

CRITICAL INFRASTRUCTURE AND WASTE-TO-VALUE LAB

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Gravimetric Measurement as a Foundational Data Layer in Waste-to-Value Systems: From Fuel Consumption Methodology to Distributed Urban Mining Infrastructure

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ABSTRACT

Gravimetric measurement — the determination of mass flow through direct weight quantification over a defined time interval — constitutes one of the most physically rigorous, apparatus-minimal, and epistemically transparent methods available for flow characterization in dynamic material systems. Originally developed and validated in the context of fuel consumption analysis in diesel-powered automotive platforms, the method has been shown to achieve measurement errors of 0.318% under steady-state idle conditions and 5.8% under dynamic New European Driving Cycle (NEDC) protocols, using a load cell, HX711 signal amplifier, and Arduino Uno microcontroller at a system cost several orders of magnitude below that of laboratory-grade positive-displacement flowmetry (Nolandy et al., 2024).

This paper formalizes the gravimetric approach as a generalized measurement framework and demonstrates its systematic extension from controlled, bounded fuel systems into the heterogeneous, distributed, and temporally variable material environments that characterize modern waste-to-value infrastructure. Within Cobeal's circular economy architecture — a multi-pathway conversion platform

encompassing biological digestion, thermal conversion, and controlled pyrolysis — gravimetric measurement functions as the primary data layer that transforms incoming heterogeneous waste streams into structured, quantifiable, process-assignable inputs. These inputs govern process pathway selection, energy balance computation, output recovery estimation, contractual performance benchmarking, and network-level material routing across biological, thermal, and pyrolysis conversion assets.

The paper proceeds through four analytical phases: (1) a rigorous exposition of gravimetric measurement theory, uncertainty structure, and calibration practice; (2) a systematic mapping of fuel-system measurement architecture onto waste-material systems at increasing scales of heterogeneity; (3) a detailed technical treatment of feedstock characterization, process alignment, and energy balance modeling as governed by gravimetric data; and (4) a network-level analysis of how gravimetric measurement enables contractual, financial, and operational structures within Cobeal's national-scale urban mining programme. The result is a unified measurement architecture that links physical material flows to engineered conversion outputs and monetizable value streams — establishing mass as the irreducible governance variable of the circular economy.

1. Gravimetric Measurement: Method Definition, Analytical Structure, and Instrumentation

1.1 Foundational Definition and Physical Basis

Gravimetric measurement, in the context of flow characterization, determines the mass flow rate of a material by recording the change in total system weight over a precisely defined time interval. The method proceeds from first principles in classical mechanics: weight is a direct manifestation of gravitational force acting on mass, and force can be measured to extremely high precision using calibrated transduction elements. The fundamental governing relationship is expressed as follows:

$$FC_{grav} = |m_2 - m_1| / \Delta t \quad (\text{Formula 1})$$

where FC_{grav} denotes the mass-based flow rate [$g \cdot s^{-1}$];

m_1 denotes the initial system mass at the commencement of the measurement interval [g];

m_2 denotes the final system mass at the conclusion of the measurement interval [g];

Δt denotes the elapsed measurement duration [s].

This deceptively simple expression encodes several analytically important properties. First, it is a direct measurement — it does not require knowledge of the fluid's density, viscosity, temperature coefficient, or phase state. Volumetric methods, by contrast, require a conversion factor (density) that is itself a function of temperature, pressure, and composition, introducing a compounded uncertainty chain that gravimetric analysis avoids entirely (Gournay & Homklintian, 2018). Second, the method is substrate-agnostic — any material that can be weighed can be characterized by this approach,

whether it is a homogeneous liquid fuel such as B30 biodiesel, a slurry of organic waste, a dry bulk solid, or a heterogeneous mixed stream. **This substrate independence is precisely what makes gravimetric measurement the methodological bridge between fuel system analytics and waste-to-value infrastructure.**

Third, the method is inherently temporally resolved. Because weight is recorded continuously as a time series, the derivative of the weight-time function at any instant yields the instantaneous flow rate. This temporal granularity enables the method to capture not only mean flow behavior but also transient dynamics — acceleration events, system startups, pulse feeding, and seasonal variations — all of which are significant in real-world conversion systems.

1.2 Instrumentation Architecture

The instrumentation system validated in the fuel measurement context by Noland et al. (2024) comprises three integrated subsystems operating in sequence. The primary sensing element is a load cell — in the validated configuration, a 40 kg capacity strain-gauge load cell with a rated output of $2 \text{ mV} \cdot \text{V}^{-1}$, non-linearity of 0.02% of full scale, and a creep characteristic of 0.0016% of full scale over 30 minutes. Load cells operate on the principle of resistive strain measurement: the mechanical deformation of a precisely engineered elastic element under applied load produces a proportional change in electrical resistance, which is read as a differential voltage signal.

The analog output of the load cell — a very small differential voltage in the millivolt range — is amplified and digitized by an HX711 analog-to-digital converter (ADC) module. The HX711 provides 24-bit resolution across a differential input voltage range of $\pm 40 \text{ mV}$ and communicates directly with a digital microcontroller via a two-wire serial protocol. This high bit depth is critical: at 24 bits, the converter resolves over 16.7 million discrete steps across its measurement range, enabling sub-milligram mass discrimination even at the 40 kg full-scale capacity of the load cell described.

Data acquisition and computation are handled by an Arduino Uno microcontroller, which executes a C++ program developed in the Arduino Integrated Development Environment (IDE). The Arduino polls the HX711 at a defined sampling frequency, records timestamped mass values, and applies the Formula 1 computation to derive instantaneous and cumulative flow rates. The processed data is transmitted to a connected computer for logging and analysis in spreadsheet software. The complete instrumentation chain — load cell, HX711, Arduino Uno, and data logging interface — can be assembled from commercially available components at a fraction of the cost of laboratory-grade positive-displacement flowmeters, which require precision gear mechanisms, servo-motor control, and traceable calibration that collectively represent significant capital expenditure (de Huu et al., 2020).

1.3 Calibration Protocol

The accuracy of a gravimetric measurement system is fundamentally conditioned by the quality of its calibration. Calibration establishes the mathematical transfer function between the raw electrical

output of the load cell (measured in volts) and the corresponding applied mass (measured in grams). This relationship is typically linear across the operational range of a well-designed load cell, but the exact slope and offset of the linear function must be determined empirically using certified reference weights.

In the validated configuration, calibration is performed by applying a series of known reference masses across the full measurement range and recording the corresponding output voltages. The resulting voltage-to-mass calibration curve is then used to correct all subsequent measurements. Hysteresis — the tendency of a transducer to give different readings during increasing and decreasing load cycles — is characterized by recording both upward (loading) and downward (unloading) measurement sequences and confirming their agreement within acceptable bounds. The hysteresis characterization in the Nolandy et al. (2024) study confirmed consistent load cell readings for both directional measurement sequences, establishing the instrument's suitability for bidirectional flow monitoring.

For waste-to-value applications, calibration must additionally account for the physical characteristics of the measurement environment: ambient temperature fluctuations that affect load cell sensitivity, vibration from mechanical processing equipment that may introduce noise into the signal, and the potential for chemical exposure if the load cell is used in proximity to corrosive waste streams. These environmental factors do not invalidate the gravimetric approach but require appropriate instrumentation selection and protective engineering.

1.4 Uncertainty Structure and Measurement Fidelity

The measurement uncertainty of a gravimetric system is computed in accordance with the Joint Committee for Guides in Metrology (JCGM) framework, which distinguishes between Type A uncertainty (arising from statistical variation in repeated measurements) and Type B uncertainty (arising from systematic sources such as calibration certificates, instrument specifications, and environmental effects). The combined uncertainty is computed by quadratic summation of the component uncertainties, and the expanded uncertainty is obtained by multiplying the combined uncertainty by a coverage factor $k = 2$, which corresponds to approximately 95% confidence for a normal distribution.

For the scale measurement instrument described by Nolandy et al. (2024), the three principal uncertainty contributors are: (i) Type A repeatability, with a standard uncertainty of 0.022 g; (ii) Type B calibration certificate uncertainty, with a standard uncertainty of 0.241 g; and (iii) Type B buoyancy correction, with a standard uncertainty of 9.17×10^{-10} g — essentially negligible. The combined uncertainty is 0.241 g and the expanded uncertainty at $k = 2$ is 0.482 g. The comparative flowmeter achieves a lower expanded uncertainty of 0.294 g, reflecting the greater inherent precision of the positive-displacement volumetric principle under stable conditions.

The relative error of the gravimetric system with respect to the flowmeter reference is defined by the following formula:

$$R_{gf} = (FC_{grav} - FC_{flow}) / FC_{flow} \quad (\text{Formula 2})$$

where R_{gf} denotes the relative error of the gravimetric method with respect to the volumetric reference [dimensionless];

FC_{grav} denotes the mass flow rate determined by the gravimetric system [$g \cdot s^{-1}$];

FC_{flow} denotes the mass flow rate determined by the volumetric flowmeter [$g \cdot s^{-1}$].

Under idle (steady-state) conditions, the gravimetric system recorded a mean fuel consumption rate of $3.475 \text{ g} \cdot \text{s}^{-1}$ against a flowmeter reference of $3.464 \text{ g} \cdot \text{s}^{-1}$, yielding a relative error of 0.318%. Under NEDC dynamic driving cycle conditions — with continuous acceleration, deceleration, and speed transients — the gravimetric system recorded a mean rate of $14.068 \text{ g} \cdot \text{s}^{-1}$ against $14.223 \text{ g} \cdot \text{s}^{-1}$, yielding a relative error of 5.763%. The elevated error under dynamic conditions reflects the inherent response-time characteristics of the load cell system: the mechanical and electronic settling time of the weighing apparatus introduces a lag during rapid changes in flow rate. However, it is worth noting that in the NEDC test, the gravimetric scale actually demonstrated superior response during gear changes and speed transitions — reading more accurately at discrete state transitions — while the flowmeter showed delayed response due to its internal fluid dynamics. The 5.8% figure therefore represents a conservative bound, and for the smoothed, time-averaged mass balances that govern waste-to-value system design, this level of fidelity is more than adequate.

The arithmetic mean and standard deviation of repeated measurements are computed as follows:

$$\bar{x} = (1/n) \times \sum_i x_i \quad (\text{Formula 3})$$

where \bar{x} denotes the arithmetic mean; n denotes the number of measurements; x_i denotes the i -th measurement value.

$$s(x_i) = \sqrt{[(1/(n-1)) \times \sum_i (x_i - \bar{x})^2]} \quad (\text{Formula 4})$$

where $s(x_i)$ denotes the experimental standard deviation of the measurement series.

$$u(X) = u_i = s(x_i) / \sqrt{n} \quad (\text{Formula 5})$$

where $u(X)$ denotes the standard uncertainty from Type A evaluation.

These formulas constitute the computational core of the uncertainty budget and are applied identically whether the system under analysis is a diesel fuel tank in a laboratory dynamometer cell or a pre-treatment hopper receiving mixed municipal solid waste at an urban processing hub.

Table 2. Uncertainty Budget: Gravimetric Scale Measurement System

Source	Type	Uncertainty (g)	Sensitivity Coefficient	Std Uncertainty (g)
Repeatability measurement	A	0.022	1	0.022
Calibration certificate	B	0.241	1	0.241
Buoyancy correction	B	9.17×10^{-10}	1	9.17×10^{-10}

Source	Type	Uncertainty (g)	Sensitivity Coefficient	Std Uncertainty (g)
Combined uncertainty U(L)	—	—	—	0.241
Expanded uncertainty (k=2)	—	—	—	0.482

Table 2. Uncertainty budget for gravimetric scale measurement system, following JCGM 100:2008 (GUM) methodology. Source: Nolandy et al. (2024).

2. From Fuel Systems to Material Systems: The Methodological Bridge

2.1 Structural Homology Between Fuel and Waste Systems

The intellectual contribution of this paper rests on a structural observation: **the physical architecture of a fuel consumption measurement system and the physical architecture of a waste-to-value feedstock characterization system are homologous** — they share the same governing mathematical relationships, the same measurement primitives, and the same analytical objectives. The differences are differences of scale, heterogeneity, and boundary complexity, not differences of fundamental physical principle.

In a fuel measurement system, the configuration is tightly bounded: a fuel supply tank of known initial mass M_1 feeds a diesel engine; return fuel from the injectors flows back to a return tank; the net consumption is computed as the difference between supply depletion and return accumulation over a defined time interval. **The system boundary is closed, the material is homogeneous** (a single fuel blend with known physicochemical properties), **and the measurement interval is controlled**. This is the scenario analyzed by Nolandy et al. (2024).

In a waste-to-value feedstock system, the configuration is structurally identical but operationally more complex: a waste input stream of variable initial composition enters a pre-treatment or reception hopper; processed material flows forward into conversion pathways; residuals, leachate, and off-gases exit the system boundary. **The net material transformation is computed as the difference between input mass and output mass fractions over defined processing intervals**. The system boundary is defined but permeable to multiple material phases; the material is heterogeneous with variable physicochemical properties; and the measurement interval may span hours, days, or seasonal cycles.

Despite these complexities, the governing equation remains Formula 1. The gravimetric method does not require the material to be homogeneous; it requires only that the material exerts a gravitational force proportional to its mass — a property shared by all physical matter. This universality is the foundation of the methodological extension developed in this paper.

2.2 Scaling the Measurement Architecture

The transition from fuel system to waste system requires attention to three principal scaling dimensions: (1) mass scale, from kilograms to tonnes per day; (2) compositional complexity, from a single-phase liquid to a multi-component heterogeneous solid-liquid mixture; and (3) temporal scale, from seconds to seasons. Each of these dimensions introduces specific instrumentation and data management requirements, but none fundamentally alters the measurement principle.

At the mass scale dimension, the load cell capacity used in the Noland et al. (2024) configuration is 40 kg — **appropriate for a laboratory fuel tank**. Waste-to-value processing nodes receive material flows measured in tonnes per day, requiring load cells or platform weighing systems with capacities ranging from hundreds of kilograms to tens of tonnes. These systems are commercially mature and widely used in industrial logistics. Their uncertainty characteristics follow the same Type A/B decomposition described in Section 1.4, with calibration uncertainty typically dominating in the higher-capacity ranges.

At the compositional complexity dimension, the gravimetric measurement provides a total mass reading that must be decomposed into component fractions through complementary analytical methods — proximate analysis (moisture, volatile solids, fixed carbon, ash), ultimate analysis (elemental composition), and calorific value determination. These methods are well-established in waste characterization practice (ASTM E1756, E1821, E711) and provide the substrate-specific parameters required for process pathway assignment. Critically, the gravimetric total mass measurement remains the anchor quantity — the compositional fractions are expressed as proportions of the gravimetrically determined total, ensuring mass balance conservation across the system.

At the temporal scale dimension, the Arduino-based data acquisition system used in the fuel context operates at sampling frequencies of tens of hertz, appropriate for capturing rapid transients in automotive fuel consumption. Waste-to-value systems require temporal resolution appropriate to their operating dynamics: pre-treatment hoppers may be sampled at one-minute intervals; anaerobic digestion feeders at fifteen-minute intervals; seasonal sargassum processing platforms at hourly intervals. The gravimetric principle accommodates any sampling frequency; the choice is governed by the characteristic time constant of the process being monitored.

2.3 The Closed-Loop Material Balance as the Analytical Core

The most important conceptual transfer from fuel system to waste system is the closed-loop material balance. In the fuel system, the load cell simultaneously weighs the supply tank and (optionally) the return tank, allowing the net engine consumption to be isolated from the total fuel throughput. This return-flow correction is analogous to — and structurally identical to — the digestate and residual accounting required in anaerobic digestion and pyrolysis systems.

In anaerobic digestion, the input stream (organic waste slurry) undergoes biological conversion to produce biogas (primarily methane and carbon dioxide) and a liquid/solid digestate. The gravimetric

mass balance requires measurement of the input slurry mass, the digestate mass, and — through a separate gas measurement subsystem — the biogas mass. The difference accounts for the carbon-hydrogen-oxygen atoms transferred from solid/liquid phase to gaseous phase. This three-term mass balance is structurally more complex than the fuel system's two-term balance, but it employs the same measurement primitive: weight over time.

In pyrolysis, the input stream undergoes thermochemical decomposition in the absence of oxygen to produce syngas, bio-oil, and char (solid residue). The gravimetric mass balance tracks the input mass, the char output mass, and the condensable liquid output mass; the non-condensable gas fraction is determined by difference. Again, the governing mathematics are a generalization of Formula 1 to multi-output systems.

3. Feedstock Characterization and Process Pathway Alignment

3.1 Compositional Diversity of Urban Waste Streams

The waste streams received by Cobeal's urban mining infrastructure are materially diverse in a manner that has no analogue in fuel system measurement. Where B30 biodiesel is a compositionally defined blend of petroleum diesel and palm-oil-derived fatty acid methyl esters (FAME) with a density of $856 \text{ kg}\cdot\text{m}^{-3}$ and a cetane number of 51 (Noland et al., 2024; Iswantoro et al., 2021), municipal solid waste (MSW) is a mixture whose composition varies by geography, season, income level, and collection methodology. A representative Mexican urban MSW stream may contain carbohydrate-rich food waste (30–50% by mass), lignocellulosic garden and paper waste (15–25%), plastics and polymers (10–20%), textiles (3–8%), metals and inert minerals (5–15%), and residual moisture in variable proportions (SEMARNAT, 2020).

Each of these component classes exhibits a radically different response to biological and thermochemical conversion processes. Carbohydrate-rich organic materials undergo rapid hydrolysis and acidification in anaerobic digestion environments, requiring careful co-digestion management to prevent reactor acidification. Protein-rich materials (animal waste, food processing residuals) yield high methane production — up to 468 m^3 per tonne of volatile solids — but generate ammonia during digestion, which can inhibit methanogenic archaea at elevated concentrations. Lipid-rich materials (fats, oils, greases) yield the highest theoretical methane production per unit mass but can cause flotation layers and mass transfer limitations in continuously stirred tank reactors. Plastics and polymers are refractory to biological degradation but constitute a significant energy resource for thermochemical processing, with lower heating values (LHVs) ranging from 20 to $42 \text{ MJ}\cdot\text{kg}^{-1}$ depending on polymer type.

Gravimetric measurement, combined with the compositional characterization methods described in Section 2.2, converts this compositional complexity into a structured dataset of mass fractions that can be systematically processed through process selection algorithms.

3.2 Process Pathway Assignment Logic

Cobeal's conversion platform operates as a three-pathway system. The biological conversion pathway — anaerobic digestion — accepts high-moisture, high-volatile-solids organic fractions with carbon-to-nitrogen (C:N) ratios in the range of 20:1 to 30:1 (Mata-Alvarez et al., 2014). Feedstocks with C:N ratios below this range (nitrogen-rich, such as protein wastes) require co-digestion with carbon-rich materials (straw, cellulose) to achieve stable methane production. Feedstocks with C:N ratios above this range (carbon-rich, such as paper) may require addition of nitrogen-containing co-substrates or supplemental nutrients.

The thermal conversion pathway — combustion or gasification — accepts mixed residual fractions with sufficient calorific value to sustain autothermal operation. A minimum lower heating value (LHV) of approximately $7\text{--}8 \text{ MJ}\cdot\text{kg}^{-1}$ on a wet basis is typically required for autothermal gasification; combustion systems may accommodate lower LHV feedstocks if pre-dried. High-moisture feedstocks (moisture content $>50\%$) are generally unsuitable for direct thermal processing without prior mechanical or thermal drying.

The controlled pyrolysis pathway accepts homogeneous, energy-dense material streams — most commonly segregated plastics, rubber, or lignocellulosic fractions — where feedstock consistency is essential for product quality control. Heterogeneous feedstocks produce pyrolysis oils with variable composition that may be difficult to utilize in downstream applications requiring defined fuel specifications.

Gravimetric measurement provides the quantitative basis for assigning incoming material to these pathways by resolving the mass-fraction composition of each incoming batch. The decision logic can be formalized as follows. Let F_{bio} , F_{therm} , and F_{pyr} represent the mass fractions of the incoming stream assigned to biological, thermal, and pyrolysis pathways respectively, subject to the constraint $F_{bio} + F_{therm} + F_{pyr} = 1$. The assignment is governed by a hierarchical sorting algorithm that first separates the biologically degradable organic fraction (defined by volatile solids content and biodegradability index), then allocates the high-calorific residual to thermal or pyrolysis pathways based on homogeneity and moisture content. The gravimetrically determined total mass provides the denominator for all fraction calculations.

3.3 Co-Digestion Design and Pretreatment Selection

The design of co-digestion recipes — the blending of complementary waste streams to optimize biological conversion performance — is a mass-balance problem of exactly the form addressed by gravimetric measurement. Given a set of available feedstocks with known masses M_i and known compositional properties (C:N ratio, volatile solids content, lipid fraction, moisture content), the co-digestion blending problem seeks the mass proportions w_i such that the mixture achieves target process parameters.

The methane yield of a co-digested mixture can be estimated from the weighted sum of component-specific methane potentials, where the weighting is the gravimetrically determined mass fraction of

each component. This approach, known as the Biochemical Methane Potential (BMP) additive model, is the industry-standard method for predicting co-digestion performance (Labatut et al., 2011). Its accuracy depends entirely on the precision of the mass-fraction measurements, which are anchored by gravimetric analysis.

Pretreatment selection is similarly governed by feedstock characterization. Mechanical pretreatment (shredding, maceration) reduces particle size and increases surface area available for microbial attack, improving hydrolysis rates for lignocellulosic materials. Thermal pretreatment (pasteurization, thermal hydrolysis at 150–180°C) disrupts cell walls and decomposes complex organic polymers, increasing bioavailability. Chemical pretreatment (alkaline or acid hydrolysis) is applicable to specific recalcitrant fractions. Each pretreatment type modifies the mass-specific yield of the downstream conversion process and must be evaluated in terms of its net energy balance — the energy invested in pretreatment versus the incremental methane production achieved. This cost-benefit calculation requires precise knowledge of input and output masses, both provided by gravimetric analysis.

3.4 Sargassum as a High-Value Specialty Feedstock

The coastal geography of Mexico's Caribbean and Gulf coasts creates a distinctive waste characterization challenge: massive, episodic influxes of pelagic sargassum macroalgae. Sargassum presents a feedstock profile that differs substantially from terrestrial MSW: it has high moisture content (70–80% wet basis), elevated potassium and bromine concentrations, moderate volatile solids content, and a fibrous lignocellulosic structure that can create challenges in mechanical pretreatment.

From a gravimetric measurement perspective, sargassum processing introduces a temporal variability challenge analogous to the transient conditions of the NEDC driving cycle in fuel measurement. Just as the NEDC produces rapid fluctuations in fuel consumption rate that test the dynamic response of the measurement system, seasonal sargassum influx events produce rapid fluctuations in feedstock availability that test the dynamic responsiveness of the waste-to-value processing network. Time-resolved mass flow data — collected continuously at receiving stations — provides the operational intelligence required to trigger adaptive responses: increased digestate output, temporary storage activation, or redirection of sargassum to specialist thermal processing if biological pathway capacity is exceeded.

The potassium-rich digestate produced from sargassum anaerobic digestion has been identified as a high-value fertilizer co-product with significant export market potential, particularly for agricultural markets in the United States and Europe where potassium-containing biostimulants command premium prices. The value of this co-product stream is directly proportional to the mass of potassium-rich digestate produced, which is in turn directly proportional to the gravimetrically measured input mass of sargassum processed. This direct mass-to-revenue linkage illustrates the financial significance of measurement precision at the feedstock characterization stage.

4. Energy Balance Modeling and System Scaling

4.1 The Energy Balance as a Mass-Derived Quantity

The energy balance of a waste-to-value facility — the ratio of energy output to energy input — is the primary determinant of system viability. A facility achieving an energy balance ratio greater than unity produces net energy and can participate in electricity markets or provide process heat to adjacent industrial users. A facility with an energy balance ratio below unity is a net energy consumer and requires subsidy or cross-subsidization from co-product revenues to achieve financial viability.

The energy balance is computed from feedstock mass flow data through the following chain of relationships. The mass flow rate of volatile solids (VS) entering the digester is calculated as:

$$\dot{m}_{VS} = FC_{grav} \times f_{VS} \quad (\text{Formula 6})$$

where \dot{m}_{VS} denotes the volatile solids mass flow rate [$g \cdot s^{-1}$ or $t \cdot d^{-1}$];

FC_{grav} denotes the total feedstock mass flow rate from gravimetric measurement [$g \cdot s^{-1}$ or $t \cdot d^{-1}$];

f_{VS} denotes the volatile solids fraction determined by proximate analysis [dimensionless, $0 < f_{VS} < 1$].

The theoretical methane production rate is then:

$$Q_{CH4} = \dot{m}_{VS} \times Y_{CH4} \quad (\text{Formula 7})$$

where Q_{CH4} denotes the methane production rate [$m^3 \cdot d^{-1}$];

Y_{CH4} denotes the substrate-specific methane yield [m^3 CH4 per tonne VS].

The electrical energy output from combined heat and power (CHP) conversion of the biogas is:

$$E_{elec} = Q_{CH4} \times \rho_{CH4} \times LHV_{CH4} \times \eta_{CHP} \quad (\text{Formula 8})$$

where E_{elec} denotes the electrical energy output [$MWh \cdot d^{-1}$];

ρ_{CH4} denotes the density of methane at standard conditions [$0.717 \text{ kg} \cdot m^{-3}$];

LHV_{CH4} denotes the lower heating value of methane [$55.5 \text{ MJ} \cdot \text{kg}^{-1}$];

η_{CHP} denotes the electrical efficiency of the CHP unit [typically 0.35–0.42].

Each step in this calculation chain is directly proportional to the gravimetrically measured input mass flow FC_{grav} . An error in this quantity propagates linearly through Formulas 6, 7, and 8 to produce a proportional error in the predicted electrical energy output. At the 0.318% accuracy level demonstrated under steady-state conditions by Noland et al. (2024), the energy output prediction error attributable to the gravimetric measurement is less than 0.4% — well within the tolerance required for financial modeling and contract performance benchmarking.

4.2 Minimum Viable Scale and Network Node Classification

A critical output of the energy balance analysis is the identification of the minimum feedstock throughput at which a biological conversion facility achieves positive energy balance — that is, produces more energy than it consumes in processing operations. Below this threshold, the facility is a net energy consumer regardless of the quality of its conversion efficiency.

In Cobeal's national systems architecture for Mexico, biological conversion facilities achieve positive energy balance at treatment capacities exceeding approximately 8 tonnes per day of organic feedstock, with 476 identified sites across the national territory meeting or exceeding this threshold when assessed against available waste generation data from SEMARNAT census streams. This threshold is not a fixed constant but a function of feedstock composition: high-VS feedstocks (food waste, grease trap residuals) achieve positive energy balance at lower throughputs than low-VS feedstocks (dilute slurries, garden waste with high moisture content).

Gravimetric measurement enables dynamic recalculation of the minimum viable threshold for each facility as its feedstock composition varies over time. A facility receiving a mixed feedstock with average VS content of 45% in winter (when garden waste fraction is low and food waste fraction is high) will have a different minimum viable throughput than the same facility in summer (when garden waste fraction increases and reduces average VS content). Time-resolved gravimetric data, combined with periodic compositional analysis, enables operators to anticipate and respond to these seasonal variations.

4.3 Scaling Relationships and Specific Energy Consumption

Waste-to-value systems exhibit characteristic economies of scale: as processing capacity increases, the specific energy consumption per unit of feedstock processed decreases, and the specific capital cost per unit of installed capacity decreases. These scaling relationships are well-documented in the biogas and waste management engineering literature (De Clercq et al., 2017) and follow approximate power-law functions of the form:

$$SEC = SEC_0 \times (Q/Q_0)^{-\alpha} \quad \text{(Formula 9)}$$

where SEC denotes the specific energy consumption [$kWh \cdot t^{-1}$] at processing capacity Q [$t \cdot d^{-1}$]; SEC_0 denotes the reference specific energy consumption at reference capacity Q_0 [$t \cdot d^{-1}$]; α denotes the scaling exponent [typically 0.2–0.4 for anaerobic digestion systems].

The quantification of Q — the actual throughput of the facility — requires continuous gravimetric measurement of feedstock input. Without accurate mass flow data, scaling analysis is based on design estimates rather than operational reality, and the divergence between design and actual throughput can be substantial in the early operational phases of a facility receiving heterogeneous MSW streams with variable seasonal composition. Gravimetric measurement transforms scaling analysis from a design-time estimate into an ongoing operational intelligence function.

Table 4. Energy Balance Parameters: Biological Conversion Pathway (Representative Mexico Urban Organic Fraction)

Parameter	Symbol	Value / Range	Unit	Measurement Source
Feedstock mass flow	FC_grav	8 – 150	t·d ⁻¹	Gravimetric
Volatile solids fraction	f_VS	0.40 – 0.65	kg VS·kg ⁻¹ FM	Proximate analysis

Parameter	Symbol	Value / Range	Unit	Measurement Source
VS mass flow	\dot{m}_{VS}	3.2 – 97.5	t VS·d ⁻¹	Formula 6
Methane yield (food waste)	Y _{CH4}	280 – 468	m ³ CH ₄ ·t ⁻¹ VS	BMP testing
CHP electrical efficiency	η_{CHP}	0.35 – 0.42	—	Equipment specification
Net electrical output	E _{elec}	0.18 – 8.5	MWh·d ⁻¹	Formula 8
Positive energy balance threshold	Q _{min}	>8	t·d ⁻¹	System modeling

Table 4. Energy balance calculation chain for biological conversion pathway, illustrating how gravimetrically measured feedstock mass propagates through to electrical energy output. FM = fresh matter basis.

5. Output Stream Quantification and Material Recovery

5.1 Multi-Product Output Accounting

A defining characteristic of waste-to-value systems — and a primary source of their economic attractiveness — is that they produce multiple valuable outputs from a single input stream. Anaerobic digestion produces biogas (or biomethane after upgrading), digestate (liquid and solid fractions), and recovered water. Pyrolysis produces syngas, bio-oil, and char (which may contain carbon black, a high-value specialty chemical). Gasification produces syngas, ash (potentially suitable for construction materials), and process heat. Each of these outputs represents a revenue stream, and the aggregate revenue across all outputs determines the financial viability of the facility.

The quantification of each output stream is a mass-balance exercise anchored by gravimetric measurement of the input. The principle of mass conservation requires that the total mass of all outputs — gas, liquid, and solid — equals the total mass of all inputs, subject only to measurement uncertainty. This mass balance identity provides a powerful consistency check: if the sum of measured output masses diverges significantly from the gravimetrically measured input mass, an instrumentation fault, process inefficiency, or unaccounted loss pathway has occurred and must be investigated.

5.2 Digestate Characterization and Fertilizer Market Value

Digestate — the biological residue remaining after anaerobic digestion of organic feedstocks — is a complex mixture of partially digested organic matter, microbial biomass, mineral nutrients (nitrogen, phosphorus, potassium), and water. Its agronomic value as a fertilizer or soil amendment depends critically on its nutrient concentrations, which in turn reflect the nutrient profile of the original feedstock.

Gravimetric measurement establishes the total mass of digestate produced, which — combined with nutrient concentration analysis (typically by ICP-OES or colorimetric methods) — enables calculation of the total nutrient mass contained in each batch of digestate. This mass-based nutrient accounting

is the foundation for pricing digestate in agricultural markets, where contracts are typically structured around delivered nutrient content per tonne of product.

For sargassum-derived digestates, potassium concentrations are particularly high, reflecting the macroalgae's characteristic potassium accumulation from seawater. Digestate from sargassum-rich feedstocks can achieve potassium concentrations of 3–6 g·kg⁻¹ wet weight, significantly exceeding those of conventional manure-based digestates. **At export market prices for potassium-containing biostimulants, this represents a meaningful revenue premium per tonne of digestate produced. The mass of potassium-rich digestate — and therefore the revenue it generates — is directly traceable to the gravimetrically measured mass of sargassum that entered the digestion system.**

5.3 Carbon Black and High-Value Material Recovery from Pyrolysis

Controlled pyrolysis of segregated plastic waste — particularly polyethylene, polypropylene, and polystyrene fractions — produces a char residue that, under optimized pyrolysis conditions, contains recoverable carbon black. Carbon black is a high-value industrial commodity used in rubber compounding, pigment production, and battery electrode manufacturing, with global market prices ranging from USD 900 to USD 2,500 per tonne depending on grade and purity.

The mass of carbon black recoverable from a given batch of plastic pyrolysis feedstock is a function of the carbon content of the feedstock (determined by ultimate analysis) and the pyrolysis conditions (temperature, residence time, atmosphere). Gravimetric measurement of the char output mass, combined with carbon content analysis of the char, enables calculation of the recoverable carbon black mass and its associated revenue. The feedstock-to-product mass ratio for carbon black recovery — typically 0.10 to 0.15 kg of recoverable carbon black per kg of plastic feedstock — is a key performance indicator for pyrolysis operations and is tracked through continuous gravimetric monitoring of input and output streams.

6. Temporal Resolution, Dynamic Systems, and Real-Time Process Control

6.1 Mass Flow as a Time Series

One of the most analytically valuable properties of gravimetric measurement is its inherent temporal resolution. As established in Section 1.1, the method produces a continuous time series of mass measurements from which instantaneous flow rates can be derived at any desired temporal granularity. This time-series character transforms gravimetric measurement from a snapshot characterization technique into a dynamic monitoring tool capable of informing real-time process control decisions.

In the fuel measurement context, this property was demonstrated by the NEDC test results of Noland et al. (2024), where the gravimetric system tracked rapid fluctuations in fuel consumption rate through

the urban driving cycle's repeated acceleration-deceleration sequences. The time-resolved data showed that the gravimetric scale actually responded more accurately than the flowmeter at discrete gear-change events, where the positive-displacement meter's internal fluid dynamics introduced a response lag. This finding — that a simpler, lower-cost instrument outperforms a more expensive one in dynamic measurement scenarios — is directly analogous to situations encountered in waste-to-value operations, where feedstock delivery rates fluctuate in response to collection vehicle scheduling, market-driven supply variations, and seasonal availability patterns.

6.2 Adaptive Routing and Process Optimization

Real-time gravimetric data enables adaptive routing — the dynamic reallocation of incoming feedstock mass among available conversion pathways based on current process conditions. This capability is particularly valuable in multi-pathway systems such as Cobeal's architecture, where the three conversion pathways (biological, thermal, pyrolysis) have different optimal feedstock specifications, different processing lead times, and different output market relationships.

Consider a scenario in which a receiving station observes a sudden increase in the mass flow rate of high-moisture organic material (indicating, perhaps, a large delivery of food processing waste). Real-time gravimetric monitoring detects this influx immediately; the system's process control algorithm assesses current digester loading relative to capacity; and if the digester is approaching its hydraulic retention time limit, the algorithm can divert a portion of the incoming mass to temporary storage or redirect it to an alternative receiving hub in the network. This adaptive response is only possible if mass flow data is available in real time — a condition satisfied by gravimetric instrumentation with continuous data acquisition.

More formally, the adaptive routing problem can be stated as a constrained optimization: at each time step t , allocate the gravimetrically measured incoming mass flow $FC_{grav}(t)$ among pathways $i = \{bio, therm, pyr\}$ such that the allocation maximizes a system objective function (net revenue, energy output, or waste diversion rate) subject to capacity constraints on each pathway. The gravimetric measurement $FC_{grav}(t)$ is the decision variable's binding input; without it, the optimization problem is under-determined.

6.3 Seasonal Variability and Long-Horizon Planning

Beyond real-time process control, temporal gravimetric data accumulated over weeks and months provides the basis for long-horizon operational planning. Seasonal patterns in feedstock composition — higher organic fraction in summer, higher packaging waste fraction in holiday periods, higher garden waste fraction in spring — create predictable variation in system energy balance and output composition. Gravimetric records from previous seasons provide the empirical basis for anticipating these variations and pre-positioning system resources: adjusting digester loading protocols, arranging co-substrate procurement contracts, scheduling maintenance during anticipated low-throughput periods.

This planning function echoes the use of historical fuel consumption data in automotive fleet management, where gravimetric consumption records from previous duty cycles inform predictive maintenance scheduling, fuel procurement budgeting, and route optimization. The analytical method is identical; only the operational context differs.

7. Contractual Structures, Financial Modeling, and Revenue Architecture

7.1 Measurement as the Foundation of Commercial Agreements

Waste-to-value infrastructure operates under long-term commercial agreements that allocate responsibilities, risks, and revenues among multiple parties: waste generators (municipalities, industrial producers), processing facility operators, energy off-takers, digestate purchasers, and project financiers. **The integrity of these agreements depends on the availability of verifiable, defensible measurements of the quantities that define contractual performance.**

Gravimetric measurement provides exactly this foundation. A waste supply contract specifies the mass of waste to be delivered per day or per month, within defined composition bands (e.g., minimum 40% organic fraction, maximum 20% moisture content). Compliance with these specifications is verified by gravimetric mass measurement at the receiving station, combined with periodic compositional analysis. **Payment for waste processing services is calculated on the basis of verified delivered mass, with adjustments for composition quality relative to contract specifications.**

On the output side, energy supply agreements with electricity off-takers or gas network operators specify the quantity and quality of energy delivered. The delivered energy quantity is derived from the gravimetrically measured biogas volume (converted to mass using density) and its measured methane concentration. Digestate supply agreements with agricultural purchasers specify delivered mass per batch and minimum nutrient concentrations. **Carbon black supply agreements with industrial purchasers specify delivered mass and purity grade.** In each case, the commercial obligation is expressed in units of mass or mass-derived energy, and gravimetric measurement provides the primary verification instrument.

7.2 Performance Guarantees and Risk Allocation

In build-own-operate (BOO) project structures — the preferred delivery model for Cobeal's large-scale processing facilities — the project company assumes operational risk in exchange for a revenue stream linked to facility performance. Performance guarantees typically cover: (i) minimum waste processing throughput (expressed in tonnes per day); (ii) minimum energy conversion efficiency (expressed as electrical output per tonne of feedstock processed); (iii) maximum residual disposal rate (the fraction of input mass that must be landfilled rather than recovered); and (iv) compliance with environmental emission standards (which depend on combustion or digestion process parameters that are in turn influenced by feedstock mass and composition).

Gravimetric measurement provides the verifiable data layer against which these guarantees are assessed. An independent monitoring body — whether a technical advisor to the project lender, a municipal regulator, or a third-party verification agent — can audit the gravimetric records to confirm compliance with each performance dimension. The expandable uncertainty of the gravimetric system (0.482 g at laboratory scale, or an equivalent relative uncertainty of less than 1% at industrial scale with appropriate instrumentation) is well within the tolerance required for contract compliance verification.

Risk allocation between project parties is informed by the statistical properties of the gravimetric measurement record. If gravimetric data over a six-month operating period demonstrates that feedstock composition has systematically deviated from contract specifications — for example, moisture content consistently exceeding the contracted maximum — the data record provides the evidentiary basis for a force majeure claim or a contract renegotiation. The precision and traceability of gravimetric measurement thus serves not only operational but also legal and financial functions within the project structure.

7.3 Financial Modeling and Revenue Formation

The financial model of a waste-to-value facility translates physical performance — tonnes processed, megawatt-hours generated, tonnes of digestate delivered — into revenue and operating cash flow. The revenue formation process follows a hierarchical structure in which gravimetrically measured mass flows are the primary input variable.

The gate fee revenue — charged to waste generators for accepting and processing their waste — is typically expressed in USD per tonne of waste received. The total gate fee revenue in period T is therefore:

$$R_{gate} = \int_t FC_{grav}(t) \times \Delta t \times p_{gate} \quad (\text{Formula 10})$$

where R_{gate} denotes gate fee revenue [USD];

$FC_{grav}(t)$ denotes the instantaneous feedstock mass flow rate [$t \cdot d^{-1}$];

Δt denotes the integration time interval [d];

p_{gate} denotes the contracted gate fee [$USD \cdot t^{-1}$].

The energy revenue — from electricity sales or gas injection — is derived from the gravimetrically measured feedstock mass through the energy balance chain described in Section 4.1 (Formulas 6–8). The fertilizer/digestate revenue and the carbon black revenue follow analogous mass-to-revenue chains as described in Sections 5.2 and 5.3. The total facility revenue is the sum across all output streams, each of which traces its origin to a gravimetrically measured input mass. This end-to-end traceability from physical measurement to financial outcome is the defining architectural property of the gravimetrically anchored waste-to-value business model.

8. Network-Level Architecture and Multi-Site System Integration

8.1 Cobecal's National Waste-to-Value Network

Cobecal's urban mining programme is designed as a nationally integrated network comprising facilities of different types and scales, connected by logistics infrastructure and governed by a unified data and operational management platform. The network architecture encompasses: (i) metropolitan processing hubs receiving large volumes of mixed MSW and sorted organic fractions from dense urban areas; (ii) regional organics platforms serving mid-size cities and agricultural districts with anaerobic digestion capacity optimized for food waste and agricultural residuals; (iii) specialized conversion assets — pyrolysis units and thermal gasification plants — positioned to receive high-calorific residual fractions from mechanical-biological treatment (MBT) operations; and (iv) pre-processing and transfer nodes that sort, size-reduce, and dewater incoming waste streams before forwarding them to the appropriate conversion facility.

Each node in this network is an independent measurement domain with its own gravimetric instrumentation, generating a continuous record of mass input and output. The aggregation of these node-level records creates a system-wide mass flow dataset that enables network-level analysis: identification of underperforming nodes, optimization of inter-node routing decisions, and computation of the network's aggregate environmental performance metrics (tonnes of waste diverted from landfill, tonnes of CO₂-equivalent greenhouse gas avoided, litres of groundwater contamination prevented).

8.2 Standardization and Data Interoperability

For node-level gravimetric data to be meaningfully aggregated at the network level, measurement standards and data formats must be harmonized across all facilities. This is not a trivial requirement: facilities may be constructed at different times, equipped with different instrumentation vendors, and operated by different facility management teams. The establishment of a network-wide measurement standard — defining load cell accuracy requirements, calibration frequency, data reporting formats, and uncertainty reporting conventions — is a governance function of the first order.

The standardization framework draws directly on the Type A/B uncertainty methodology described in Section 1.4 and on traceable calibration protocols referenced to national metrology standards. Each facility's measurement system must demonstrate compliance with the network standard through periodic independent calibration audits. Non-compliant facilities are flagged for instrumentation upgrade or calibration correction before their data is admitted into the network-level mass balance.

Data interoperability — the ability to transmit, receive, and process mass flow data across facilities in a common format — is addressed through a network data management platform that ingests time-stamped mass records from all nodes, validates their uncertainty and calibration status, and aggregates them into the system-wide mass balance. This platform constitutes the digital twin of the physical material network: a data representation of the physical mass flows that is updated in near-real time and provides the operational intelligence for network management decisions.

8.3 System-Wide Energy Balance and Environmental Accounting

At the network level, the gravimetrically measured mass flows from all nodes are combined to compute the aggregate energy balance of the Cobeal system. This calculation follows the same structure as the facility-level energy balance described in Section 4.1, applied across all facilities in the network simultaneously. The result is a system-wide energy productivity metric — total electrical energy output per tonne of waste received across the entire network — that is the primary performance indicator for the programme as a whole.

The environmental accounting function is similarly anchored by gravimetric data. The carbon accounting methodology for waste-to-value projects — following ISO 14064 or GHG Protocol Scope 3 frameworks — requires demonstration that the mass of waste processed through biological or thermochemical conversion pathways would otherwise have been disposed of in landfill, generating landfill gas emissions. The gravimetrically verified mass of waste diverted from landfill, multiplied by the methane emission factor for the relevant landfill type and climate zone, yields the greenhouse gas avoidance credit attributable to the project.

These avoidance credits, when registered in voluntary or compliance carbon markets, generate carbon credit revenue that contributes to the financial model. Their value is directly proportional to the gravimetrically verified diverted mass — providing yet another dimension of the measurement-to-revenue chain that constitutes the commercial logic of Cobeal's urban mining programme.

Table 1. Gravimetric System Measurement Performance: Fuel Validation Reference (Noland et al., 2024)

Test Condition	Gravimetric Mean (g·s ⁻¹)	Flowmeter Mean (g·s ⁻¹)	Difference (g·s ⁻¹)	Relative Error (%)
Idle (700 RPM, steady-state)	3.475	3.464	0.011	0.318
NEDC Cycle (dynamic driving)	14.068	14.223	0.155	5.763

Table 1. Comparative measurement performance of gravimetric system versus volumetric flowmeter under steady-state and dynamic conditions. Data sourced from Noland et al. (2024).

Table 3. Cobeal Conversion Pathway Feedstock Requirements and Gravimetric Measurement Role

Pathway	Feedstock Moisture (%wb)	VS Content Required	C:N Ratio Target	Min. LHV (MJ·kg ⁻¹)	Gravimetric Function
Anaerobic Digestion	60–85%	>40%	20:1 – 30:1	N/A	Co-digestion mass balancing; BMP prediction
Thermal Gasification	10–40%	Variable	N/A	7–8	Energy density verification; autothermal check

Pathway	Feedstock Moisture (%wb)	VS Content Required	C:N Ratio Target	Min. LHV (MJ·kg ⁻¹)	Gravimetric Function
Controlled Pyrolysis	<15%	>80%	N/A	>25	Homogeneity verification; char yield tracking

Table 3. Process pathway feedstock requirements and the specific gravimetric measurement function at each stage within Cobeal's conversion architecture.

9. Limitations, Future Directions, and Research Agenda

9.1 Known Limitations of Gravimetric Measurement in Waste Contexts

Despite its generality and robustness, gravimetric measurement in waste-to-value contexts faces several challenges that must be acknowledged and addressed through complementary methods. The most significant is the issue of in-situ compositional determination: gravimetric measurement quantifies total mass but does not, by itself, resolve the compositional fractions within that mass. The assignment of incoming waste mass to specific conversion pathways requires complementary analytical methods (proximate analysis, calorimetric testing, chromatographic analysis of key indicators) that introduce their own measurement uncertainties and analytical time lags.

In the fuel measurement context, this limitation is negligible because the fuel composition is known and standardized (B30 biodiesel has defined cetane number, density, viscosity, and flash point). In the waste measurement context, the composition must be determined empirically for each incoming batch — a requirement that creates a temporal lag between the gravimetric mass measurement (which can be instantaneous) and the compositional assignment (which may require hours of laboratory analysis). Near-infrared spectroscopy (NIR) and X-ray fluorescence (XRF) technologies offer the prospect of real-time compositional sensing that could close this lag, and their integration with gravimetric mass measurement represents a significant research opportunity.

A second limitation is the challenge of measuring gaseous output streams gravimetrically. While solid and liquid output masses can be weighed directly, the biogas output from anaerobic digestion must be measured by a combination of volumetric gas metering and gas composition analysis — reverting to the volumetric measurement approach that gravimetric methods seek to avoid. The integration of gravimetric total input measurement with volumetric gas output measurement is a hybrid approach that introduces the density-conversion uncertainty of the volumetric method for the gas fraction. Research into direct gravimetric gas mass measurement at the scale and conditions relevant to biogas systems would strengthen the methodological coherence of the approach.

9.2 Technology Roadmap: From Arduino to Industrial IoT

The instrumentation system demonstrated by Noland et al. (2024) — Arduino Uno microcontroller, HX711 ADC, load cell, spreadsheet logging — represents a minimum-viable implementation appropriate for **laboratory-scale validation and field pilot studies**. For industrial deployment

across Cobeal's network, this instrumentation chain must evolve toward certified industrial-grade systems with the following capabilities: ATEX/IECEX certification for use in potentially explosive atmospheres (relevant for biogas plants); IP67 or higher environmental protection rating for outdoor and wet-area applications; traceable calibration to national or international metrology standards; redundant measurement channels with automatic cross-validation; and integration with industrial data acquisition systems supporting OPC-UA or MQTT protocols for real-time data transmission to the network management platform.

The cost premium of industrial-grade instrumentation over the Arduino-based prototype is significant but well-justified by the revenue implications of measurement accuracy at commercial scale. At a facility processing 50 tonnes per day at a gate fee of USD $30 \cdot t^{-1}$, a 1% measurement error translates to USD 5,475 per year in revenue misaccounting — an amount that justifies substantial investment in high-accuracy instrumentation. The Arduino prototype demonstrates the principle; industrial implementation demands the engineering.

The future research agenda for gravimetric measurement in waste-to-value systems encompasses four priority areas: (i) integration of real-time spectroscopic compositional sensing with gravimetric mass measurement to close the composition lag identified above; (ii) development of gravimetric measurement protocols specifically validated for slurry and heterogeneous solid waste streams, analogous to the validation study performed by Noland et al. (2024) for liquid fuels; (iii) establishment of a formal uncertainty propagation model for the multi-step mass-to-revenue calculation chain described in Sections 4–7, enabling confidence interval computation for financial projections; and (iv) development of machine learning models trained on gravimetric time-series data to predict near-term feedstock availability and composition, enabling proactive rather than reactive operational decisions.

10. Conclusion

This paper has developed and substantiated the proposition that gravimetric measurement — the direct determination of mass flow through weight quantification over time — constitutes the foundational data layer of any rigorous waste-to-value system. The proposition rests on three complementary arguments.

The first argument is methodological: gravimetric measurement, as validated by Noland et al. (2024) in the fuel consumption context, achieves measurement accuracy of 0.318% under steady-state conditions and 5.8% under dynamic conditions using instrumentation of modest cost and technical complexity. This performance profile is fully adequate for the time-averaged mass balances required for energy balance computation, contract performance verification, and revenue formation in waste-to-value operations.

The second argument is structural: the mathematical architecture of gravimetric measurement — expressed in the deceptively simple Formula 1 — is substrate-agnostic, temporally resolved, and directly interpretable without the density-conversion auxiliary that renders volumetric methods

substrate-dependent. This universality enables a genuine methodological transfer from the bounded, homogeneous fuel system analyzed in the original study to the distributed, heterogeneous waste material systems that characterize urban mining infrastructure. The governing physics are identical; the engineering context differs.

The third argument is systemic: within Cobeal's circular economy architecture, the gravimetric measurement is not merely an operational convenience but an architectural necessity. It is the quantity from which process pathway assignment, energy balance computation, output recovery calculation, contractual performance verification, carbon credit quantification, and financial revenue formation are all derived. Remove the accurate mass measurement, and each of these downstream functions loses its quantitative foundation. Retain it, and the entire system — from the receiving hopper to the carbon credit registry — operates on a coherent, traceable, defensible data architecture.

The transformation of urban waste into energy, materials, and value is, at its deepest level, an exercise in applied mass conservation. Matter is neither created nor destroyed; it is measured, characterized, converted, and accounted. Gravimetric measurement is the instrument through which this conservation principle is given operational reality. It is, in the most precise sense of the term, the foundation upon which the circular economy is built.

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