  $\text{Ni}(\text{OH})_2$
- **Blue precipitate at pH 8–9** →  $\text{Cu}(\text{OH})_2$
- **Black precipitate after heating** →  $\text{CuO}$

### 7.5 Gravimetric Conversion Factors

To convert the weights of the precipitates into elemental form, use the following conversion formulas:



$$M_{Ag} = M_{AgCL} \times \frac{107.87}{143.32}$$

$$M_{Al} = M_{Al(OH)_3} \times \frac{26.98}{78.00}$$

$$M_{Cu} = M_{Cu(OH)_2} \times \frac{63.55}{97.56}$$

$$M_{Cu} = M_{CuO} \times \frac{63.55}{75.55}$$

## 7.4 Testing Results

Chemical analysis was done on the middle and distal feed samples, as they would have the highest amount of metals. A visible difference between the Distal and Middle samples is the difference in particle size. The middle feed has larger particles as compared to the Distal sample. This can be attributed to the fact that the prototype can only attract small-sized metal particles due to the lower voltage of 6000 volts. Typical industrial electrostatic separators generate upwards of 30000 volts, which can readily attract even larger metal particles. Additionally, some bronze copper particles were also observed in the middle feed, but they were not attracted towards the distal feed due to their larger size.



**Figure 13:** *Difference in particle size between Distal (left) and Middle (right) samples.*



**Figure 14:** *Difference in Copper Nitrate concentration between the Middle (left) and Distal (right) samples.*

The filtration provided definitive proof that the electrostatic separator is indeed separating metals from non-metals. The blue color, which indicates the presence of Copper Nitrate, is much more intense in blue color for the Distal sample as compared to the Middle sample. When 100 mL of Hydrochloric Acid (3M) was added to form Silver Chloride, Copper Chloride is also formed as a side reaction.

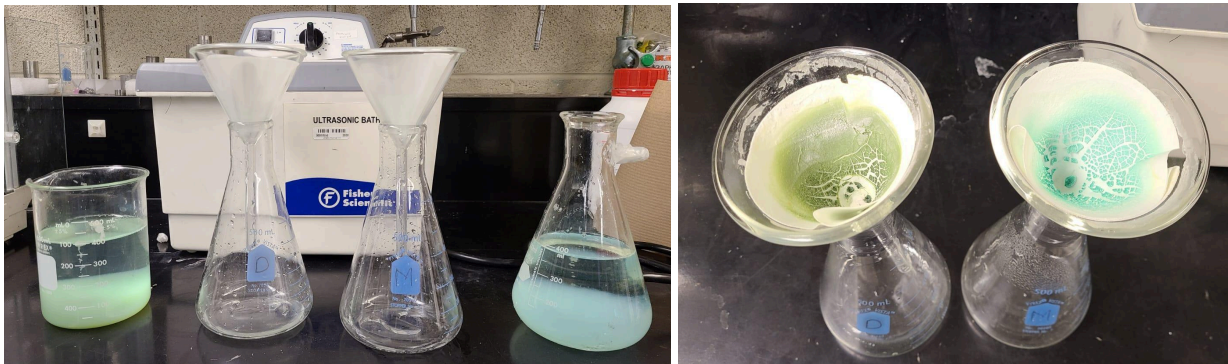


**Figure 15:** *Difference in Copper Chloride concentration between the Middle (left) and Distal (right) samples.*

The green color, distinctive to Copper Chloride, is much more intense in the distal sample as compared to the middle sample.



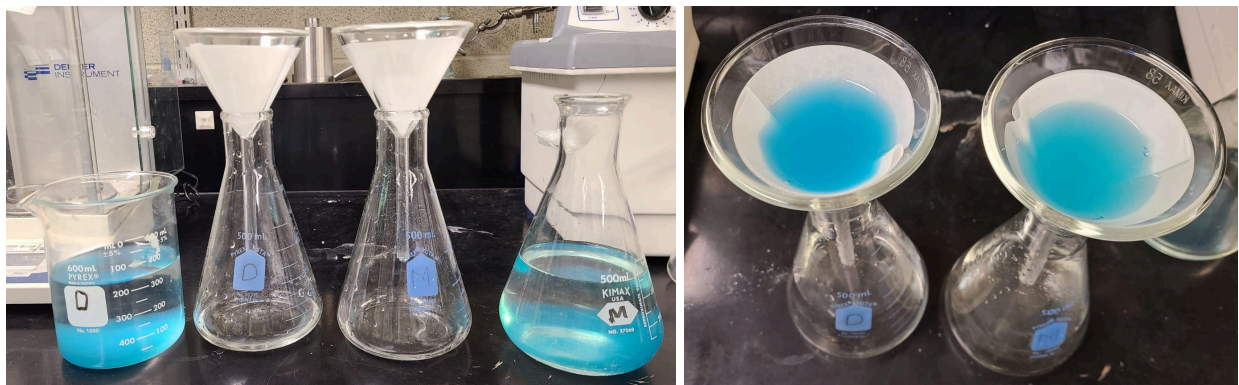
**Figure 16:** *Difference in Silver Chloride precipitate between Middle (left) and Distal (right) samples.*



**Figure 17:** *Distal sample precipitate shows a darker green color which may indicate presence of Nickel Hydroxide.*

When the pH of filtrate was increased to 5 for  $\text{Al}(\text{OH})_3$  precipitation, solution will turn blue. This is because some  $\text{Cu}(\text{OH})_2$  will also start to form even at this pH. Observing filtrate for both the Distal and Middle samples, the Distal sample showed a dark green hue along which may indicate presence of Nickel Hydroxide ( $\text{Ni}(\text{OH})_2$ ). However, this has to be confirmed through X-ray Fluorescence or Scanning Electron Microscopy methods.

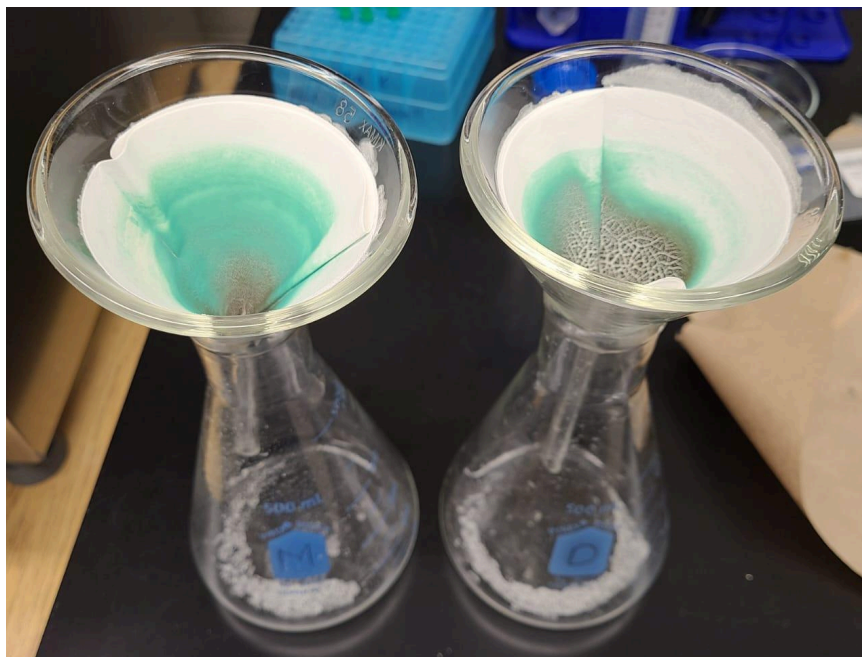




**Figure 18:** *Distal sample has more copper Copper content indicated by a darker blue hue.*

When pH is increased to 10 or 11, Copper Chloride will precipitate. Distal sample has a more darker blue color which indicates taht more copper content is present. Separate the copper hydroxide from solvent through filtering and dry it.

When drying the copper hydroxide sample, it will start to convert into Copper Oxide. Leave it in the oven or dryer for 48 hours or more till all the Copper Hydroxie is dehydrated.



**Figure 19:** *Distal sample has more copper Copper content indicated by a darker blue hue.*

## 7.5 Safety and Waste Disposal

- **Acid Handling:** Always use a fume hood and add acid to water, never water to acid to prevent splashes.
- **Neutralization:** Any remaining acid waste should be neutralized with NaOH before disposal. Use pH strips to verify neutralization.
- **Proper Waste Storage:**
  - **Liquid Waste:** Store in labeled acid-waste containers for disposal.
  - **Solid Waste:** Collect silicon residues separately for further use or analysis.
  - **PPE Compliance:** Always wear gloves, safety goggles, and a lab coat.

## 8 Conclusions and Recommendations for Future Work

This project demonstrated that with a modest budget, interdisciplinary effort, and thoughtful design, a **functional and safe electrostatic recycling system** can be developed to address the pressing challenge of solar panel waste. The knowledge gained here serves as a launchpad for future innovation in sustainable material recovery and circular economy technology.

We hope that future groups will take advantage of our documentation, insights, and groundwork to improve and scale this project into a solution that contributes meaningfully to global sustainability goals.

### 8.1 Summary of Lessons Learned and Project Outcomes

The development of the **Solar Panel Recycling Sorter** has provided valuable insights into the design, construction, testing, and optimization of a low-cost, energy-efficient, and environmentally friendly **electrostatic separator**. The project successfully met its goal of demonstrating a functional prototype capable of separating conductive and non-conductive materials from shredded solar panel waste. The use of **triboelectric charging** and **electrostatic**

**deflection** proved effective in validating the feasibility of a chemical-free and modular separation method.

Through iterative prototyping, we learned the importance of:

- **Particle size control:** The efficiency of electrostatic separation is significantly affected by the size, dryness, and uniformity of the particles.
- **Voltage optimization:** Charge generation at 6–7.5 kV was sufficient for small particles, but inadequate for consistent attraction of larger metallic fragments.
- **Chemical validation:** The combination of **acid dissolution**, **precipitation**, and **pH-controlled separation** allowed for accurate identification of metals such as **Ag**, **Cu**, and **Al**, confirming the functional sorting performed by the system.
- **System grounding and environmental control:** Humidity, poor grounding, or misalignment caused inconsistent separation, emphasizing the need for strict environmental and setup protocols.
- **Manual calibration:** Small physical adjustments to tray angle, electrode distance, and motor speed dramatically influenced separation behavior.

Despite the functional success, we also encountered limitations in terms of **mechanical robustness**, **voltage constraints**, and **scalability**, which inform our recommendations for future improvements.

## 8.2 Implications and Significance

The outcomes of this project suggest that **electrostatic separation** offers a viable and sustainable alternative to traditional PV recycling methods. Unlike high-temperature or acid-intensive processes, this prototype is:

- **Non-destructive:** It avoids altering or damaging recoverable metals.
- **Modular and replicable:** It uses affordable components that can be upgraded or scaled.
- **Educationally valuable:** It serves as a functional demonstration tool for electrostatics, material recovery, and sustainability principles.

This system lays the foundation for a **larger initiative in circular solar economy research**, enabling future student teams, startups, or research groups to build upon an already validated base.

### 8.3 Remaining Challenges and Future Recommendations

Although we made significant progress, several areas require further work for this prototype to evolve into a scalable, industry-ready solution.

#### 1. Voltage Scaling and Charge Enhancement

- **Challenge:** The prototype was limited to ~6–7.5 kV due to component and safety constraints. This restricts its ability to separate heavier or larger metallic particles.
- **Recommendation:** Future teams should investigate using **boost converter modules** or **transformer-based power supplies** to reach ~30–40 kV while implementing stricter safety enclosures (e.g., Faraday cages).

#### 2. Automated Material Feeding

- **Challenge:** Manual feeding led to inconsistent flow rates and particle clumping.
- **Recommendation:** Integrate **sensor-controlled vibration motors** or stepper-driven feeder screws to regulate input flow automatically.

#### 3. Enhanced Material Analysis

- **Challenge:** Chemical testing relied on visual observation and gravimetric estimation.
- **Recommendation:** Introduce **quantitative techniques** like **XRF**, **AAS**, or **ICP-MS** to measure metal content and validate purity of recovered materials more accurately.

#### 4. Replace Latex Belt

- **Challenge:** Latex belts offered good flexibility but wore out quickly and were sensitive to humidity.
- **Recommendation:** Test alternative materials like **conductive nylon**, **rubberized Kevlar**, or **thermoplastic polyurethane (TPU)** for improved durability and charge response.

## 5. Integrated Safety Interlocks

- **Challenge:** The system currently requires manual safety adherence.
- **Recommendation:** Add **interlock switches**, **voltage indicators**, and **emergency stop buttons** to improve lab safety and usability for non-technical users.

## 6. Industrial Scalability

- **Challenge:** The prototype is currently limited to small-scale lab testing.
- **Recommendation:** Redesign components with **aluminum framing**, **industrial-grade motors**, and **enclosed dust management** for continuous operation in industrial testbeds.

## 7. Abandoned or Delayed Features (due to Time Constraints)

If we had more time, we would have:

- Developed a **feedback-based control system** using Arduino to automate the vibration and roller speeds based on load.
- Created a **web dashboard or GUI** to visualize separation efficiency or trigger process adjustments.
- Designed **more refined collection bins** with automated weight sensors to track output in real time.
- Expanded testing to include **multi-material blends** (e.g., batteries, e-waste) to explore cross-application potential.



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