LAPORAN PENELITIAN ISPO

BINSAI: Pengembangan Sistem Monitoring Bak Sampah Berbasis Sensor Jarak Non-Kontak dan *Node Internet Of Things* (IoT) Terintegrasi dengan Aplikasi *Mobile* Blynk dalam Mendukung *Smart Waste Management* di Kota Yogyakarta

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Abstrak

Permasalahan penumpukan sampah di perkotaan, khususnya di Kota Yogyakarta karena terbatasnya kapasitas TPA Piyungan, membutuhkan pendekatan pengelolaan yang lebih cerdas dan responsif. Penelitian ini bertujuan untuk mengembangkan dan menguji BINSAI (Bin Intelligence Sensor and Internet), prototipe sistem pemantauan tempat sampah berbasis Internet of Things (IoT) yang terintegrasi. Sistem ini dirancang untuk mengoptimalkan operasi pengangkutan sampah melalui pemantauan kapasitas secara real-time dan indikasi dekomposisi sampah organik. Metode penelitian menggunakan pendekatan Penelitian dan Pengembangan (R&D) yang memanfaatkan mikrokontroler ESP32 yang terintegrasi dengan sensor ultrasonik HC-SR04 untuk pengukuran volume dan sensor gas MQ-135 untuk mendeteksi konsentrasi amonia. Data diproses dan dikirimkan ke platform Blynk untuk visualisasi, sedangkan modul GSM SIM800L dan GPS NEO-6M memberikan pemberitahuan prioritas dan pelacakan lokasi melalui SMS ketika kondisi kritis terdeteksi. Hasil pengujian menunjukkan bahwa sensor ultrasonik memiliki akurasi 99,46%, model deteksi gas memiliki validitas (R^2 = 0,987), dan transmisi notifikasi memiliki keandalan 100%. Konsep tempat sampah pintar modular memungkinkan implementasi yang fleksibel di area publik dengan fluktuasi volume tinggi. Penelitian ini menyimpulkan bahwa BINSAI berpotensi menjadi solusi transformatif dalam mendukung pengelolaan sampah yang cerdas, meningkatkan efisiensi operasional, dan berkontribusi dalam mengurangi beban TPA. Semua dokumentasi teknis dan kode sumber dipublikasikan secara terbuka di repositori GitHub untuk memastikan transparansi dan keberlanjutan pengembangan.

Kata kunci: *Smart Waste Management*, *Internet of Things* (IoT), *Ultrasonic Sensor*, Gas Sensor, Blynk, *Modularity*, Kota Yogyakarta.

BAB 1. PENDAHULUAN

1.1 LATAR BELAKANG

Indonesia sebagai negara kepulauan terbesar di dunia menghadapi tantangan serius dalam pengelolaan sampah seiring dengan pertumbuhan penduduk, ekonomi, dan konsumsi masyarakat. Pengelolaan sampah merupakan tanggung jawab kolektif yang efektivitasnya masih terkendala oleh banyak faktor, salah satunya yakni keterbatasan sarana (Arifin, 2024; Vedita, 2022). Berdasarkan data Kementerian Lingkungan Hidup dan Kehutanan (KLHK), timbulan sampah nasional pada tahun 2023 mencapai 69,7 juta ton (Sumbitmele, 2024). Penumpukan sampah yang tidak terkelola secara deterministik dapat memicu degradasi lingkungan, risiko banjir, ancaman kesehatan masyarakat, dan merusak estetika lingkungan perkotaan.

Masalah tersebut semakin nyata di kota-kota besar, termasuk Kota Yogyakarta dimana evakuasi sampah ke TPA Piyungan mengalami stagnasi akibat keterbatasan kapasitas (Pangaribowo & Hartik, 2025). Kisaran tahun 2021 hingga 2025, telah terjadi penumpukan sampah di TPA Piyungan, dengan jumlah sampah terbanyak yaitu mencapai 700 ton sampah per hari (Pemerintah Kabupaten Bantul, 2025). Krisis ini diperparah oleh lonjakan jumlah wisatawan yang diperkirakan mencapai 1,1 juta orang diprediksi menambah sekitar 550 ton sampah tambahan per hari (Suhamdani, 2025). Sedangkan, Kota Yogyakarta saat ini per harinya menghasilkan sekitar 300 ton sampah, sementara kuota yang diperbolehkan masuk ke TPA hanya 600 ton per bulan (Adminwarta, 2025). "Hanya kota yang evakuasi ke TPA Piyungan", ucap Aris Prasena selaku Kepala Balai Pengelolaan Sampah DLHK, DIY. Disamping itu, penutupan sementara Tempat Pembuangan Akhir (TPA) Piyungan telah dimulai sejak pertengahan 2024 yang lalu (Daeng, 2024).

Mengingat kompleksitas dinamika perkotaan yang kian akseleratif, pendekatan manajemen sampah konvensional yang bersifat *fixed-schedule* telah mencapai titik stagnansi sehingga tidak lagi memadai untuk memitigasi laju timbulan limbah. Fenomena ini menuntut adanya pergeseran paradigma menuju *evidence-based waste management* yang mengintegrasikan ekosistem *Internet of Things* (IoT) sebagai pilar utamanya. Implementasi konvergensi sensor yang meliputi sensor ultrasonik untuk analisis volumetrik dan sensor gas amonia untuk mendeteksi kinetika dekomposisi organik, memungkinkan terjadinya ekstraksi telemetri secara *real-time*. Melalui sinkronisasi data tersebut, sistem mampu mereduksi ambivalensi informasi di lapangan, sehingga proses mobilisasi armada pengangkutan dapat dilakukan berdasarkan prioritisasi presisi yang mengoptimalkan alokasi sumber daya serta meningkatkan agilitas operasional dalam manajemen limbah perkotaan.

Penelitian ini mengembangkan BINSAI (*Bin Intelligence Sensor and Internet*) sebagai prototipe sistem monitoring bak sampah cerdas yang terintegrasi dengan platform Blynk. Penelitian ini terbatas pada *prototype* sistem monitoring dengan dua parameter utama, yakni kapasitas dan dispersi gas hasil dekomposisi organik. Klasifikasi sampah bersifat indikatif berdasarkan *threshold empiris*, bukan identifikasi kimiawi. Berbeda dengan sistem statis, BINSAI dirancang secara modular dengan sistem notifikasi prioritas berbasis lokasi (GPS dan GSM) untuk meningkatkan agilitas operasional petugas. Guna menjamin reproduksibilitas riset dan transparansi data, seluruh kode sumber dan dokumentasi teknis sistem BINSAI dipublikasikan secara terbuka melalui repositori GitHub dengan Lisensi MIT.

Implementasi sistem IoT ini merupakan langkah awal dalam akselerasi transformasi digital pengelolaan sampah di Yogyakarta. Hal ini tidak hanya mendukung pengurangan beban TPA Piyungan, tetapi juga memperkuat pilar *Smart City* melalui penyediaan dataset *time-series* yang terukur dan saintifik (Sa'diyah et al., 2020; Lianawati, 2024).

1.2 RUMUSAN MASALAH

Adapun rumusan masalah terkait penelitian ini adalah sebagai berikut.

1. Bagaimana merancang sistem BINSAI berbasis *Internet of Things* (IoT) yang mengintegrasikan mendeteksi ketinggian, indikasi dekomposisi sampah terhadap kadar gas amonia, dan geolokasi ke dalam dashboard Blynk secara *real-time*?
2. Bagaimana tingkat responsivitas dan akurasi sistem prioritisasi notifikasi berbasis *adaptive threshold* dalam mengoptimalkan manajemen pengangkutan sampah?
3. Bagaimana merancang konsep *modular smart bin* dalam mengakomodasi fluktuasi volume sampah di kawasan publik dengan lonjakan aktivitas tinggi?
4. Bagaimana mengelola dokumentasi teknis dan kode sumber BINSAI pada repositori terbuka guna menjamin reproduksibilitas riset bagi pengembangan *Smart City* di masa depan?

1.3 TUJUAN PENELITIAN

Berdasarkan rumusan masalah, dapat disimpulkan tujuan penelitian sebagai berikut.

1. Merancang sistem BINSAI berbasis mikrokontroler ESP32 yang mampu melakukan ekstraksi telemetri data kapasitas dan indikasi dekomposisi secara akurat melalui akuisisi data jarak jauh.
2. Menganalisis performa sistem notifikasi terprioritaskan dalam memberikan informasi presisi mengenai urgensi penanganan titik sampah kritis.

3. Merancang dan menguji agilitas operasional konsep *modular smart bin* dalam platform BINSAI yang efektif untuk mendukung pengelolaan sampah di kawasan publik dan area dengan aktivitas tinggi.
4. Mengakselerasi transparansi dan reproduksibilitas riset melalui publikasi komprehensif seluruh kode sumber serta dokumentasi teknis perangkat keras pada repositori GitHub di bawah naungan lisensi terbuka.

1.4 MANFAAT PENELITIAN

Berdasarkan rumusan masalah dan tujuan penelitian, manfaat penelitian ini adalah sebagai berikut.

1.4.1 Manfaat Teoritis

Penelitian ini berkontribusi pada pengayaan literatur Internet of Things (IoT) melalui pengembangan BINSAI yang mengintegrasikan multi sensor konvergen (jarak dan gas) secara *real-time*. Inovasi ini memungkinkan mitigasi operasional preventif seperti persiapan material khusus sebelum evakuasi, memperkuat konsep *open science* dalam pengembangan teknologi, serta memperkuat konsep smart bin modular sebagai pilar teknologi ramah lingkungan dalam mendukung ekosistem *Smart City*.

1.4.2 Manfaat Praktis

1. Optimasi Alokasi Kuota TPA: Transformasi pengelolaan sampah melalui prioritisasi presisi berbasis lokasi dan data *real-time*. Dengan *adaptive threshold*, sistem memastikan kuota terbatas TPA Piyungan dialokasikan secara selektif pada titik kritis (>90% + organik), guna mereduksi beban lingkungan secara signifikan dibanding distribusi konvensional.
2. Meskipun transmisi data pada fase *proof of concept* ini masih bersifat lokalitas-dependen, arsitektur BINSAI dirancang dengan interoperabilitas tinggi guna mengintegrasikan infrastruktur publik dan sinergi CSR sektor privat.
3. Agilitas Operasional Modular: Implementasi konsep modular smart bin yang fleksibel dan plug-and-play, memungkinkan mobilisasi perangkat secara dinamis untuk mengantisipasi lonjakan volume sampah di kawasan strategis dan pusat aktivitas publik.

BAB 2. TINJAUAN PUSTAKA

2.1 Kajian Teori

Penelitian BINSAI dibangun di atas integrasi sistem tertanam, sensor cerdas, dan komunikasi nirkabel untuk mewujudkan tata kelola limbah yang responsif.

2.1.1 Arsitektur Perangkat Keras: ESP32 dan Sensorik

Unit kendali utama menggunakan mikrokontroler ESP32, sebuah *System on a Chip* (SoC) berbasis *dual-core* yang mengintegrasikan konektivitas Wi-Fi dan Bluetooth untuk transmisi data IoT yang efisien (Nizam et al., 2022). Akuisisi data volume sampah dilakukan oleh Sensor Ultrasonik HC-SR04 yang memanfaatkan prinsip pantulan gelombang dengan presisi hingga 3 mm (Prastyo, 2022). Sementara itu, aspek kualitas udara dipantau melalui Sensor Gas MQ-135 yang dapat mendeteksi peningkatan konsentrasi berbagai gas volatil, salah satunya amonia sebagai *proxy* indikatif dekomposisi organik (Swagatam, 2019). Sinergi antar-komponen ini memungkinkan pemantauan kondisi fisik dan kimiawi bak sampah secara simultan.

2.1.2 Smart Waste Management dan Konsep Modularitas

Smart waste management didefinisikan sebagai optimalisasi logistik limbah melalui data *real-time* untuk menekan biaya operasional dan meningkatkan efisiensi sumber daya (Longhi et al., 2012). BINSAI mengadopsi konsep Modular Smart Bin, yaitu unit sensor cerdas yang bersifat adaptif dan dapat dimobilisasi ke area berkepadatan tinggi sesuai kebutuhan operasional (Zhao et al., 2022). Implementasi ini mendukung prinsip pembangunan berkelanjutan melalui manajemen sampah yang proaktif.

2.1.3 Sistem Peringatan Dini dan Geolokasi

Integrasi GPS NEO-6M dan modul SIM800L bertindak sebagai mekanisme *Early Warning System* (EWS). GPS NEO-6M menyediakan data spasial (*latitude* dan *longitude*) yang presisi melalui ekstraksi sinyal satelit (Prastyo, 2024). Data tersebut dikirimkan melalui SIM800L sebagai kanal komunikasi redundan berbasis SMS, menjamin keterhubungan informasi meskipun terjadi gangguan pada jaringan internet (Bitfoic, 2023). Hal ini krusial untuk manajemen logistik pengangkutan sampah yang lebih terukur (Ghiani et al., 2014).

2.1.4 Ekosistem IoT: Blynk dan Produk BINSAI Blynk

Platform Blynk berperan sebagai *cloud platform* untuk visualisasi dan kontrol perangkat jarak jauh secara *real-time* (Hakim, 2023). Melalui platform ini, BINSAI (*Bin Intelligence Sensor and Internet*) mengintegrasikan algoritma *threshold-based* untuk mengklasifikasikan kondisi sampah secara deterministik. BINSAI mentransformasi bak sampah konvensional menjadi node sensor cerdas yang mampu memberikan notifikasi berbasis prioritas lokasi, meningkatkan efisiensi respons tanpa kompleksitas algoritma yang tinggi). Adapun antarmuka grafik pada aplikasi *mobile* Blynk adalah sebagai berikut.

Gambar 1: Antarmuka Aplikasi *Mobile* Blynk

(Sumber: https://shorturl.at/8G8QK)

2.2 Penelitian Relevan

Sejumlah kajian terdahulu memberikan validasi terhadap efektivitas IoT dalam pengelolaan limbah. Qur'ainny *et al*. (2024) menyatakan bahwa penggunaan IoT dan aplikasi digital dapat meningkatkan efektivitas pengelolaan sampah, khususnya dalam aspek pengangkutan dan pemantauan sampah. Selain itu, penerapan teknologi ini juga terbukti dapat meningkatkan kesadaran masyarakat dalam melakukan pemilahan dan pengelolaan sampah secara mandiri.

Penelitian lain oleh Gusdevi *et al*. (2023) menunjukkan bahwa penerapan IoT mampu menjadi solusi efektif dan efisien dalam sistem pengelolaan sampah. Teknologi ini memungkinkan pemantauan kondisi bak sampah secara *real-time* dan mendukung pengambilan keputusan yang lebih cepat dan tepat oleh petugas kebersihan. Selanjutnya, Prabowo *et al*. (2025) mengembangkan sistem berbasis mikrokontroler Arduino Uno yang dilengkapi sensor ultrasonik untuk mendeteksi keberadaan pengguna. Sistem ini memungkinkan pintu bak sampah membuka dan menutup secara otomatis, sehingga meningkatkan kenyamanan pengguna dan efisiensi pengelolaan sampah.

Berbeda dengan penelitian Prabowo et al. (2025) yang fokus pada automasi fisik, atau penelitian Qur'ainny et al. (2024) yang bersifat general, berfokus pada integrasi sensor bimodal (volume dan gas) dengan mekanisme prioritisasi dan komunikasi redundan, BINSAI hadir sebagai solusi fundamental dalam mewujudkan tata kelola limbah yang presisi dan berkelanjutan, khususnya untuk menjawab tantangan urban di Kota Yogyakarta.

BAB 3. BAHAN DAN METODE PENELITIAN

3.1 Waktu dan Tempat Penelitian

Penelitian ini dilaksanakan dengan durasi total lima bulan, terhitung sejak tahap persiapan hingga pelaporan hasil akhir. Lokasi penelitian dipusatkan di Laboratorium MAS Assalafiyyah Mlangi, Sleman, Kabupaten Sleman, Daerah Istimewa Yogyakarta.

3.2 Alat dan Bahan

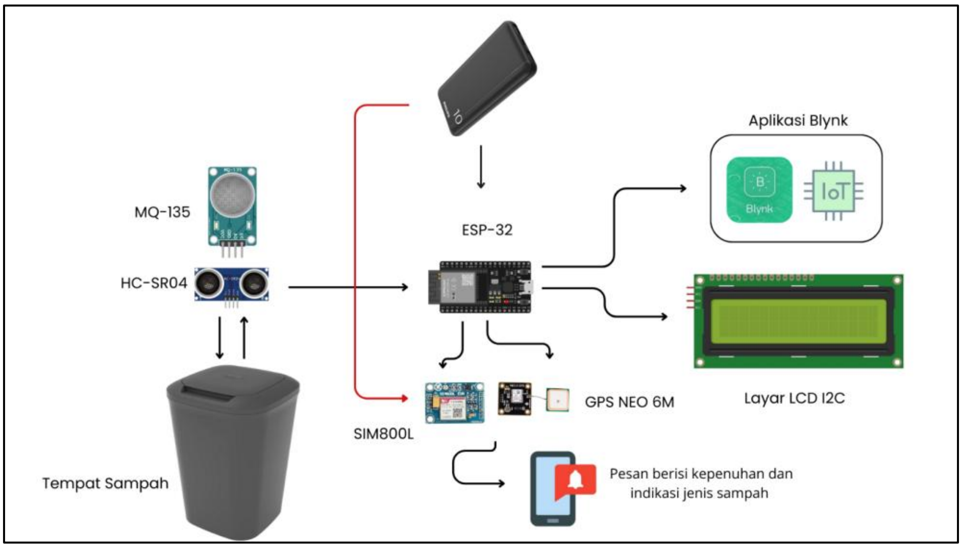
Komponen teknis yang digunakan meliputi: Sensor ultrasonik HC-SR04, mikrokontroler ESP32, modul GSM SIM800L dengan *board*, kartu SIM (aktif dengan pulsa), modul GPS NEO-6M, sensor gas MQ-135, *power bank* 10.000mAh dengan output 5V 3A, *casing* tahan air, *cloud server* Blynk, *breadboard*, kabel jumper (digunakan pada fase percobaan dan setelah desain final, koneksi dilakukan dengan soldering pada PCB universal), klem penjepit samping, LCD I2C, laptop untuk pemrograman dan monitoring, *software* Arduino IDE dan VS Code, alat solder dan perlengkapan perakitan, dan terakhir adalah bak sampah dengan kapasitas 50 L.

3.3 Rancangan dan Prosedur Penelitian

Adapun rancangan dan prosedur terkait penelitian adalah sebagai berikut.

3.3.1 Desain Penelitian

Penelitian ini menerapkan metode eksperimental dengan pendekatan *Research and Development* (R&D). Prototipe BINSAI dirancang sebagai sistem monitoring cerdas yang mampu mengidentifikasi parameter fisik (volume) dan kimiawi (gas dekomposisi) sampah secara otomatis. Adapun konsep desain secara garis besar adalah sebagai berikut.



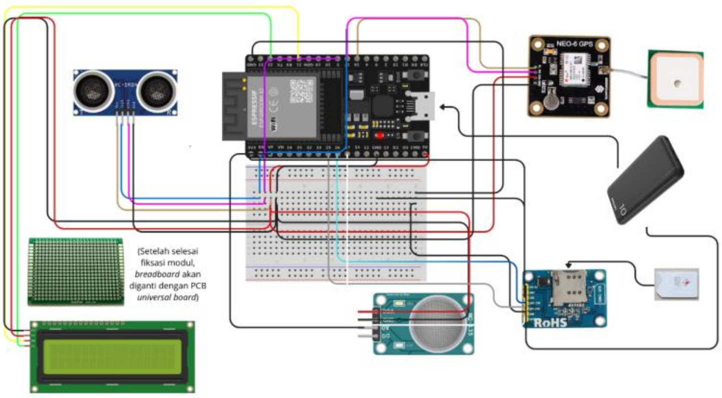
Gambar 2: Desain Alat BINSAI

(Sumber: Dokumentasi Pribadi peneliti)

3.3.2 Prosedur Penelitian

Tahapan fabrikasi dimulai dengan persiapan komponen sesuai dengan tabel pada Lampiran 1. Secara teknis, prosedur perakitan meliputi:.

1. Integrasi Sensorik: Penyambungan sensor HC-SR04 dan MQ-135 ke ESP32. Khusus untuk sensor MQ-135, diterapkan prosedur pre-heat selama 120 detik sebelum pembacaan data dilakukan guna menstabilkan elemen pemanas sensor. Dilakukan pula RZero Calibration di lingkungan udara bersih (*baseline*) dengan kalibrasi sensor MQ-135 untuk mendapatkan hubungan yang bermakna antara nilai ADC (Analog-to-Digital Converter) dan ppm (part per million) suatu gas spesifik (seperti amonia) untuk menentukan nilai hambatan referensi (*Ro*).
2. Pemrograman Firmware: Mengunggah kode program yang mencakup algoritma konversi jarak ke persentase, klasifikasi status sampah, dan interval transmisi data setiap 2 detik ke Blynk serta log riset setiap 60 detik.
3. Manajemen Daya Prosedural: Implementasi *delay optimization* pada kode program untuk memastikan konsumsi daya tetap efisien saat sistem dalam kondisi *standby*.
4. Finalisasi: Perakitan seluruh komponen ke dalam casing tahan air dan pengujian fungsionalitas di laboratorium sebelum *deployment*. Setelah perangkat disambungkan sesuai dengan teknik yang telah disebutkan, maka akan menghasilkan rancangan sesuai Gambar 3 sebagai berikut.



Gambar 3: Rancangan Alat Monitoring BINSAI berbasis *Internet of Things*

(Sumber: Dokumentasi Pribadi Peneliti)

3.3.3 Integrasi Antarmuka *Mobile* Blynk dan Protokol Notifikasi Spasial

Konfigurasi *dashboard* Blynk memanfaatkan pengalamatan *Virtual Pin* (V-Pin) untuk sinkronisasi data secara *real-time*. Protokol *Early Warning System* (EWS) diaktifkan melalui SIM800L untuk mengirimkan koordinat geolokasi (*latitude* dan *longitude*) dari GPS NEO-6M via SMS otomatis ketika kapasitas bak mencapai *threshold* (≥90%).

3.3.4 Konstruksi Unit *Modular Smart Bin* Berbasis Mobilitas Tinggi

Konsep modularitas diwujudkan melalui desain perangkat yang kompak dan mandiri (*self-contained*). Hal ini memungkinkan unit BINSAI dipindahkan secara fleksibel (*plug-and-play*) ke titik-titik kepadatan tinggi. Sistem ini memastikan setiap node tetap teridentifikasi pada database pusat melalui sinkronisasi *device ID* yang unik.

3.3.5 *Repository* Kode dan Dokumentasi

Untuk memastikan transparansi, reproduktibilitas, dan kontribusi pada komunitas *open-source*, seluruh kode sumber dan dataset penelitian telah dipublikasikan pada *repository* GitHub, seperti yang telah terlampir pada Gambar 7 pada Lampiran 4. *Repository* ini mengadopsi praktik version control dengan Git, memungkinkan pelacakan perubahan dan kolaborasi berkelanjutan. Lisensi MIT diterapkan untuk mendukung adopsi dan pengembangan lebih lanjut oleh peneliti lain.

3.4 Pengolahan dan Analisis Data

Pengolahan dan analisis data penelitian ini adalah sebagai berikut.

3.4.1 Pengolahan Data

Data yang diperoleh melalui sensor ditransmisikan secara kontinu setiap 2 detik ke *server* IoT melalui protokol komunikasi Wi-Fi untuk visualisasi pada antarmuka *mobile* Blynk. Secara paralel, sistem melakukan log data riset ke *cloud* setiap 60 detik untuk kebutuhan analisis statistik. Parameter data yang dikelola meliputi: (a) elevasi tumpukan sampah (cm), (b) konsentrasi gas (ppm), (c) tingkat prioritas pengangkutan, (d) koordinat geospasial, dan (e) *timestamp* pengukuran.

Data mentah dari sensor ultrasonik diproses menjadi nilai persentase kepenuhan untuk memberikan interpretasi volume yang lebih intuitif. Konversi ini dilakukan menggunakan formulasi matematis sebagai berikut:

$$Persentase\ Kepenuhan = \left(1 - \frac{Jarak\ Terukur}{Tinggi\ Maksimal\ Bak}\right) \times 100\%$$

Hasil perhitungan tersebut kemudian diklasifikasikan secara otomatis oleh mikrokontroler ke dalam empat kategori status operasional berdasarkan *threshold* yang telah ditentukan sebagai berikut.

1. 0–35%: “Kosong”
2. 36–50%: “Setengah”
3. 51–90%: “Hampir Penuh”
4. 91–100% : “Penuh”

3.4.2 Analisis Data

Tahap analisis dilakukan secara kritis untuk memvalidasi performa BINSAI melalui dua pendekatan utama. Pertama, uji akurasi sensorik dilakukan dengan membandingkan data digital dari sensor terhadap pengukuran manual menggunakan penggaris untuk menghitung nilai galat (*error rate*). Kedua, uji reliabilitas transmisi untuk menghitung persentase keberhasilan pengiriman SMS koordinat lokasi saat kondisi kritis terpenuhi.

Evaluasi khusus dilakukan terhadap aspek modularitas BINSAI dengan meninjau mobilitas unit dan agilitas aktivasi perangkat di titik-titik kepadatan tinggi. Kinerja modularitas diukur berdasarkan efektivitas unit dalam mengantisipasi lonjakan volume sampah secara temporer.

Tabel 1: Matriks Parameter Evaluasi Performa BINSAI

No	Indikator Efektivitas	Parameter Pengukuran	Target Keberhasilan (*Threshold*)
1	Akurasi Sensorik	Deviasi antara nilai sensor dengan pengukuran manual	Galat (Error) <3 cm
2	Responsivitas IoT	Latensi pengiriman data dari ESP32 ke Blynk *Cloud*	Waktu respon <2 detik
3	Reliabilitas SMS	Rasio notifikasi lokasi yang diterima tepat waktu	Keberhasilan >90%
4	Mobilitas Modular	Durasi waktu *deployment* hingga sistem online	Waktu aktif <10 menit
5	Indikasi Jenis Sampah	Ketepatan klasifikasi organik/anorganik via MQ-135	Akurasi indikasi >98%

Matriks di atas difungsikan sebagai instrumen validasi sistem yang komprehensif guna menjamin objektifitas dan fungsionalitas BINSAI dalam kondisi riil. Penetapan indikator kuantitatif ini bukan sekadar prosedur formal, melainkan upaya kritis untuk mentransformasi penelitian ini dari tahap *proof of concept* menjadi solusi teknologi yang memiliki *system robustness* yang teruji secara saintifik.

BAB IV. HASIL DAN PEMBAHASAN

4.1 Hasil Rancangan Sistem BINSAI

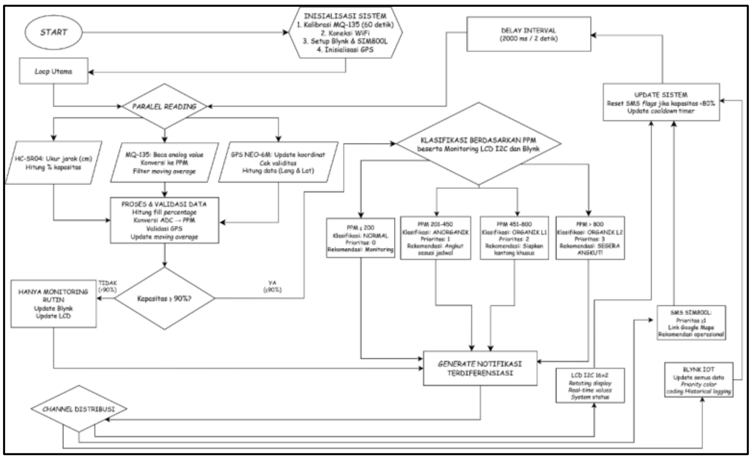
Pengembangan BINSAI (Bin Intelligence Sensor and Internet) merealisasikan arsitektur *Cyber-Physical System* (CPS) yang mengintegrasikan instrumentasi sensorik dengan konektivitas cloud. Sistem ini dirancang dalam empat modul strategis untuk menjawab tantangan manajemen limbah secara terukur.

4.1.1 Modul Monitoring Cerdas: Sinergi Analisis Volumetrik dan Kinetika Gas

Modul ini mengonvergensi parameter fisik dan kimiawi berbasis mikrokontroler ESP32, yang mengoordinasi akuisisi data secara simultan dari dua sensor inti:

1. Sensor Ultrasonik HC-SR04: Melakukan analisis volumetrik berdasarkan prinsip *Time-of-Flight (ToF)* untuk mengukur elevasi tumpukan sampah.
2. Sensor Gas MQ-135: Berfungsi sebagai indikator kualitatif untuk mendeteksi keberadaan gas amonia (NH_3) sebagai *proxy* proses dekomposisi organik. Stabilitas pembacaan dijaga dengan algoritma *moving average*.

Sinergi data tersebut memungkinkan mekanisme *tiered response* (respon bertingkat). Berbeda dengan sistem konvensional yang hanya reaktif terhadap kapasitas fisik, BINSAI dapat bersifat proaktif dengan menetapkan prioritas berdasarkan potensi risiko lingkungan (seperti emisi bau dan daya tarik vektor penyakit) sebelum bak mencapai kapasitas penuh. Hasil pemrosesan data ditampilkan secara *real-time* pada antarmuka lokal LCD I2C untuk petugas lapangan dan ditransmisikan ke platform IoT Blynk via Wi-Fi untuk pemantauan jarak jauh, menjamin transparansi dan kelangsungan *monitoring* dengan seluruh logika prosedural sistem diatur secara sistematis sebagaimana diilustrasikan dalam *flowchart* pada Gambar 4 sebagai berikut.



Gambar 4: *Flowchart* Pengembangan Sistem Monitoring BINSAI dengan Fitur Deteksi Ketinggian dan Jenis Sampah terhadap Respon Terdiferensiasi

(Sumber: Dokumentasi Pribadi Peneliti)

Arsitektur logika sistem BINSAI dioptimasi dengan mengintegrasikan sensor MQ-135 sebagai instrumen deteksi dini dekomposisi material organik. Mekanisme kerjanya bersifat deterministik, bertumpu pada korelasi simultan antara parameter fisik (kapasitas >90%) dan parameter kimiawi (konsentrasi gas ≥ *threshold*), yang diproses oleh mikrokontroler ESP32. Stabilitas pembacaan sensor gas ditingkatkan dengan algoritma *moving average*, menghasilkan nilai PPM yang konsisten untuk membedakan fase degradasi sampah mulai dari normal, indikasi awal, hingga level kritis (Gambar 4).

Saat kedua *threshold* kritis terpenuhi, sistem mengaktifkan protokol notifikasi darurat. Protokol ini menyertakan rekomendasi operasional spesifik: (1) penggunaan kantong sampah berlapis untuk retensi bau, (2) alokasi kompartemen khusus pada truk pengangkut, dan (3) penetapan status prioritas tinggi dalam jadwal. Transmisi data lokasi presisi melalui modul GPS NEO-6M dan GSM SIM800L memungkinkan BINSAI melakukan pemetaan dinamis berbasis urgensi material.Kategorisasi prioritas dirancang berdasarkan gradien konsentrasi gas yang diakuisisi *real-time*. *Threshold* PPM ditetapkan melalui kalibrasi empiris yang merujuk pada karakteristik sensitivitas sensor MQ-135 terhadap gas amonia dan sulfida (Hanwei Electronics, 2010). Kategori dibedakan menjadi fase inisiasi degradasi organik ('Organik Level 1') dan fase dekomposisi akseleratif dengan aktivitas mikrobial tinggi ('Organik Level 2') yang berpotensi risiko kesehatan (Karthi & Sangeetha, 2020). Kategorisasi lengkap dirinci dalam Tabel 4 (Lampiran 5).

Implikasi dari mekanisme respons bertingkat (*tiered response*) ini adalah optimalisasi alokasi sumber daya operasional. Sistem memungkinkan distingsi kritis berbasis bukti telemetri antara status 'Kapasitas Penuh Standar' dan 'Kondisi Kritis-Mendesak' (Srivastava et al., 2017). Dengan demikian, melalui pendekatan *evidence-based*, BINSAI berevolusi dari alat monitoring *voluTe* menjadi instrumen manajemen risiko lingkungan yang presisi.

Sistem perangkat lunak diimplementasikan dalam arsitektur kode modular yang fungsional dan responsif. Pada modul monitoring, dua rutin algoritmik utama—didefinisikan sebagai sekumpulan instruksi terprogram deterministik dalam konteks IoT—dieksekusi paralel oleh ESP32. Rutin ini beroperasi berdasarkan prinsip pemrograman prosedural dan protokol terstruktur, yang menjamin sinkronisasi antara akuisisi data sensoris di lapangan dan transmisi ke *cloud server*. Mekanisme operasional tiap rutin diuraikan pada bagian berikut.

4.1.1.1 Rutin Pengukuran Ketinggian Sampah dan Tampilan LCD I2C

Rutin pertama difokuskan pada pemrosesan data fisik melalui sensor ultrasonik HC-SR04 untuk menentukan elevasi tumpukan sampah. Jarak terukur *(d)* dihitung berdasarkan waktu pantulan gelombang *(t)* melalui persamaan LaTeX sebagai berikut:

$$Jarak\ (cm) = \frac{t \times 0.0343}{2}$$

Data jarak tersebut kemudian ditransformasikan menjadi nilai persentase kepenuhan *(K)* terhadap tinggi maksimal bak *(h)* dengan formulasi:

$$K = \left(1 - \frac{d}{Tinggi\ Maksimal\ Bak}\right) \times 100\%$$

Sistem melakukan klasifikasi otomatis ke dalam empat status operasional: Kosong (0–35%), Setengah (36–50%), Hampir Penuh (51–90%), dan Penuh (>90%). Informasi ini divisualisasikan secara *real-time* melalui LCD I2C 16x2, dimana layar menampilkan kapasitas numerik dan status kondisi serta indikasi jenis sampah yang diperoleh dari sensor MQ-135 secara bergantian. Proses ini berjalan secara kontinu di dalam loop utama, sehingga data pada LCD akan selalu diperbarui setiap kali sensor melakukan pembacaan baru. Kode sumber (*source code*) untuk rutin pengukuran ketinggian sampah dan antarmuka LCD I2C disajikan dalam kode yang telah lengkap pada Lampiran 3.

4.1.1.2 Rutin dalam *Internet of Things* (IoT) melalui Platform Blynk

Rutin kedua mengelola aspek komunikasi data jarak jauh menggunakan platform Blynk.io. Setelah fase inisialisasi jaringan WiFi dan autentikasi token, ESP32 mentransmisikan data kapasitas ke *Virtual Pin* V0 untuk ditampilkan pada *widget Gauge*. Secara simultan, sistem mengontrol empat *widget* LED virtual (V1-V4) sebagai indikator visual cepat bagi petugas di pusat kendali. Proses transmisi ini memanfaatkan protokol MQTT internal dengan frekuensi pembaruan data setiap 1 detik untuk menjamin aktualitas informasi. Penomoran virtual pin yang lainnya telah tersedia pada Lampiran 2. Sedangkan untuk spesifikasi algoritmik dan implementasi kode pemrograman rutin dalam *Internet of Things* (IoT) melalui platform Blynk disajikan secara lengkap pada Lampiran 3. Dengan demikian, rutin ini berfungsi sebagai antarmuka visual yang mendukung konsep smart monitoring pada sistem s*mart bin*.

Sebelum dilakukan *deployment* di lapangan, dilakukan serangkaian pengujian fungsional untuk memastikan reliabilitas setiap modul teknis. Tahapan pengujian awal tersebut didokumentasikan dan dijelaskan secara lengkap pada Gambar 8 Lampiran 4.

4.1.2 Modul Notifikasi Terprioritaskan dan *Early Warning System* (EWS) melalui Inetgrasi Komponen GSM dan GPS

Modul ini merupakan mekanisme mitigasi redundan yang mengintegrasikan unit GSM SIM800L dan GPS NEO-6M untuk menjamin kontinuitas informasi di tengah instabilitas jaringan Wi-Fi. Melalui algoritma *adaptive threshold*, sistem *Early Warning System* (EWS) ini mentransformasi koordinat geospasial menjadi instruksi logistik presisi dalam format SMS ketika parameter kapasitas dan kinetika dekomposisi mencapai ambang kritis (≥90%). Keunggulan strategis pemanfaatan jaringan seluler terletak pada reliabilitas dan inklusivitasnya; notifikasi tetap terdistribusi ke seluruh tipe perangkat genggam petugas tanpa dependensi terhadap paket data maupun aplikasi pihak ketiga. Implementasi rutin ketiga dalam komunikasi *hybrid* ini memfasilitasi mobilisasi armada secara selektif dan efisien, sekaligus memastikan transparansi lokasi titik kritis di area publik yang luas. Penjelasannya adalah sebagai berikut.

4.1.2.1 Rutin Komunikasi Hybrid: Geopolitik Spasial dan Notifikasi SMS

Rutin ketiga dalam sistem BINSAI merupakan subsistem komunikasi *hybrid* yang mengintegrasikan modul GPS NEO-6M dan GSM SIM800L untuk menjamin ketersediaan data pada kondisi *blank-spot* internet. Mengenai rute penyambungan pin komunikasi, termasuk pula pin *Serial UART*, telah dicantumkan pada Lampiran 1. Adapun logika dari rutin ini yang beroperasi melalui dua tahapan deterministik adalah sebagai berikut.

1. Ekstraksi Data Geospasial: Mikrokontroler melakukan *parsing* terhadap data mentah berformat NMEA dari modul GPS menggunakan *library* TinyGPS++. Proses ini bertujuan untuk memperoleh koordinat *latitude* dan *longitude* yang valid secara kontinu.
2. Transmisi Notifikasi Prioritas: Ketika variabel kapasitas mencapai ambang kritis (>90%), sistem mengaktifkan instruksi AT *Command* untuk mengirimkan SMS berisi tautan Google Maps lokasi bak sampah. Guna menjaga efisiensi biaya operasional dan mencegah redundansi data, diimplementasikan variabel logika smsSent. Mekanisme ini memastikan notifikasi hanya dikirimkan satu kali per siklus pengisian, dan hanya akan ter-reset setelah sensor mendeteksi pengosongan bak secara fisik. Lampiran 3 memuat implementasi algoritma sistem peringatan dini dan pelacakan lokasi *real-time* berbasis geolokasi secara lengkap. Contoh format pesan yang dikirim tersedia di Gambar 9 pada Lampiran 4.

4.1.3 Arsitektur Modular Smart Bin untuk Mobilitas Tinggi

Kesadaran global, khususnya di kawasan Asia Tenggara, telah mencapai titik krusial di mana metode pengelolaan limbah konvensional dianggap tidak lagi relevan akibat inefisiensi biaya dan waktu. Pengembangan modular *smart bin* pada platform BINSAI hadir sebagai respons teknologis terhadap eskalasi populasi perkotaan (Mark, 2025). Sistem ini mengedepankan prinsip portabilitas tinggi, di mana *self-contained* dapat terintegrasi secara fungsional pada bak sampah dalam waktu kurang dari 10 menit. Secara ekonomi, agilitas operasional ini didukung oleh studi Kermanshachi & Rouhanizadeh (2020) mengenai potensi *Return on Investment* (ROI) yang 40% lebih cepat dibanding sistem statis, selaras dengan prinsip *Time Value of Money*. Di Yogyakarta, fleksibilitas BINSAI memungkinkan *deployment* dinamis berdasarkan dataset *time-series*, mentransformasi pengelolaan limbah dari sekadar layanan publik menjadi instrumen investasi cerdas pemerintah daerah, seperti yang ditujukan oleh Gambar 10 (Lampiran 4).

4.1.4 Modul Repositori Terbuka dan Dokumentasi *Open Science*

Sebagai bentuk kontribusi terhadap ekosistem *Smart City* yang transparan, seluruh aset intelektual penelitian ini—mencakup *firmware* ESP32, skematik perangkat keras, dan *library*—dipublikasikan melalui repositori GitHub dengan lisensi MIT. Langkah ini menjamin reproduksibilitas riset (*research reproducibility*) dan membuka peluang kolaborasi pengembangan fitur lebih lanjut oleh komunitas global dengan kemudahan secara prosedural oleh README.md yang tellah disertakan, seperti yang terdapat pada Gambar 7 di Lampiran 4.

4.2 Implementasi dan Integrasi Sistem

Tahap implementasi menerjemahkan desain arsitektur menjadi artefak fisik fungsional. Integrasi perangkat keras dilakukan dengan menghubungkan sensor HC-SR04, MQ-135, GPS, dan GSM pada mikrokontroler ESP32 melalui papan sirkuit kustom (*custom PCB/Universal Board*) untuk meminimalisir *noise* sinyal.

Interkoneksi Antarmuka: Sistem *backend* ESP32 dihubungkan dengan *frontend* aplikasi Blynk melalui protokol *Virtual Pin*.

1. Visualisasi Data: Data kapasitas dan konsentrasi gas ditampilkan melalui *Gauge Widget* (V0 dan V10) untuk pemantauan *real-time*.
2. Indikator Status: Status operasional dikonversi menjadi indikator warna spektral pada *LED Widget* (Hijau: Aman s.d. Merah: Kritis). Dokumentasi implementasi fisik dan antarmuka digital ditunjukkan pada Gambar 11 di Lampiran 4.

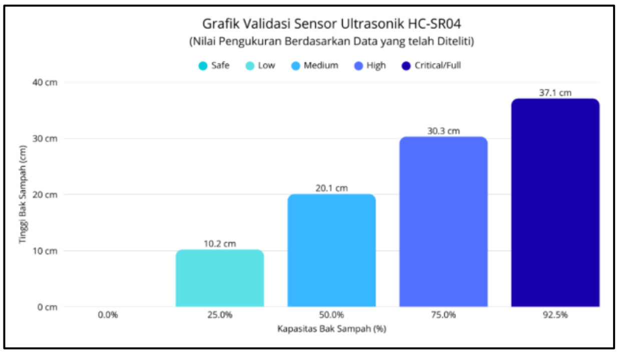
4.3 Hasil Pengujian dan Analisis

Validasi kinerja sistem dilakukan melalui pendekatan empiris kuantitatif untuk mengukur akurasi, linearitas, dan reliabilitas transmisi data.

4.3.1 Pengujian Multi-Sensor (HC-SR04 dan MQ-135)

Pengujian diawali dengan menganalisis linearitas sensor ultrasonik HC-SR04 dengan membandingkan pembacaan sensor terhadap pengukuran manual pada variasi ketinggian bak 40 cm sebagai berikut.

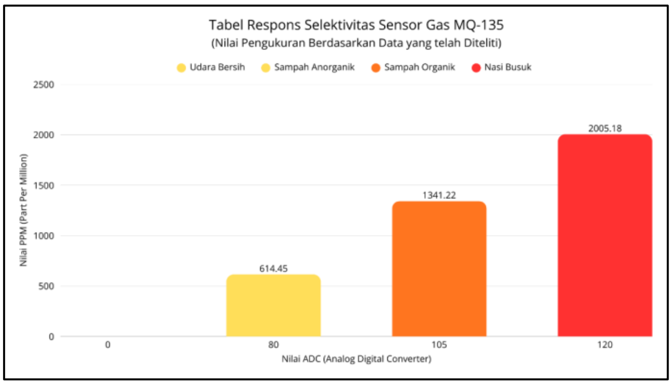
1. Akurasi Eksperimental: Hasil uji menunjukkan tingkat akurasi rata-rata mencapai 99,46% dengan *relative error* sebesar 0,54%. Deviasi absolut maksimal tercatat hanya 0,2 cm pada kapasitas penuh (37,1 cm).
2. Blind Zone Analysis: Teridentifikasi adanya zona buta (*blind zone*) pada jarak < 3 cm dari transduser. Sistem telah dikalibrasi untuk menangani anomali ini dengan menetapkan status *default* aman guna mencegah kesalahan pembacaan (*aliasing*).
3. Kesimpulan: Karakteristik linearitas sensor membuktikan reliabilitas tinggi dalam konversi data analog ke persentase kapasitas digital, seperti yang direpresentasikan dengan Gambar 5 sebagai berikut.



Gambar 5: Grafik Validasi Sensor HC-SR04

(Sumber: Dokumentasi Pribadi Peneliti)

Setelah data diperoleh dari pengujian HC-SR04, penelitian dilanjutkan dengan menganalisis selektivitas sensor gas MQ-135 dengan transformasi data mentah ADC menjadi satuan PPM (*Parts Per Million*) menggunakan pendekatan Regresi *Power-Law* seperti pada Gambar 6 sebagai berikut.



Gambar 6: Diagram Batang mengenai Respon Sensor MQ-135

(Sumber: Dokumentasi Pribadi Peneliti)

Persamaan empiris yang dihasilkan adalah:

$$PPM = 0,002348 \times ADC^{2.856}$$

Model ini memiliki validitas statistik yang sangat kuat dengan koefisien determinasi (R^2) sebesar 0.987 atau 98,7%. Pengukuran dilakukan dengan diferensiasi dua fase berikut yaitu fase udara bersih dan fase dekomposisi kritis menggunakan nasi busuk seperti pada Gambar 12 pada Lampiran 4 disertai dengan penjelasannya.

Secara kritis, penggunaan model non-linear ini sangat relevan dengan karakteristik fisik sensor kimiawi yang memiliki kurva sensitivitas eksponensial terhadap polutan gas organik. Hasil pengujian menunjukkan kontras fungsional yang tajam; di mana kondisi udara bersih menghasilkan rata-rata ADC < 60 (PPM < 200), sementara paparan terhadap nasi busuk memicu lonjakan ADC > 120 yang berkorelasi dengan konsentrasi gas > 800 PPM. Validasi ini membuktikan bahwa BINSAI secara efektif mampu melakukan klasifikasi material secara deterministik melalui analisis gradien kimiawi, membedakan antara sampah anorganik yang stabil dengan sampah organik yang telah mencapai fase kritis dekomposisi.

4.3.2 Evaluasi Telemetri dan Geolokasi (GPS & GSM)

Pengukuran tingkat akurasi data spasial dari modul GPS NEO-6M dilakukan dengan memvalidasi koordinat dengan membandingkan data telemetri modul GPS terhadap titik referensi geospasial presisi tinggi (Google Maps). Adapun dokumentasi yang mengindikasikan nilai koordinat terdapat pada Gambar 13 di Lampiran 4 kemudian dilanjutkan dengan perhitungan error sebagai berikut.

$$\text{Error} = -7,764200 - (-7,764205)| = 0,000005^{\circ}$$

Tingkat Akurasi: Analisis menunjukkan akurasi spasial mencapai 99,99%. Deviasi mikroskopis pada desimal kelima diidentifikasi sebagai efek pembulatan (*truncation*) variabel *float* pada transmisi IoT, yang secara teknis tidak memengaruhi presisi navigasi armada logistik (toleransi radius < 1 meter).

Berdasarkan perbandingan antara pembacaan perangkat BINSAI yang terdapat pada Gambar 13 di Lampiran 4, diperoleh penjelasan sebagai berikut.

Rumus Persentase Akurasi:

$$\text{Akurasi}(\%) = \left(1 - \frac{|\text{Nilai Referensi} - \text{Nilai Terukur}|}{|\text{Nilai Referensi}|}\right) \times 100\backslash\%$$

Perhitungan Kasus (Lat):

1. Referensi (Laptop): -7.764200 (asumsi 6 desimal)
2. Terukur (Blynk): -7.764205 (terdapat deviasi desimal ke-5)
3. Error: 0.000005°
4. Hasil: Akurasi Spasial ≈ 99,99%

Terdapat perbedaan angka di belakang koma bukan disebabkan oleh kegagalan sensor, melainkan presisi transmisi variabel *float* pada protokol IoT. ESP32 mengirimkan data koordinat sebagai variabel *float* yang sering kali mengalami pembulatan atau *truncation* saat diproses oleh server Blynk. Deviasi sebesar 0,000005 derajat setara dengan presisi ≈ 0,5 meter, yang secara teknis sangat dapat diterima untuk navigasi armada sampah.

Sedangkan terkait modul GSM, berdasarkan perhitungan matematis mengenai akurasi dan efisiensi, diperoleh pengukuran melalui parameter akurasi dan redundansi sistem. Berdasarkan uji coba terhadap 10 entitas pesan, diperoleh indikator sebagai berikut.

1. Akurasi Transmisi (*Success Rate*):

$$SR = \left(\frac{\sum P_{\text{sukses}}}{\sum P_{\text{total}}}\right) \times 100\% = 100\%$$

Hasil ini menunjukkan reliabilitas mutlak dalam penyampaian informasi dari node ke pengguna.

2. Laju Redundansi (*Redundancy Rate*):

Teridentifikasi adanya deviasi transmisi berupa satu pesan duplikat (10%) yang dihitung melalui rasio redundansi:

$$\%Error = \left(\frac{P_{\text{ duplikat}}}{P_{\text{total}}}\right) \times 100\% = 10\%$$

Hubungan antara variabel percobaan (x) dan data diterima (y) dipetakan melalui model regresi linear sederhana y = 1,1x. Koefisien deterministik yang melampaui nilai ideal (1,0) mengindikasikan adanya skema *over-provisioning* data sebesar 10%.

Secara kritis, fenomena ini merupakan manifestasi dari mekanisme *guaranteed delivery* sebagai respons terhadap latensi *handshake* pada jaringan seluler. Perangkat BINSAI menginisiasi pengiriman ulang secara otomatis untuk memitigasi risiko *packet loss* akibat fluktuasi sinyal. Hal ini menegaskan keunggulan sistem yang memprioritaskan integritas data di atas efisiensi *bandwidth*, sebuah parameter krusial bagi fungsionalitas *Early Warning System* (EWS) dalam manajemen limbah perkotaan yang responsif dan deterministik.

4.3.3 Integrasi Sistem Terpadu

Secara holistik, hasil pengujian pada sub-bab 4.3.1 dan 4.3.2 membuktikan bahwa integrasi komponen modular BINSAI telah memenuhi standar operasional *Smart City*. Konvergensi antara akurasi sensorik (98-99%) dan reliabilitas telemetri (100% *success rate*) menegaskan kelayakan sistem ini untuk diimplementasikan sebagai solusi mitigasi krisis sampah yang berbasis data (*evidence-based*).

4.4 Pembahasan Hasil

Sintesis temuan eksperimental mengonfirmasi efektivitas BINSAI sebagai instrumen mitigasi berbasis data, dengan capaian dan batasan kritis sebagai berikut.

4.4.1 Sinergi Data Multidimensi dan Pergeseran Paradigma Proaktif

Nilai utama BINSAI terletak pada mekanisme *Tiered Response* hasil konvergensi data sensorik. Akurasi tinggi sensor ultrasonik (99,46%) memvalidasi okupansi volumetrik, sementara integrasi sensor MQ-135 (R^2=0,987) menambahkan dimensi kualitatif. Sinergi ini mentransformasi sistem dari pendekatan reaktif (berbasis kapasitas penuh) menjadi proaktif. Deteksi dini peningkatan gas amonia memungkinkan prioritisasi pengangkutan berdasarkan tingkat bahaya lingkungan (bau, potensi patogen), bukan sekadar keterisian fisik, sehingga secara signifikan mereduksi risiko kesehatan masyarakat di area padat.

4.4.2 Resiliensi Arsitektur Telemetri dalam Kondisi Realistik

Evaluasi modul komunikasi membuktikan reliabilitas untuk skala urban. Fenomena *over-provisioning* data sebesar 10% (dimodelkan dengan regresi y=1.1x) merupakan manifestasi mekanisme *guaranteed delivery* yang disengaja, memastikan integritas notifikasi tetap terjaga meski dalam kondisi latensi jaringan seluler tinggi. Akurasi spasial GPS 99,99% memberikan presisi lokasi mutlak. Kombinasi presisi lokasi dan kepastian transmisi ini membentuk sistem *dispatch* armada yang jauh lebih efisien dibanding rute statis konvensional, berpotensi mereduksi biaya operasional logistik secara substansial.

4.4.3 Evaluasi Limitasi Fisik dan Kompensasi Sistemik

Penelitian secara kritis mengidentifikasi batasan teknis, seperti ***blind zone*** pada jarak <3 cm dari sensor ultrasonik. Namun, limitasi ini berhasil dikompensasi oleh logika firmware yang secara deterministik menetapkan status "Kritis" saat objek memasuki zona tersebut, sehingga tidak mengurangi utilitas fungsional karena kondisi itu sudah merepresentasikan kelebihan kapasitas.

4.4.4 Relevansi Strategis terhadap Implementasi *Smart City*

Implementasi BINSAI memiliki relevansi langsung dengan konteks krisis TPA di Yogyakarta. Arsitektur *open-source* dan modular menawarkan solusi dengan *entry barrier* rendah namun dampak tinggi. *Dashboard* cloud Blynk memfasilitasi transparansi data *real-time* bagi pengambil kebijakan. Secara teoretis, implementasi masif dapat menggeser paradigma dari *Routine Collection* menuju *Demand-Driven Collection*, yang tidak hanya menyelesaikan masalah estetika dan kesehatan, tetapi juga mendukung pencapaian *Sustainable Development Goals* (SDGs) melalui digitalisasi infrastruktur publik yang inklusif.

4.5 Kendala dan Solusi

Pengembangan BINSAI dihadapkan pada hambatan teknis yang memerlukan solusi strategis untuk menjamin keberlanjutan fungsional.

4.5.1 Kendala secara Teknis

Hambatan utama teridentifikasi pada kerusakan modul GPS NEO-6M akibat ***power instability***. Analisis menunjukkan kegagalan disebabkan oleh penggunaan *shared pinout* 3.3V dari ESP32 yang tidak mampu menyuplai arus konstan pada beban puncak, menyebabkan degradasi komponen. Solusi korektif diimplementasikan melalui isolasi catu daya dengan mengintegrasikan *Dedicated Low-Dropout Regulator (LDO)*. Regulator mandiri ini terbukti menstabilkan fluktuasi voltase dan memberikan proteksi terhadap lonjakan arus, sehingga menjamin integritas modul GPS jangka panjang.

4.5.2 Limitasi Komputasi dan Strategi Inklusivitas Teknologi

Kendala teknis kedua muncul dari kapasitas komputasi terbatas ESP32 yang tidak memadai untuk menjalankan algoritma *optimasi rute dinamis* (*multi-point routing*) yang kompleks. Ketergantungan pada server eksternal berisiko menghambat skalabilitas. Sebagai solusi pragmatis, sistem dikonfigurasi ulang untuk berfokus pada mekanisme notifikasi SMS yang menyertakan tautan geospasial Google Maps. Strategi ini tidak hanya mereduksi beban komputasi *on-board*, tetapi juga menciptakan ekosistem yang inklusif. Format SMS memastikan aksesibilitas informasi bagi petugas lapangan tanpa ketergantungan pada koneksi internet stabil atau perangkat canggih, sehingga menjaga fungsionalitas sistem dalam kondisi operasional nyata.

BAB V. KESIMPULAN DAN SARAN

5.1 Kesimpulan

Penelitian ini berhasil memvalidasi sistem BINSAI (Bin Intelligence Sensor and Internet) sebagai instrumen strategis transformasi digital manajemen limbah urban. Berdasarkan evaluasi empiris, ditarik kesimpulan sebagai berikut.

1. Presisi Volumetrik & Telemetri: Implementasi sensor ultrasonik berbasis Time-of-Flight mencapai akurasi rata-rata 99,46%. Transformasi data fisik ke digital terbukti andal dengan reliabilitas transmisi notifikasi mencapai 100% melalui kanal ganda (Blynk dashboard & SMS Gateway).
2. Klasifikasi Deterministik: Integrasi sensor MQ-135 menggunakan model regresi Power-Law menghasilkan validitas tinggi (R^2 = 0.987). Hal ini memberikan dimensi kecerdasan baru pada sistem untuk mendiferensiasi sampah anorganik stabil dan dekomposisi organik aktif secara presisi.
3. Eliminasi *Blind Spot* Operasional: Desain modular BINSAI secara efektif meniadakan inefisiensi pemantauan konvensional. Sistem ini menawarkan solusi yang skalabel dan proaktif, menjadikannya model feasible untuk akselerasi infrastruktur *Smart City* di Yogyakarta.

5.2 Saran

Untuk mengelevasi BINSAI menjadi ekosistem manajemen sampah yang prediktif dan berkelanjutan, direkomendasikan pengembangan berikut:

1. Elevasi Kecerdasan Buatan: Integrasi *Edge Computing* dan *Machine Vision* pada *firmware* untuk memungkinkan pemilahan otomatis dan *real-time* di sumbernya (*sorting at source*).
2. Resiliensi Infrastruktur: Adopsi jaringan komunikasi hibrida (LoRaWAN) dan manajemen daya berbasis panel surya untuk menjamin operasional mandiri di area dengan kendala sinyal atau listrik (*off-grid*).
3. Kebijakan Berbasis Data: Pengembangan *dashboard* dengan fitur *predictive analytics* untuk mendukung pengambilan keputusan strategis (*evidence-based policy*) oleh otoritas lingkungan hidup.
4. Sinergi *Triple Helix*: Penguatan kolaborasi Pemerintah-Akademisi-Masyarakat melalui skema insentif partisipatif guna mendorong perubahan perilaku kolektif dalam pengelolaan sampah.

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LAMPIRAN

Lampiran 1: Tabel Rute Penyambungan Antar Komponen

Komponen	Pin ESP32	Pin Komponen	Fungsi Utama
Power Management			
Power Bank 10.000mAh	VIN/5VIN (SIM800L)	OUT (+)	Distribusi daya
Power Bank 10.000mAh	GND	OUT (-)	*Common Grounding System*
Sensor Ultrasonik HC-SR04			
	GPIO 5	TRIG	*Trigger Pulse*
	GPIO 18	ECHO	*Echo Signal*
	5V	VCC	Sumber daya sensor
	GND	GND	Jalur negatif
Sensor Gas MQ-135			
	GPIO 34	AOUT	Transmisi data analog konsentrasi gas (PPM)
	3.3V	VCC	Sumber daya sensor (Logika 3.3V)
	GND	GND	Jalur negatif
LCD I2C (16x2)			
	GPIO 21	SDA	Serial *Data Line* (Protokol I2C)
	GPIO 22	SCL	Serial *Clock Line* (Protokol I2C)
	5V	VCC	Sumber daya backlight dan logika LCD
	GND	GND	Jalur negatif
GPS NEO-6M			
	GPIO 13	TX	Data *Transmission* koordinat ke ESP32 (RX1)

	GPIO 15	RX	Data *Reception* perintah dari ESP32 (TX1)
	3.3V	VCC	Sumber daya modul GPS
	GND	GND	Jalur negatif
Modul GSM SIM800L			
	GPIO 16	TX	Transmisi data serial SMS/GPRS (RX2)
	GPIO 17	RX	Penerimaan data serial SMS/GPRS (TX2)
	GPIO 27	PWRKEY	Kontrol *Power-on*/Reset modul secara programatik
	Out Step-down	5VIN	Catu daya khusus
	GND	GND	Jalur negatif (*Shared Ground*)

Lampiran 2: Tabel Konfigurasi Datastream dan Dashboard Blynk Cloud

No	Nama Datastream	Virtual Pin	Tipe Data	Rentang Nilai	Satuan	Deskripsi Widget & Fungsi
1	Fill Percentage	V0	Integer	0 – 100	%	Gauge & SuperChart: Monitoring volume sampah secara kontinu.
2	LED Red	V1	Integer	0 / 255	-	LED Widget: Indikator status "PENUH" (>90%).
3	LED Orange	V2	Integer	0 / 255	-	LED Widget: Indikator status "HAMPIR PENUH" (51-90%).
4	LED Yellow	V3	Integer	0 / 255	-	LED Widget: Indikator status "SETENGAH" (36-50%).
5	LED Green	V4	Integer	0 / 255	-	LED Widget: Indikator status "KOSONG" (0-35%).
6	Distance	V5	Double	0 – 400	cm	Labeled Value: Data mentah pembacaan sensor ultrasonik.
7	Capacity Status	V6	String	-	-	Labeled Value: Interpretasi tekstual kondisi bak sampah.
8	PPM Value	V10	Integer	0 – 2000	ppm	Gauge & SuperChart: Intensitas gas amonia (MQ-135).
9	Priority Level	V11	Integer	0 – 3	-	Value Display: Skala urgensi penanganan sampah.
10	Waste Type	V12	String	-	-	Label: Klasifikasi otomatis (Organik/Anorganik).
11	Recommendation	V13	String	-	-	Label: Instruksi preventif/APD bagi petugas.
12	Latitude	V20	Double	-	GPS	Map Widget: Titik koordinat lintang lokasi perangkat.
13	Longitude	V21	Double	-	GPS	Map Widget: Titik koordinat bujur lokasi perangkat.

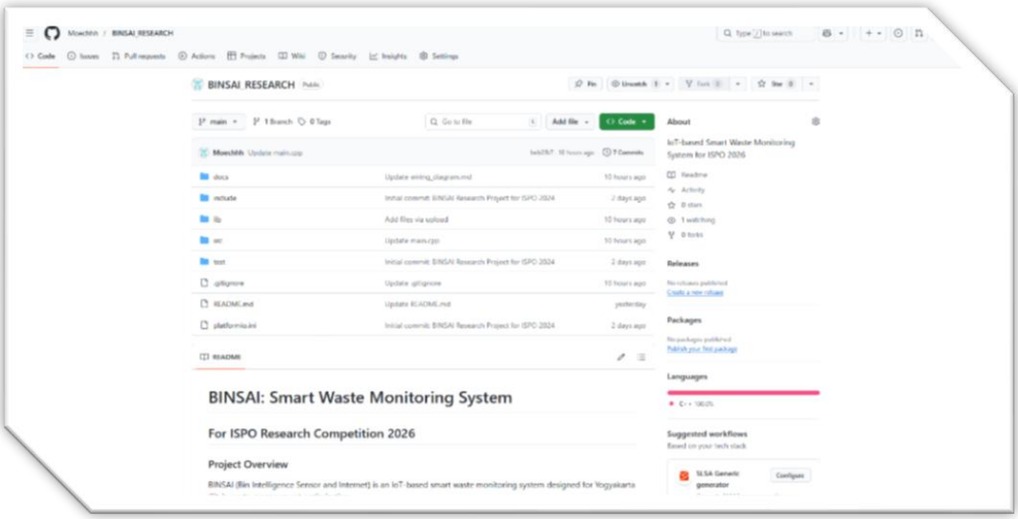
Lampiran 3: Algoritma *Full Code* C++ *Language* pada Arduino IDE

Link: https://github.com/Moechhh/BINSAI_RESEARCH/blob/main/src/main.cpp

Lampiran 4: Dokumentasi Gambar

Dokumentasi Github

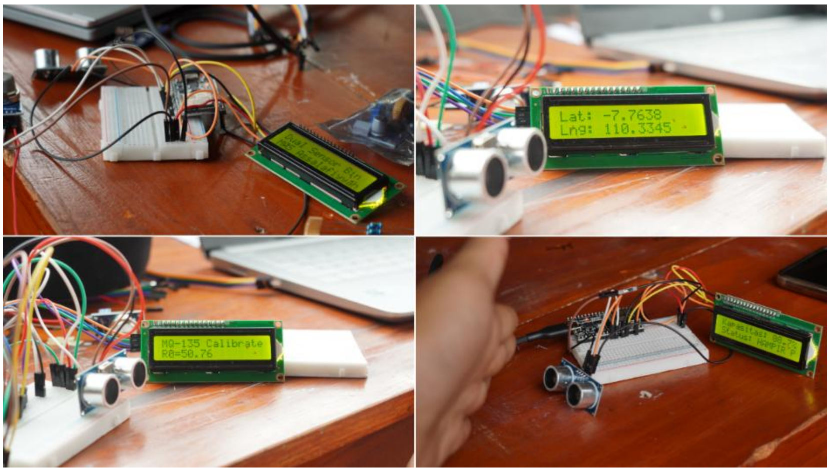
Link *repository*: https://github.com/Moechhh/BINSAI_RESEARCH.git



Gambar 7: Dashboard GitHub

(Sumber: Dokumentasi Pribadi Peneliti)

Gambar Rakitan Awal BINSAI dalam Penelitian



Gambar 8: Rakitan dan Pengujian Awal pada Modul BINSAI

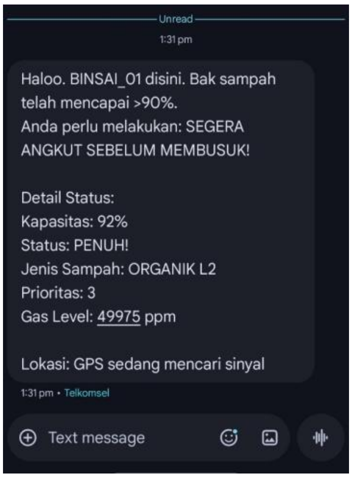
(Sumber: Dokumentasi Pribadi Peneliti)

Rangkaian pengujian pada Gambar 8 di atas menunjukkan proses verifikasi sistem yang meliputi:

1. (a) Pengujian Inisialisasi Antarmuka (Kiri Atas): Verifikasi pembukaan tampilan pada LCD I2C untuk memastikan jalur komunikasi I2C dan *power supply* ke layar beroperasi dengan benar saat perangkat pertama kali dinyalakan.

2. (b) Verifikasi Spasial GPS (Kanan Atas): Pengujian modul GPS NEO-6M dalam mengakuisisi sinyal satelit untuk mendapatkan koordinat *latitude* dan *longitude* yang presisi di lokasi penelitian.
3. (c) Kalibrasi Dinamis MQ-135 (Kiri Bawah): Proses penentuan nilai *R0* (hambatan sensor di udara bersih) untuk menjamin akurasi pembacaan PPM gas amonia agar terhindar dari galat pembacaan akibat kondisi lingkungan awal.
4. (d) Uji Akurasi Kapasitas (Kanan Bawah): Simulasi pengukuran jarak terhadap objek untuk memvalidasi algoritma konversi jarak ke persentase, memastikan status yang ditampilkan pada LCD sesuai dengan kondisi fisik keterisian bak.

Gambar Format SMS yang Terkirim



Gambar 9: Format Pesan yang Dikirim melalui Aplikasi *Mobile* Blynk pada Sistem BINSAI

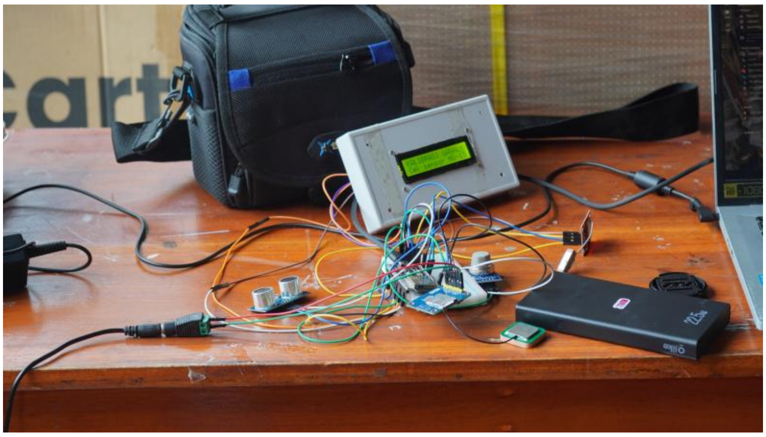
(Sumber: Dokumentasi Pribadi Peneliti)

Gambar *Modular Smart Bin*

Gambar 10: Modularisasi BINSAI dengan *compacting* pada *enclosure*

(Sumber: Dokumentasi Pribadi Peneliti)

Gambar Integrasi Komponen



Gambar 11: Integrasi Antar Komponen

(Sumber: Dokumentasi Pribadi Peneliti)

Gambar Pengujian Sensor MQ-135

Gambar 12: Pemerolehan ADC (*Analog-to-Digital Converter*) sebagai Referensi terhadap Nilai PPM

(Sumber:Dokumentasi Pribadi Peneliti)

Berdasarkan Gambar 12, diperoleh hasil sebagai berikut.

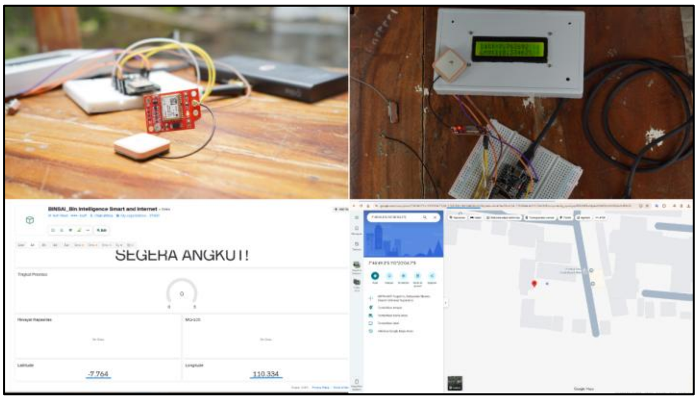
Analisis Visual Pengujian Empiris.

1. Gambar A kiri atas (Baseline Udara Bersih): Menunjukkan tahap inisialisasi di mana sensor terpapar udara luar ruangan yang bersih (*clean air phase*). Data menunjukkan nilai ADC stabil pada angka 0 selama 14 detik awal, yang mengonfirmasi bahwa sensor tidak mendeteksi kontaminan amonia (NH_3) di atas *threshold* latar.
2. Gambar B kanan atas (Transmisi Data Real-Time): Merupakan dokumentasi *Serial Monitor* yang menangkap kinetika kenaikan kadar gas saat sensor mulai dipaparkan pada objek sampah organik. Pada detik ke-14, nilai ADC menunjukkan

tren peningkatan namun belum mencapai titik puncak (120), merepresentasikan fase transisi difusi gas ke permukaan sensor.

3. Gambar C kiri bawah (Interaksi Sensor dan Polutan): Menunjukkan perangkat MQ-135 yang ditempatkan secara proksimal di atas nasi yang telah mengalami dekomposisi selama 3 hari. Paparan langsung ini memicu reaksi reduksi pada permukaan material semikonduktor sensor akibat emisi gas hasil aktivitas mikrobial.
4. Gambar D kanan bawah (Validasi Hasil Akhir): Tahap akhir pengujian di mana sistem berhasil mencapai saturasi data pada nilai ADC ≥120 di 10 detik terakhir pengujian. Data ini menjadi basis final bagi model regresi untuk mengklasifikasikan objek sebagai sampah organik tingkat lanjut (Organik Level 2).

Gambar Pengujian Modul GPS NEO-6M



Gambar 13: Pengujian GPS NEO-6M

(Sumber: Dokumentasi Pribadi Peneliti)

Gambar B (kanan atas) dan referensi Google Maps pada laptop, Gambar D (kanan bawah), maka diperoleh perhitungan persentase akurasi koordinat yang telah dijelaskan pada 4.3.2 Pengujian Modul GPS dan GSM.

Lampiran 5: Tabel *Threshold* Indikasi Jenis Sampah

Tabel 4. *Threshold* Deteksi Indikasi Jenis Sampah Berbasis Sensor MQ-135

Kondisi	BINSAI (PPM)	Referensi Ilmiah (PPM)	Sumber
Udara Bersih / Normal	0 - 199	< 250 - 350	WHO & EPA: Level latar belakang CO_2‹ di udara luar biasanya 350-400 ppm. MQ-135 sering kali menunjukkan nilai rendah (0-200) setelah dikalibrasi *RZero* di udara bersih.
Anorganik / Bau Ringan	200 - 449	350 - 600	Srivastava et al. (2017): Udara dalam ruangan atau area dengan sedikit polusi/gas organik ringan berada di rentang ini.
Organik (Mulai Membusuk)	450 - 800	> 600 - 1000	Karthi & Sangeetha (2020): Menetapkan >700 ppm sebagai indikator adanya gas metana/amonia dari tumpukan sampah basah.
Kritis (Busuk Tinggi)	> 800	> 1000	Datasheet Hanwei Electronics: MQ-135 memiliki sensitivitas tinggi hingga 1000 ppm. Nilai >800 menandakan konsentrasi gas berbahaya yang pekat.

Lampiran 6 : Matriks Agenda Kegiatan

Kegiatan	Bulan…Minggu ke…																			
	September				Oktober				November				Desember				Januari			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Berdiskusi tentang ide penelitian																				
Mencari studi literatur																				
Survei permasalahan																				
Fiksasi judul penelitian																				
Pembuatan proposal penelitian																				
Persiapan alat dan bahan penelitian																				
Pengumpulan komponen																				
Pembuatan																				
Penerapan																				
Pengujian																				
Pengujian																				
Pengujian																				
Pengumpulan data awal																				
Uji lanjutan																				
Analisis data dan interpretasi hasil																				
Penelitian																				
Penyusunan laporan akhir																				

ENGLISH VERSION

INDONESIAN SCIENCE PROJECT OLYMPIAD 2026

ISPO RESEARCH REPORT

BINSAI: Development of a Non-Contact Distance Sensor-Based Waste Bin Monitoring System and Internet of Things (IoT) Node Integrated with the Blynk Mobile Application to Support Smart Waste Management in the City of Yogyakarta

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Abstract

The problem of waste accumulation in urban areas, particularly in the city of Yogyakarta due to the limited capacity of the Piyungan landfill, requires a more intelligent and responsive management approach. This study aims to develop and test BINSAI (Bin Intelligence Sensor and Internet), a prototype of an integrated Internet of Things (IoT)-based waste bin monitoring system. This system is designed to optimize waste transportation operations through real-time monitoring of capacity and indications of organic waste decomposition. The research method uses a Research and Development (R&D) approach utilizing an ESP32 microcontroller integrated with an HC-SR04 ultrasonic sensor for volume measurement and an MQ-135 gas sensor to detect ammonia concentration. The data is processed and transmitted to the Blynk platform for visualization, while the GSM SIM800L and GPS NEO-6M modules provide priority notifications and location tracking via SMS when critical conditions are detected. Test results show that the ultrasonic sensor has an accuracy of 99.46%, the gas detection model has a validity (R^2 = 0.987), and notification transmission has a reliability of 100%. The modular smart bin concept allows for flexible implementation in public areas with high volume fluctuations. This study concludes that BINSAI has the potential to be a transformative solution in supporting smart waste management, improving operational efficiency, and contributing to reducing landfill burden. All technical documentation and source code are published openly on the GitHub repository to ensure transparency and sustainability of development.

Keywords: Smart Waste Management, Internet of Things (IoT), Ultrasonic Sensor, Gas Sensor, Blynk, Modularity, Yogyakarta City.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Indonesia, as the largest archipelagic country in the world, faces serious challenges in waste management in line with population growth, economic growth, and community consumption. Waste management is a collective responsibility whose effectiveness is still constrained by many factors, one of which is limited facilities (Arifin, 2024; Vedita, 2022). Based on data from the Ministry of Environment and Forestry (KLHK), national waste generation in 2023 reached 69.7 million tons (Sumbitmele, 2024). The accumulation of unmanaged waste can trigger environmental degradation, flood risks, threats to public health, and damage to the aesthetics of the urban environment.

This problem is even more apparent in big cities, including Yogyakarta, where waste evacuation to the Piyungan landfill has stagnated due to capacity limitations (Pangaribowo & Hartik, 2025). Between 2021 and 2025, there has been an accumulation of waste at the Piyungan landfill, with the highest amount reaching 700 tons of waste per day (Bantul Regency Government, 2025). This crisis is exacerbated by a surge in the number of tourists, estimated to reach 1.1 million people, which is predicted to add around 550 tons of additional waste per day (Suhamdani, 2025). Meanwhile, the city of Yogyakarta currently produces around 300 tons of waste per day, while the quota allowed to enter the landfill is only 600 tons per month (Adminwarta, 2025). “Only cities that evacuate to the Piyungan landfill,” said Aris Prasena, Head of the DLHK Waste Management Office, DIY. In addition, the temporary closure of the Piyungan Final Disposal Site (TPA) began in mid-2024 (Daeng, 2024).

Given the accelerating complexity of urban dynamics, the conventional fixed-schedule waste management approach has reached a point of stagnation and is no longer adequate to mitigate the rate of waste generation. This phenomenon demands a paradigm shift towards evidence-based waste management that integrates the Internet of Things (IoT) ecosystem as its main pillar. The implementation of sensor convergence, which includes ultrasonic sensors for volumetric analysis and ammonia gas sensors to detect the kinetics of organic decomposition, enables real-time telemetry extraction. Through the synchronization of this data, the system is able to reduce information ambivalence in the field, so that the process of mobilizing the transportation fleet can be carried out based on precision prioritization that optimizes resource allocation and increases operational agility in urban waste management.

This research developed BINSAI (Bin Intelligence Sensor and Internet) as a prototype for a smart trash bin monitoring system integrated with the Blynk platform. This research was limited to a prototype monitoring system with two main parameters, namely capacity and dispersion of gases resulting from organic decompositionWaste classification is indicative based on empirical thresholds, not chemical identification. Unlike static systems, BINSAI is designed modularly with a location-based (GPS and GSM) priority notification system to improve the operational agility of officers. To ensure research reproducibility and data transparency, all source code and technical documentation for the BINSAI system are published openly through the GitHub repository under the MIT License.

The implementation of this IoT system is the first step in accelerating the digital transformation of waste management in Yogyakarta. This not only supports the reduction of the burden on the Piyungan landfill, but also strengthens the pillars of a Smart City through the provision of measurable and scientific time-series datasets (Sa'diyah et al., 2020; Lianawati, 2024).

1.2 PROBLEM FORMULATION

The problem formulation related to this research is as follows.

5. How to design an Internet of Things (IoT)-based BINSAI system that integrates height detection, waste decomposition indication of ammonia gas levels, and geolocation into the Blynk dashboard in real-time?
6. How responsive and accurate is the adaptive threshold-based notification prioritization system in optimizing waste transportation management?
7. How to design a modular smart bin concept to accommodate fluctuations in waste volume in public areas with high activity spikes?
8. How to manage BINSAI technical documentation and source code in an open repository to ensure research reproducibility for future Smart City development?

1.3 RESEARCH OBJECTIVES

Based on the problem formulation, the research objectives can be summarized as follows.

5. Designing an ESP32 microcontroller-based BINSAI system capable of accurately extracting telemetry data on capacity and decomposition indicators through remote data acquisition.
6. Analyzing the performance of a prioritized notification system in providing precise information on the urgency of handling critical waste points.
7. Design and test the operational agility of the modular smart bin concept in an effective BINSAI platform to support waste management in public areas and areas with high activity.
8. Accelerate research transparency and reproducibility through comprehensive publication of all source code and technical documentation of hardware on the GitHub repository under an open license.

1.4 RESEARCH BENEFITS

Based on the research questions and objectives, the benefits of this research are as follows.

1.4.1 Theoretical Benefits

This research contributes to the enrichment of the Internet of Things (IoT) literature through the development of BINSAI, which integrates convergent multi-sensors (distance and gas) in real-time. This innovation enables preventive operational mitigation, such as the preparation of special materials before evacuation, reinforces the concept of open science in technology development, and strengthens the concept of modular smart bins as a pillar of environmentally friendly technology in supporting the Smart City ecosystem.

1.4.2 Practical Benefits

5. Optimization of Landfill Quota Allocation: Transformation of waste management through location-based precision prioritization and real-time data. With adaptive thresholds, the system ensures that the limited quota of the Piyungan landfill is selectively allocated at critical points (>90% + organic), in order to significantly reduce the environmental burden compared to conventional distribution.
6. Although data transmission in this proof of concept phase is still locality-dependent, the BINSAI architecture is designed with high interoperability to integrate public infrastructure and private sector CSR synergies.
7. Modular Operational Agility: Implementation of a flexible, plug-and-play modular smart bin concept enables dynamic mobilization of devices to anticipate spikes in waste volume in strategic areas and public activity centers.

CHAPTER 2. LITERATURE REVIEW

2.1 Theoretical Study

The BINSAI research is based on the integration of embedded systems, smart sensors, and wireless communication to realize responsive waste management.

2.1.1 Hardware Architecture: ESP32 and Sensors

The main control unit uses an ESP32 microcontroller, a dual-core System on a Chip (SoC) that integrates Wi-Fi and Bluetooth connectivity for efficient IoT data transmission (Nizam et al., 2022). Waste volume data acquisition is performed by an HC-SR04 Ultrasonic Sensor that utilizes the principle of wave reflection with a precision of up to 3 mm (Prastyo, 2022). Meanwhile, air quality is monitored through an MQ-135 Gas Sensor that can detect increases in the concentration of various volatile gases, one of which is ammonia as an indicative proxy for organic decomposition (Swagatam, 2019). The synergy between these components enables simultaneous monitoring of the physical and chemical conditions of the trash bin.

2.1.2 Smart Waste Management and Modularity Concept

Smart waste management is defined as the optimization of waste logistics through real-time data to reduce operational costs and improve resource efficiency (Longhi et al., 2012). BINSAI adopts the Modular Smart Bin concept, which is an adaptive smart sensor unit that can be mobilized to high-density areas according to operational needs (Zhao et al., 2022). This implementation supports the principle of sustainable development through proactive waste management.

2.1.3 Early Warning System and Geolocation

The integration of GPS NEO-6M and the SIM800L module acts as an Early Warning System (EWS) mechanism. GPS NEO-6M provides precise spatial data (latitude and longitude) through satellite signal extraction (Prastyo, 2024). The data is sent via SIM800L as a redundant SMS-based communication channel, ensuring information connectivity even in the event of internet network disruptions (Bitfoic, 2023). This is crucial for more measurable waste transportation logistics management (Ghiani et al., 2014).

2.1.4 IoT Ecosystem: Blynk and BINSAI Products Blynk

The Blynk platform acts as a cloud platform for real-time visualization and remote control of devices (Hakim, 2023). Through this platform, BINSAI (Bin Intelligence Sensor and Internet) integrates threshold-based algorithms to classify waste conditions deterministically. BINSAI transforms conventional waste bins into smart sensor nodes capable of providing location-based priority notifications, improving response efficiency without high algorithm complexity. The graphical interface on the Blynk mobile application is as follows.

Figure 1: Blynk Mobile Application Interface

(Source: https://shorturl.at/8G8QK)

2.2 Relevant Research

A number of previous studies have validated the effectiveness of IoT in waste management. Qur'ainny et al. (2024) stated that the use of IoT and digital applications can improve the effectiveness of waste management, particularly in terms of waste transportation and monitoring. In addition, the application of this technology has also been proven to increase public awareness in sorting and managing waste independently.

Another study by Gusdevi et al. (2023) shows that the application of IoT can be an effective and efficient solution in waste management systems. This technology enables real-time monitoring of waste bin conditions and supports faster and more accurate decision-making by sanitation workers. Furthermore, Prabowo et al. (2025) developed a system based on the Arduino Uno microcontroller equipped with ultrasonic sensors to detect the presence of users. This system allows the trash bin door to open and close automatically, thereby increasing user convenience and waste management efficiency.

Unlike the research by Prabowo et al. (2025), which focuses on physical automation, or the research by Qur'ainny et al. (2024), which is general in nature, focusing on the integration of bimodal sensors (volume and gas) with prioritization mechanisms and redundant communication, BINSAI presents itself as a fundamental solution in realizing precise and sustainable waste management, especially in addressing urban challenges in the city of Yogyakarta.

CHAPTER 3. RESEARCH MATERIALS AND METHODS

3.1 Research Time and Location

This research was conducted over a total period of five months, from the preparation stage to the reporting of the final results. The research was centered at the MAS Assalafiyyah Mlangi Laboratory, Sleman, Sleman Regency, Special Region of Yogyakarta.

3.2 Tools and Materials

The technical components used included: HC-SR04 ultrasonic sensor, ESP32 microcontroller, SIM800L GSM module with board, SIM card (active with credit), NEO-6M GPS module, MQ-135 gas sensor, 10,000mAh power bank with 5V 3A output, waterproof casing, Blynk cloud server, breadboard, jumper cables (used during the experimental phase; after final design, connections are made via soldering on a universal PCB), side clamps, I2C LCD, laptop for programming and monitoring, Arduino IDE and VS Code software, soldering tools and assembly equipment, and finally a 50 L capacity trash bin.

3.3 Research Design and Procedures

The research design and procedures are as follows.

3.3.1 Research Design

This study applied an experimental method with a Research and Development (R&D) approach. The BINSAI prototype was designed as an intelligent monitoring system capable of automatically identifying the physical (volume) and chemical (decomposition gas) parameters of waste. The design concept is outlined as follows..

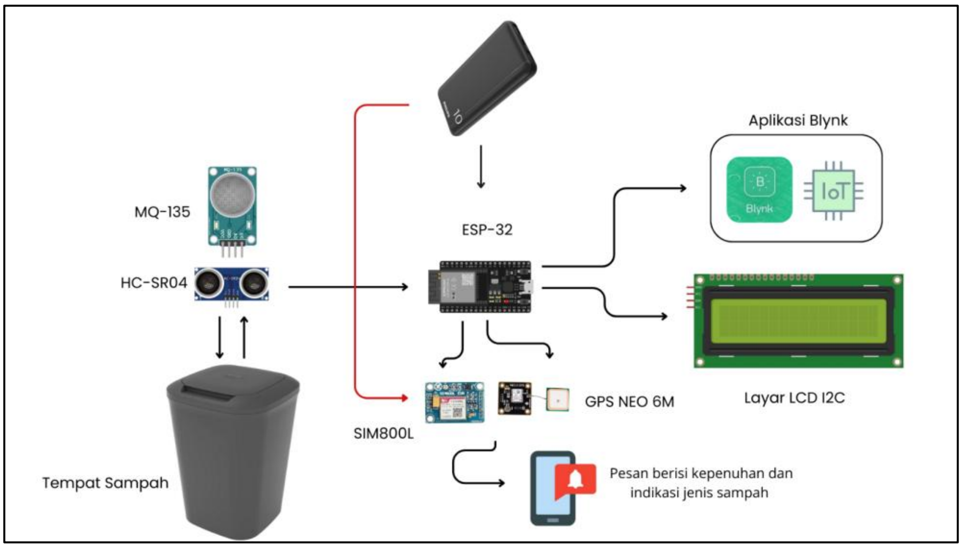

Figure 2: BINSAI Device Design

(Source: Researcher's personal documentation)

3.3.2 Research Procedures

The fabrication stage begins with the preparation of components according to the table in Appendix 1. Technically, the assembly procedure includes:.

5. Sensory Integration: Connecting the HC-SR04 and MQ-135 sensors to the ESP32. Specifically for the MQ-135 sensor, a pre-heat procedure lasting 120 seconds is applied before data reading is performed in order to stabilize the sensor's heating element. RZero Calibration is also performed in a clean air environment (baseline) with MQ-135 sensor calibration to obtain a meaningful relationship between the ADC (Analog-to-Digital Converter) value and ppm (parts per million) of a specific gas (such as ammonia) to determine the reference resistance (Ro) value.
6. Firmware Programming: Uploading program code that includes distance-to-percentage conversion algorithms, waste status classification, and data transmission intervals every 2 seconds to Blynk and research logs every 60 seconds.
7. Procedural Power Management: Implementing delay optimization in the program code to ensure power consumption remains efficient when the system is in standby mode.
8. Finalization: Assembling all components into a waterproof casing and testing functionality in the laboratory before deployment. Once the device is connected according to the techniques mentioned above, it will produce a design as shown in Figure 3 below.

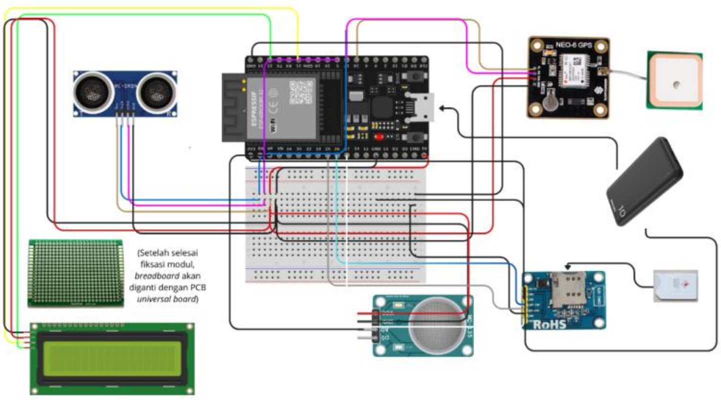

Figure 3: Design of the BINSAI Monitoring Device based on the Internet of Things
(Source: Researcher's Personal Documentation)

3.3.3 Integration of the Blynk Mobile Interface and Spatial Notification Protocol

The Blynk dashboard configuration utilizes Virtual Pin (V-Pin) addressing for real-time data synchronization. The Early Warning System (EWS) protocol is activated via

SIM800L to send geolocation coordinates (latitude and longitude) from GPS NEO-6M via automatic SMS when the bin capacity reaches the threshold (≥90%).

3.3.4 Construction of a High Mobility-Based Smart Bin Modular Unit

The concept of modularity is realized through a compact and self-contained device design. This allows the BINSAI unit to be flexibly moved (plug-and-play) to high-density points. This system ensures that each node remains identified in the central database through synchronization of a unique device ID.

3.3.5 Code and Documentation Repository

To ensure transparency, reproducibility, and contribution to the open-source community, all source code and research datasets have been published on the GitHub repository, as attached in Figure 7 in Appendix 4. This repository adopts version control practices with Git, enabling change tracking and continuous collaboration. The MIT license is applied to support adoption and further development by other researchers.

3.4 Data Processing and Analysis

The processing and analysis of data for this study are as follows.

3.4.1 Data Processing

Data obtained through sensors is transmitted continuously every 2 seconds to the IoT server via Wi-Fi communication protocol for visualization on the Blynk mobile interface. In parallel, the system logs research data to the cloud every 60 seconds for statistical analysis purposes. The data parameters managed include: (a) garbage pile elevation (cm), (b) gas concentration (ppm), (c) transportation priority level, (d) geospatial coordinates, and (e) measurement timestamp.

Raw data from ultrasonic sensors is processed into a percentage of fullness to provide a more intuitive interpretation of volume. This conversion is performed using the following mathematical formula:

$$\text{Percentage of Fullness} = \left(1 - \frac{\text{Measured Distance}}{\text{Maximum Tank Height}}\right) \times 100\%$$

The results of these calculations are then automatically classified by the microcontroller into four operational status categories based on the following predetermined thresholds.

5. 0–35%: “Empty”
6. 36–50%: “Half”
7. 51–90%: “Almost Half”
8. 91–100% : “Full”

3.4.2 Data Analysis

The analysis stage was conducted critically to validate BINSAI's performance through two main approaches. First, sensory accuracy tests were carried out by comparing digital data from sensors with manual measurements using a ruler to calculate the error rate. Second, transmission reliability tests were conducted to calculate the percentage of successful SMS transmission of location coordinates when critical conditions were met.

A special evaluation was conducted on the modularity aspect of BINSAI by reviewing the mobility of the unit and the agility of device activation at high-density points. Modularity performance was measured based on the effectiveness of the unit in anticipating temporary spikes in waste volume.

Table 1: BINSAI Performance Evaluation Parameter Matrix

No	Effectiveness Indicator	Measurement Parameter	Success Target (Threshold)
1	Sensory Accuracy	Deviation between sensor values and manual measurements	Error <3 cm
2	I oT Responsiveness	Data transmission latency from ESP32 to Blynk Cloud	Response time <2 seconds
3	SMS Reliability	atio of location notifications received on time	Success rate >90%
4	Modular Mobility	ime from deployment to system online	Active time <10 minutes
5	Waste Type Indication	Accuracy of organic/inorganic classification via MQ-135	Indication accuracy >98%

The above matrix serves as a comprehensive system validation instrument to ensure the objectivity and functionality of BINSAI in real conditions. The establishment of these quantitative indicators is not merely a formal procedure, but a critical effort to transform this research from the proof of concept stage into a technological solution with scientifically tested system robustness.

CHAPTER IV. RESULTS AND DISCUSSION

4.1 Results of the BINSAI System Plan

The development of BINSAI (Bin Intelligence Sensor and Internet) realizes a Cyber-Physical System (CPS) architecture that integrates sensory instrumentation with cloud connectivity. The system is designed in four strategic modules to address waste management challenges in a measurable manner.

4.1.1 Smart Monitoring Module: Synergy of Volumetric Analysis and Gas Kinetics

The module converges the physical and chemical parameters based on the ESP32 microcontroller, which coordinates the simultaneous data acquisition of two core sensors:

3. HC-SR04 Ultrasonic Sensor: Performs volumetric analysis based on the principle of Time-of-Flight (ToF) to measure the elevation of the garbage pile.
4. MQ-135 Gas Sensor: Serves as a qualitative indicator to detect the presence of ammonia gas (NH_3) as a proxy for the organic decomposition process. The stability of the readings is maintained with the moving average algorithm.

The synergy of data allows for a tiered response mechanism. In contrast to conventional systems that are only reactive to physical capacity, BINSAI can be proactive by setting priorities based on potential environmental risks (such as odor emissions and disease vector attraction) before the tub reaches full capacity. The data processing results are displayed in real-time on the I2C LCD's local interface for field workers and transmitted to Blynk's IoT platform via Wi-Fi for remote monitoring, ensuring transparency and continuity of monitoring with the entire system procedural logic systematically set as illustrated in the flowchart in Figure 4 below.

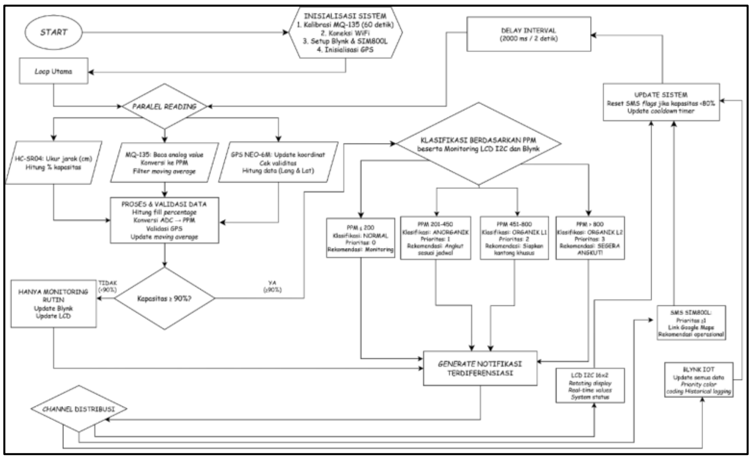

Figure 4: Flowchart of the Development of the BINSAI Monitoring System with Detection Feature of Height and Type of Waste to Differentiated Response
(Source: Researcher's Personal Documentation)

The logic architecture of the BINSAI system is optimized by integrating the MQ-135 sensor as an instrument for early detection of organic material decomposition. Its mechanism of action is deterministic, resting on the simultaneous correlation between physical parameters (capacity >90%) and chemical parameters (gas concentration ≥ threshold), which are processed by the ESP32 microcontroller. The stability of the gas sensor readings was improved by the moving average algorithm, resulting in consistent PPM values to distinguish the waste degradation phases from normal, initial indication, to critical levels (Figure 4).

When both critical thresholds are met, the system activates the emergency notification protocol. The protocol includes specific operational recommendations: (1) the use of layered garbage bags for odor retention, (2) the allocation of special compartments on transport trucks, and (3) the designation of high priority status in the schedule. Precise location data transmission via NEO-6M and GSM GPS modules SIM800L enables BINSAI to perform dynamic mapping based on material urgency. Priority categorization is designed based on real-time acquired gas concentration gradients. The PPM threshold is set through empirical calibration that refers to the sensitivity characteristics of the MQ-135 sensor to ammonia and sulfide gases (Hanwei Electronics, 2010). The categories are differentiated into the initiation phase of organic degradation ('Organic Level 1') and the accelerated decomposition phase with high microbial activity ('Organic Level 2') that have potential health risks (Karthi & Sangeetha, 2020). The full categorization is detailed in Table 4 (Appendix 11).

The implication of this tiered response mechanism is the optimization of operational resource allocation. The system allows for a telemetry evidence-based critical distinction between the 'Standard Full Capacity' and 'Critical-Urgent Condition' status (Srivastava et al., 2017). Thus, through an evidence-based approach, BINSAI evolved from a volume monitoring tool to a precise environmental risk management instrument.

The software system is implemented in a modular code architecture that is functional and responsive. In the monitoring module, two main algorithmic routines—defined as a set of deterministic programmatic instructions in the context of IoT—are executed in parallel by ESP32. It operates on the basis of procedural programming principles and structured protocols, which guarantee synchronization between the acquisition of sensory data in the field and the transmission to the cloud server. The operational mechanism of each routine is described in the following section.

4.1.1.1 Routine Garbage Height Measurement and I2C LCD Display

The first routine is focused on processing physical data through the HC-SR04 ultrasonic sensor to determine the elevation of the garbage pile. The measured distance (d) is calculated based on the wave bounce time (t) through the LaTeX equation as follows:

$$\text{Distance (cm)} = \frac{\text{t} \times 0.0343}{2}$$

The distance data is then transformed into a value of the percentage of fullness (K) to the maximum height of the tub (h) with the formulation:

$$\text{K} = \left(1 - \frac{\text{d}}{\text{Maximum Height of The Tub}}\right) \times 100\%$$

The system automatically classifies into four operational states: Empty (0–35%), Half (36–50%), Almost Full (51–90%), and Full (>90%). This information is visualized in real-time via a 16x2 I2C LCD, where the display displays numerical capacity and condition status as well as indications of the type of waste obtained from the MQ-135 sensor alternately. This process runs continuously inside the main loop, so the data on the LCD will always be updated every time the sensor performs a new reading. The source code for routine garbage height measurements and the I2C LCD interface are presented in the complete code in Appendix 3.

4.1.1.2 Routine in the Internet of Things (IoT) through the Blynk Platform

The second routine manages the remote data communication aspect using Blynk.io platform. After the WiFi network initialization and token authentication phase, ESP32 transmits the capacity data to the Virtual Pin V0 to be displayed on the Gauge widget. Simultaneously, the system controls four virtual LED widgets (V1-V4) as quick visual indicators for officers in the control center. This transmission process utilizes the internal MQTT protocol with a frequency of data updates every 1 second to ensure the actuality of the information. Other virtual pin numbering is available in Appendix 2. Meanwhile, algorithmic specifications and the implementation of routine programming code in the Internet of Things (IoT) through the Blynk platform are presented in full in Appendix 3. Thus, this routine functions as a visual interface that supports the concept of smart monitoring in the smart bin system.

Before deployment in the field, a series of functional tests were carried out to ensure the reliability of each technical module. The initial testing stages are documented and fully described in Figure 8 in Appendix 4.

4.1.2 Priority Notification Module and Early Warning System (EWS) through GSM and GPS Component Integration

This module is a redundant mitigation mechanism that integrates the GSM SIM800L and GPS units of the NEO-6M to ensure information continuity in the midst of Wi-Fi network instability. Through the adaptive threshold algorithm, the Early Warning System (EWS) transforms geospatial coordinates into precise logistics instructions in SMS format when the capacity and kinetics parameters of decomposition reach a critical threshold (≥90%). The strategic advantage of mobile network utilization lies in its reliability and inclusivity; Notifications are still distributed to all types of officers' handheld devices without dependency on data packages or third-party applications. This third routine implementation of hybrid communication facilitates the selective and efficient mobilization of fleets, while ensuring transparency of the location of critical points in large public areas. The explanation is as follows.

4.1.2.1 Hybrid Communication Routine: Spatial Geopolitics and SMS Notifications

The third routine in the BINSAI system is a hybrid communication subsystem that integrates the NEO-6M GPS and GSM SIM800L modules to ensure the availability of data in the blank-spot internet conditions. Regarding the connection route of communication pins, including UART Serial pins, has been listed in Appendix 1. The logic of this routine which operates through two deterministic stages is as follows.

3. Geospatial Data Extraction: The microcontroller parses NMEA-formatted raw data from the GPS module using the TinyGPS++ library. This process aims to obtain continuously valid latitude and longitude coordinates.
4. Transmission of Priority Notifications: When the capacity variable reaches a critical threshold (>90%), the system activates the AT Command instruction to send an SMS containing a link to Google Maps the location of the bin. In order to maintain operational cost efficiency and prevent data redundancy, the smsSent logic variable is implemented. This mechanism ensures that notifications are only sent once per charge cycle, and will only be reset once the sensor detects physical body emptying. Appendix 3 contains the implementation of the early warning system algorithm and complete geolocation-based real-time location tracking . An example of the format of a sent message is available in Figure 9 in Appendix 4

4.1.3 Smart Bin Modular Architecture for High Mobility

Global awareness, particularly in the Southeast Asian region, has reached a crucial point where conventional waste management methods are no longer considered relevant due to cost and time inefficiencies. The development of modular smart bin on the BINSAI platform is present as a technological response to the escalation of the urban population (Mark, 2025). This system prioritizes the principle of high portability, where self-contained units can be functionally integrated into the trash can in less than 10 minutes. Economically, this operational agility is supported by a study by Kermanshachi & Rouhanizadeh (2020) on the potential for Return on Investment (ROI) which is 40% faster than static systems, in line with the principle of Time Value of Money. In Yogyakarta, BINSAI's flexibility enables dynamic deployment based on time-series datasets, transforming waste management from a mere public service to a smart investment instrument for local governments, as envisaged by Figure 10 in Appendix 7.

4.1.4 Open Repository and Documentation Module Open Science

As a contribution to a transparent Smart City ecosystem , all of the research's intellectual assets—including ESP32 firmware, hardware schematics, and libraries—are published through a GitHub repository under the MIT license. This step ensures research reproducibility and opens up opportunities for further feature development collaboration by the global community with procedural ease by the README.md already included, as contained in Figure 7 in Appendix 4.

4.2 System Implementation and Integration

The implementation stage translates architectural design into functional physical artifacts. Hardware integration is carried out by connecting HC-SR04, MQ-135, GPS, and GSM sensors on the ESP32 microcontroller via a custom circuit board (custom PCB/Universal Board) to minimize signal noise.

Interface Interconnection: The ESP32 backend system is connected to the Blynk application frontend via the Virtual Pin protocol.

3. Data Visualization: Gas capacity and concentration data are displayed via Gauge Widgets (V0 and V10) for real-time monitoring.
4. Status Indicator: Operational status is converted to a spectral color indicator on the Widget LED (Green: Safe to Red: Critical). Documentation of the physical implementation and digital interface is shown in Figure 11 Appendix 4.

4.3 Test and Analysis Results

System performance validation is carried out through a quantitative empirical approach to measure the accuracy, linearity, and reliability of data transmission.

4.3.1 Multi-Sensor Testing (HC-SR04 dan MQ-135)

The testbegan by analyzing the linearity of the HC-SR04 ultrasonic sensor by comparing the sensor readings to manual measurements at the 40 cm tub height variation as follows.

4. Experimental Accuracy: The test results showed an average accuracy rate of 99.46% with a relative error of 0.54%. The maximum absolute deviation was recorded at only 0.2 cm at full capacity (37.1 cm).
5. Blind Zone Analysis: A blind zone was identified at a distance of < 3 cm from the transducer. The system has been calibrated to handle this anomaly by setting a safe default state to prevent aliasing errors.
6. Conclusion: The linearity characteristics of the sensor attest to the high reliability in the conversion of analog data to a percentage of digital capacity, as represented by Figure 5 as follows.

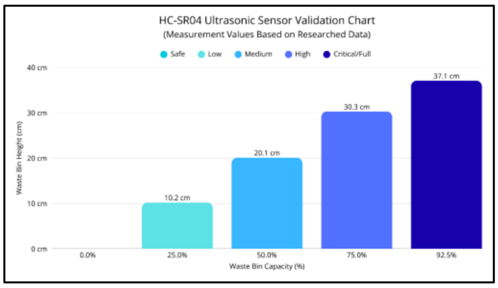

Figure 5: HC-SR04 Sensor Validation Graph

(Source: Researcher's Personal Documentation)

After the data were obtained from the HC-SR04 test, the study continued by analyzing the selectivity of the MQ-135 gas sensor by transforming the raw ADC data into PPM (Parts Per Million) units using the Power-Law Regression approach as shown in Figure 6 as follows.

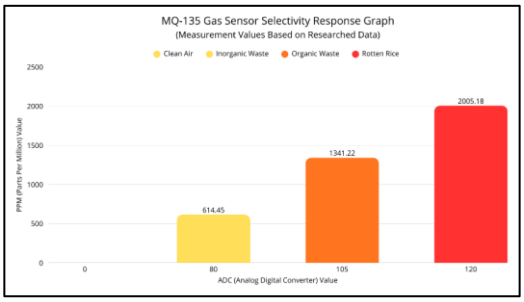

Figure 6: Bar Diagram of MQ-135 Sensor Response

(Source: Researcher's Personal Documentation)

The resulting empirical equations are:

PPM = 0.002348 x ADC2.856

This model has very strong statistical validity with a coefficient of determination (R2) of 0.987 or 98.7%. The measurement was carried out by differentiating the following two phases, namely the clean air phase and the critical decomposition phase using rotten rice as shown in Figure 12 in Appendix 4 accompanied by an explanation.

Critically, the use of this non-linear model is particularly relevant to the physical characteristics of chemical sensors that have an exponential sensitivity curve to organic gas pollutants. Test results show sharp functional contrast; where clean air conditions produced an average of < 60 ADC (PPM < 200), while exposure to rotten rice triggered a spike in ADC > 120 correlated with a gas concentration of > 800 PPM. This validation proves that BINSAI is effectively able to deterministically classify materials through chemical gradient analysis, distinguishing between stable inorganic waste and organic waste that has reached the critical phase of decomposition.

4.3.2 Telemetry and Geolocation Evaluation (GPS & GSM)

The measurement of the level of spatial data accuracy of the NEO-6M GPS module is carried out by validating the coordinates by comparing the GPS module's telemetry data against high-precision geospatial reference points (Google Maps). The documentation that indicates the coordinate value is in Figure 13 in Appendix 4 then continued with the following error calculation.

Error = -7.764200 - (-7.764205)| = 0.000005◦

Accuracy Rate: Analysis shows spatial accuracy to reach 99.99%. The microscopic deviation in the fifth decimal was identified as the truncation effect of the float variable on IoT transmission, which technically did not affect the navigation precision of the logistics fleet (radius tolerance < 1 meter).

Based on the comparison between the readings of the BINSAI device contained in Figure 13 in Appendix 4, the following explanation is obtained.

Percentage Accuracy Formula:

$$\text{Accuracy (\%)} = \left(1 - \frac{|\text{Reference Value} - \text{Measured Value}|}{|\text{Reference Value}|}\right) \times 100\backslash\%$$

Case Calculation (Lat):

5. Reference (Laptop): -7.764200 (6 decimal assumptions)

6. Measurable (Blynk): -7.764205 (5th decimal deviation is available)
7. Error: 0.000005◦
8. Result: Spatial Accuracy ≈ 99.99%

The difference in numbers after the comma is not due to sensor failure, but to the precision of the transmission of float variables in the IoT protocol. ESP32 sends coordinate data as a float variable that is often rounded or truncated when processed by the Blynk server. A deviation of 0.000005 degrees is equivalent to a precision ≈ 0.5 meters, which is technically very acceptable for trash fleet navigation.

Meanwhile, regarding the GSM module, based on mathematical calculations regarding accuracy and efficiency, measurements are obtained through the parameters of accuracy and system redundancy. Based on the trial of 10 message entities, the following indicators were obtained.

3. Transmission Accuracy (Success Rate):

$$\mathrm{SR} = \left(\frac{\sum \mathrm{P_{success}}}{\sum \mathrm{P_{total}}}\right) \times 100\% = 100\%$$

These results demonstrate absolute reliability in the transmission of information from nodes to users.

4. Laju redundancy (redundancy rate):

A transmission deviation in the form of one duplicate message (10%) was identified calculated through the redundancy ratio:

$$\%\mathrm{Error} = \left(\frac{\mathrm{P}_{\text{ duplicate}}}{\mathrm{P_{total}}}\right) \times 100\% = 10\%$$

The relationship between the experimental variable (x) and the received data (y) was mapped through a simple linear regression model y = 1.1x. A deterministic coefficient that exceeds the ideal value (1.0) indicates a data over-provisioning scheme of 10%.

Critically, this phenomenon is a manifestation of the guaranteed delivery mechanism in response to handshake latency on the cellular network. The BINSAI device initiates retransmission automatically to mitigate the risk of packet loss due to signal fluctuations. This confirms the advantages of a system that prioritizes data integrity over bandwidth efficiency, a crucial parameter for the functionality of the Early Warning System (EWS) in responsive and deterministic urban waste management.

4.3.3 Integrated System Integration

Holistically, the test results in sub-chapters 4.3.1 and 4.3.2 prove that the integration of BINSAI modular components has met the operational standards of Smart City. The convergence between sensory accuracy (98-99%) and telemetry reliability (100% success rate) confirms the feasibility of this system to be implemented as an evidence-based waste crisis mitigation solution.

4.4 Results Discussion

The synthesis of experimental findings confirms the effectiveness of BINSAI as a data-driven mitigation instrument, with the following critical achievements and limitations.

4.4.1 Multidimensional Data Synergy and Proactive Paradigm Shift

The main value of BINSAI lies in the Tiered Response mechanism resulting from sensory data convergence. The high accuracy of the ultrasonic sensor (99.46%) validates the volumetric occupancy, while the integration of the MQ-135 sensor (R^2=0.987) adds a qualitative dimension. This synergy transforms the system from a reactive (full capacity-based) approach to proactive. Early detection of increased ammonia gas allows prioritization of transportation based on the level of environmental hazard (odor, potential pathogen), rather than just physical occupancy, thereby significantly reducing public health risks in congested areas.

4.4.2 Telemetry Architecture Resiliency under Realistic Conditions

The evaluation of the communication module proves its reliability for an urban scale. The phenomenon of data over-provisioning of 10% (modeled with regression y=1.1x) is a manifestation of a deliberate guaranteed delivery mechanism, ensuring that notification integrity is maintained even in conditions of high mobile network latency. 99.99% GPS spatial accuracy provides absolute location precision. This combination of location precision and transmission certainty creates a fleet dispatch system that is much more efficient than conventional static routes, potentially reducing logistics operational costs substantially.

4.4.3 Evaluation of Physical Limitations and Systemic Compensation

The research critically identified technical limitations, such as **blind zones** at a distance of <3 cm from ultrasonic sensors. However, this limitation is successfully compensated by firmware logic that deterministically assigns a "Critical" state when an object enters the zone, thus not detracting from functional utility because that condition already represents excess capacity.

4.4.4 Strategic Relevance to Smart City Implementation

The implementation of BINSAI has direct relevance to the context of the landfill crisis in Yogyakarta. The open-source and modular architecture offers a solution with a low entry barrier but high impact. Blynk's cloud dashboard facilitates real-time data transparency for policymakers. Theoretically, massive implementation could shift the paradigm from Routine Collection to Demand-Driven Collection, which not only solves aesthetic and health issues, but also supports the achievement of the Sustainable Development Goals (SDGs) through the digitalization of inclusive public infrastructure.

4.5 Obstacles and Solutions

The development of BINSAI is faced with technical obstacles that require strategic solutions to ensure functional sustainability.

4.5.1 Technical Constraints

The main obstacle was identified in the failure of the NEO-6M GPS module due to **power instability**. Analysis showed the failure was caused by the use of a 3.3V shared pinout of the ESP32 which was unable to supply a constant current at peak load, causing component degradation. The corrective solution is implemented through power supply isolation by integrating a Dedicated Low-Dropout Regulator (LDO). This self-regulating regulator is proven to stabilize voltage fluctuations and provide protection against current surges, thus guaranteeing the long-term integrity of the GPS module.

4.5.2 Computational Limitations and Technology Inclusivity Strategies

The second technical constraint arose from the ESP32's limited computing capacity which was insufficient to run complex dynamic route optimization algorithms (multi-point routing). Reliance on external servers risks hindering scalability. As a pragmatic solution, the system was reconfigured to focus on an SMS notification mechanism that included Google Maps geospatial links. This strategy not only reduces the burden of on-board computing, but also creates an inclusive ecosystem. The SMS format ensures information accessibility for field officers without reliance on stable internet connections or advanced devices, thus maintaining system functionality in real operational conditions.

CHAPTER V. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusion

This research successfully validated the BINSAI (Bin Intelligence Sensor and Internet) system as a strategic instrument for the digital transformation of urban waste management. Based on empirical evaluation, the following conclusions were drawn.

4. Volumetric Precision & Telemetry: The implementation of Time-of-Flight-based ultrasonic sensors achieves an average accuracy of 99.46%. The transformation of physical data to digital has proven to be reliable with 100% notification transmission reliability through dual channels (Blynk dashboard & SMS Gateway).
5. Deterministic Classification: The integration of the MQ-135 sensor using the Power-Law regression model resulted in high validity (R2 = 0.987). This gives a new dimension of intelligence to the system to precisely differentiate stable inorganic waste and active organic decomposition.
6. Elimination of Operational Blind Spots: BINSAI's modular design effectively negates the inefficiencies of conventional monitoring. This system offers a scalable and proactive solution, making it a feasible model for accelerating Smart City infrastructure in Yogyakarta.

5.2 Suggestions

To elevate BINSAI into a predictive and sustainable waste management ecosystem, the following developments are recommended:

5. Elevation of Artificial Intelligence: Integration of Edge Computing and Machine Vision on firmware to enable automated, real-time sorting at source.
6. Infrastructure Resiliency: Adoption of hybrid communication networks (LoRaWAN) and solar panel-based power management to ensure self-sustaining operations in areas with signal or electricity constraints (off-grid).
7. Data-Based Policy: Development of a dashboard with predictive analytics features to support strategic decision-making (evidence-based policy) by environmental authorities.
8. Triple Helix Synergy: Strengthening Government-Academic-Community collaboration through participatory incentive schemes to encourage collective behavior change in waste management.

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APPENDIX

Appendix 1: Table of Connecting Routes Between Components

Components	Pin ESP32	Component Pins	Main Functions
Power Management			
Power Bank 10.000mAh	VIN/5VIN (SIM800L)	OUT (+)	Power distribution
Power Bank 10.000mAh	GND	OUT (-)	Common Grounding System
Sensor Ultrasonik HC-SR04			
	GPIO 5	TRIG	Trigger Pulse
	GPIO 18	ECHO	Echo Signal
	5V	VCC	Sensor power source
	GND	GND	Negative path
Sensor Gas MQ-135			
	GPIO 34	AUGUST	Gas concentration analog data (PPM) transmission
	3.3V	VCC	Sensor power source (Logic 3.3V)
	GND	GND	Negative path
LCD I2C (16x2)			
	GPIO 21	SDA	Serial Data Line (I2C protocol)
	GPIO 22	SCL	Serial Clock Line (I2C protocol)
	5V	VCC	Backlight and LCD logic power source
	GND	GND	Negative path
GPS NEO-6M			
	GPIO 13	TX	Data Transmission coordinates to ESP32 (RX1)

	GPIO 15	RX	Data Reception command from ESP32 (TX1)
	3.3V	VCC	GPS module resources
	GND	GND	Negative path
Module GSM SIM800L			
	GPIO 16	TX	SMS/GPRS serial data transmission (RX2)
	GPIO 17	RX	SMS/GPRS serial data reception (TX2)
	GPIO 27	PWRKEY	Programmatically Power-on/Reset control of the module
	Out Step-down	5VIN	Dedicated power supply
	GND	GND	Negative Path (Shared Ground)

Appendix 2: Blynk Cloud Datastream and Dashboard Configuration Table

No	Nama Datastream	Virtual Pin	Data Type	Value Range	Units	Widget & Function Description
1	Fill Percentage	V0	Integer	0 – 100	%	Gauge & SuperChart: Continuous monitoring of the volume of waste.
2	LED Red	V1	Integer	0 / 255	-	Widget LED: "FULL" status indicator (>90%).
3	LED Orange	V2	Integer	0 / 255	-	Widget LED: "ALMOST FULL" status indicator (51-90%).
4	LED Yellow	V3	Integer	0 / 255	-	LED Widget: Status indicator "HALF" (36-50%).
5	LED Green	V4	Integer	0 / 255	-	LED Widget: Status indicator "EMPTY" (0-35%).
6	Distance	V5	Double	0 – 400	cm	Labeled Value: Raw data of ultrasonic sensor readings.
7	Capacity Status	V6	String	-	-	Labeled Value: A textual interpretation of the condition of the garbage can.
8	PPM Value	V10	Integer	0 – 2000	ppm	Gauge & SuperChart: Intensitas gas amonia (MQ-135).
9	Priority Level	V11	Integer	0 – 3	-	Value Display: Scale the urgency of waste handling.
10	Waste Type	V12	String	-	-	Label: Automatic classification (Organic/Inorganic).
11	Recommendation	V13	String	-	-	Label: Preventive instructions/PPE for officers.
12	Latitude	V20	Double	-	GPS	Widget Map: The point of the latitude coordinate point of the device's location.

13	Longitude	V21	Double	-	GPS	Widget Map: The longitude coordinate point of the device's location.

Appendix 3: Full Code C++ Language Algorithm on Arduino IDE

Link:
https://github.com/Moechhh/BINSAI_RESEARCH/blob/main/src/main.cpp

Appendix 4: Documentation Figure

GitHub Documentation

Repository link: https://github.com/Moechhh/BINSAI_RESEARCH.git

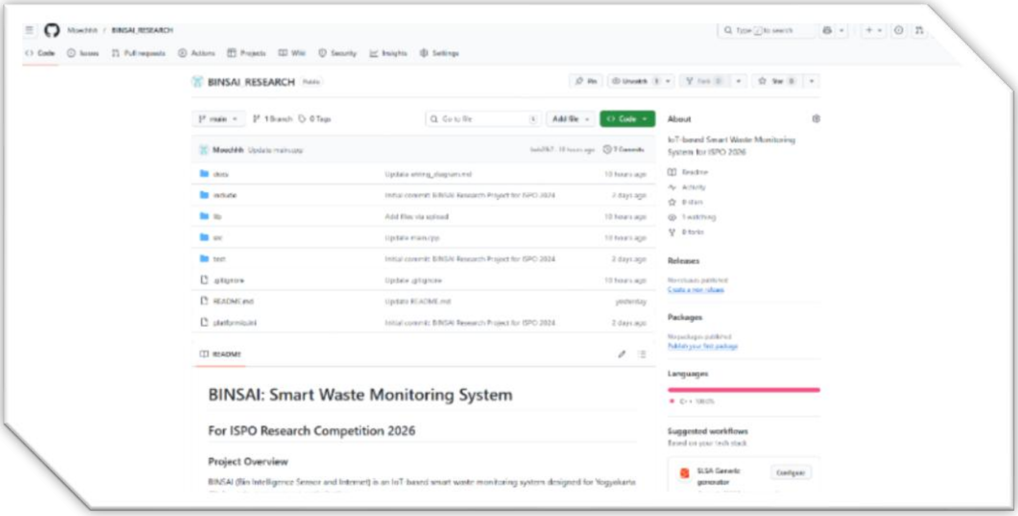

Figure 7: GitHub Dashboard

(Source: Researcher's Personal Documentation)

Figure Preliminary Assembly Drawings

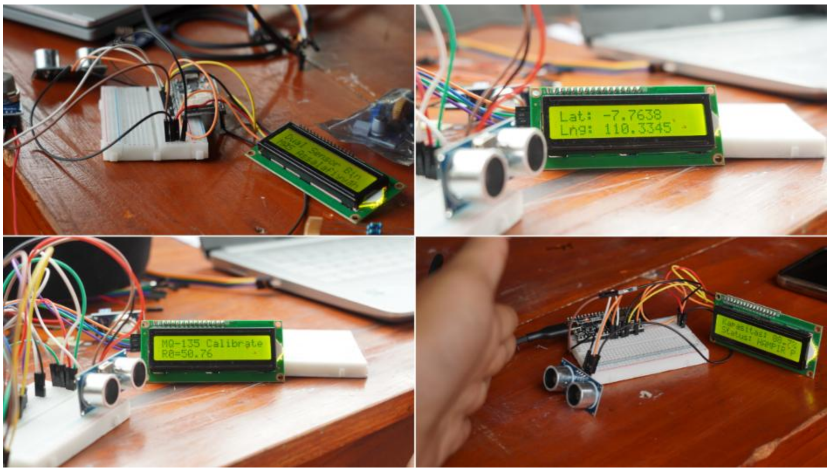

Figure 8: Assembly and Initial Testing on the BINSAI Module

(Source: Researcher's Personal Documentation)

The test series in Figure 8 above shows the system verification process which includes:

5. (a) Interface Initialization Test (Top Left): Verify the display opening on the I2C LCD to ensure the I2C communication line and power supply to the display are operating correctly when the device is first turned on.

6. (b) GPS Spatial Verification (Top Right): Testing of the NEO-6M GPS module in acquiring satellite signals to obtain precise latitude and longitude coordinates at the research site.
7. (c) MQ-135 Dynamic Calibration (Bottom Left): The process of determining the R0 value (sensor resistance in clean air) to ensure the accuracy of the ammonia gas PPM reading to avoid reading errors due to initial environmental conditions.
8. (d) Capacity Accuracy Test (Bottom Right): Simulation of distance measurement against objects to validate the distance to percentage conversion algorithm, ensuring the status displayed on the LCD corresponds to the physical condition of the body occupancy.

Figure of Sent SMS Format

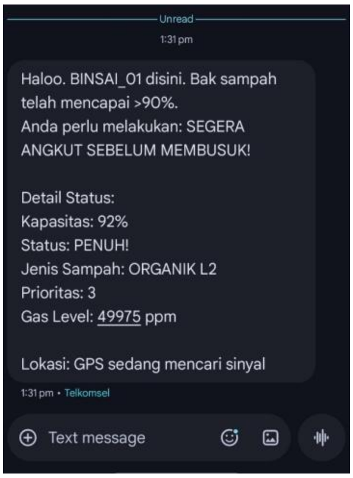

Figure 9: Format of Messages Sent through the Blynk Mobile Application on the BINSAI System

(Source: Researcher's Personal Documentation)

Figure of Modular Smart Bin

Figure 10: Modularization of BINSAI by compacting in enclosure

(Source: Researcher's Personal Documentation)

Component Integration Drawings

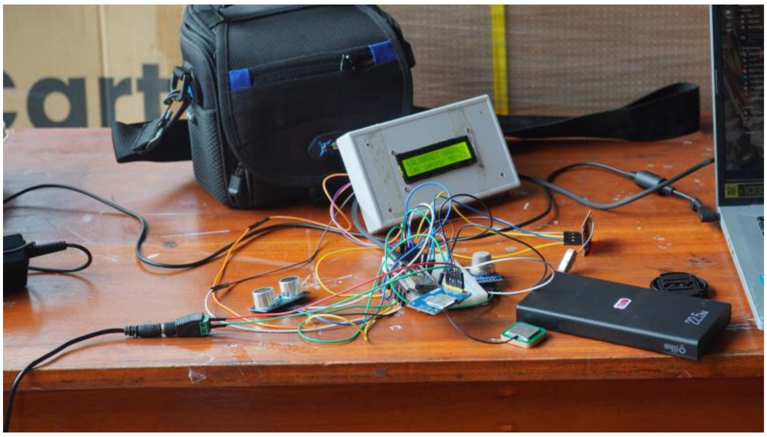

Figure 11: Integration Between Components

(Source: Researcher's Personal Documentation)

MQ-135 Sensor Testing Drawings

Figure 12: Acquisition of ADC (Analog-to-Digital Converter) as a Reference to PPM Value

(Source: Researcher's Personal Documentation)

Based on Figure 12, the following results are obtained.

Visual Analysis of Empirical Testing.

5. Figure A top left (Clean Air Baseline): Shows the initialization stage where the sensor is exposed to clean air (clean air phase). The data showed a stable ADC value at 0 for the initial 14 seconds, which confirmed that the sensor did not detect ammonia (NH3) contaminants above the background threshold.
6. Figure B top right (Real-Time Data Transmission): This is a Serial Monitor documentation that captures the kinetics of rising gas levels as the sensor begins to be exposed to organic waste objects. At the 14th second, the ADC value shows an upward trend but has not yet reached the peak point (120), representing the transition phase of gas diffusion to the sensor surface.

7. Figure C bottom left (Sensor and Pollutant Interactions): Shows the MQ-135 device placed proximal on top of rice that has been decomposed for 3 days. This direct exposure triggers a reduction reaction on the surface of the sensor semiconductor material due to gas emissions from microbial activity.
8. Figure D bottom right (Final Result Validation): The final stage of the test where the system successfully achieves data saturation at the ADC value ≥120 in the last 10 seconds of the test. This data becomes the final basis for the regression model to classify objects as advanced organic waste (Organic Level 2).

NEO-6M GPS Module Testing

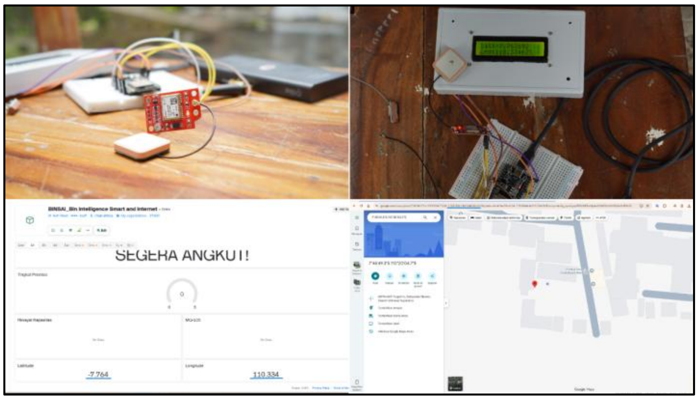

Figure 13: NEO-6M GPS Testing

(Source: Researcher's Personal Documentation)

Figure B (top right) and the Google Maps reference on the laptop, Figure D (bottom right), then the calculation of the percentage of coordinate accuracy that has been described in 4.3.2 GPS and GSM Module Testing is obtained.

Appendix 5: Waste Type Indication Threshold Table

Table 4. MQ-135 Sensor-Based Waste Type Indication Detection Threshold

Conditions	BINSAI (PPM)	Scientific Reference (PPM)	Source
Clean/Normal Air	0 - 199	< 250 - 350	WHO & EPA: Background levels of CO2‹ in the air are typically 350-400 ppm. MQ-135 often shows low values (0-200) after RZero calibration in clean air.
Inorganic / Light Odor	200 - 449	350 - 600	Srivastava et al. (2017): Indoor air or areas with little pollution/light organic gases are in this range.
Organic (Starting to Rot)	450 - 800	> 600 - 1000	Karthi & Sangeetha (2020): Setting >700 ppm as an indicator of the presence of methane/ammonia gas from wet garbage piles.
Critical (High Rot)	> 800	> 1000	Hanwei Electronics datasheet: MQ-135 has a high sensitivity of up to 1000 ppm. A value of >800 indicates a concentrated concentration of hazardous gases.

Appendix 6 : Activity Agenda Matrix

Activities	Moon... Week to...																			
	September				October				November				December				January			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Discuss research ideas																				
Looking for literature studies																				
Problem survey																				
Fixation of research titles																				
Creation of research proposals																				
Preparation of research tools and materials																				
Component collection																				
Manufacturing																				
Application																				
Testing																				
Testing																				
Testing																				
Initial data collection																				
Advanced test																				
Data analysis and interpretation of results																				
Research																				
Preparation of the final report																				