

Hardware Layer – Detailed Technical Specifications

The hardware layer forms the foundation of the Smart Waste Bin Monitoring System. It is designed to be **low-power, reliable, and scalable**, enabling long-term deployment across urban environments with minimal maintenance.

1. Microcontroller Unit (MCU)

Component: ESP32 with Integrated LoRa Module (e.g., ESP32 + SX1276/SX1278)

Technical Specifications

- **Processor:**
Dual-core Xtensa® 32-bit LX6
Clock frequency up to **240 MHz**
- **Memory:**
SRAM: ~520 KB
Flash: 4 MB (typical)
- **Wireless Interfaces:**
Integrated **LoRa transceiver**
Optional Wi-Fi & Bluetooth (disabled in normal operation to save power)
- **Operating Voltage:**
3.3 V
- **Deep Sleep Current:**
~10–15 µA (ideal for battery-powered nodes)

2. Waste Level Sensor

Component: HC-SR04 Ultrasonic Distance Sensor

Technical Specifications:

- **Operating Voltage:** 5 V (regulated from battery)
- **Measuring Range:** 2 cm – 400 cm
- **Accuracy:** ±3 mm
- **Measurement Principle:**
 - Time-of-Flight (ToF) using ultrasonic sound waves

Working Principle

- Sensor emits an ultrasonic pulse from the bin lid.
- Pulse reflects off the waste surface.
- Time taken for echo return is used to calculate distance.
- Fill level is computed as:

$$\text{Fill \%} = (\text{Bin Height} - \text{Measured Distance}) / \text{Bin Height} \times 100$$

3. Power Supply System

Components:

- **Battery:** 18650 Li-ion Cell (2500 mAh)
- **Battery Management System (BMS)**

Technical Specifications

- **Battery Voltage:**
 - Nominal: 3.7 V
 - Fully charged: 4.2 V
- **Capacity:**
 - 2500 mAh
- **BMS Features:**
 - Over-charge protection
 - Over-discharge protection
 - Short-circuit protection

Power Strategy

- ESP32 remains in **deep sleep mode** for most of the time.
- System wakes up:
 - Every 30–60 minutes for sensing
 - Immediately when threshold change occurs
- Average current consumption remains extremely low, enabling **multi-year battery life**.

4. Networking & Communication

Technology: LoRaWAN

Network Architecture

- **Topology:** Star-of-Stars
 - Bin Nodes → LoRa Gateway → Cloud Server
- **Range:**
 - 2–5 km (urban)
 - Up to 10 km (open areas)

- **Frequency Band:**
 - 865–867 MHz (India ISM band)

Communication Characteristics

- **Low data rate** (ideal for sensor telemetry)
- **Small payload size** (bin ID, fill %, battery level)
- **Asynchronous transmission** reduces power consumption
- Supports **hundreds of nodes per gateway**

Justification

- LoRaWAN avoids network congestion seen in Wi-Fi systems.
- One gateway can manage **100+ bins across multiple zones**.
- Highly suitable for smart city deployments due to:
 - Low operational cost
 - Long range
 - High scalability

5. Overall Hardware Design Benefits

- **Low Power Consumption:** Enables long-term deployment
- **Scalable Architecture:** Supports city-wide expansion
- **Cost-Effective:** Affordable per-node hardware
- **Robust Communication:** Reliable in dense urban areas
- **Maintenance-Friendly:** Minimal human intervention required