

BDF Methodology for Recovered Food Carbon

A Quantification and Monitoring Methodology for Avoided Disposal Emissions, Built on the Bio-Digital Footprint Protocol

Fair Food Data (FFD)

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Abstract

This methodology quantifies greenhouse gas emission reductions from the recovery and stabilization of food matter that would otherwise have been disposed in regional baseline pathways (landfill, anaerobic digestion, compost, incineration, or animal feed). The methodology is anchored to the Bio-Digital Footprint (BDF) protocol [Fair Food Data, 2026a], which provides cryptographically verifiable evidence at four progressively rigorous tiers covering provenance, telemetry coherence, finished product identity, and laboratory forensic verification. Where existing carbon methodologies rely on document based audit, this methodology delivers continuous, machine readable, signed evidence at every stage of the avoidance pathway from harvest to crediting.

The methodology is initially submitted to the International Carbon Registry (ICR) for the Recovered Food Carbon credit class and is structured to parallel Verra VM0085 and ISO 18752 to support a subsequent submission to Verra or Gold Standard. Regional counterfactual scenarios are derived for Spain, Colombia, the European Union, and the United States, with country specific emission factors and a conservative uncertainty discount. The differentiating section (Section 6) maps each MRV requirement to the BDF tier that delivers it, replacing periodic document audit with continuous detector evaluation over signed attestation vectors.

A worked example with real pilot data (Appendix A) illustrates the full calculation, including the empirical 11 percent mass balance bias that BDF Tier 2 detection turns from an undetectable error in a paper based methodology into a calibrated correction visible to verifiers and bounded in the uncertainty assessment.



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1 Sources, Definitions, and Applicability

1.1 Title and Sectoral Scope

This methodology, hereinafter the *BDF Methodology for Recovered Food Carbon*, quantifies greenhouse gas emission reductions achieved by diverting food matter from regional disposal pathways into stabilised forms suitable for human consumption or other valorisation. The sectoral scope spans both *Waste Handling and Disposal* (avoidance of methane and nitrous oxide from landfill, anaerobic diges-

tion, and compost) and *Agriculture, Forestry and Other Land Use (AFOLU)* where the recovered matter is of agricultural origin and the avoided pathway is on farm or post farm loss. The methodology is initially submitted to the International Carbon Registry (ICR) for the Recovered Food Carbon credit class [International Carbon Registry, 2025] and is structured to support a subsequent submission to Verra and Gold Standard, paralleling Verra VM0085 [Verra, 2024] and ISO 18752 [International Organization for Standardization, 2024].

1.2 Normative References

The methodology incorporates the following normative references. Where any reference is updated in a future edition, the most recent edition applicable at the time of project validation governs.

- BDF Protocol main paper [Fair Food Data, 2026a] for the typed digital twin, attestation vectors, tier semantics, and cryptographic infrastructure.
- BDF Security Analysis [Fair Food Data, 2026b] for the formal threat model, trust assumptions, and security reductions.
- BDF Standards Stack [Fair Food Data, 2026c] for the open standards composing each attestation vector.
- ISO 14064-2:2019 [International Organization for Standardization, 2019] for project level GHG quantification, monitoring, and reporting.
- ISO 18752 [International Organization for Standardization, 2024] for quantification of avoided emissions from food loss and waste reduction.
- ISO 14067:2018 [International Organization for Standardization, 2018] for product carbon footprint quantification.
- ISO/IEC 17025:2017 [International Organization for Standardization, 2017] for laboratory accreditation requirements applicable to External Attestations at Tier 4.
- IPCC 2019 Refinement, Volume 5 (Waste) [IPCC, 2019] for emission factors of disposal pathways.
- IPCC AR6 Working Group III [IPCC, 2022] for global warming potentials and AFOLU baselines.
- ICVCM Core Carbon Principles [Integrity Council for the Voluntary Carbon Market, 2024] for high integrity tier compliance.
- GHG Protocol Scope 3 Standard [World Resources Institute and World Business Council for Sustainable Development, 2011] for downstream user reporting compatibility under categories 11 and 12.

1.3 Definitions

Recovered Food Lot.	A bounded
mass of edible or near edible food matter that, in the absence of the project, would have entered a documented regional disposal pathway, and that the project diverts into a stabilised form (freeze dried, dehydrated, or otherwise preserved) intended for human consumption or other documented valorisation.	
Avoided Disposal Pathway.	The set
of waste handling routes that would have processed the Recovered Food Lot in the absence of the project, weighted by their regional shares. The Avoided Disposal Pathway is determined by	

the regional counterfactual scenario (Section 2) and is specific to the jurisdiction in which the lot originates.	
Counterfactual Reference Scenario.	The most plausible documented baseline state of the Recovered Food Lot in the absence of the project activity, expressed as a probability weighted mix of disposal pathways with their associated emission factors.
Crediting Period.	The interval over which emission reductions are quantified and credited. The default crediting period under this methodology is one calendar year (vintage year), renewable upon revalidation.
Vintage Year.	The calendar year during which the Recovered Food Lot was harvested or otherwise removed from its original supply chain. Credits are assigned to the vintage year of the lot, not the year of issuance.
Permanence Window.	The period during which the avoided emissions remain effective. For Recovered Food Carbon, permanence is defined by the consumption or final disposal of the stabilised product (Section 10).
Bio-Digital Twin (BDT).	As defined in the BDF Protocol [Fair Food Data, 2026a]: a typed canonical digital object whose identity is derived from its data through deterministic canonical serialisation, accumulating signed attestation vectors over its lifecycle.
Attestation Vector.	A signed payload of structured data from a defined stage of the lifecycle: Agronomic ($\vec{A}$), Logistic ($\vec{L}$), Process ($\vec{P}$), or Recipe ($\vec{R}$).
External Attestation.	A signed laboratory measurement issued by an ISO 17025 accredited laboratory and anchored to the BDT, providing Tier 4 forensic evidence.
BDF Tier.	One of the four progressively rigorous evidence classes defined in the BDF Protocol: T_1 Cryptographic Floor, T_2 Telemetry Anomaly Detection, T_3 Spectroscopic Classification, T_4 Laboratory Forensic.
Detection Verdict.	A signed output of a BDF detector at any tier, recording whether the observed evidence is consistent with the declared claim, with supporting parameters and a Bayesian posterior where applicable.
Verifier.	An independent third party accredited by the registry to validate the project design and verify the emission reductions over each crediting period.

1.4 Applicability Conditions

A project is eligible to use this methodology if and only if all of the following conditions hold.

C1. Recoverable food matter. The input matter is human food grade or near food grade at the moment of recovery. Matter that is already inedible at the point of project intervention (rotted, contaminated, or otherwise unfit) is excluded; such matter would not have produced credits under any methodology and its inclusion would inflate baselines.

C2. Documented avoided pathway. The avoided disposal pathway is documented at the regional level by a recognised authority (Eurostat [European Commission, 2024], US EPA [United States Environmental Protection Agency, 2024], the Spanish MITECO [Ministerio para la Transición Ecológica y el Reto Demográfico, 2023], DANE Colombia [DANE Colombia, 2023], or equivalent national statistical office). Projects in jurisdictions without a published regional disposal mix shall apply the most conservative IPCC default for the geographic context.

C3. Stabilisation transformation. The recovery includes a stabilisation transformation (freeze drying, dehydration, fermentation, or other documented process) that extends usable shelf life by at least a factor of ten relative to the fresh product. Processes that do not extend shelf life are excluded.

C4. BDF instrumented supply chain. The full project supply chain, from the moment of recovery to the issuance of stabilised product, is instrumented with the BDF protocol at a minimum tier of T_2 . Specifically: every Recovered Food Lot is the subject of an Agronomic Vector or equivalent recovery vector at genesis; the Logistic Vector covers all transit segments; the Process Vector covers the stabilisation transformation; and the Recipe Vector commits the operator’s process parameters before the cycle begins. T_1 structural integrity is provided by construction once the protocol is instantiated.

C5. Additionality. The project activity is not required by law or by binding policy in the jurisdiction of operation at the start of the crediting period. The avoidance is incremental to the regulatory baseline. Projects in jurisdictions with binding food waste reduction targets (e.g. EU Directive 2018/851) shall demonstrate that the project’s avoidance exceeds the regulatory baseline rate; only the incremental fraction is creditable.

C6. No double counting. The Recovered Food Lot has not been claimed under another methodology, by another project, or by another registry. The BDF protocol’s content addressed identity (Section 6) makes double counting publicly detectable: any verifier can detect the same canonical hash claimed under two distinct projects.

C7. Geographic scope. The methodology applies to projects located in any jurisdiction provided conditions C1 to C6 hold and a regional counterfactual can be constructed (Section 2). Specific counterfactual templates are provided in this document for Spain, Colombia, the European Union, and the United States.

C8. Exclusions. The following are explicitly excluded from this methodology:

- Projects whose avoided pathway is animal feed, where the displaced feedstock would have generated comparable or higher emissions in the displaced source.
- Projects relying on imported food matter where the import was undertaken solely to enable the project (manufactured demand).
- Projects that double recover, i.e. where the input is itself the output of another carbon project.

- Projects whose stabilised product is destined for landfill or incineration after a short shelf life, eliminating the avoidance benefit.

1.5 Project Types Covered

The methodology accommodates three project archetypes, all subject to the applicability conditions above.

Type A: On farm recovery. Surplus or substandard produce diverted at the farm gate before entering conventional disposal. The Recovered Food Lot has its genesis attestation at the moment of recovery on farm. The Logistic Vector covers the cold chain from farm to processing plant.

Type B: Post farm recovery. Food matter recovered from intermediate stages of the conventional supply chain (sorting facilities, wholesale markets, distribution centres) that has been rejected for cosmetic, logistical, or contractual reasons but remains food grade. The genesis attestation occurs at the recovery point with documentation of the upstream origin where feasible.

Type C: Retail and food service recovery. Food matter recovered from retail, food service, or institutional kitchens before disposal. This type carries the highest baseline emissions (because retail food waste is heavily landfilled in most jurisdictions) and the lowest project emissions (because the matter has already absorbed most of the upstream supply chain emissions).

A project may include multiple types within its boundary, with each Recovered Food Lot tagged by type at genesis. Baseline and project emissions are computed per type and aggregated.

2 Project Boundary and Counterfactual

The project boundary specifies which physical, temporal, and operational elements are accounted for in the quantification of baseline emissions, project emissions, and leakage. The counterfactual reference scenario specifies what would have happened to each Recovered Food Lot in the absence of the project activity.

2.1 Spatial Boundary

The spatial boundary of a project under this methodology comprises the physical locations where attestation vectors are signed and where GHG sources are accounted. It begins at the *point of recovery* (the location at which the genesis attestation of each Recovered Food Lot is signed) and ends at the *point of issuance* (the location at which the stabilised product is committed to its first owner outside the project boundary).

The boundary explicitly includes the following elements:

- The point of recovery, including any sorting, weighing, and conditioning operations performed before the lot enters transport.
- All transport segments between the point of recovery and the stabilisation facility, including intermediate storage where applicable.
- The stabilisation facility, including all energy use directly attributable to the freeze drying or equivalent transformation, refrigerant losses from chamber operation, and embodied emissions of consumables prorated to the project mass.
- Packaging and palletisation immediately downstream of the stabilisation transformation.
- The first transport segment from the stabilisation facility to the first independent owner.

The boundary explicitly excludes the following elements, which are accounted for in upstream or downstream reporting under other frameworks:

- Upstream agricultural production emissions of the food matter prior to its rejection from the conventional supply chain. These emissions would have occurred regardless of the project and are common to both the baseline and the project scenarios.
- Construction emissions of the stabilisation facility and capital equipment, which are amortised under operator level inventory reporting and not attributable to specific Recovered Food Lots.
- Downstream emissions from the use phase of the stabilised product (cooking, refrigeration in the consumer's home, etc.) and from the eventual disposal of the stabilised product. Permanence treatment of the latter is addressed in Section 10.

2.2 Temporal Boundary

The default crediting period is one calendar year, hereinafter the *vintage year* of the project. A project may register multiple consecutive vintage years; each is validated independently. The vintage year of a Recovered Food Lot is the calendar year during which its genesis attestation is signed, irrespective of the year in which the stabilisation cycle is completed or the credits are issued.

A project under this methodology has a *validation date* (the date on which the project design document is approved by the registry) and a *verification date* per vintage year (the date on which the verifier issues a verification report). Credits may only be issued for emission reductions occurring between the validation date and the most recent verification date. Retroactive crediting prior to validation is permitted only under the registry's standard rules and is bounded to no more than two vintage years before the validation date.

2.3 Greenhouse Gas Sources

The methodology accounts for the following GHG sources, with global warming potentials drawn from IPCC AR6 [IPCC, 2021] on a 100 year horizon: CO₂ at 1, CH₄ (non fossil) at 27, and N₂O at 273.

Baseline sources (avoided in the project scenario).

- CH₄ from anaerobic decomposition in landfill, dominant pathway in jurisdictions without source separation.

- CH₄ slip from anaerobic digestion, where capture is imperfect.
- N₂O from aerobic and semi aerobic compost.
- CO₂ (non fossil) from incineration with energy recovery, accounted under the methodology only when the displaced energy generation does not offset the emission.
- CO₂ from transport of waste matter to its disposal site, prorated to the project share.

Project sources (incurred in the project scenario).

- CO₂ from electricity consumption during the stabilisation cycle, computed using the country specific grid emission factor [International Energy Agency, 2024].
- Refrigerant losses from chamber and condenser operation, weighted by the GWP of the refrigerant in use (typically R 404A, R 449A, or R 410A; emerging deployments use natural refrigerants with negligible GWP).
- CO₂ from logistics within the project boundary, computed using country specific tonne kilometre emission factors [UK Department for Energy Security and Net Zero, 2024].
- Embodied CO₂e of packaging materials prorated to the project mass.
- Embodied CO₂e of consumables (filtration, hygiene, lubricants) prorated to the project mass.

Leakage sources.

- Market displacement: if the recovered matter substitutes for fresh food production elsewhere, the displaced production avoids upstream agricultural emissions.
- Activity shifting: the stabilisation facility may displace energy use from another productive activity in the same location or grid.
- Rebound: improved availability of stabilised food at low cost may increase total food consumption and the associated upstream emissions.

Each leakage source is treated formally in Section 5.

2.4 Counterfactual Reference Scenario

The counterfactual reference scenario expresses, for each Recovered Food Lot, the set of disposal pathways that would have processed the lot in the absence of the project, weighted by their regional shares. Formally, for a project located in jurisdiction j and recovering food matter of category c at supply chain stage s , the counterfactual is a probability distribution

$$\pi_{j,c,s} = \{(\rho_p, \text{EF}_p) \mid p \in \mathcal{P}\}, \quad \text{with } \sum_{p \in \mathcal{P}} \rho_p = 1,$$

where $\mathcal{P}$ is the canonical set of disposal pathways defined below, $\rho_p \in [0, 1]$ is the regional share of pathway p for the (jurisdiction, category, stage) tuple, and EF_p is the emission factor per unit mass for pathway p as defined in Section 3 and tabulated in Appendix B.

Canonical pathway set. The methodology recognises six canonical disposal pathways:

- P1. **Sanitary landfill** with or without methane capture.
- P2. **Open dump** (uncontrolled landfill), applicable in some jurisdictions.
- P3. **Anaerobic digestion** with biogas capture.
- P4. **Composting** (aerobic or in vessel).
- P5. **Incineration** with or without energy recovery.
- P6. **Animal feed** (direct feed or rendering).

A jurisdiction’s regional disposal mix is the joint distribution ρ over $\mathcal{P}$ for each food category. The methodology provides reference distributions for Spain, Colombia, the European Union average, and the United States in Section 2.5.

Selection rule. A project shall apply the counterfactual reference scenario specific to the jurisdiction of recovery. Where a Recovered Food Lot is recovered in jurisdiction j_1 but transported to a stabilisation facility in jurisdiction j_2 , the counterfactual is computed using j_1 (the jurisdiction in which the lot would have been disposed). Cross border imports of food matter solely for the purpose of project participation are excluded under applicability condition C8 (Section 1).

Conservative bias. Where two pathways are plausible and the regional data does not unambiguously support one over the other, the project shall apply the lower emission factor of the two. Where regional disposal data is unavailable for a jurisdiction, the project shall apply the IPCC global default for that food category at the lowest applicable emission factor. This rule prevents inflation of the baseline through optimistic interpretation of incomplete data.

2.5 Reference Counterfactual Templates

The methodology provides reference templates for four jurisdictions. Projects shall apply the template corresponding to the jurisdiction of recovery, refining the shares with locally measured data where available and verifiable. The templates below are stated for illustrative aggregate food categories; per category breakdowns are provided in Appendix B.

Table 1: Reference counterfactual disposal mix by jurisdiction for aggregate food matter. Shares ρ_p are illustrative and shall be confirmed against the most recent national statistics at the time of project validation. Sources: Eurostat [European Commission, 2024], US EPA [United States Environmental Protection Agency, 2024], MITECO [Ministerio para la Transición Ecológica y el Reto Demográfico, 2023], DANE Colombia [DANE Colombia, 2023].

Pathway	Spain	Colombia	EU avg	US
Sanitary landfill	0.42	0.31	0.36	0.56
Open dump	0.00	0.39	0.00	0.00
Anaerobic digestion	0.18	0.04	0.22	0.06
Composting	0.16	0.10	0.20	0.13
Incineration	0.21	0.04	0.18	0.20
Animal feed	0.03	0.12	0.04	0.05

Spain. The Spanish disposal mix is dominated by sanitary landfill, with growing shares of incineration in coastal regions and anaerobic digestion in catalonian and basque facilities. Composting is the dominant pathway for source separated organic matter under Decree 553/2020 implementation.

Colombia. The Colombian disposal mix retains a significant open dump fraction (39 percent), particularly outside the major metropolitan areas. Sanitary landfill operations exist primarily near Bogotá, Medellín, and Cali. Composting and anaerobic digestion are emerging pathways in pilot programmes; the methodology applies a conservative low share until national data is updated.

European Union average. The EU average disposal mix reflects the integrated single market policy framework under the Circular Economy Action Plan and the Waste Framework Directive. The mix shifts toward composting and anaerobic digestion in northern member states and toward incineration in central and eastern member states.

United States. The US disposal mix is dominated by sanitary landfill (56 percent), reflecting low landfill tipping fees and limited federal level mandate for source separation. Anaerobic digestion is concentrated in California, Massachusetts, and a small number of other states with disposal bans.

Other jurisdictions. Projects in jurisdictions not covered by these templates shall construct a counterfactual using national or subnational statistical data with publication date no more than five years prior to the project validation date. Where no such data exists, the project shall apply the IPCC 2019 default disposal mix for the relevant geographic and economic context [IPCC, 2019], with an additional 20 percent conservative discount applied to the baseline.

2.6 Eligibility Decision Tree

A project's eligibility under this methodology is determined by sequential application of the following decision tree. Failure at any step renders the project ineligible.

- Step 1. Verify applicability conditions C1 through C8 (Section 1). If any fails, the project is ineligible.
- Step 2. Assign each Recovered Food Lot to a project type (A on farm, B post farm, C retail and food service) and to a food category. Mixed lots are decomposed into homogeneous sublots.
- Step 3. Determine the jurisdiction of recovery for each lot and apply the corresponding counterfactual template (Section 2.5).
- Step 4. Apply the conservative bias rule (Section 2.4) where multiple counterfactuals are plausible.
- Step 5. Confirm that the BDF protocol is instantiated at minimum tier T_2 across the project boundary (applicability condition C4) and that all four attestation vectors are signed by independent attestors at their respective stages.
- Step 6. If all preceding steps are satisfied, the project proceeds to baseline determination (Section 3).

3 Baseline Determination

The baseline is the volume of GHG emissions that would have occurred in the counterfactual reference scenario absent the project activity. This section defines the baseline emission formula, the per pathway emission factors, and the rules for refining the baseline with project specific data.

3.1 Baseline Emissions Formula

For a project recovering a set of Recovered Food Lots $\mathcal{L}$ in vintage year y , the baseline emissions are computed per lot and aggregated. For each lot $\ell \in \mathcal{L}$ with mass m_ℓ (in tonnes of fresh matter at recovery), category c_ℓ , and jurisdiction of recovery j_ℓ , the baseline emission is

$$\text{BE}_\ell = m_\ell \cdot \sum_{p \in \mathcal{P}} \rho_{j_\ell, c_\ell, s_\ell, p} \cdot \text{EF}_{p, c_\ell}^{\text{baseline}}, \quad (1)$$

where $\rho_{j_\ell, c_\ell, s_\ell, p}$ is the share of pathway p in the regional disposal mix for category c_ℓ at supply chain stage s_ℓ in jurisdiction j_ℓ (Section 2.5), and $\text{EF}_{p, c_\ell}^{\text{baseline}}$ is the emission factor for pathway p and category c_ℓ as defined in this section. The total baseline emission for the vintage year is

$$\text{BE}_y = \sum_{\ell \in \mathcal{L}} \text{BE}_\ell. \quad (2)$$

The mass m_ℓ is read from the Agronomic Vector or, for project types B and C, from the equivalent recovery vector signed at genesis. The mass is verified at T_2 by the conservation invariant of the BDT lifecycle (Section 6).

3.2 Per Pathway Emission Factors

3.2.1 P1. Sanitary Landfill

Sanitary landfill emissions are dominated by methane from anaerobic decomposition. The methodology applies the First Order Decay (FOD) model from IPCC 2019 Refinement [IPCC, 2019], with regional decay rate constants and degradable organic carbon fractions drawn from Volume 5 Chapter 3.

For projects integrating over a single vintage year and assuming steady state regional landfill operation, the methodology accepts a simplified emission factor:

$$\text{EF}_{\text{P1}, c} = \text{DOC}_c \cdot \text{DOC}_f \cdot F \cdot \frac{16}{12} \cdot (1 - r_c) \cdot (1 - \text{OX}) \cdot \text{GWP}_{\text{CH}_4}, \quad (3)$$

with DOC_c the degradable organic carbon fraction of category c (default values per IPCC 2019 Table 2.4), DOC_f the fraction that effectively decomposes (0.5 default), F the methane fraction in landfill gas (0.5 default), r_c the methane recovery rate of the regional landfill stock (jurisdiction specific), and OX the methane oxidation factor in cover material (0.10 for sanitary landfills, 0.0 for open dumps).

3.2.2 P2. Open Dump

Open dump emissions follow the same FOD model with $r_c = 0$ (no recovery), $OX = 0$ (no cover oxidation), and a higher DOC_f default of 0.6 reflecting partially anaerobic conditions at depth.

3.2.3 P3. Anaerobic Digestion

Anaerobic digestion processes the matter under controlled conditions with biogas capture. Net emissions are limited to methane slip:

$$EF_{P3,c} = B_{0,c} \cdot MCF_{AD} \cdot s_{AD} \cdot GWP_{CH_4}, \quad (4)$$

with $B_{0,c}$ the maximum methane producing potential of category c (default values per IPCC 2019), $MCF_{AD} = 0.9$ the methane conversion factor under controlled digestion, and $s_{AD} = 0.03$ the default slip fraction for biogas capture systems. Where the regional facility stock is dominated by older systems, s_{AD} rises to 0.05.

3.2.4 P4. Composting

Composting emissions are dominated by nitrous oxide:

$$EF_{P4,c} = N_c \cdot k_{N_2O} \cdot \frac{44}{28} \cdot GWP_{N_2O}, \quad (5)$$

with N_c the nitrogen content of category c (per dry weight, jurisdiction specific food composition tables) and $k_{N_2O} = 0.015$ the default fraction of N converted to N_2O N. Methane emissions from composting are typically lower than from landfill but non zero; the methodology adds a small methane term:

$$EF_{P4,CH_4,c} = 0.04 \cdot B_{0,c} \cdot GWP_{CH_4}, \quad (6)$$

reflecting partial anaerobic pockets in poorly aerated piles.

3.2.5 P5. Incineration

Incineration emissions of biogenic matter consist of CO_2 that is largely considered carbon neutral on a global mass balance, plus N_2O from combustion:

$$EF_{P5,c} = C_c \cdot \frac{44}{12} \cdot f_{fossil} + N_c \cdot k_{N_2O,comb} \cdot \frac{44}{28} \cdot GWP_{N_2O}, \quad (7)$$

with f_{fossil} the fossil carbon fraction of category c (zero for pure food matter, non zero where mixed with packaging) and $k_{N_2O,comb} = 0.0005$. Where the incineration plant operates with energy recovery, the methodology applies a credit equal to the avoided grid emissions per unit energy delivered, capped at

the gross emission of the incineration step. The methodology does not credit incineration with energy recovery as net negative.

3.2.6 P6. Animal Feed

Animal feed pathway is treated under applicability condition C8 (Section 1). Where the project recovers matter that would have entered animal feed, the methodology assigns a baseline emission factor of zero and excludes the pathway from the counterfactual. The rationale is that the displaced feedstock would have emitted comparable or higher upstream emissions in the displaced production. Including this pathway would inflate the baseline through hypothetical avoided emissions.

3.3 Regional Refinement

A project may refine the baseline through any combination of the following, subject to the conservative bias rule.

Locally measured disposal mix. Where a project demonstrates, through verifiable third party data published within five years of the project validation date, that the local disposal mix differs from the reference template, the project may substitute the local mix. The substitution shall be approved by the verifier. The data source, publication date, and methodology shall be cited in the project design document.

Per category emission factors. Where the project's recovered matter is concentrated in a specific food category (e.g. berries, leafy greens, dairy), the project shall apply category specific emission factors from Appendix B. Aggregate factors are permitted only for diversified projects with no single category exceeding 40 percent of project mass.

Methane recovery rate. Where the regional landfill stock has a published methane recovery rate, the project shall apply that rate in equation 3. Where no rate is published, the project shall apply $r_c = 0$ (no recovery), the most conservative default.

3.4 Conservative Defaults and Discounts

Where a parameter required by this section is unavailable for the project's jurisdiction or category, the methodology applies the conservative default with a documented discount. The aggregate of these discounts is applied to the baseline emission BE_ℓ multiplicatively:

$$BE_\ell^{\text{conservative}} = BE_\ell \cdot \prod_k (1 - d_k), \quad (8)$$

where the index k runs over the discounts listed in Table 2 and $d_k \in [0, 1]$ is the corresponding discount fraction. The minimum aggregate discount across all unavailable parameters is bounded below by 0.10 (10 percent). Projects supplying complete and recent regional data may apply a zero discount.

Table 2: Conservative discount fractions applied to the baseline when corresponding parameters are unavailable or stale.

Parameter	Condition	Discount d_k
Disposal mix	Regional data older than five years	0.10
Disposal mix	No regional data, IPCC default applied	0.20
Methane recovery	No regional landfill capture data	0.05
Food category EF	Aggregate factor used (no per category)	0.05
Nitrogen content	Default applied, no jurisdiction data	0.05

3.5 Baseline Stability and Updates

The baseline is fixed for the duration of the crediting period and updated at each renewal. Updates apply to subsequent vintage years and do not retroactively adjust prior years. Where regulatory changes (e.g. new mandatory source separation laws) shift the regional disposal mix, the project shall update the counterfactual at the next crediting period renewal and document the regulatory cause of the shift.

The methodology recognises that baseline drift over time in jurisdictions actively reforming waste policy creates a tension between conservative crediting and accurate quantification. The methodology resolves this tension by applying the prevailing regional disposal mix at the start of each crediting period, weighted toward the lower emission alternative where two paths are plausible.

4 Project Emissions

Project emissions are the GHG emissions actually incurred by the project activity within the spatial boundary of Section 2.1. They are subtracted from the baseline to compute the gross emission reduction.

4.1 Project Emissions Formula

For vintage year y , total project emissions are the sum of four components:

$$PE_y = PE_y^{\text{elec}} + PE_y^{\text{ref}} + PE_y^{\text{log}} + PE_y^{\text{cons}}, \quad (9)$$

where the four terms account for electricity consumption during stabilisation, refrigerant losses, logistics within the project boundary, and consumables and packaging. Each term is computed at the lot level and aggregated.

4.2 Electricity Consumption

Electricity is the dominant component of project emissions for freeze drying. The methodology requires per cycle measurement and signature in the Process Vector $\vec{P}$, with the lot's electricity attribution computed by allocating cycle electricity to the lots co processed in that cycle in proportion to their mass of water removed.

For lot ℓ co processed in cycle κ with total cycle electricity E_κ (in kWh, signed in $\vec{P}$) and total water mass removed W_κ (computed by the conservation invariant from the masses of input matter and stabilised output), the lot's allocated electricity is

$$E_\ell = E_\kappa \cdot \frac{w_\ell}{W_\kappa}, \quad (10)$$

where w_ℓ is the lot's water removed mass. The corresponding emission is

$$\text{PE}_\ell^{\text{elec}} = E_\ell \cdot \text{EF}_{\text{grid},j_\ell,y}, \quad (11)$$

with $\text{EF}_{\text{grid},j_\ell,y}$ the country specific grid emission factor for the jurisdiction of the stabilisation facility in the vintage year, drawn from IEA Emissions Factors [International Energy Agency, 2024]. Projects operating with on site renewable generation may substitute a project specific emission factor where the renewable generation is metered, signed in the Process Vector, and verified by the registry.

4.3 Refrigerant Losses

Freeze drying chambers and condensers operate with refrigerants whose leakage is non negligible on a GWP weighted basis. The methodology applies an annual leakage rate to the installed refrigerant charge:

$$\text{PE}_y^{\text{ref}} = \sum_r M_r \cdot \lambda_r \cdot \text{GWP}_r, \quad (12)$$

with M_r the installed mass of refrigerant r (kg, declared by the operator), λ_r the annual leakage rate (default 0.10 for hermetic systems with annual maintenance, 0.15 for older or unmaintained systems, per DEFRA [UK Department for Energy Security and Net Zero, 2024]), and GWP_r the global warming potential of refrigerant r on a 100 year horizon. The default values for common refrigerants are tabulated in Appendix B.

The methodology rewards transitions to natural refrigerants (CO_2 as R 744, ammonia as R 717, propane as R 290) with their respective GWPs (1, 0, 3) effectively eliminating this component for compliant deployments. Refrigerant choice shall be declared in the Recipe Vector $\vec{R}$ and verified annually.

4.4 Logistics within the Project Boundary

Logistics emissions cover all transport segments within the spatial boundary (Section 2.1). Each segment is signed in the Logistic Vector $\vec{L}$ with origin, destination, distance, mass, mode, and dwell. Segment emissions are

$$\text{PE}_{\ell,k}^{\text{log}} = m_{\ell,k} \cdot d_k \cdot \text{EF}_{\text{tkm},\text{mode},j_k}, \quad (13)$$

with $m_{\ell,k}$ the mass of lot ℓ in segment k (in tonnes), d_k the great circle adjusted segment distance (in kilometres, computed from signed origin and destination geolocations in $\vec{L}$), and $\text{EF}_{\text{tkm},\text{mode},j_k}$

the tonne kilometre emission factor for the transport mode and jurisdiction of segment k (DEFRA [UK Department for Energy Security and Net Zero, 2024], with regional adjustments per IEA [International Energy Agency, 2024] for electrified rail).

Lot level aggregation:

$$\text{PE}_\ell^{\log} = \sum_{k \in \mathcal{K}_\ell} \text{PE}_{\ell,k}^{\log}. \quad (14)$$

Refrigerated transport applies an additional 0.20 multiplier to the base emission factor, reflecting the energy cost of cold chain integrity. The refrigeration status of each segment is declared in $\vec{L}$.

4.5 Consumables and Packaging

Consumables (filtration cartridges, hygiene chemicals, lubricants, refrigerant top ups) and packaging (primary, secondary, palletisation) carry embodied emissions that are prorated to the project mass. The methodology accepts default embodied factors per material from Ecoinvent 3.10 [Ecoinvent Centre, 2024] or jurisdiction equivalent databases.

$$\text{PE}_y^{\text{cons}} = \sum_{\mu \in \mathcal{M}} M_\mu \cdot \text{EF}_\mu^{\text{embodied}}, \quad (15)$$

with $\mathcal{M}$ the set of materials consumed, M_μ the mass per material, and $\text{EF}_\mu^{\text{embodied}}$ the embodied factor. Lot level allocation of consumables follows the same water mass weighting as electricity (equation 10). Lot level allocation of packaging follows the dry mass of each lot's stabilised output.

4.6 Verifiability of Project Emissions

Each project emission term is verifiable from the BDF attestation vectors:

- Electricity: signed cycle aggregate in $\vec{P}$, conservation cross checked against per stage power draw.
- Refrigerant: charge mass declared in $\vec{R}$, leakage applied as default unless metered top ups in $\vec{P}$ override.
- Logistics: per segment data signed in $\vec{L}$ by the carrier or its IoT gateway.
- Consumables and packaging: declared in $\vec{R}$ and reconciled with operator inventory at vintage year close.

A verifier can reproduce the full project emission for any lot or vintage year directly from the public record by reading the four attestation vectors, applying the formulas of this section, and checking the conservation invariants of the BDT lifecycle. No off chain operator declaration is required to compute PE_y .

5 Net Emission Reductions

The net emission reduction is the credited quantity, computed by subtracting project emissions and leakage from the conservatively adjusted baseline.

5.1 Net ER Formula

For vintage year y , the net emission reduction is

$$ER_y = BE_y^{\text{conservative}} - PE_y - LE_y, \quad (16)$$

with $BE_y^{\text{conservative}}$ defined in equation 8, PE_y in equation 9, and LE_y the total leakage emissions defined below. If $ER_y \leq 0$, no credits are issued for the vintage year and the project shall investigate the cause.

The credited quantity is further reduced by the buffer pool contribution defined in Section 10:

$$\text{Credits}_y = ER_y \cdot (1 - \beta), \quad (17)$$

with β the buffer pool fraction (default 0.10, refined per project risk assessment in Section 10).

5.2 Leakage Analysis

Leakage is the unintended emission consequence of the project occurring outside the project boundary. The methodology quantifies three classes of leakage.

5.2.1 Market Displacement

If the stabilised product substitutes for fresh food production elsewhere, the displaced fresh production avoids upstream agricultural emissions and the displaced upstream emissions reduce the project's net benefit:

$$LE_y^{\text{md}} = -\alpha_{\text{md}} \cdot \sum_{\ell} m_{\ell}^{\text{stab}} \cdot EF_{\text{upstream}, c_{\ell}}, \quad (18)$$

with $\alpha_{\text{md}} \in [0, 1]$ the market displacement coefficient (the fraction of stabilised product that substitutes for fresh production elsewhere; default 0.50 absent project specific market analysis), m_{ℓ}^{stab} the dry mass of stabilised output of lot ℓ , and $EF_{\text{upstream}, c_{\ell}}$ the upstream agricultural emission factor per unit of stabilised mass for category c_{ℓ} [Poore and Nemecek, 2018].

The market displacement term enters the leakage with a negative sign because it represents an additional emission saving and would credit the project if applied without check. The methodology applies it conservatively only where the project demonstrates, through documented market analysis, that the

displacement is real and not inflated by the project's own marketing claims. Default treatment in the absence of such analysis sets $\alpha_{\text{md}} = 0$ (no displacement credited).

5.2.2 Activity Shifting

The stabilisation facility may displace the energy or operational capacity of another productive activity in the same location or grid. Activity shifting is positive leakage and applies where the facility was previously used for a different productive purpose.

$$\text{LE}_y^{\text{as}} = \alpha_{\text{as}} \cdot \text{PE}_y^{\text{elec}}, \quad (19)$$

with α_{as} the activity shifting coefficient. Default treatment assumes a new build or formerly idle facility ($\alpha_{\text{as}} = 0$). For repurposed facilities, the coefficient defaults to 0.10 unless documented otherwise.

5.2.3 Rebound

Improved availability of stabilised food at low cost may stimulate additional consumption, with associated upstream emissions. Rebound is positive leakage:

$$\text{LE}_y^{\text{rb}} = \alpha_{\text{rb}} \cdot \sum_{\ell} m_{\ell}^{\text{stab}} \cdot \text{EF}_{\text{upstream}, c_{\ell}}, \quad (20)$$

with α_{rb} the rebound coefficient (default 0.05 across all project types, per IPCC AR6 WG3 [IPCC, 2022] food consumption elasticity assessment).

5.2.4 Total Leakage

Total leakage in the vintage year is the sum of the three classes, with the market displacement term capped at zero unless documented:

$$\text{LE}_y = \max(0, \text{LE}_y^{\text{md}}) + \text{LE}_y^{\text{as}} + \text{LE}_y^{\text{rb}}. \quad (21)$$

5.3 Vintage Assignment and Crediting

Vintage of issuance. Each credit is assigned to the vintage year of the lots that generated it. Lots harvested in year y but processed and stabilised in year $y + 1$ are credited to vintage y , consistent with the genesis convention of Section 2.

Issuance window. Credits for vintage year y shall be issued no later than 24 months after the close of year y . Issuance requires verification by an accredited verifier (Section 9).

Crediting period and renewal. The default crediting period is one year. A project may register multiple consecutive crediting periods, each requiring renewal of the project design document and updated counterfactual at the renewal date.

Conservative rounding. Credits issued shall be rounded down to the nearest tonne CO₂e. Fractional remainders accumulate to the next vintage year's verification.

5.4 Treatment of Detected Anomalies

The BDF protocol's T_2 detectors generate signed verdicts on conservation, envelope, and cross vector tests over the project's attestation vectors. Where a detector verdict is negative for a lot or cycle, the methodology applies the following rules.

Conservation violation. A conservation invariant violation (e.g. mass balance bias detected against the recipe and process vectors) triggers a corrective action. The project shall investigate the cause within 30 days. If the violation is determined to be a measurement artefact (e.g. field weight overestimation, as observed in the empirical pilot), the project shall apply a calibration correction in subsequent vintage years and document the correction in the verification report. Lots in the affected vintage year are credited at the corrected mass.

Envelope violation. A telemetry envelope violation in the Process Vector (e.g. pressure excursion in a freeze drying stage) does not invalidate the lots in the affected cycle. The methodology requires that the operator declare the excursion in the verification report, evaluate whether the stabilisation effectiveness was compromised (Tier 4 lab evidence may be required for a sample of the affected lots), and proceed accordingly.

Cross vector incoherence. A cross vector incoherence flag (e.g. a Logistic Vector segment whose dwell time is incompatible with the declared mass loss in the Process Vector) requires investigation. Where the verifier cannot reconcile the discrepancy, the affected lots are excluded from the vintage year's credited mass.

Evidentiary value. The methodology recognises that signed detector verdicts on the public record are stronger evidence than retrospective document review. Where prior methodologies treat anomaly detection as a verifier burden, this methodology treats it as a continuous protocol output, with verifier attention focused on adjudicating flagged events rather than discovering them.

6 Monitoring with the BDF Protocol

This section is the differentiating contribution of the methodology. It maps every monitoring, reporting, and verification (MRV) requirement to the BDF tier that delivers it, replacing periodic document

audit with continuous detector evaluation over signed attestation vectors. Where Verra and Gold Standard methodologies require a verifier to reconstruct evidence from operator declarations, this methodology requires the operator to publish signed structured evidence at the moment of measurement, and requires the verifier to evaluate detector outputs that are computed and signed automatically.

6.1 MRV Requirement Mapping

Each MRV requirement of an emission reduction methodology resolves into one of four evidence classes: chain of custody, mass and energy accounting, identity assurance, and forensic verification under dispute. The BDF protocol delivers each class at a specific tier (Section 1). Table 3 fixes the mapping; the remainder of this section unfolds each entry.

Table 3: MRV requirements mapped to the BDF tier that delivers them. T1 through T4 are defined in the BDF Protocol main paper [Fair Food Data, 2026a] and summarised in Section 1.

MRV requirement	Tier	BDF mechanism
Provenance and chain of custody	T_1	Append only ownership chain on Single Owner Chunks; transformation burn semantics; distribution conservation
Mass conservation	T_2	Conservation invariant across $\vec{A}$, $\vec{L}$, $\vec{P}$; signed verdict per lot or cycle
Energy attribution per lot	T_2	Allocation by water mass weighting in $\vec{P}$ aggregate; cross checked against per stage power draw
Logistic envelope (cold chain, distance, dwell)	T_2	Envelope tests on $\vec{L}$ conditional on segment mode
Process envelope (pressure, temperature)	T_2	Envelope tests on $\vec{P}$ conditional on stage
Cross vector coherence	T_2	Independent vectors checked for mutual consistency (e.g. recipe vs process)
Origin and identity assurance	T_3	Spectroscopic classification of finished product against reference base
Composition under dispute	T_4	ISO 17025 laboratory analysis as External Attestation, anchored to the BDT
Double counting prevention	T_1	Content addressed canonical hash; same hash claimed twice is publicly detectable
Right to erasure compliance	T_1	Crypto shredding and DREAM revocation; deletion event is itself a signed object

6.2 Required Attestation Vectors per Parameter

The methodology requires four attestation vectors instantiated at minimum tier T_2 across the project boundary. Each vector covers a specific stage of the lifecycle and is signed by an independent attester. The required content per vector is summarised below; canonical schemas are documented in

Appendix C.

Agronomic Vector $\vec{A}$ or Recovery Vector. Signed at the genesis of each Recovered Food Lot. Required fields: lot identifier, mass at recovery (calibrated scale), category, project type (A, B, or C), recovery point geolocation, recovery date and time, minter type (human_operator or proplet_attestation), and operator identifier. For project type A (on farm), additional fields: cultivar or variety, block or parcel, harvest method. For project type C (retail or food service), additional fields: rejection reason, preceding owner identifier, declared upstream provenance.

Logistic Vector $\vec{L}$. Signed at the end of each transport segment within the project boundary. Required fields per segment: lot identifier, origin geolocation, destination geolocation, segment distance (computed from coordinates), segment mode (road, rail, air, sea), segment duration, refrigeration status, mass at segment start, mass at segment end (calibrated scale at destination), carrier identifier.

Process Vector $\vec{P}$. Signed at the end of each stabilisation cycle by the SCADA system of the stabilisation facility. Required fields per cycle: cycle identifier, list of input lots and their masses, list of output lots and their stabilised masses, total water mass removed (computed by mass conservation), total cycle electricity (kWh), per stage telemetry aggregates (chamber pressure mean and percentiles, chamber temperature mean and percentiles, per heater temperature aggregates, per stage duration), refrigerant top up events, cycle start and end timestamps.

Recipe Vector $\vec{R}$. Signed by the plant operator before the cycle begins, committing to process parameters. Required fields: recipe identifier, target chamber pressure profile per stage, target chamber temperature profile per stage, target heater temperature profile per stage, target stage durations, refrigerant type and charge, declared input lots, declared expected stabilised yield, allowable deviation tolerances per parameter.

A project may extend these vectors with additional fields at its discretion, subject to canonicalisation under beeson [Tron et al., 2026]. Required fields are necessary but not sufficient; the verifier may request supplementary evidence under the dispute procedure (Section 9).

6.3 Sampling Plans and Frequency

Per lot evidence. Every Recovered Food Lot is the subject of an Agronomic or Recovery Vector at genesis and a Logistic Vector for each transport segment within the boundary. There is no sampling plan at the lot level: every lot is evidenced. This is the defining characteristic of BDF compared to existing methodologies that audit a sample of supply chain events.

Per cycle evidence. Every stabilisation cycle is the subject of a Process Vector and a Recipe Vector. There is no sampling plan at the cycle level: every cycle is evidenced.

Per parameter cadence within $\vec{P}$. The Process Vector is signed once per cycle, but the underlying telemetry is sampled at higher frequency. The methodology requires a minimum sampling cadence per parameter:

- Chamber pressure: at most 60 second intervals during all active stages.
- Chamber temperature: at most 60 second intervals during all active stages.
- Heater temperatures: at most 60 second intervals during all active stages.
- Power consumption: at most 60 second intervals during all active stages.
- Cumulative process energy: continuous, signed at end of cycle.

The signed Process Vector aggregates these at minimum to the per stage statistics enumerated in Section 6.2; the underlying time series remains in the operator’s signed log and is producible upon verifier request.

Tier 3 reference base sampling. Where the project asserts origin or identity claims requiring spectroscopic classification at T_3 , the reference base shall be constructed from a calibration cohort sized as follows. Per cultivar (or equivalent identity class), the reference base shall include at least 50 finished product samples spanning at least three vintages and three production batches per vintage. The reference base is rebuilt at semestral cadence under the responsibility of the project operator. Detailed sampling protocols are in Appendix C.

Tier 4 verification cadence. External Attestations at T_4 are not required for routine credit issuance. They are triggered under dispute, under suspected fraud detected at T_2 or T_3 , or under a verifier’s risk based sampling plan covering at minimum 1 percent of vintage year credited mass, randomly sampled and signed by an ISO 17025 accredited laboratory.

6.4 Detection Thresholds

The Tier 2 detectors operate on the signed vectors at the granularity defined above. Each detector returns a verdict in {pass, warn, fail} with a recorded threshold and observed value. The methodology fixes the minimum acceptable thresholds below; projects may adopt stricter thresholds with documentation.

Mass conservation threshold. For each lot ℓ entering a transport segment with declared origin mass m_o and destination mass m_d , the relative discrepancy is

$$\delta_\ell = \frac{m_d - m_o}{m_o}. \quad (22)$$

The detector returns **pass** if $|\delta_\ell| \leq 0.05$ (5 percent), **warn** if $0.05 < |\delta_\ell| \leq 0.15$, and **fail** if $|\delta_\ell| > 0.15$. A **warn** on a single segment is logged but does not halt issuance. A **warn** pattern across more than 30 percent of segments in a vintage year, or any **fail**, triggers corrective action under Section 5 (treatment of detected anomalies). The empirical 11 percent aggregate bias from the

pilot section of the BDF main paper [Fair Food Data, 2026a] sits in the `warn` band, consistent with its diagnosis as a measurement provenance issue rather than fraud.

Cycle conservation threshold. For each cycle κ with input mass M_{in} , output stabilised mass M_{out} , and computed water mass removed $W_\kappa = M_{in} - M_{out}$, the energy density check applies:

$$\eta_\kappa = \frac{E_\kappa}{W_\kappa}, \quad (23)$$

with E_κ the cycle electricity in kWh and W_κ the water mass removed in kg. The detector returns `pass` if $1.0 \leq \eta_\kappa \leq 2.0$ kWh per kg (the industrial benchmark for freeze drying [Ratti, 2001]), `warn` if η_κ is outside this range by less than 30 percent, and `fail` otherwise.

Pressure envelope threshold. For each chamber pressure reading at stage s , the envelope is jurisdiction independent and recipe specific. The default envelope is

$$P_{\min,s} \leq P_{s,t} \leq P_{\max,s}, \quad (24)$$

with default values $(P_{\min,s}, P_{\max,s})$ stored in the Recipe Vector $\vec{R}$. The detector returns `pass` if all readings fall within the envelope, `warn` if at most three consecutive readings (less than three minutes at 60 second cadence) fall outside, and `fail` otherwise. The pilot data exhibits three readings above 5×10^4 mTorr in stage 7 [Fair Food Data, 2026a], classifying the cycle as `fail` on this detector and triggering the Section 5 corrective action.

Temperature envelope threshold. Analogous to pressure envelope, with stage specific bands committed in the Recipe Vector. Default envelope for chamber temperature in primary sublimation: -40 to -20 degrees Celsius. Default envelope for secondary drying: -40 to $+30$ degrees Celsius depending on product class.

Logistic envelope threshold. For each transport segment, the envelope tests speed and dwell. Speed envelope: the segment distance divided by segment duration shall not exceed the maximum plausible speed for the declared mode (default 110 km per hour for road, 200 km per hour for rail, 800 km per hour for air, 50 km per hour for sea). Dwell envelope: the segment duration shall not exceed the maximum plausible duration for the declared distance times an inverse minimum speed (default 30 km per hour for road, 50 km per hour for rail). Refrigeration envelope: where refrigerated, the in segment temperature record (if instrumented) shall remain within ± 2 degrees Celsius of the declared setpoint for at least 95 percent of the segment duration. Excursions outside these envelopes return `warn` or `fail` per the same banded structure as mass conservation.

Cross vector coherence thresholds. The recipe versus process coherence test compares the signed Recipe Vector targets against the Process Vector aggregates. For each parameter declared in $\vec{R}$, the corresponding aggregate in $\vec{P}$ shall fall within the recipe's allowable deviation tolerance. `warn` and `fail` bands follow the same banded structure with thresholds inherited from $\vec{R}$ where declared.

6.5 Calibration and Recalibration Cadence

The methodology distinguishes three calibration regimes by tier.

T1 calibration. None required. T1 evidence is structural and does not depend on physical measurement. Software upgrades to canonicalisation libraries follow the reference implementation maintained at [Fair Food Data, 2026c].

T2 calibration. The detection thresholds defined in Section 6.4 are tuned per project against a calibration cohort of at least 100 lot or cycle samples covering at least three months of routine operation. The tuning fixes the project specific `warn` and `fail` bands within the methodology’s outer thresholds. Recalibration is required at each crediting period renewal (default annual) and after any structural change to the supply chain (new recovery point, new transport mode, new stabilisation facility, or significant SCADA upgrade).

T3 calibration. Spectroscopic classifiers are trained against the reference base described in Section 6.3. Recalibration is semestral at the analytical cost of order a few thousand euros, plus full reference base rebuild at three to five year cadence at the cost of order four to eight hundred thousand euros depending on cultivar and matrix coverage [Fair Food Data, 2026a].

T4 calibration. The laboratory issuing External Attestations is ISO 17025 accredited. Reaccreditation cycles follow the standard’s requirements (typically four years). The methodology accepts External Attestations from any ISO 17025 accredited laboratory provided the laboratory’s accreditation number, signing date, and applied method standard are embedded in the External Attestation payload.

6.6 Verification Boundary

The methodology distinguishes which evidence the verifier consumes directly from the public record from what requires controlled disclosure or laboratory cooperation.

Direct from public record. Tier 1 structural evidence (canonical hashes, ownership chains, burn semantics, distribution conservation) and Tier 2 detector verdicts on signed payloads are directly readable from the content addressed storage layer of the BDF protocol. The verifier reproduces every detector verdict by replaying the detection algorithm against the signed inputs. No operator cooperation is required.

Through selective disclosure. The Recipe Vector $\vec{R}$ is encrypted on the storage layer; its plaintext is disclosed selectively to the verifier under NDA. The disclosure event is itself a signed object on the public record, providing auditable evidence that the verifier received the recipe. Other commercially sensitive vectors may follow the same pattern.

Through External Attestations. Tier 4 evidence is provided by an ISO 17025 accredited laboratory at the request of the verifier. The verifier specifies the sampling plan, the laboratory performs the analysis, and the resulting signed External Attestation is anchored to the BDT and stored on the public record.

Independent reproducibility. A second verifier reading the same public record at any later time shall arrive at identical Tier 1 and Tier 2 detector verdicts (modulo software version pinning of the reference implementation). This is a stronger reproducibility guarantee than methodologies that depend on auditor access to operator records.

6.7 Selective Disclosure to Carbon Registries and Buyers

The registry receives a project specific public summary view of the BDF record. The summary view contains all Tier 1 structural data, all Tier 2 detector verdicts, all External Attestations, and the cryptographic anchors of every payload. Encrypted payloads are not disclosed to the registry by default but are disclosable on request under selective disclosure.

A buyer of credits issued under this methodology may request a buyer specific selective disclosure scope at the time of credit retirement, allowing the buyer to verify the underlying evidence stack as part of due diligence. The buyer view is signed by the project, recorded on the public record, and the buyer’s right to inspect is bounded by the contractual scope.

Right to erasure compatibility. A previous owner of a BDT who has exercised the right to erasure under GDPR Article 17 [Fair Food Data, 2026a] has destroyed the encryption keys for the payloads they contributed. The structural evidence remains on the public record (hashes, ownership transitions) but the encrypted payloads they signed become uniform random bytes. The verifier reading the record encounters the structural anchor but not the plaintext, and shall record the erasure event as part of the verification report. The methodology does not penalise a project for prior erasures provided the structural anchor and the corresponding T_2 detector verdict on the original signed payload were recorded before the erasure.

7 Uncertainty Assessment

The uncertainty assessment quantifies the precision of the emission reduction estimate and translates that precision into a conservative deduction on issued credits. This section follows the structure of ISO 14064-2 [International Organization for Standardization, 2019] adapted to the BDF protocol’s continuous evidence stream, and it documents the BDF advantage that systematic bias becomes a calibrated correction rather than a hidden component of the uncertainty bound.

7.1 Per Parameter Uncertainty

For each input parameter to the emission reduction calculation, the methodology assigns a relative uncertainty u_x corresponding to the 95 percent confidence interval. Default uncertainties are tabulated

below. Projects may substitute lower uncertainties where supported by direct measurement under signed attestation; substitution is approved by the verifier.

Table 4: Default per parameter relative uncertainties at 95 percent confidence. Lower values are achievable with direct calibrated measurement; higher values apply where the parameter is estimated from defaults.

Parameter	Default u_x	Direct measurement u_x
Lot mass at recovery	0.10	0.02
Lot mass at facility	0.05	0.01
Cycle electricity (signed in $\vec{P}$)	0.03	0.01
Refrigerant charge (declared in $\vec{R}$)	0.10	0.05
Refrigerant leakage rate	0.30	0.15
Logistic distance (geolocation derived)	0.05	0.01
Logistic emission factor per ton km	0.15	0.10
Grid electricity emission factor	0.10	0.05
Disposal pathway share ρ_p	0.20	0.10
Pathway emission factor EF_p	0.30	0.15
Methane recovery rate r	0.40	0.20
Upstream agricultural EF	0.30	0.20

7.2 Uncertainty Propagation

The methodology propagates uncertainty through the emission reduction formula using first order error propagation. For the baseline BE_y , project emissions PE_y , and leakage LE_y separately, the relative uncertainty is

$$u(X)^2 = \sum_i \left(\frac{\partial X}{\partial x_i} \cdot \frac{x_i}{X} \cdot u_{x_i} \right)^2, \quad (25)$$

evaluated at the central estimate of each parameter x_i . For the net emission reduction, the relative uncertainty is

$$u(ER_y)^2 = \frac{BE_y^2 \cdot u(BE_y)^2 + PE_y^2 \cdot u(PE_y)^2 + LE_y^2 \cdot u(LE_y)^2}{(BE_y - PE_y - LE_y)^2}. \quad (26)$$

The relative uncertainty $u(ER_y)$ is reported in the verification report alongside the credited quantity.

7.3 Conservative Deduction

Where $u(ER_y)$ exceeds an acceptable threshold, the methodology applies a conservative deduction following Verra style [Verra, 2024]:

$$ER_y^{\text{adjusted}} = ER_y \cdot \zeta(u(ER_y)), \quad (27)$$

with the deduction factor ζ defined as

$$\zeta(u) = \begin{cases} 1.00 & \text{if } u \leq 0.10, \\ 0.95 & \text{if } 0.10 < u \leq 0.20, \\ 0.90 & \text{if } 0.20 < u \leq 0.30, \\ 0.85 & \text{if } 0.30 < u \leq 0.50, \\ 0.70 & \text{if } u > 0.50. \end{cases} \quad (28)$$

Projects with $u(\text{ER}_y) > 0.50$ are issued at 70 percent of the central estimate and shall present a remediation plan to reduce uncertainty in the next vintage year.

7.4 BDF Advantage: Calibrated Bias Correction

The principal uncertainty advantage of this methodology over document audit methodologies is that systematic bias detected by Tier 2 conservation invariants is converted into a calibrated correction rather than absorbed as an enlarged uncertainty bound.

The conventional treatment. Under ISO 14064-2 [International Organization for Standardization, 2019] as applied by Verra, Gold Standard, and ICR, a verifier performing a document audit may discover a systematic discrepancy between operator declared masses and physical measurements only at the verification step, after credits for the vintage have already been computed. The verifier's options are limited: invalidate the affected lots, accept them with an enlarged uncertainty band, or request remediation that delays issuance. None of these options retains the original credit estimate.

The BDF treatment. Under this methodology, the conservation invariant detector at T_2 produces signed verdicts continuously, lot by lot. A systematic bias appears in the verdict stream as a recurring `warn` pattern. The project operator receives the warning at the lot level, well before vintage close. The operator can either deploy corrective infrastructure (calibrated scales at the recovery point, Proplet attestation) to close the gap in subsequent lots, or formally re label the field weighing role as an estimation rather than measurement and apply a calibration correction factor to past lots in the vintage.

Calibration correction factor. Where a recurring `warn` pattern reflects a measurable bias rather than fraud, the project applies a calibration correction. Let $\overline{m}^{\text{ref}}$ be the cohort mean of the calibrated reference scale measurement (typically the facility scale weight) and $\overline{m}^{\text{decl}}$ the cohort mean of the declared measurement at the point under calibration. The cohort scaling factor is

$$\kappa = \frac{\overline{m}^{\text{ref}}}{\overline{m}^{\text{decl}}}, \quad (29)$$

and the corrected mass for a subsequent lot ℓ at the point under calibration is

$$m_\ell^{\text{corrected}} = \kappa \cdot m_\ell^{\text{declared}}. \quad (30)$$

The correction is documented in the verification report with the cohort statistics and propagated into the uncertainty assessment with the residual variance after correction. The corrected masses replace the declared masses in the baseline emission formula 1. The correction may move the corrected mass either above or below the declared mass depending on the direction of the bias.

Worked illustration from pilot data. The empirical pilot (BDF main paper [Fair Food Data, 2026a]) reports a cohort sum of declared origin weights $\overline{m}^{\text{decl}} = 48.00$ kg against a calibrated cohort sum of facility scale weights $\overline{m}^{\text{ref}} = 53.27$ kg across fifteen baskets, an 11.0 percent systematic underestimation at the field. The bias is concentrated in operator estimated origin weights anchored to the 3 kg basket nominal capacity. The calibration scaling factor is $\kappa = 53.27/48.00 = 1.110$, applicable to declared origin weights in subsequent lots until field weighing infrastructure is deployed. After correction, the residual variance across the cohort drops from a standard deviation of 17.4 percent on declared weights to an estimated residual of 4 to 6 percent depending on cultivar and operator, computed on the back checked facility weight. The uncertainty propagation in equations 25 and 26 uses the residual variance, not the original.

Audit trail of correction events. Each calibration correction is itself a signed object on the public record, with a reference to the cohort that triggered it, the computed correction factor, and the date of application. A verifier reviewing the project at any point in the future can reproduce the correction’s derivation and assess its applicability to subsequent lots. This is structurally distinct from a one off auditor adjustment that lives in a verification report and is not directly auditable by third parties.

7.5 Disclosure of Uncertainty in the Verification Report

The verification report shall disclose:

- The central estimate ER_y and the conservatively adjusted estimate ER_y^{adjusted} .
- The relative uncertainty $u(ER_y)$ at 95 percent confidence.
- The dominant contributors to u ranked by partial derivative magnitude.
- Any calibration correction factors applied during the vintage and their cohort sizes.
- A list of T_2 detector verdicts in the `warn` or `fail` bands and their disposition.
- A list of External Attestations consulted at T_4 and their findings.

The disclosed quantities allow downstream buyers, regulators, and ICVCM CCP assessors [Integrity Council for the Voluntary Carbon Market, 2024] to independently evaluate the methodology’s robustness against the principles of conservativeness and transparency.

8 Stakeholder Consultation and Safeguards

A project under this methodology shall conduct stakeholder consultation prior to validation and shall implement Do No Harm safeguards with documented compliance throughout the crediting period. The structure of this section follows the ICVCM Core Carbon Principles [Integrity Council for the Voluntary Carbon Market, 2024] and incorporates IFC Performance Standards on Environmental and Social

Sustainability [International Finance Corporation, 2012] and UNDP SDG Impact Standards [United Nations Development Programme, 2021].

8.1 Stakeholder Identification

The project shall identify and engage the following stakeholder categories, with the engagement record signed and anchored to the project record alongside the BDF attestation vectors.

Direct stakeholders. Persons or entities directly affected by the project activity, including: farm operators and farmworkers contributing recovered matter, transport operators, employees of the stabilisation facility, end consumers of the stabilised product, and food security organisations operating in the project region.

Indirect stakeholders. Persons or entities not directly involved but materially affected by the project's existence, including: incumbent waste management operators whose disposal volumes shrink, animal feed operators where the recovered matter would have been routed to feed in the counterfactual, local civil society organisations in the project region, indigenous communities where the project operates on or near their traditional territories, and local government authorities responsible for waste regulation.

Identification record. The project shall produce a stakeholder map at validation, listing each identified party, their interest in the project, and the engagement modality. The map is updated annually at crediting period renewal.

8.2 Local Consultation Requirements

The project shall conduct at least one in person consultation event prior to validation, accessible to all identified direct stakeholders, with an open invitation to indirect stakeholders.

Consultation modalities. Consultations shall be conducted in the prevailing local language or languages and at venues accessible to the affected community without travel cost to participants. Where the project operates in regions with indigenous communities, consultation modalities shall respect the principles of Free, Prior, and Informed Consent (FPIC) and the protocols of the relevant communities.

Documentation. Each consultation event shall produce a record including: date, venue, attendee list (anonymised where required by privacy regulation), agenda, summary of feedback, and documented project response to each substantive concern. The record is signed by the project and anchored to the project's BDF record as a non commercial vector. Anonymised participant lists protect personal data under GDPR Article 5 minimisation [Fair Food Data, 2026a].

Frequency. A formal consultation event shall be held at validation and at each crediting period renewal. Continuous engagement channels (a project website, a publicly accessible email or telephone

hotline, and a designated complaints contact) shall remain operational between formal events.

8.3 Do No Harm Checklist

The project shall demonstrate, at validation and at each verification, that the activity does not cause net harm in any of the dimensions below. The methodology accepts a structured questionnaire signed by the project and reviewed by the verifier; the questionnaire is anchored to the project record.

Food security. The project shall not divert food matter that would have been consumed by food insecure populations in the project region. Where the avoided pathway is animal feed (under exclusion C8 of Section 1), the project shall demonstrate that the displaced feed source has alternative supply at comparable cost. The project shall additionally document the destination of the stabilised product and confirm that it is accessible to a food market broader than premium niche segments.

Labour. The project shall comply with the labour laws of each jurisdiction in which it operates. Wages of farmworkers and stabilisation facility employees shall meet or exceed the legal minimum, and working hours shall comply with the statutory cap. The project shall implement an internal grievance mechanism (Section 8.4). Subcontracted transport operators shall provide evidence of compliance with their jurisdiction's labour requirements as a condition of project participation.

Biodiversity. The project shall not incentivise land conversion. Specifically, recovery operations on farms shall not extend production into previously non agricultural land, and the project shall not credit recovery of matter from new cultivation areas established within the crediting period unless conditions C1 to C8 are satisfied independently of land conversion. The project shall record the parcel boundaries of the supplying farms in the Agronomic Vector and check them against jurisdictional land use registries at each verification.

Water. The project shall report water consumption of the stabilisation facility per kilogram of stabilised output and shall demonstrate, at validation, that the consumption does not stress the local watershed beyond regulatory allowance. Where the project operates in a water stressed region (per WRI Aqueduct or equivalent classification), the project shall implement a water management plan reviewed at each crediting period renewal.

Air quality. The project shall report air emissions of the stabilisation facility (other than the GHG sources covered in Section 4) and confirm compliance with local ambient air quality standards.

Cultural heritage. The project shall not interfere with cultural heritage sites, sacred areas, or tangible cultural property in the project region. Where the project area overlaps such sites, the consultation record shall document the agreement of the relevant heritage authority.

Economic equity. The project shall demonstrate that the financial benefits of credit issuance reach the parties contributing recovered matter in proportion to their contribution. The benefit sharing formula shall be declared in the project design document and reported in each verification.

8.4 Grievance Redress Mechanism

The project shall operate a grievance redress mechanism accessible to all identified stakeholders.

Channels. The mechanism shall accept grievances through at least three channels: an in person designated contact at the stabilisation facility, a telephone hotline, and a written submission via email or postal mail. Submissions shall be accepted in the prevailing local languages.

Acknowledgement and resolution. The project shall acknowledge each grievance within seven calendar days and shall provide a substantive response within thirty calendar days. Where the grievance pertains to a non immediate concern, the project may extend the response window with written notice and a revised timeline.

Escalation. Where the complainant is dissatisfied with the project's response, the mechanism shall provide a documented escalation path to: an independent mediator agreed at validation, the verifier, and the registry. The escalation path shall be summarised in plain language in the consultation materials.

Reporting. The verification report at each vintage year shall include a summary of grievances received, their disposition, and any patterns indicative of systemic issues. The summary preserves complainant anonymity where required by jurisdiction.

8.5 SDG Mapping

The methodology supports project alignment with the United Nations Sustainable Development Goals [United Nations Development Programme, 2021]. The principal SDG contributions of a project under this methodology are:

- SDG 2 Zero Hunger: recovery and stabilisation of edible matter that would have entered disposal.
- SDG 12 Responsible Consumption and Production: reduction of food loss and waste in line with Target 12.3.
- SDG 13 Climate Action: avoided emissions credited under this methodology.
- SDG 8 Decent Work: project labour standards and benefit sharing with farmworkers.
- SDG 15 Life on Land: avoidance of land conversion and biodiversity safeguards.

A project may declare additional SDG contributions in the project design document, supported by indicators measurable from the BDF record where applicable.

9 Verification Procedure

Verification under this methodology differs structurally from document audit verification used by Verra and Gold Standard. This section defines the verifier’s role, what evidence the verifier consumes from each source, the audit frequency, the dispute mechanism, and the certificate issuance procedure.

9.1 Verifier Qualifications

A verifier under this methodology shall be:

- Accredited by the registry receiving the methodology submission (ICR, Verra, or Gold Standard).
- Independent of the project, with no commercial or contractual relationship to the project operator other than the verification engagement.
- Competent in the technical domains covered by the BDF protocol: cryptographic verification of signed payloads, statistical anomaly detection, freeze drying and food preservation processes, and the regulatory frameworks of the project jurisdictions.
- Free of conflicts of interest with the project’s supply chain participants.

The verifier may engage subject matter experts to support specific tasks (e.g. a freeze drying engineer to assess process telemetry, a laboratory chemist to evaluate External Attestations); the verifier remains responsible for the final verification report.

9.2 Verification Inputs and Their Provenance

The verifier consumes evidence from three sources, with distinct provenance and trust profiles.

Public record (Tier 1 and Tier 2). The verifier reads the project’s signed BDT records from the content addressed storage layer of the BDF protocol and the ownership transitions from the public chain. This includes: every Agronomic, Logistic, Process, and Recipe Vector signed during the vintage year; every T_2 detector verdict; every distribution event and its conservation invariant. The verifier reproduces every detector verdict by replaying the detection algorithm against the signed inputs. No operator cooperation is required for this step.

Selective disclosure (Recipe Vector and other commercially sensitive payloads). The verifier requests the encryption keys for the Recipe Vector $\vec{R}$ and any other selectively encrypted payloads. The disclosure event is itself a signed object on the public record, and the verifier countersigns receipt. The plaintext is decrypted locally by the verifier and consumed for the cross vector coherence test against the Process Vector. Disclosed plaintext is not redistributed; any retention by the verifier is bounded by the engagement contract.

External Attestations (Tier 4). The verifier may request additional Tier 4 evidence beyond the project’s routine T_4 sampling. The request specifies the lots to sample, the analyses to perform, and the laboratory to engage (which shall be ISO 17025 accredited). The resulting External Attestations are

signed by the laboratory and anchored to the affected BDTs. The verifier consumes these attestations as direct evidence of composition, identity, or contamination.

Operator submissions. The verifier may request operator submissions for evidence not covered by the four mechanisms above, such as legal compliance documentation, employment records, or grievance redress logs. Operator submissions are reviewed on a cooperative basis and are the most fragile evidence class; the methodology limits their scope to questions not answerable from signed payloads.

9.3 Verification Tasks

The verifier shall perform, at minimum, the following tasks per vintage year.

Task V1: Reproduce T_1 structural integrity. Confirm that every signed object referenced by the project verifies under its declared signer’s public key, that all ownership transitions are valid (no double signing, no forking), that distribution events conserve metadata quantity (Section 2), and that no canonical hash referenced in the project also appears in another project’s record.

Task V2: Reproduce T_2 detector verdicts. Replay the detection algorithm against the signed vectors. Confirm pass, warn, or fail bands match the project’s recorded verdicts. Investigate any discrepancy and resolve before the verification report is finalised.

Task V3: Validate calibration corrections. Where the project has applied calibration corrections (Section 7.4), confirm that the cohort statistics support the correction factor and that the residual variance after correction is consistent with subsequent lot data.

Task V4: Sample T_4 External Attestations. Confirm that the project’s routine T_4 sampling covers at least 1 percent of vintage year credited mass and is randomly selected. Optionally request additional samples for risk based assessment.

Task V5: Validate baseline counterfactual. Confirm that the regional disposal mix used in the baseline corresponds to current published statistics for the project’s jurisdiction (within five years of the vintage year), or that the conservative discount has been applied.

Task V6: Validate stakeholder consultation and Do No Harm. Review the consultation record, the Do No Harm checklist, the grievance redress log, and confirm material compliance with Section 8.

Task V7: Validate uncertainty assessment and conservative deduction. Confirm $u(ER_y)$ is computed correctly per Section 7 and that ζ is applied correctly.

Task V8: Issue verification statement. Issue a signed verification statement summarising the credited quantity, the conservative deduction, the buffer pool contribution, the relative uncertainty, and any unresolved findings. The verification statement is anchored to the project record.

9.4 Verification Cadence

Initial validation. The verifier conducts an initial validation of the project design document prior to the start of the first crediting period. This validation reviews applicability conditions, the chosen counterfactual, the BDF instrumentation, the stakeholder consultation, and the Do No Harm framework. The validation outcome is a signed validation statement anchored to the project record.

Annual verification. A verification is conducted annually at the close of each vintage year, performing tasks V1 through V8 above. The verification report is delivered no later than 24 months after vintage close (Section 5.3).

Continuous monitoring. Between verifications, the project's T_2 detector verdicts are continuously published on the public record. Any verifier or third party may inspect the verdicts at any time. The methodology recognises this continuous evidence as the principal mechanism for maintaining trust between annual verifications.

9.5 Dispute Mechanism

A dispute may be raised by any of: the verifier (during verification), the registry (at any time), a buyer of issued credits (within the credit's lifetime), a stakeholder via the grievance mechanism, or a third party with substantive evidence.

Filing. A dispute is filed with the registry, including the contested claim, the supporting evidence, and the desired remediation. The registry forwards the dispute to the project and to a designated independent mediator.

Investigation. The mediator reviews the contested claim against the signed BDF record, the External Attestations, and any additional evidence the parties submit. The investigation has a default duration of 90 calendar days, extendable by mutual agreement.

Outcomes. The investigation may conclude in: dismissal (the claim is not substantiated), correction (the project amends the affected lots, vintage years, or methodology application), invalidation (the affected credits are voided and any retired credits are replaced from the project's buffer pool), or methodology revision (where the dispute reveals a structural gap in the methodology, requiring update at the next revision).

Public record. The dispute filing, the investigation, and the outcome are all anchored to the project record as signed objects, providing a public audit trail of the dispute history.

9.6 Certificate Issuance

Upon successful verification, the registry issues credits according to the verification statement.

Quantity. The issued quantity equals $Credits_y$ as defined in equation 17, after the conservative deduction ζ from Section 7 and the buffer pool contribution β from Section 10.

Vintage tagging. Each credit is tagged with the vintage year of the lots that generated it. Vintage information accompanies the credit through transfer and retirement.

Anchoring. The issuance event is itself a signed object on the registry's record and is anchored to the corresponding BDF project record. A buyer or auditor inspecting the credit at any time can trace it back to the underlying signed evidence stack.

Selective disclosure to buyers. A buyer of issued credits may request a buyer specific selective disclosure scope at retirement (Section 6.7), allowing inspection of the underlying evidence as part of due diligence. The buyer's right to inspect is bounded by the contractual scope and recorded on the public record.

10 Permanence and Reversal

Permanence is the property that an emission reduction, once achieved, remains achieved. This section defines permanence for Recovered Food Carbon, identifies reversal events, and establishes the buffer pool sizing and remediation procedures.

10.1 Permanence of Recovered Food Carbon

The avoided emissions credited under this methodology arise from preventing the disposal of food matter through pathways that would have generated GHG emissions. Permanence of these reductions has a different character from permanence in AFOLU sequestration projects, and the methodology treats it accordingly.

Avoided emissions are permanent if the lot is consumed. Once a Recovered Food Lot has been stabilised and consumed (or otherwise valorised in a non disposing pathway), the avoided baseline emissions are realised in full and cannot be reversed. The recovered matter has not entered landfill, anaerobic digestion, compost, or incineration; the methane, nitrous oxide, and combustion emissions

of those pathways have not occurred and will not occur. This is structurally distinct from carbon sequestration, where atmospheric carbon stored in biomass or soil can be released by fire, decomposition, or land use change at any future date.

Limited horizon of reversal risk. The reversal risks for Recovered Food Carbon are concentrated in the period between stabilisation and consumption. After consumption, no reversal pathway exists. The methodology therefore defines a bounded permanence window, summarised in Section 10.2 below, and sizes the buffer pool against the risks within that window only.

End of life of the stabilised product. The methodology does not credit the project for emissions associated with the disposal of the stabilised product at the end of its consumption life. These downstream emissions are typically small relative to the avoided baseline (the stabilised product is dehydrated and a small fraction of the original biological mass) and are accounted under consumer or municipal inventory frameworks. The methodology nonetheless flags this asymmetry and addresses it through the buffer pool sizing in Section 10.4.

10.2 Reversal Events

A reversal event is an event after credit issuance that invalidates the avoidance basis of one or more credited lots. The methodology recognises four classes of reversal event.

R1: Disposal of the stabilised product before consumption. A stabilised Recovered Food Lot that is disposed (rather than consumed) within the permanence window enters a disposal pathway with non zero emissions, partially or fully reversing the credited avoidance. The Single Owner Chunk record of the lot's ownership chain (Section 6) supports detection of this event when the terminal owner declares disposal as the lifecycle event rather than consumption.

R2: Diversion to animal feed. If the stabilised product is sold or transferred for use as animal feed rather than human consumption, the project shall update the credited mass for the affected lots, applying the animal feed exclusion of Section 1. This is treated as a partial reversal proportional to the diverted fraction.

R3: Discovery of fraud or misrepresentation. Post issuance discovery of fraud (e.g. proven through a dispute under Section 9.5) invalidates the affected credits. The buffer pool replaces the invalidated quantity if any of the issued credits have been retired by buyers acting in good faith.

R4: Methodology revision invalidating prior assumptions. A future revision of this methodology that determines a previously credited approach was not conservative may apply to outstanding (un retired) credits prospectively. Retired credits are not invalidated retroactively. The buffer pool is not engaged for R4 events affecting outstanding credits because the affected credits have not yet been retired.

10.3 Reversal Detection

The BDF protocol provides structural detection mechanisms for several reversal classes.

R1 detection: terminal lifecycle event. The methodology requires that the terminal owner of a stabilised lot declare a lifecycle event when the lot leaves the BDT lifecycle: `consumption`, `disposal`, `rejection`, `export`, or `loss`. The declaration is signed and anchored to the BDT. Where the terminal event is `disposal` within the permanence window, the project shall report a reversal at the next vintage year close.

R1 detection: non declaration default. Where the project's lots leave the BDT lifecycle without a terminal declaration (the public record terminates with the lot held by an owner who has not declared an event), the methodology applies a default permanence assumption proportional to the project's average historical reversal rate. New projects without history apply a conservative default of 5 percent assumed reversal absent declaration, decreasing as project history accumulates.

R2 detection: ownership transfer to feed buyer. Where a stabilised lot is transferred to an entity classified as an animal feed processor (registered as such in the receiving jurisdiction's commercial registry), the methodology treats the transfer as a Class R2 reversal event upon ownership change.

R3 detection: dispute outcome. A dispute investigation under Section 9.5 that concludes in invalidation triggers a Class R3 reversal automatically.

10.4 Buffer Pool Sizing

The buffer pool is a project specific reserve of credits set aside at issuance to cover post issuance reversals.

Default buffer fraction. The methodology applies a default buffer fraction of $\beta = 0.10$ on the issued quantity (equation 17). This fraction is moderate by carbon market standards because the underlying permanence risk for Recovered Food Carbon is structurally lower than for AFOLU sequestration: the avoided emissions are fully realised within the permanence window, rather than depending on continued carbon storage over decades or centuries.

Risk based adjustment. A project may justify a reduced buffer fraction down to $\beta = 0.05$ where the project demonstrates: a documented track record of terminal declarations covering at least three vintages, an aggregate reversal rate below 2 percent across those vintages, and a fraud detection record showing zero substantiated R3 events. Conversely, the verifier may require an increased buffer fraction up to $\beta = 0.15$ where the project's reversal history exceeds 5 percent or where structural risks (e.g. a high share of buyers in markets with weak end of life tracking) justify additional reserve.

Buffer composition. The buffer pool consists of credits issued under the same vintage as the project credits but withheld at issuance. Buffer credits are not transferable until released by the registry. Where the project belongs to a pooled registry buffer (such as the Verra AFOLU buffer with cross project sharing), the project's contribution shall be aggregated into the pool with proportional risk sharing.

Buffer release. Buffer credits are released back to the project after a documented post issuance period without reversal, by default five years after vintage close. The release is approved by the verifier and recorded on the project record.

10.5 Remediation of Reversals

When a reversal event is detected and recorded, the methodology applies the following remediation.

Outstanding (un retired) credits. The reversal quantity is debited directly from the project's outstanding credits at the registry. The project's account balance is reduced; no buffer pool engagement is needed.

Retired credits acquired in good faith. Where the reversal exceeds the project's outstanding balance and the over commitment was retired by buyers acting in good faith, the buffer pool is engaged. Buffer credits equivalent to the over commitment are cancelled, restoring atmospheric integrity.

Repeated reversals. A project with reversal events exceeding 10 percent of any single vintage's issuance is placed on a remediation plan by the registry, including: increased verification frequency at subsequent verifications, additional Tier 4 sampling, and an increased buffer fraction in subsequent vintages until the reversal rate normalises.

Persistent fraud. A project with substantiated R3 events affecting more than 5 percent of any single vintage's issuance is subject to suspension by the registry pending remediation. Resumption requires a registry approved remediation plan addressing the root causes.

11 Crosswalk to Existing Frameworks

This section provides a structural alignment of the methodology against the principal existing frameworks in the voluntary carbon market and adjacent regulatory regimes. The alignment is intended to support eligibility for cross registry recognition: a project validated under this methodology should be portable to Verra and Gold Standard with minimal additional adaptation, and the underlying evidence stack should be reusable for corporate Scope 3 reporting under the GHG Protocol.

11.1 Framework Coverage Map

The methodology is structurally aligned with five frameworks. Table 5 records the alignment at the section level.

Table 5: Framework coverage map. Each row identifies a methodology section and the corresponding section or principle in each external framework.

This methodology	ICR Standard	Verra VM0085	ISO 18752	ICVCM CCP
§1 Sources & Defs	§2.1, §2.2	§1, §3	Cl. 3	Principle 1
§2 Boundary & Counterfactual	§4.1	§5	Cl. 5	Principle 4
§3 Baseline	§4.2	§6	Cl. 6	Principle 5
§4 Project Emissions	§4.3	§7	Cl. 7	Principle 5
§5 Net ER	§4.4	§8	Cl. 8	Principle 6
§6 Monitoring	§5 (dMRV)	§9, §10	Cl. 9	Principle 7
§7 Uncertainty	§5.4	§11	Cl. 10	Principle 5
§8 Stakeholder	§6	§13	Cl. 11	Principle 9
§9 Verification	§7	§12	Cl. 12	Principle 8
§10 Permanence	§4.5	§14	Cl. 13	Principle 6

11.2 ICR Recovered Food Class

The International Carbon Registry’s standard for the Recovered Food Carbon credit class [International Carbon Registry, 2025] is the primary submission target for this methodology. Alignment is structural: every requirement of the ICR standard maps to a section of this methodology, and the BDF protocol’s continuous evidence stream satisfies the ICR digital MRV (dMRV) requirements without adaptation.

ICR specific provisions. The ICR standard requires: clearly defined Recovered Food Lot and Avoided Disposal Pathway (Section 1); regional counterfactual with documented disposal mix (Section 2); IPCC compliant baseline emission factors (Section 3); per project monitoring of mass and energy with auditable evidence (Section 6); independent verifier annually (Section 9); buffer pool against reversal (Section 10); stakeholder consultation (Section 8); ICVCM CCP labellable methodology (the labelling is consequential, addressed below).

ICR digital MRV alignment. The ICR standard’s dMRV provisions specifically request: signed structured data at the source, content addressed storage, anomaly detection over signed payloads, and independent reproducibility of detection verdicts. The BDF protocol satisfies all four by design [Fair Food Data, 2026a]; this methodology operationalises them for the Recovered Food Carbon use case.

11.3 Verra VM0085 Parallel Structure

Verra VM0085 [Verra, 2024] is the methodology for sustainable aviation fuel produced from low value forest biomass. While the feedstock and the transformation differ, the structural elements of VM0085 (counterfactual disposal mix, project boundary, baseline factor application, energy audit, verification cadence) parallel this methodology closely. A project under this methodology can be reframed for Verra submission with the following adaptations.

Adaptations required for Verra submission. The following adaptations apply to convert this methodology to Verra submission format:

- Reformat the project design document to Verra’s PD template.
- Specify additionality with the Verra additionality tool (typically the investment analysis or barrier analysis).
- Specify validation and verification body (VVB) credentials per Verra accreditation list.
- Specify the buffer pool contribution to Verra’s AFOLU buffer if eligible, or to a pool specific to Recovered Food Carbon if Verra establishes one.
- Restate the BDF dMRV evidence stack as the monitoring plan.

The substantive content of the methodology (counterfactual derivation, baseline emission factors, project emission accounting, uncertainty assessment, BDF monitoring) is portable without revision.

11.4 Gold Standard Compatibility

Gold Standard’s methodology framework emphasises sustainable development outcomes alongside emission reductions. This methodology’s stakeholder consultation (Section 8) and Do No Harm checklist support a Gold Standard submission. A project pursuing Gold Standard certification should additionally:

- Document at least three SDG outcomes beyond SDG 13 with quantified indicators.
- Conduct a Gold Standard specific stakeholder feedback round in addition to the consultation event under Section 8.2.
- Apply Gold Standard’s labour and human rights safeguards in addition to the IFC Performance Standards baseline.

11.5 ICVCM Core Carbon Principles Assessment

The ICVCM Core Carbon Principles [Integrity Council for the Voluntary Carbon Market, 2024] are the integrity benchmark for the high integrity tier of the voluntary carbon market. A methodology that earns CCP labelling is positioned to access the premium tier that survived the 2023 trust collapse. Table 6 maps each CCP to the methodology mechanism that addresses it.

Table 6: Mapping of methodology mechanisms to the ICVCM Core Carbon Principles [Integrity Council for the Voluntary Carbon Market, 2024].

CCP	Principle	Methodology mechanism
1	Effective governance	ICR (or Verra, Gold Standard) registry oversight; verifier accreditation (Section 9.1); dispute mechanism (Section 9.5)
2	Tracking	Single Owner Chunk identifier per BDT; ownership chain on public chain; registry tagging at issuance (Section 9.6)
3	Transparency	Public record of attestation vectors, T_2 verdicts, External Attestations, verification reports, and dispute outcomes; selective disclosure for sensitive payloads (Section 6.7)
4	Robust independent verification	Annual third party verification with T_1 to T_4 evidence consumption (Section 9)
5	Additionality	Applicability condition C5 (Section 1); regulatory baseline subtraction
6	Permanence	Bounded permanence window with recovered food specific reasoning; buffer pool with risk based sizing (Section 10)
7	Robust quantification of emission reductions	IPCC compliant baseline (Section 3); conservative counterfactual; per parameter uncertainty with conservative deduction (Section 7); BDF T_2 continuous detection
8	No double counting	Content addressed canonical hash makes double claim publicly detectable; registry serial numbering (Section 6, Section 9.6)
9	Sustainable development benefits and safeguards	Stakeholder consultation, Do No Harm checklist, grievance redress, SDG mapping (Section 8)
10	Contribution to net zero transition	Recovered Food Carbon as documented avoidance pathway aligned with SDG 12 Target 12.3

11.6 ISO 18752 and ISO 14064-2 Compliance

The methodology is designed to comply with ISO 18752 [International Organization for Standardization, 2024] for quantification of avoided emissions from food loss and waste reduction and with ISO 14064-2 [International Organization for Standardization, 2019] for project level GHG quantification. The clauses of each standard are referenced in Table 5.

ISO 18752 specific elements. ISO 18752 requires explicit definition of food loss and waste boundaries, documentation of disposal pathways, and uncertainty assessment per parameter. Sections 2, 3, and 7 satisfy these requirements directly.

ISO 14064-2 specific elements. ISO 14064-2 requires documented project boundary, baseline scenario justification, monitoring plan, uncertainty assessment, and validation and verification provisions. Sections 2, 3, 6, 7, and 9 provide these elements.

11.7 GHG Protocol Scope 3 Reporting Compatibility

Buyers of credits issued under this methodology may use the underlying signed evidence stack to support reporting under GHG Protocol Scope 3 categories 11 (use of sold products) and 12 (end of life treatment of sold products) [World Resources Institute and World Business Council for Sustainable Development, 2011]. Specifically, a corporate buyer reporting recovered food carbon impacts in its Scope 3 inventory may attach the BDF record of acquired credits as primary evidence, with selective disclosure to the buyer’s auditor.

CSRD compatibility. The European Corporate Sustainability Reporting Directive (CSRD) requires high quality data with verifiable provenance for material climate disclosures. The methodology’s signed attestation vectors and continuous detector verdicts provide the data quality and provenance evidence that CSRD assurance providers expect [Fair Food Data, 2026a].

CBAM compatibility. Where credit retirement is associated with carbon adjustment under the Carbon Border Adjustment Mechanism (CBAM), the BDF record provides the verifiable provenance the customs authority requires. The methodology does not at this time credit CBAM eligible reductions but is structurally compatible with the underlying evidence requirements.

A Worked Example with Pilot Data

This appendix works the full emission reduction calculation through the methodology using real data from the pilot reported in the BDF Protocol main paper [Fair Food Data, 2026a]. The example is presented for transparency; the resulting numbers are deliberately small because the pilot was a single cycle with a limited cohort. Subsection A.9 extrapolates to operationally meaningful scale and Subsection A.10 compares the result against alternate counterfactual jurisdictions to illustrate the methodology’s sensitivity to baseline disposal mix.

A.1 Pilot Configuration and Inputs

Project type.

Type A on farm recovery, blueberry cultivars Biloxi, Ventura, O’Neal.

Jurisdiction of recovery.

Spain (illustrative, applying the Spanish counterfactual template of Section 2.5).

Stabilisation facility.

Single freeze drying line, single cycle in this dataset.

Recovered Food Lots.

Fifteen baskets completing the full origin to reception pipeline.

Aggregate calibrated mass at recovery.

$M = 53.27$ kg (facility scale, used after applying the calibration correction described below).

Aggregate declared mass at recovery.

$M^{\text{decl}} = 48.00$ kg (operator declared in field, biased low by 11 percent).

Cycle electricity.

$$E = 87.61 \text{ kWh, signed in } \vec{P}.$$

Cycle duration.

43.5 hours across seven sequential stages.

Energy density.

$$\eta = 1.93 \text{ kWh per kg of water removed.}$$

Refrigerant.

Project assumes propane (R 290, GWP = 3) for the worked example, given the natural refrigerant trajectory of new deployments.

Logistics.

Single transport segment from field to plant; declared distance 100 km, refrigerated road transport.

Vintage year.

2026 (illustrative).

A.2 Calibration Correction

The Tier 2 conservation invariant detector returns a recurring `warn` verdict on the field versus facility weight comparison: the cohort mean field declaration is 48.00 kg against a calibrated facility cohort mean of 53.27 kg (Section 6.4). The verdict is in the `warn` band ($5\% < \delta = 11\% \leq 15\%$) rather than `fail`, consistent with diagnosis as a measurement provenance artefact rather than fraud.

Applying the calibration correction of equation 29: $\kappa = 53.27/48.00 = 1.110$. The corrected origin mass for the cohort is $48.00 \times 1.110 = 53.27$ kg, equal to the facility scale measurement. For subsequent lots until field weighing infrastructure is deployed, declared origin masses are multiplied by κ to obtain the credited recovery mass. In what follows, the worked example uses $M = 53.27$ kg as the credited recovery mass.

A.3 Baseline Emissions

The baseline applies the Spanish counterfactual template (Table 1) and the per pathway emission factors of Section 3.2 for fruit category. Approximate values used in the worked example (full per category tables in Appendix B):

EF_{P1} landfill (Spain stock, $r = 0.30$, $OX = 0.10$).

0.85 kg CO₂e per kg fresh.

EF_{P3} AD (MCF = 0.9, $s = 0.03$).

0.07 kg CO₂e per kg fresh.

EF_{P4} compost (mostly N₂O).

0.08 kg CO₂e per kg fresh.

EF_{P5} incineration (biogenic, energy recovery).

0.05 kg CO₂e per kg fresh.

EF_{P6} animal feed.

0.00 (excluded, applicability C8).

Spanish disposal mix shares: $\rho_{P1} = 0.42$, $\rho_{P3} = 0.18$, $\rho_{P4} = 0.16$, $\rho_{P5} = 0.21$, $\rho_{P6} = 0.03$.

Weighted baseline emission factor:

$$EF_{ES}^{\text{baseline}} = 0.42 \times 0.85 + 0.18 \times 0.07 + 0.16 \times 0.08 + 0.21 \times 0.05 + 0.03 \times 0 = 0.394 \text{ kg CO}_2\text{e per kg fresh.}$$

Baseline emission for the cohort (equations 1 and 2):

$$BE = M \cdot EF_{ES}^{\text{baseline}} = 53.27 \times 0.394 = 20.99 \text{ kg CO}_2\text{e.}$$

Conservative discount: regional MITECO data current within five years (no stale data discount), per category factor used (no aggregate discount), Spain published methane recovery rate available (no methane discount), nitrogen content default applied (5 percent). Aggregate discount: $1 - 0.05 = 0.95$. The methodology floor of 10 percent applies: $1 - 0.10 = 0.90$. Conservative baseline:

$$BE^{\text{conservative}} = 20.99 \times 0.90 = 18.89 \text{ kg CO}_2\text{e.}$$

A.4 Project Emissions

Electricity. Spain grid emission factor for vintage 2026 (illustrative, IEA [International Energy Agency, 2024]): $EF_{\text{grid,ES}} = 0.16 \text{ kg CO}_2\text{e per kWh}$. Per equation 11:

$$PE^{\text{elec}} = E \cdot EF_{\text{grid,ES}} = 87.61 \times 0.16 = 14.02 \text{ kg CO}_2\text{e.}$$

Refrigerant. Propane (R 290), $M_r = 1.0 \text{ kg charge}$, $\lambda_r = 0.10$ annual leakage rate, $GWP_r = 3$. Allocation to the cohort follows the cohort's water mass fraction of the facility annual throughput. For an illustrative annual throughput of 25,000 kg fresh, the cohort fraction is $53.27/25,000 = 0.21\%$. Per equation 12:

$$PE^{\text{ref}} = 1.0 \times 0.10 \times 3 \times 0.0021 = 6.4 \times 10^{-4} \text{ kg CO}_2\text{e.}$$

The natural refrigerant choice essentially eliminates this term. For comparison, the same calculation with R 404A ($GWP_r = 3922$) would yield 0.83 kg CO₂e for the cohort, an order of magnitude relative to the other terms.

Logistics. Single segment, 100 km road refrigerated. DEFRA tonne kilometre factor for refrigerated articulated lorry [UK Department for Energy Security and Net Zero, 2024]: 0.144 kg CO₂e per tonne km (with the refrigeration multiplier already included in this aggregate value). Cohort mass in segment is the recovery mass:

$$PE^{\text{log}} = 0.05327 \text{ tonnes} \times 100 \text{ km} \times 0.144 = 0.77 \text{ kg CO}_2\text{e.}$$

Consumables and packaging. Packaging at 0.05 kg CO₂e per kg of stabilised dry product, with stabilised mass equal to fresh recovery mass times $(1 - 0.85) = 0.15$ (water content of fresh blueberry) so $53.27 \times 0.15 = 7.99 \text{ kg stabilised}$:

$$PE^{\text{pack}} = 7.99 \times 0.05 = 0.40 \text{ kg CO}_2\text{e.}$$

Consumables (filtration, hygiene, lubricants) prorated to cohort water mass at 0.02 kg CO₂e per kg fresh:

$$PE^{\text{cons,other}} = 53.27 \times 0.02 = 1.07 \text{ kg CO}_2\text{e}.$$

Total consumables and packaging:

$$PE^{\text{cons}} = 0.40 + 1.07 = 1.47 \text{ kg CO}_2\text{e}.$$

Total project emissions.

$$PE = 14.02 + 6.4 \times 10^{-4} + 0.77 + 1.47 = 16.26 \text{ kg CO}_2\text{e}.$$

A.5 Leakage

Market displacement. Default $\alpha_{\text{md}} = 0$ in the absence of documented market analysis (Section 5.2). $LE^{\text{md}} = 0$.

Activity shifting. New build assumption, $\alpha_{\text{as}} = 0$. $LE^{\text{as}} = 0$.

Rebound. Default $\alpha_{\text{rb}} = 0.05$. Upstream blueberry agricultural EF approximately 1.0 kg CO₂e per kg fresh [Poore and Nemecek, 2018], applied to stabilised mass:

$$LE^{\text{rb}} = 0.05 \times 7.99 \times 1.0 = 0.40 \text{ kg CO}_2\text{e}.$$

Total leakage.

$$LE = 0 + 0 + 0.40 = 0.40 \text{ kg CO}_2\text{e}.$$

A.6 Net Emission Reduction

Per equation 16:

$$ER = BE^{\text{conservative}} - PE - LE = 18.89 - 16.26 - 0.40 = 2.23 \text{ kg CO}_2\text{e}.$$

A.7 Uncertainty and Conservative Adjustment

Applying default per parameter uncertainties (Table 4) and propagation per equation 25, the dominant uncertainty contributors at this scale are the disposal pathway shares ($u = 0.20$), the landfill methane recovery rate ($u = 0.40$), and the per pathway emission factors ($u = 0.30$).

Approximate compound relative uncertainty for the cohort: $u(ER) \approx 0.45$. Per equation 27, the deduction factor at this uncertainty is $\zeta = 0.85$. Adjusted emission reduction:

$$ER^{\text{adjusted}} = 2.23 \times 0.85 = 1.90 \text{ kg CO}_2\text{e}.$$

A.8 Buffer Pool and Credits Issued

Default buffer fraction $\beta = 0.10$ (Section 10.4). Credits issued to the project:

$$\text{Credits} = \text{ER}^{\text{adjusted}} \cdot (1 - \beta) = 1.90 \times 0.90 = 1.71 \text{ kg CO}_2\text{e}.$$

The remaining 0.19 kg CO₂e enters the project buffer pool.

A.9 Scaling to Operational Throughput

The pilot cycle yields a small absolute number because the dataset covers a single cycle with 53.27 kg of fresh matter. A real deployment operates at higher throughput. Two illustrative scaling scenarios:

Scenario 1: small commercial line. Fifty cycles per year of average 50 kg per cycle: 2,500 kg fresh per year. Linear scaling of the per cycle ER (allowable because the per kg breakdown is dominated by per kg terms): $\text{ER}_y \approx 2,500/53.27 \times 2.23 = 105 \text{ kg CO}_2\text{e per year}$, $\approx 90 \text{ kg CO}_2\text{e adjusted}$, $\approx 80 \text{ kg CO}_2\text{e credited per year}$. Carbon revenue at indicative voluntary market price 30 EUR per tonne: $\approx 2.40 \text{ EUR per year}$. The carbon revenue is not material at this scale; the project case rests on premium product price differentiation.

Scenario 2: industrial line. Five hundred cycles per year of average 80 kg per cycle: 40,000 kg fresh per year. Linear scaling: $\text{ER}_y \approx 40,000/53.27 \times 2.23 = 1,675 \text{ kg CO}_2\text{e per year}$, $\approx 1,425 \text{ kg adjusted}$, $\approx 1,280 \text{ kg credited per year}$. Carbon revenue at 30 EUR per tonne: $\approx 38 \text{ EUR per year}$. Still not material; carbon revenue at this configuration is supplementary.

Both scenarios indicate that for Spain, with a relatively clean grid (0.16 kg CO₂e per kWh) and a baseline dominated by sanitary landfill with non zero methane capture, the carbon credit value is small. The project case for Recovered Food Carbon in this configuration depends on market displacement of higher emission food products, premium pricing of the stabilised output, and stakeholder benefits beyond carbon.

A.10 Counterfactual Sensitivity

The same physical operation produces dramatically different ER under different counterfactual jurisdictions. Table 7 summarises.

Reading the table. The methodology produces zero credits in jurisdictions where project emissions exceed the conservatively adjusted baseline ($\text{ER} \leq 0$, no credits issued, project investigates cause per Section 5). Jurisdictions with relatively clean grids and modern landfill stocks (EU average, US in the mix used here) require either on site renewable generation or a focus on premium markets to justify the project economics. Jurisdictions with significant open dump shares (Colombia at 39 percent) or older landfill stocks with low methane capture produce materially higher ER, validating the project case where the avoided pathway is structurally worse.

Table 7: Sensitivity of the worked example to counterfactual jurisdiction. The physical inputs (53.27 kg cohort, 87.61 kWh cycle electricity, propane refrigerant) are identical across rows; only the disposal mix and grid emission factor change.

Jurisdiction	EF^{baseline} (kg CO ₂ e/kg)	EF_{grid} (kg CO ₂ e/kWh)	ER per cycle (kg CO ₂ e)	ER credited per cycle (kg CO ₂ e)
Spain	0.394	0.16	2.23	1.71
European Union	0.357	0.21	-2.10	—
United States	0.696	0.40	-3.40	—
Colombia	0.862	0.30	14.0	10.7

On site renewable scenario. A Spain deployment with on site solar generation supplying 80 percent of the cycle electricity reduces PE^{elec} from 14.02 to $0.20 \times 14.02 = 2.80$ kg CO₂e, raising the per cycle ER to approximately 13.43 kg CO₂e. In this configuration, Spain becomes operationally comparable to Colombia under the grid mix.

The methodology does not adjudicate which configurations are operationally preferable. It quantifies them honestly.

A.11 Detector Verdict Summary for the Pilot

The pilot’s signed evidence stack produces the following T_2 detector verdicts, each anchored to the BDF record and reproducible by any verifier (Section 6.6).

Table 8: Tier 2 detector verdicts on the pilot dataset.

Detector	Verdict	Disposition
Mass conservation (cohort)	warn	11.0 percent systematic underestimation at field; calibration correction $\kappa = 1.110$ applied; subsequent lots use corrected origin masses.
Cycle energy density	pass	$\eta = 1.93$ kWh per kg, within 1.0 to 2.0 industrial benchmark; close to upper bound of efficiency.
Pressure envelope, stage 7	fail	Three readings above 5×10^4 mTorr; cycle subjected to corrective action (incident report, declaration in verification report, optional Tier 4 sample of affected lots).
Cross vector coherence (logistic vs process)	warn	Two baskets (CAN-034 Ventura, CAN-072 O’Neal) exhibit per basket weight changes inconsistent with reported transit times; logged for individual review.

The detector verdicts are signed objects on the public record. A verifier reproducing the verdicts from the same signed vectors at any later time arrives at the same outcomes. This is the structural property that distinguishes the methodology’s evidence stack from document audit alternatives.

B Default Emission Factor Tables

This appendix tabulates default emission factors for application in the absence of project specific data. Where a project supplies verifiable jurisdiction or category specific data, the project may substitute the project specific value with verifier approval. All values are reported as kg CO₂e per kg fresh matter on a 100 year horizon using IPCC AR6 GWPs (CH₄ non fossil = 27, N₂O = 273, CO₂ = 1).

B.1 Per Pathway Emission Factors by Food Category

The methodology defines six food categories for emission factor lookup. Categories are not exhaustive; projects with materials not fitting any category apply the closest category and document the choice in the project design document.

- C1. **Fruit and vegetables (low DOC).** Berries, leafy greens, root vegetables, citrus, top fruit. Default DOC 0.10, water content 0.85.
- C2. **Cereals and bread (high DOC, low water).** Bread, baked goods, breakfast cereals. Default DOC 0.40, water content 0.35.
- C3. **Dairy (medium DOC, high water).** Milk, yoghurt, cream, soft cheese. Default DOC 0.20, water content 0.85.
- C4. **Meat and fish (high N, medium DOC).** Cuts, processed products, fish products. Default DOC 0.20, nitrogen 0.025, water 0.65.
- C5. **Mixed prepared foods.** Ready meals, soups, stews. Default DOC 0.20, water 0.65.
- C6. **Sugar and confectionery (high DOC, low water).** Confectionery, chocolate, sugar based products. Default DOC 0.50, water 0.10.

Table 9: Default per pathway emission factors by food category, in kg CO₂e per kg fresh matter. Computed from IPCC 2019 Refinement Volume 5 [IPCC, 2019] with the parameters of Section 3.2, assuming sanitary landfill methane recovery $r = 0.30$ for the EF P1 column (representative of EU average).

Pathway	C1 Fruit	C2 Cereal	C3 Dairy	C4 Meat	C5 Mixed	C6 Sugar
P1 Sanitary landfill	0.55	1.85	1.10	1.20	1.10	2.30
P2 Open dump	1.20	3.95	2.40	2.55	2.35	4.90
P3 Anaerobic digestion	0.05	0.18	0.10	0.10	0.10	0.22
P4 Composting	0.06	0.14	0.12	0.34	0.16	0.10
P5 Incineration (energy rec)	0.04	0.09	0.05	0.07	0.05	0.10
P6 Animal feed	0.00	0.00	0.00	0.00	0.00	0.00

Adjustments for jurisdictional methane recovery rate. The P1 emission factor scales with $(1-r)$ where r is the methane recovery rate. Jurisdictions with published r values:

Spain.

$r = 0.30$ (MITECO 2023 [Ministerio para la Transición Ecológica y el Reto Demográfico, 2023]).

European Union average.

$r = 0.45$ (Eurostat composite [European Commission, 2024]).

United States.

$r = 0.20$ (EPA inventory [United States Environmental Protection Agency, 2024]; older landfill stock with mixed capture).

Colombia.

$r = 0.05$ (DANE [DANE Colombia, 2023]; methane capture limited to a small number of sanitary landfills).

For other jurisdictions, the methodology requires either a published national value or the conservative default $r = 0.20$ with the additional methane discount per Table 2.

B.2 Grid Electricity Emission Factors

Grid emission factors are drawn from IEA Emissions Factors [International Energy Agency, 2024]. The methodology requires the most recent vintage available at the time of project verification.

Table 10: Grid electricity emission factors for selected jurisdictions, vintage 2024. Values in kg CO₂e per kWh, ISO scope 2 location based.

Jurisdiction	EF _{grid} (kg CO ₂ e/kWh)
Spain	0.16
Portugal	0.18
France	0.05
Germany	0.34
European Union average	0.21
United Kingdom	0.20
United States average	0.40
California (US)	0.22
Texas (US)	0.39
Colombia	0.30
Mexico	0.45
Brazil	0.10

B.3 Refrigerant Global Warming Potentials

Default leakage rates. The methodology applies the following default annual leakage rates (Section 4.3):

Hermetic, annual maintenance.

$$\lambda = 0.10.$$

Hermetic, no documented maintenance.

$$\lambda = 0.15.$$

Semi hermetic.

$$\lambda = 0.20.$$

Older or unmaintained systems.

$$\lambda = 0.30.$$

Table 11: Common refrigerant global warming potentials, AR6 100 year horizon [IPCC, 2021].

Refrigerant	Designation	GWP (100 yr)
CO ₂	R 744	1
Ammonia	R 717	0
Propane	R 290	3
HFO 1234yf	R 1234yf	4
HFC 32	R 32	771
HFC 134a	R 134a	1,530
HFC blend (407C)	R 407C	1,908
HFC blend (449A)	R 449A	1,397
HFC blend (404A)	R 404A	3,922
HFC blend (410A)	R 410A	2,256

B.4 Tonne Kilometre Logistics Emission Factors

Table 12: Default tonne kilometre emission factors by transport mode, drawn from DEFRA [UK Department for Energy Security and Net Zero, 2024]. Values in kg CO₂e per tonne km. The refrigerated multiplier is already embedded in the refrigerated rows.

Transport mode	Ambient (kg/tkm)	Refrigerated (kg/tkm)
Articulated lorry (HGV)	0.090	0.144
Rigid lorry (medium duty)	0.180	0.260
Light commercial van	0.350	0.480
Rail freight (electrified, EU avg)	0.020	0.030
Rail freight (diesel)	0.030	0.045
Container ship	0.012	0.020
Air freight (short haul)	1.500	1.620
Air freight (long haul)	0.580	0.700

B.5 Upstream Agricultural Emission Factors

Table 13: Default upstream agricultural emission factors by food category, used for leakage calculation in equation 20. Values in kg CO₂e per kg fresh matter at farm gate, drawn from [Poore and Nemecek, 2018].

Category	EF _{upstream} (kg CO ₂ e/kg fresh)
C1 Fruit and vegetables	1.00
C2 Cereals and bread	1.40
C3 Dairy	3.20
C4 Meat and fish	25.00
C5 Mixed prepared foods	5.00
C6 Sugar and confectionery	3.00

Sub category refinement. Where the project recovers a specific sub category whose upstream emission factor differs materially from the default (e.g. beef at 60 versus chicken at 9 within C4), the project shall apply the sub category factor with citation in the project design document.

B.6 Embodied Emission Factors for Consumables and Packaging

Table 14: Default embodied emission factors for common project consumables and packaging materials, drawn from Ecoinvent 3.10 [Ecoinvent Centre, 2024]. Values in kg CO₂e per kg of material.

Material	EF ^{embodied} (kg CO ₂ e/kg)
Polyethylene film (LDPE)	2.50
Polyethylene terephthalate (PET)	3.10
Polypropylene (PP)	2.00
Aluminium (primary)	11.00
Aluminium (recycled, EU avg)	1.80
Cardboard (corrugated)	0.95
Glass jar	1.10
Wood pallet (treated)	0.30
Filtration cartridge (mixed)	4.50
Hygiene chemicals (caustic)	0.85
Lubricant (mineral oil)	1.40

C Required Attestation Schemas

This appendix documents the canonical schemas required by the methodology for each attestation vector and for the External Attestation payload. The schemas are expressed in beeson [Tron et al., 2026], the canonical object notation underlying the BDF protocol [Fair Food Data, 2026a]. The reference type system is documented in the BDF Standards Stack companion paper [Fair Food Data, 2026c]; this appendix defines the methodology specific instantiations.

C.1 Notation

Beeson types are written as typed attribute value matrices. Field names are in lowercase with underscore separators. Types include: `string`, `int`, `float`, `bool`, `timestamp` (ISO 8601 UTC), `geopoint` (latitude, longitude in WGS 84 decimal degrees), `hash` (32 byte BMT hash), `signature` (65 byte secp256k1 signature), `enum` (constrained string from a documented set). Composite types are written with brace notation. Optional fields are marked with a question mark suffix.

A canonical mapping from each schema field to the open standards stack (SenML, GS1 EPCIS 2.0, FoodOn, SAREF4AGRI, PROV-O, W3C Verifiable Credentials 2.0) is documented in the BDF Standards Stack companion paper [Fair Food Data, 2026c].

C.2 Agronomic and Recovery Vector Schema

The Agronomic Vector $\vec{A}$ (project type A on farm) and the Recovery Vector (project types B and C, post farm and retail) share a common required schema. Type specific fields extend the common base.

type AgronomicVector – vectorid : hash

```

lotid          : string
contentid      : string
vintageyear    : int
projectid      : string
recoverypoint  : geopoint
recoverydate   : timestamp
massatrecoverykg: float
foodcategory   : enum -C1, C2, C3, C4, C5, C6
projecttype    : enum -A, B, C
mintertype     : enum -humanoperator, automatediot,
                  propletattestation, certifiedlab
operatorid     : string
operatorrole    : string
signingkeyid   : hash
signature     : signature

// Type A specific
cultivar?      : string
block?         : string
parcelid?      : string
harvestmethod? : enum -hand, mechanised, mixed

// Type B specific
upstreamorigin? : string
upstreamownerid? : string
rejectionreason? : enum -cosmetic, logistical, contractual,
                    datelapse, other

// Type C specific
retaillocation? : string
precedingownerid?: string
upstreamprovenance?: string

```

Required field interpretation.

- `vector_id`: BMT hash of the canonical serialisation of all preceding fields, used as the primary identifier.
- `lot_id`: human readable lot identifier, unique within the project.
- `content_id`: cross reference identifier shared with the Logistic Vector for the same lot.
- `mass_at_recovery_kg`: calibrated scale measurement at the recovery point. For the pilot, this corresponds to the corrected origin mass per equation 30.
- `minter_type`: declared type of the principal signing the vector, used by verifiers to apply trust profiles per the Hardening Pathways section of the main paper [Fair Food Data, 2026a].

C.3 Logistic Vector Schema

```

type LogisticVector -
  vectorid          : hash
  lotid             : string
  contentid         : string

```

```

segmentindex      : int
segmentorigin     : geopoint
segmentdestination: geopoint
segmentdistancekm: float
segmentmode       : enum -road, rail, air, sea, intermodal
segmentstart      : timestamp
segmentend        : timestamp
refrigerated      : bool
setpointtempc?    : float
observedtempp95c?: float
massatoriginkg    : float
massatdestinationkg: float
carrierid         : string
driverid?         : string
signingkeyid      : hash
signature        : signature

```

Conservation invariant. The conservation invariant for transport segments tests $|m_d - m_o|/m_o$ against the threshold of Section 6.4. The invariant is computed by detector code consuming `mass_at_origin_kg` and `mass_at_destination_kg` fields.

Refrigeration envelope. Where `refrigerated` is true, the methodology requires `observed_temp_p95_c` and tests against `setpoint_temp_c` ± 2 degrees Celsius.

C.4 Process Vector Schema

The Process Vector aggregates per cycle telemetry signed by the SCADA system after the cycle ends. The full underlying time series is preserved in the operator's signed log, anchored by reference.

```

type ProcessVector -
  vectorid          : hash
  cycleid           : string
  facilityid        : string
  cyclestart        : timestamp
  cycleend          : timestamp
  inputlots         : [-lotid: string, masskg: float ]
  outputlots        : [-lotid: string, stabilisedmasskg: float ]
  totalwaterremovedkg: float
  totalelectricitykwh: float
  recipevectorid    : hash
  stages            : [StageAggregate]
  refrigerant       : RefrigerantState
  underlyingloganchor: hash
  signingkeyid      : hash
  signature        : signature

type StageAggregate -
  stageindex        : int

```

```

stagestart      : timestamp
stageend        : timestamp
durationmin     : float
pressuremtorr   : -mean: float, p05: float, p50: float,
                  p95: float, max: float
chambertempc    : -mean: float, p05: float, p50: float,
                  p95: float, max: float
heatertempc     : [HeaterStat]
powerw          : -mean: float, p95: float, max: float
energykwh       : float
envelopeviolations: int

type HeaterStat -
  heaterindex    : int
  tempc          : -mean: float, p05: float, p95: float, max: float

type RefrigerantState -
  designation     : enum -R744, R717, R290, R1234yf, R32, R134a,
                    R407C, R449A, R404A, R410A
  installedchargekg: float
  topupevents     : [-timestamp: timestamp, masskg: float ]
  gwp100yr        : float

```

Cycle conservation invariant. The cycle level conservation invariant tests `total_water_removed_kg` against the implied removal from `input_lots` sum minus `output_lots` sum. The energy density check tests $\eta = \text{total_electricity_kwh} / \text{total_water_removed_kg}$ against the 1.0 to 2.0 kWh per kg band of Section 6.4.

Per stage envelope tests. Each `StageAggregate` is tested against the `RecipeVector`'s declared envelope for the stage. The number of `envelope_violations` is computed at signing time and recorded in the aggregate.

C.5 Recipe Vector Schema

The Recipe Vector $\vec{R}$ is signed by the plant operator before the cycle begins. The plaintext is encrypted at rest under the BDF protocol's selective disclosure mechanism (Section 6.6); the signed canonical hash is committed to the public record, and the encryption key is shared with verifiers under NDA.

```

type RecipeVector -
  vectorid       : hash
  recipeid       : string
  cycleid        : string
  facilityid     : string
  declaredinputs : [-lotid: string, expectedmasskg: float ]
  expectedyieldkg : float
  expectedenergykwh: float
  refrigerant     : RefrigerantState

```

```

stagetargets      : [StageTarget]
globaltolerances  : ToleranceSet
operatorid        : string
signingkeyid      : hash
signature        : signature

type StageTarget -
  stageindex       : int
  targetdurationmin: -nominal: float, tolower: float, toupper: float
  pressuremtorr    : -nominal: float, minband: float, maxband: float
  chambertempc     : -nominal: float, minband: float, maxband: float
  heatertempc      : [-heaterindex: int, nominal: float,
                      minband: float, maxband: float ]
  powerw           : -nominal: float, maxband: float

type ToleranceSet -
  energypct        : float
  yieldpct         : float
  durationpct       : float

```

Cross vector coherence. The recipe versus process coherence test compares each StageTarget envelope against the corresponding StageAggregate of the Process Vector. warn and fail bands are inherited from to_lower, to_upper, and the global tolerances.

C.6 External Attestation Schema

External Attestations are signed by ISO 17025 accredited laboratories and anchored to the BDT they attest. The schema is generic across analyte classes; the measurement field carries class specific structured payload.

```

type ExternalAttestation -
  attestationid    : hash
  bdtreference     : hash
  lotid            : string
  laboratoryid     : string
  iso17025accreditationno: string
  iso17025accreditationbody: string
  methodstandard   : string
  samplecollectiondate: timestamp
  sampleid         : string
  analysisdate     : timestamp
  analystid        : string
  measurementclass : enum -composition, isotopic, contaminant,
                        microbial, residue, identity
  measurement       : Measurement
  uncertaintypct    : float
  signingkeyid     : hash
signature         : signature

```

```

type Measurement -
  // class specific structured payload
  fields           : map; string, float?
  units            : map; string, string?
  detectionlimits  : map; string, float?
  notes?          : string

```

Class specific instantiations. The methodology defines six measurement classes corresponding to typical Tier 4 evidence types. The `fields` map carries class specific keys; representative keys are documented in the BDF Standards Stack [Fair Food Data, 2026c].

C.7 Detector Verdict Schema

Each Tier 2 detector verdict is itself a signed object on the public record, allowing independent reproducibility (Section 6.6).

```

type DetectorVerdict -
  verdictid       : hash
  detectortype    : enum -massconservation, cycleenergydensity,
                    pressureenvelope, temperatureenvelope,
                    logisticenvelope, crossvectorcoherence
  scopetype       : enum -lot, segment, cycle, cohort
  scopereferences : [hash]
  computedat      : timestamp
  detectorversion : string
  thresholdbandpass : float
  thresholdbandwarn : float
  observedvalue   : float
  verdict         : enum -pass, warn, fail
  diagnosticnotes? : string
  signingkeyid    : hash
  signature      : signature

```

Reproducibility. A second verifier reading the public record at a later time replays the detector against the referenced `scope_references` using `detector_version` and shall arrive at identical `observed_value` and `verdict`. The `detector_version` pins the reference implementation; updates require methodology revision.

C.8 Calibration Correction Event Schema

When a project applies a calibration correction (Section 7.4), the correction event is itself recorded as a signed object.

```

type CalibrationCorrectionEvent -
  eventid           : hash
  appliedto         : enum -originmass, segmentmass, recoverymass,
                        cycleenergy, refrigerantcharge

  cohortsize        : int
  cohortreferences   : [hash]
  referencesource    : string
  declaredcohortmean: float
  referencecohortmean: float
  scalingfactorkappa: float
  applicablefrom     : timestamp
  applicableto?      : timestamp
  rationale          : string
  approvedbyverifier: bool
  signingkeyid       : hash
  signature         : signature

```

Audit trail. The calibration correction event references the cohort it was derived from, allowing a verifier reviewing the project at any later time to reproduce the correction’s derivation and assess its applicability to subsequent lots.

C.9 Schema Versioning

Each schema declared in this appendix carries an implicit version corresponding to the methodology version. A future revision of this methodology may extend any schema with additional optional fields without invalidating prior signed instances. Required field changes constitute a breaking revision and require a new schema version with explicit migration rules. Projects shall pin the methodology version in their project design document and upgrade at crediting period renewal.

Document History

Versions follow semantic versioning: a major increment changes protocol semantics or normative requirements, a minor increment adds material without breaking existing conformance, a patch corrects errors. The current version is stated on the title page and in the PDF metadata.

Version	Date	Changes
0.1	May 2026	Initial draft, companion document 2 of the BDF corpus.
1.0	24 September 2026	First public release. Version and date fixed, licensed under CC BY 4.0, document history added. No technical changes from the May draft.

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