International Journal of Hydrological and Environmental for Sustainability
Volume 5, Issue 3, 263-275.
e_ISSN: 2828-5050
https://www.journal.foundae.com/index.php/ijhes

Ceramic Floor Installation Waste and Selected Greenhouse-Gas Emissions: A Partial Installation-Related Life Cycle Inventory with Screening-Level GHG Characterisation

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Article Info

Article history:

Received: March 11, 2026
Revised: June 27, 2026
Accepted: August 18, 2026

Abstract

The installation stage (module A5) of building-material life cycles is poorly represented in life cycle assessment (LCA) databases, particularly for developing-country practice. This study reports a partial, installation-related life cycle inventory (LCI) with screening-level greenhouse-gas (GHG) characterization not a full cradle-to-grave LCA for ceramic floor tiling, and documents the installation waste generated under one observed layout. Following the four-phase procedure of ISO 14040/14044 and the modular framework of EN 15804, a functional unit of 1 m^2 of installed floor was defined. The study quantifies only selected foreground flows: tile delivery transport (A4), cutting energy and offcut generation as selected A5 activities, and offcut-transport (C2); upstream manufacturing (A1–A3), most other A5 inputs (adhesive, mortar, grout, water, packaging, cleaning, equipment), end-of-life treatment (C3–C4), and the use stage were not quantified. Detailed measurements were obtained from one regular, unobstructed 48 m^2 reference room installed with a center-referenced, straight-lay pattern within a hospital project in Central Java. A waste factor of 2.33% (unrecovered offcut area over installed area) was observed in this room; total offcut generation was 3.33% and internal reuse recovered a further 1.00%. No alternative layout, corner-referenced start points, or optimization scenario was evaluated, so the value is reported as a case-specific observation rather than evidence that the layout prevented waste. Within the selected and counted flows, and excluding A1–A3, delivery transport (A4) contributed approximately 98% of the calculated GHG under a loaded one-way assumption; including an allocated empty return raised the counted total by about 98% and the A4 share to roughly 99%. A sensitivity analysis across freight and grid emission factors, return-trip treatment, transport distance, load factor, waste baseline (5/8/10%), and reuse substitution (0/50/100%) confirmed that conclusions are contingent on the narrow boundary and adopted factors. The study's contribution is a documented primary-data case inventory for selected ceramic-tile installation activities in Indonesia, not a validated waste-prevention model.

Keywords: ceramic tile installation, construction waste prevention life cycle inventory, design for waste efficiency, installation waste

To cite this article: Nugraheni, F., Sari, S, N. and Syamsunur, D. (2026). Ceramic Floor Installation Waste and Selected Greenhouse-Gas Emissions: A Partial Installation-Related Life Cycle Inventory with Screening-Level GHG Characterisation. *International Journal of Hydrological and Environmental for Sustainability, 5*(3), 263-275. https://doi.org/10.58524/ijhes.v5i3.1457

INTRODUCTION

Construction and demolition (C&D) waste is among the largest solid-waste streams worldwide, and ceramic tiling is a persistent contributor because rigid, brittle tiles must be cut to fit room geometry

(Kabirifar et al., 2020). Field studies of material wastage consistently report that a non-trivial fraction of purchased material leaves the site as waste, with cutting losses and on-site layout among the primary sources (Fitriani et al., 2025; Kabirifar et al., 2020). Because these losses are set in motion by early decisions, analytical reviews identify the design stage as an early and cost-effective point of intervention (Wu et al., 2019).

In the Indonesian context this lever is largely undocumented. Construction waste is still managed reactively during the construction stage rather than prevented at the design stage, and surveys of Indonesian construction professionals confirm that design-stage waste-efficiency measures are commonly overlooked despite their potential (Fitriani et al., 2025). Local quantitative evidence on how much ceramic material is actually lost during installation remains scarce; Indonesian studies have identified the underlying causes of construction waste but have not linked them to a life cycle inventory (LCI) (Fitriani et al., 2022). This scarcity is not unique to Indonesia: country-specific LCI data for ceramics are lacking across much of the developing world, which constrains locally valid assessment (Vijerathne et al., 2025). The environmental burden embedded in this everyday activity is therefore effectively unmeasured for local practice.

Three distinct gaps should be distinguished. First, there is a lack of local, installation-stage inventory data for ceramic tiling in Indonesia. Second, there is a lack of quantified, comparative evidence on how the choice of layout changes installation waste. Third, there is limited environmental assessment of offcut-management routes (reuse, recycling, on-site fill, disposal). The present study directly addresses the first gap, partially addresses the third, and does not resolve the second, because only one layout was observed. It is important to state at the outset that this study documents waste under a center-referenced layout; it does not compare centre-referenced, corner-referenced, staggered, diagonal, or computationally optimized layouts, and therefore cannot establish that any layout is superior

Life cycle assessment (LCA) is the standard framework for quantifying such burdens (ISO 14040, 2006; ISO 14044, 2006). ISO 14040/14044 define general LCA principles but do not, by themselves, define the modular A/B/C/D notation used for construction products; that modular structure is set out in EN 15804 (2019), which distinguishes product manufacturing (A1–A3), transport to site (A4), installation (A5), end-of-life stages (C1–C4), and benefits and loads beyond the system boundary from reuse or recycling (module D)(Soust-Verdaguer et al., 2023). Cradle-to-gate LCA of ceramic tiles consistently shows that manufacturing (A1–A3), and firing in particular, dominates their environmental footprint (Atılgan Türkmen et al., 2021; de Brito et al., 2025; Vijerathne et al., 2025), while installation and end-of-life carry levers a specifier can influence directly (Balasbaneh et al., 2021). Among these, module A5 is the least populated in existing databases, so the magnitude of even its selected activities is essentially unknown locally. The waste factor (WF), here defined as the proportion of unrecovered offcut relative to the area installed, is the quantity that links a design decision to a material outcome. Reusing clean offcuts and recycling ceramic fragments into secondary aggregate are established but under-practiced recovery routes (Acampora et al., 2025; Kabirifar et al., 2020; Silva et al., 2019).

Because the study applies emission factors and reports GHG contributions, it goes beyond pure inventory compilation into screening-level characterization limited to climate change. It is therefore described throughout as a partial LCI with screening-level GHG characterization, not as a complete LCA. Consistent with this scope, the objectives are (1) to develop a field-based inventory of tile delivery, cutting energy, offcut generation, and selected offcut-management routes for one documented reference room; (2) to document the waste factor observed under a centre-referenced layout and to report it alongside total offcut generation and purchased-material overage; and (3) to estimate the relative GHG contributions of the selected inventory flows and examine their sensitivity to key assumptions. The novelty lies in primary local field data for selected, under-reported A5 activities chiefly cutting and offcut generation read through a design-stage prevention lens rather than an end-of-pipe one.

METHOD

The study follows the four-phase procedure of ISO 14040:2006 and ISO 14044:2006 (goal and scope, inventory, characterization, interpretation) and adopts the modular notation of EN 15804 (2019). It is explicitly a partial assessment restricted to selected installation-related flows; results are a counted installation-related burden and must not be read as total cradle-to-grave impacts.

Functional Unit and Reference Flow

The functional unit is 1 m^2 of installed ceramic floor meeting the project specification (**Table 1**): glazed ceramic tiles laid in a straight, parallel pattern on a cement-mortar bed, with a nominal 5 mm grout joint, to the technical quality required for hospital-grade circulation areas. The reference-room tile was 40 × 40 cm, 8 mm nominal thickness, areal density 20 kg/m^2. Adhesive/mortar, grout, and water are part of the installed floor's specification but were not inventoried; this is stated as a boundary limitation rather than a claim of completeness. No service life is used in any calculation, because the use stage (B) and replacement are outside scope; the previously stated 50-year figure has therefore been removed to avoid implying a use-stage assessment. All inventory flows are expressed per square meter installed.

Table 1. Material specification, case study, and functional unit

No	Parameter	Value
1	Functional unit	1 m^2 installed ceramic floor to project specification (no service life used in calculations)
2	Tile (reference room)	Glazed ceramic 40 × 40 cm; 8 mm nominal thickness; 20 kg/m^2
3	Bedding / joint	Cement-mortar bed; nominal 5 mm grout joint (not inventoried)
4	Reference room	B1-KOR-01, basement corridor, 48.00 m^2 (8.00 × 6.00 m, no obstruction)
5	Layout / start point	Straight-lay; centre-referenced (working drawing)
6	Observation period	1–10 July 2026 (10-day campaign)
7	Cutting tool	Wet cutter, 1,200 W (rated)
8	Project ceramic area	2,486.40 m^2 (multiple tile sizes)
9	Standards	ISO 14040:2006; ISO 14044:2006; module notation per EN 15804 (2019)

System Boundary (Selected Foreground Flows)

The boundary (**Figure 1**) covers only selected foreground flows: module A4 (transport of tiles from the distributor to site); selected module A5 activities (cutting time, cutting energy, and offcut generation); and module C2 (transport of the offcut stream). The following are explicitly excluded or not quantified, and no module is claimed to be fully represented:

1. Modules A1–A3 (tile manufacturing) were excluded. Because these modules are typically the dominant contributors to life-cycle impacts, the proportional shares of the modules assessed in this study would decrease substantially if A1–A3 were included.
2. Other inputs associated with module A5, including adhesive or mortar, grout, water, packaging, cleaning activities, additional equipment electricity, and the handling of installation materials, were not quantified.
3. Modules C3 (sorting and recycling processes) and C4 (landfill treatment) were not quantified. Only module C2, representing the transport of waste, was included.
4. The use stage (module B) and mid-life replacement activities were excluded from the assessment (Atılgan Türkmen et al., 2021; Vijerathne et al., 2025).

Accordingly, the analysis assesses selected installation-related flows, not complete modules. Internal reuse of offcuts within the same project is treated in the material balance, and a boundary-crossing module D credit is reported only as a separate scenario, never netted into the counted total.

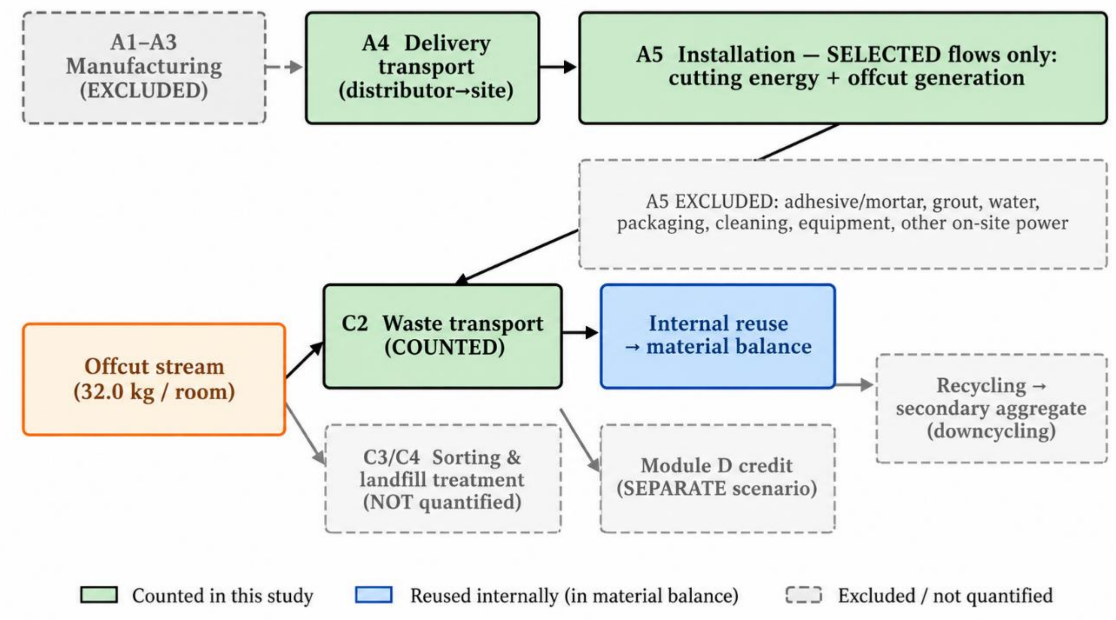

Figure 1. System boundary counted installation-related flows versus excluded/not-quantified processes (partial LCI)

Case Study, Reference-Room Selection, and Representativeness

Primary data were collected over a ten-day field campaign (1–10 July 2026) on a four-storey hospital building in Batang Regency, Central Java, with a total planned ceramic floor area of 2,486.40 m^2. Three tile types were used (40 × 40 cm, 60 × 60 cm, and a 30 × 30 cm anti-slip type), all with an areal density of 20 kg/m^2. Installation was carried out by a single tiling crew led by a head tiler with 12 years of experience, using a 1,200 W (rated) wet cutter.

Room-level completeness varied across the project. Of the rooms whose tiling was observed during the campaign, only one a basement corridor (code B1-KOR-01, 48.00 m^2) had a complete and internally consistent record of installed pieces, offcut mass, cutting operations, and delivery documentation, and it was therefore selected for the detailed inventory. The room was chosen on the basis of documentation completeness and regular rectangular geometry (8.00 × 6.00 m, four corners, no columns or obstructions), before its waste performance was computed, not because it exhibited low waste; this sequence is stated explicitly to make the potential selection bias transparent. Because a single regular room cannot capture the variation introduced by irregular geometries, physical obstructions, or alternative laying patterns, the reported waste factor should be interpreted as a documented case-specific value rather than a project-wide or national estimate. Accordingly, the project-scale figures are presented only as an indicative scenario range. The same tile type and crew were used in other basement circulation areas, but comparable complete records were not available for them.

Room Geometry and Cutting Requirement

Both nominal room dimensions are exact multiples of 0.40 m (20 × 15 modules), which, absent joints and tolerances, would require almost no cutting. Cutting nevertheless arose for three combined reasons, illustrated in the layout plan (**Figure 2**) are (i) the nominal 5 mm grout joint accumulates across the field (about 95 mm over the 8.00 m span and 70 mm over the 6.00 m span), shifting the effective module so that perimeter tiles no longer land on the wall line; (ii) the layout was referenced to the corridor center-line taken from the working drawing, so partial tiles occur symmetrically on all four edges rather than on two; and (iii) edge gaps, wall irregularity, and threshold/door conditions require trimming. Under these conditions the room required 40 cutting operations yielding 60 cut border pieces. Importantly, center-referencing a room whose dimensions are exact tile multiples increases perimeter cutting relative to a corner- or grid-aligned start; the observed cutting is therefore consistent with not evidence against the geometry, and it also means the observed layout was not the waste-minimizing option for this particular room.

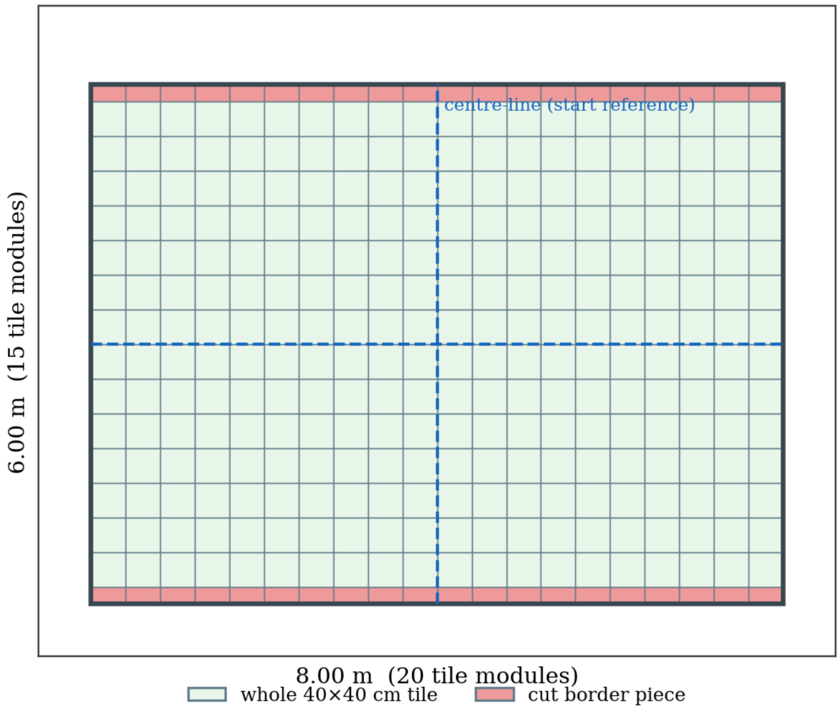

Figure 2. Centre-referenced straight-lay plan of reference room B1-KOR-01; centring forces cut border pieces on all four edges

Waste-Factor Definitions, Indicators, and Material Balance

The waste factor (WF) counts unused (Category A) offcuts only not reused offcuts and not broken tiles and is defined per room by equation (1):

$$WF = (A_{offcut} / A_{installed}) \times 100\% \qquad \text{... (1)}$$

To avoid an unequal comparison with the conventional 5–10% purchasing allowance which typically also includes breakage, defects, handling loss, contingency stock, and future replacement tiles three indicators are reported using consistent numerators and denominators (**Table 3**) are total offcut generation, unrecovered offcut waste, and purchased-material overage. A mass-based WF is also reported; because the areal density is uniform, it coincides numerically with the area-based WF. The reconciled material balance for the room (**Table 2**, **Figure 3**) is 992.0 kg purchased (20.67 kg/m^2) = 960.0 kg installed (20.00 kg/m^2; 896.0 kg whole + 64.0 kg cut-installed) + 32.0 kg offcut (22.4 kg unrecovered Category A + 9.6 kg internally reused Category B). This corrects the earlier inconsistency in which the reused fraction was omitted from the consumed figure; the correct per-unit consumption is 20.00 + 0.47 + 0.20 = 20.67 kg/m^2. Broken tiles (pieces cracked or chipped during transport, storage, or installation) were recorded in a separate damage log and are analysed separately, because they cannot be prevented by layout and conflating them with offcuts would overstate the design-stage benefit; the mass of broken tiles logged for the reference room was 6,4 kg and is excluded from the WF.

Table 2. Reconciled material balance for reference room B1-KOR-01 (48 m^2)

Flow	Mass (kg)	Area (m^2)	Per FU (kg/m^2)
Purchased / delivered (input)	**992.0**	49.60	20.67
Installed - whole tiles	896.0	44.80	18.67
Installed - cut pieces	64.0	3.20	1.33
Offcut - Category A (unrecovered waste)	22.4	1.12	0.47
Offcut - Category B (internally reused)	9.6	0.48	0.20

Cutting Time, Energy, and Transport Modelling

Cutting time was measured on a systematic subsample of 16 of the room's 40 cutting operations (every second straight cut, to avoid observer selection); n = 16 refers to the timed sample. The subsample averaged 30.62 s per piece (SD 1.20 s; range 28.7–33.2 s; 95% CI 29.98–31.26 s). Cutting energy was logged with a true-RMS power meter over five consecutive working days (8–9 comparable straight cuts per day on the same 40 × 40 cm format), giving a mean of 0.00985 kWh per cut including wet-cutter pump load during active cutting; standby draw between cuts was not captured and is noted as an exclusion. The 1,200 W figure is the rated tool power, not a measured mean. At 0.833 cuts per square metre, cutting-energy intensity was 0.0082 kWh/m^2 (**Figure 4**).

Transport work was expressed in tonne-kilometres (t·km) as transported mass × distance (equation 2). Delivery was from a distributor 92 km away (text and Figure 1 now consistently state distributor-to-site) in a 4-tonne rigid diesel truck at an 82% load factor. Rather than omitting the empty return, two transport cases are evaluated and carried through the results and sensitivity analysis: (A4-i) loaded one-way only; and (A4-ii) loaded outbound plus an allocated empty return, which approximately doubles the t·km. A partial-backhaul case and alternative load factors are examined in the sensitivity analysis.

$$TW = m \times d \quad \text{... (2)}$$

$$GHG = \Sigma\, (Q\_i \times EF\_i) \quad \text{... (3)}$$

Emission Factors, Impact Characterisation, and Module D

For screening-level characterisation of climate change only, GHG emissions were estimated with equation (3). A diesel road-freight factor of 0.21 kg CO_2e/t·km (well-to-wheel, rigid diesel truck, applied to the reported load) and a Java–Bali (Jamali) grid factor of 0.79 kg CO_2e/kWh (including upstream generation) were applied; both are treated as illustrative and tested by sensitivity analysis (Nugroho et al., 2022; Pambudi et al., 2023). The emission factors, their sources, and their geographical and temporal representativeness are described in the text. Because C3–C4 treatment factors were not modelled, waste-route emissions are limited to C2 transport. The module D reuse credit uses an avoided virgin-tile production factor of about 0.6 kg CO_2e per kg (Atılgan Türkmen et al., 2021; de Brito et al., 2025). Because the reused offcuts stayed within the same project (an adjacent service area in the same bill of quantities), the primary accounting treats reuse as an internal material saving within the balance; a boundary-crossing module D credit is presented only as a separate scenario under explicit displacement assumptions (0%, 50%, 100% substitution of new tile), never netted into the counted total. Values derived from respondent estimates were reserved for sensitivity analysis and excluded from the main inventory.

Sensitivity Analysis

A structured one-at-a-time sensitivity analysis (**Table 7**) evaluates the freight-emission factor, inclusion of the empty return, transport distance, load factor, grid-emission factor, cutting-energy factor, the conventional waste baseline (5%, 8%, 10%), the reuse substitution ratio (0/50/100%), and the avoided-production factor. Results are reported as the effect on the counted GHG per square metre and, where relevant, on the project-scale scenario range.

RESULTS AND DISCUSSION

Observed Waste Factor and Material Balance

For the reference room, 280 whole tiles (44.80 m^2) and 60 cut pieces (3.20 m^2) gave a total installed area of 48.00 m^2 from 40 cutting operations. Cutting produced 32.00 kg of offcuts (1.60 m^2), of which 22.40 kg (1.12 m^2) were unused (Category A) and 9.60 kg (0.48 m^2) were reinstalled in an adjacent service area (Category B). Applying equation (1), WF = 1.12 / 48.00 = 2.33% (**Table 3**, **Figure 3**). Total offcut generation was 3.33% and the internally reused fraction 1.00%; the purchased-material overage relative to installed area was 3.33% (excluding breakage and contingency). These indicators are lower than the 5–10% purchasing allowance commonly cited in practice, but the comparison is not like-for-like: the conventional allowance additionally includes breakage, defects, handling loss, contingency, and future spares. The appropriate statement is therefore that the room achieved a relatively low unrecovered-offcut ratio under the documented layout, not that the layout suppressed waste.

Table 3. Waste indicators on consistent bases (reference room)

Indicator	Value	Basis
Total offcut generation	3.33%	32.0 kg / 960 kg installed
Unrecovered offcut waste (WF)	2.33%	22.4 kg / 960 kg installed
Internally reused offcut	1.00%	9.6 kg / 960 kg installed
Purchased-material overage	3.33%	(992–960)/960; excl. breakage/contingency
Mass-based WF	2.33%	coincides with area WF (uniform density)
Conventional allowance (context)	5–10%	incl. breakage, defects, contingency, spares — not directly comparable

Critically, no alternative layout was tested. Centre-referencing a room whose dimensions are exact tile multiples tends to increase, not decrease, perimeter cutting relative to a corner- or grid-aligned start. The observed 2.33% is thus best read as an association specific to this room, geometry, tile size, and crew an observed case value, not a verified prevention benefit. Establishing a layout effect would require a direct comparison against a corner-referenced start, an alternative Centre line, a contractor's conventional layout, a computational tile-layout optimization, or another room of similar geometry.

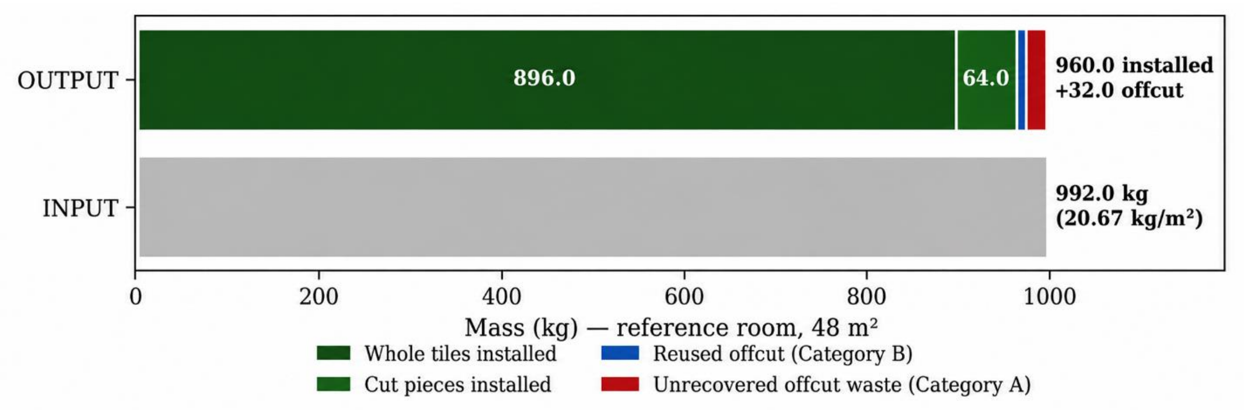

Figure 3. Reconciled mass balance for reference room B1-KOR-01 (992.0 kg purchased = 960.0 kg installed + 32.0 kg offcut)

Project-Scale Scenario Range (Not A Single Saving)

Cutting time was measured on a directly timed subsample of 16 of the room's 40 cutting operations; the remaining cuts were counted for the material balance but not individually timed, so n = 16 refers to the timed sample, not the total. The subsample averaged 30.62 s per piece (standard deviation 1.20 s; range 28.7–33.2 s). Cutting energy was logged with the power meter over five consecutive working days of the reference-room campaign, during which the crew performed comparable straight cuts on the same tile format; the wet cutter drew a mean of 0.00985 kWh per cut (**Figure 3**). The low dispersion of both quantities reflects stable tool condition and consistent cut type. At 0.833 cuts per square meter, the cutting energy intensity was only 0.0082 kWh/m^2. The practical weight of cutting time is therefore economic (labor productivity), whereas the environmental weight of module A5 lies in the offcut material it generates, not in the energy of the cutting tool.

Module Contribution and End-of-Life Routing

The timed subsample (n = 16) averaged 30.62 s per piece (95% CI 29.98–31.26 s), and cutting energy averaged 0.00985 kWh per cut, giving an intensity of 0.0082 kWh/m^2 (**Figure 4**). The low dispersion is consistent with stable tool condition and a single, repeated straight-cut type, though it is not a formal statistical demonstration. The practical weight of cutting time is economic (labor productivity); among the selected inventory flows, cutter electricity was a minor contributor. This should not be read as evidence that A5 as a whole is environmentally unimportant, because adhesive, mortar, grout, packaging, and other A5 inputs were not quantified and could be more significant.

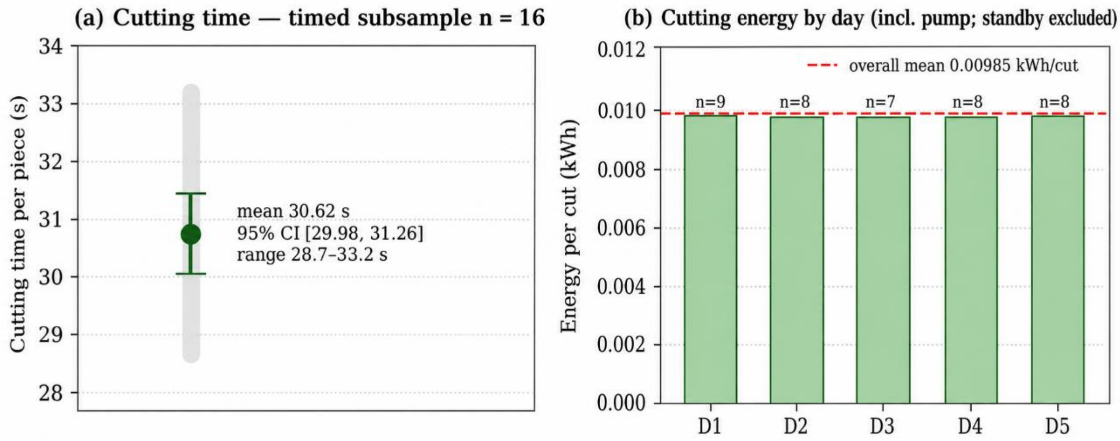

Figure 4. (**a**) Cutting time (timed subsample, n = 16, mean ± 95% CI and range) and (**b**) day-to-day cutting energy with the number of cuts per day; pump load included, standby excluded

Table 4. Installation-related inventory per functional unit (physical flows only)

Module	Inventory flow	Value (per m^2)
A4	Transport work — delivery (loaded one-way)	1.90 t·km
A5	Cutting operations	0.83 cuts
A5	Cutting energy	0.0082 kWh
A5	Unrecovered offcut (waste)	0.47 kg
C2	Waste-transport work	0.0064 t·km
(bal.)	Internally reused offcut	0.20 kg

Module Contribution Among Counted Flows

Delivery came from a distributor 92 km away in a 4-tonne rigid diesel truck at an 82% load factor, giving 1.90 t·km per square metre (loaded one-way). Characterized alongside cutting energy and waste transport (**Table 5**), module A4 accounted for approximately 98% of the counted installation-related GHG under the loaded one-way case (0.41 kg CO_2e/m^2 total), and A5 cutting energy for under 2%. When an allocated empty return is included, the counted total rises to about 0.81 kg CO_2e/m^2 and the A4 share to roughly 99% (**Figure 4a**). This dominance is a consequence of the narrow boundary it holds only within the selected counted flows and reflects the exclusion of A1–A3 and of most A5 and end-of-life processes. It must not be generalized to the full ceramic-floor life cycle; it means only that, among the specifically counted flows, delivery transport dominates. Measures that reduce delivered tile mass (waste prevention and load consolidation) therefore act on the largest lever within this limited chain.

Table 5. Screening GHG characterization (climate change only; A1–A3 excluded)

Flow	One-way (kg CO_2e/m^2)	Share	+Return (kg CO_2e/m^2)	Share
A4 delivery transport	0.399	98.1%	0.799	99.0%
A5 cutting energy	0.0065	1.6%	0.0065	0.8%
C2 waste transport	0.0013	0.3%	0.0013	0.2%
Counted total	0.407	100%	0.807	100%
Module D credit (separate; 100% displacement)	−0.12		−0.12	

End-of-Life Routing of The Offcut Stream

The routing of the 32.0 kg offcut stream (**Figure 4b**, **Table 6**) was compiled from the project's logistics records, corroborated by an interview with the site waste handler (who gave informed verbal consent for anonymous use of the information) and by direct observation: 30% reused (0–5 km), 10% third-party recycling as secondary aggregate (24 km), 25% on-site fill (0.5 km), and 35% official landfill (18 km). Reuse and recycling together diverted 40% of the offcut stream (denominator: total offcut mass, 32.0 kg). On-site fill is reported as a route but is not automatically counted as recovery, because material substitution and technical/regulatory suitability were not verified; its environmental benefit is therefore treated as unproven. C2 transport contributed less than 1% of the counted GHG; C3 recycling processing and C4 landfill treatment were not quantified and are flagged as gaps.

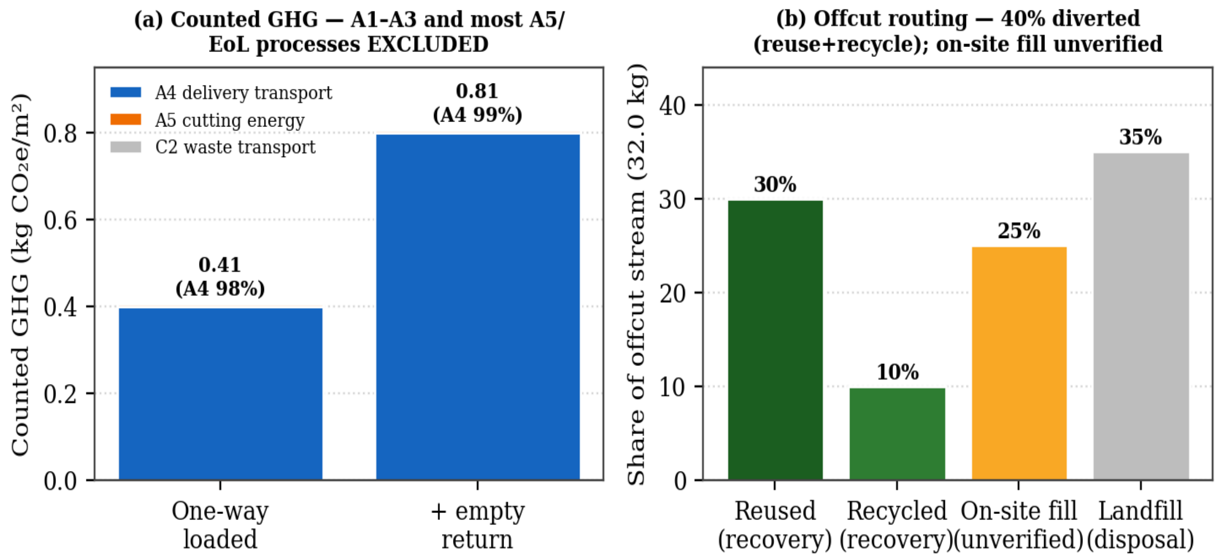

Figure 5. (a) Counted GHG by flow under loaded one-way and empty-return cases (A1–A3 and most A5/EoL processes excluded); (b) fate of the offcut stream by recovery status

Table 6. Offcut-stream routing and C2 transport (total offcut 32.0 kg)

Route	Mass (kg)	Share	Distance (km)	C2 work (kg·km)	Status / allocation
Reused	9.6	30%	0–5	24.0	Recovery - internal reuse (material balance / D scenario)
Recycled (aggregate)	3.2	10%	24	76.8	Recovery - C3 not quantified (downcycling)
On-site fill	8.0	25%	0.5	4.0	Unverified - substitution not demonstrated
Landfill	11.2	35%	18	201.6	Disposal - C2 counted; C4 not quantified
Total	32.0	100%	—	306.4	40% diverted (reuse+recycle)

Module D Reuse Credit

Treated as a boundary-crossing avoided burden, the reuse credit is 0.12 kg CO_2e/m^2 at 100% displacement of new tile, 0.06 at 50%, and 0 at 0%; under downcycling (lower-quality substitution) it would be smaller still, and transport to the reuse location would offset part of it. Because the reused offcuts remained within the same project's bill of quantities, the primary accounting already captures the benefit as reduced project material demand; the module D credit is therefore reported separately and should not be interpreted as a confirmed additional benefit.

Sensitivity Analysis

Table 7 summarizes the sensitivity results. The counted GHG per square meter is most sensitive to the treatment of the empty return (+≈98% when an allocated return is added) and to the freight-emission factor and transport distance, all of which act on the dominant A4 flow; it is essentially insensitive to the grid-emission factor (the A5 share stays below 2% even at the lower national grid factor of 0.68 kg CO_2e/kWh) and to the cutting-energy factor. The project-scale scenario range is governed almost entirely by the assumed waste baseline (5/8/10%). The module D credit scales linearly with the assumed substitution ratio. These results reinforce that the headline findings are contingent on the narrow boundary and the adopted transport assumptions.

Table 7. One-at-a-time sensitivity analysis

Parameter	Range tested	Effect
Empty return	one-way ↔ +return	Counted GHG 0.41 → 0.81 kg CO_2e/m^2 (+≈98%); A4 share 98%→99%
Freight EF	0.15–0.30 kg/t·km	Scales A4 (≈±25–45% of counted total); dominant driver
Transport distance	±20% (74–110 km)	Near-proportional change in A4 and counted total
Load factor	70–90%	Alters delivered t·km per m^2 by ≈±10%
Grid EF	0.68–0.79 kg/kWh	A5 share stays <2%; negligible on total
Cutting-energy factor	±20%	Negligible (<0.4% of counted total)
Waste baseline	5% / 8% / 10%	Project avoided tile 1.33 / 2.82 / 3.81 t (scenario range)
Reuse substitution	0% / 50% / 100%	Module D credit 0 / 0.06 / 0.12 kg CO_2e/m^2
Avoided-production factor	0.4–0.7 kg/kg	Scales module D credit linearly

A Qualitative Prevention Hypothesis

The results are consistent with an integrated prevention hierarchy advocated for the Indonesian sector (Fitriani et al., 2025) and with the broader emphasis on preventing rather than managing waste (Kabirifar et al., 2020) are fixing the layout at the design stage, consolidating deliveries and reducing empty backhaul, and keeping offcuts clean and sorted for reuse and recycling. However, because no alternative-layout simulation, avoided-mass, labor, cost, or marginal-abatement comparison was performed, the proposition that a design-stage layout change offers the highest environmental leverage per unit of effort is stated here as a qualitative hypothesis to be tested, not a demonstrated result. Established recovery routes exist recycling ceramic fragments into secondary aggregate (Silva et al., 2019), re-embedding wastes into new tile bodies (Acampora et al., 2025), and substituting virgin raw materials with waste streams to lower cradle-to-gate footprints (Vijerathne et al., 2025) but the waste handler flagged persistent barriers: mortar contamination, manual-sorting cost, the absence of an acceptance standard for recycled ceramic, and an unstable secondary-material market (**Table 8**).

Table 8. Measurement instruments, specifications, and calibration deviation

Instrument	Specification / use	Calibration deviation
Digital scale	Cap. 50 kg; res. 10 g; offcut mass	0.20%
Tape measure	Length 5 m; res. 1 mm; areas	0.10%
Vernier caliper	Res. 0.05 mm; tile thickness	0.20%
True-RMS power meter	AC true-RMS; kWh; cutting energy	0.60%
Stopwatch	Res. 0.1 s; cutting time (n = 16 timed)	0.13%
Digital map / waybill	≤100 m; transport distance	—

The interpretation of the findings is subject to several limitations. First, the detailed inventory was derived from a single regular reference room. Irregular geometries, physical obstructions, and alternative laying patterns were not represented; therefore, the reported waste factor of 2.33% should be interpreted as a documented case-specific value rather than a project-wide or national estimate. Second, no alternative or counterfactual layout was evaluated. Consequently, the study cannot demonstrate that the center-referenced layout reduced waste, and the observed geometry suggests that it may have increased perimeter cutting because the room dimensions were exact multiples of the tile size. Third, the system boundary covered only selected foreground flows. Modules A1–A3, most inputs associated with module A5, including adhesive, mortar, grout, water, packaging, cleaning, and equipment use, as well as modules C3–C4, were not quantified. Accordingly, the approximately 98% contribution of module A4 applies only to the flows included in the assessment. Fourth, the emission factors and avoided-burden coefficients were adopted from the literature for illustrative purposes, while the module D credit extends beyond the foreground boundary and remains scenario-dependent. Fifth, selecting the reference room on the basis of documentation completeness may have introduced selection bias. Sixth, the comparison with the conventional 5–10% material allowance is contextual rather than directly equivalent because the two values represent different categories. These limitations support the need for broader field sampling and direct comparisons between layout alternatives, while the primary inventory remains useful as a documented case study.

CONCLUSION

A field-measured, installation-related life cycle inventory with screening-level GHG characterisation, developed following ISO 14040/14044 and the EN 15804 module notation for a functional unit of 1 m^2, recorded a waste factor of 2.33% in a regular 48 m^2 reference room installed with a centre-referenced, straight-lay layout. Because no alternative layout was tested and because centre-referencing an exact-multiple room tends to increase perimeter cutting this value is reported as a case-specific observation, not as evidence that the layout prevented waste. On consistent bases, total offcut generation was 3.33% and purchased overage 3.33%, which are contextually lower than the conventional 5–10% allowance but not directly comparable to it. Within the selected and counted flows, and excluding A1–A3 and most A5 and end-of-life processes, delivery transport (A4) dominated the calculated GHG (≈98% one-way; ≈99% with an allocated empty return), while cutter electricity was a minor contributor among those flows. Reuse and recycling diverted 40% of the offcut stream, though contamination, sorting cost, and the absence of acceptance standards constrained further recovery, and on-site fill could not be verified as genuine recovery. The material balance and reuse allocation have been reconciled, the module D credit is scenario-dependent, and project-wide extrapolation is presented only as a scenario range. The primary contribution of this study is thus a documented primary-data case inventory for selected ceramic-tile installation activities in Indonesia, not a validated waste-prevention model. Broader field sampling across multiple rooms, tile sizes, and projects, direct comparison of alternative layouts (including computational optimisation), and inclusion of A1–A3 and C3–C4 are required before the findings can be generalised or used to set project-level waste-prevention benchmarks. A supplementary spreadsheet containing the raw observations, calculations, emission factors, and assumptions is provided to support reproducibility.

AUTHOR CONTRIBUTIONS

Conceptualization, FN and DS; methodology, FN and DS; software, FN; validation, FN and DS; formal analysis, SNS and FN; investigation, DS; resources, FN and SNS; data curation, FN; writing—original draft preparation, FN; writing—review and editing, SNS and FN; visualization, FN; supervision, FN and DS; project administration.

ACKNOWLEDGMENT

The authors sincerely thank the reviewers for their valuable comments and constructive suggestions, which have significantly improved the quality and clarity of this manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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