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# Process-Activity-Based Screening of Life-Cycle Occupational Safety Burdens: Country-Specific Characterization and Production-Line Worker-Hour Allocation in 500 mL Beverage Manufacturing

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**Abstract**

Product-level screening of occupational safety burdens requires traceable worker-hour inventories and explicit treatment of alternative workforce-allocation boundaries. This study compares four boundaries and reports conditional injury and fatality burdens for characterized pathways associated with one 500 mL bottled beverage. The 2024 manufacturing records comprise 785,659 actual productive working hours derived from working-time and shift records for separately assigned workers on six PET lines (72 line–month observations). Plant–month pooling attributes 278,268.55 h to 171,696,216 studied bottles, 5.04% more than line–month attribution; the pooling boundary is a counterfactual allocation test. The 2024 syrup supplier coefficient is 0.0005097243 h/kg from 60,347.5 contractual hours and 118,392,431 kg supplier-wide production. The agricultural source equation defines harvested-sugarcane units (h/kg cane): principal Scenario A applies recovery once and yields $3.356 \times 10^{-8}$ modeled injuries and $7.501 \times 10^{-10}$ modeled fatalities per bottle. Diagnostic Scenario B applies cane-based coefficients directly to refined sugar mass, yielding $1.096 \times 10^{-8}$ and $1.859 \times 10^{-10}$, respectively. A separate 2024 format-inventory sensitivity test evaluates bottle-count versus beverage-volume weighting; a controlled SKU comparison shows how the worker-hour allocation boundary affects the characterized ranking under common nonmanufacturing pathway inputs. These outcomes are modeled as case-equivalent screening indicators for the characterized processes, rather than observed event probabilities or complete supply-chain injury rates.

**Keywords:** occupational safety footprint; social life-cycle assessment; ISO 14075; process activity inventory; productive working hours; line-specific workforce allocation; country–sector characterization; supply-chain screening

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## 1. Introduction

Carbon footprinting demonstrates the utility of expressing a product-related burden per functional unit, but occupational safety impacts differ fundamentally from greenhouse-gas emissions. Injuries and illnesses emerge from hazards, organizational practices and worker exposure rather than from a universally measurable emission flow. Nevertheless, a life-cycle perspective can associate potential worker-related burdens with the activities

required to deliver a product, provided that the underlying activity inventory, characterization model and population coverage are coherent. The aim is an attributable potential burden, not the probability that a particular bottle caused an individual accident [1,2].

Life-cycle approaches to the social dimension were developed to make organizational and supply-chain effects visible to product decisions. Early methodological contributions addressed activity-based societal accounting, impact categories and reference baselines; subsequent syntheses documented diverse activity variables, impact pathways and application practices [3–10]. The present study focuses on the Workers stakeholder category and occupational health and safety (OHS) while deliberately excluding direct consumer health risks from the beverage consumption stage.

Occupational safety within product life cycles is not a newly introduced impact concept. Scanlon and colleagues established approaches for work-environment disability-adjusted life years (WE-DALYs) and industry-output-based work-environment characterization factors (WE-CFs). Huang and colleagues developed U.S. industry-linked occupational health factors using an economic input–output framework; they are not inherently interchangeable with worker-hour factors. Tsalidis proposed the Occupational Health and Safety Potential (OHSP) midpoint indicator using hours actually worked where available or economic activity as a fallback, while Iofrida et al. applied a psychosocial risk-factor impact pathway to garment production [11–15]. These precedents support the broader proposition that worker impacts may be represented per product, without implying that all studies measure the same endpoint or use compatible units.

Conventional Social Hotspots Database (SHDB) supply-chain modeling combines a GTAP-based monetary input–output framework with estimates of worker hours, while established PSILCA worker-hour applications use monetary intersectoral flows to scale economic activities. PSILCA also provides a distinct raw-values approach. Importantly, these databases include inventory-level information, such as country–sector worker-hour estimates and, depending on the database and version, raw social indicators; the availability and possible use of such data must be distinguished from the interpretation of database-generated risk scores. They are not used in this study because their country–sector inventories do not provide the 2024 facility line–month working-time and SKU-output observations needed to compare the specified production-allocation boundaries, not because their inventory data are intrinsically unsuitable. These methods remain useful comparators and potential sources for other S-LCA objectives [16–18].

The process-activity-first choice is deliberate: scaling material or transport activities by purchase expenditure may transmit price, currency or monetary-sector changes to labor attribution even when a physical process quantity remains unchanged. This is model dependence, not evidence that monetary input–output approaches are invalid. Tsalidis preferred actual hours worked where available and proposed monetary values as a secondary option. The contribution here is an operational inventory and allocation-boundary case study rather than the first nonmonetary occupational safety indicator [14,16,17,19].

A practical gap concerns product-level attribution of actual productive working hours when separately assigned line workers produce multiple SKUs and researchers pool records by plant, line or period. The three-facility dataset supports deterministic comparison of four allocation boundaries; it does not provide worker-by-SKU exposure observations or establish that national injury-statistics denominators cover identical worker populations. Plant-level pooling is evaluated as counterfactual, not evidence that line employees were shared across lines [1,19].

The primary research question is: To what extent do alternative allocation boundaries affect product-attributed productive working-time intensities and SKU rankings in beverage manufacturing? The secondary objective is to assess how the documented agricultural

labor coefficient unit, counterfactual unit application and heterogeneous country–sector injury factors affect conditional occupational safety burdens for characterized pathways. Accordingly, the analysis distinguishes observed line-specific production working-time totals from modeled allocation results and proxy-based life-cycle injury/fatality indicators. SKU-level accident probabilities or complete supply-chain-observed accident rates were not measured.

Worker-hour-based occupational health approaches already exist [11–14,20–22]. The contribution claimed here is the empirical line/plant accounting-boundary comparison using primary production records, supported by an explicit country-by-country characterization ledger and unit-sensitivity tests. Country–sector burdens are multiplied at their individual sources before aggregation, in accordance with normal process-based LCA accounting; this summation rule is not claimed as a new methodological invention.

## 2. Materials and Methods

### *2.1. Goal, Functional Unit, Stakeholder and Life-Cycle Boundary*

The goal is to support attribution of potential worker-related occupational safety and health burdens to the provision of one finished 500 mL bottled beverage. One bottle containing 500 mL ready-to-drink beverage is the declared functional unit and the product reference flow. The assessment target is the Workers stakeholder category; employee and relevant contractor activities are included in principle when supported by coherent inventory and characterization boundaries. The direct health and safety consequences to consumers during beverage consumption are outside the topic selection, not an undisclosed omission of upstream or end-of-life workers [1,2].

The life-cycle model includes agriculture, packaging materials, inbound road and maritime freight, beverage manufacturing, outbound distribution and packaging end of life. Consumer health consequences during beverage consumption are outside the Workers stakeholder category. This study uses primary 2024 ERP production/working-time records, supplier operating summaries and data-owner-confirmed 2024 K-PCR physical inventory references. Source material quantities reported per liter are normalized once to the 500 mL functional unit. The K-PCR product format series is used as a separate production format sensitivity reference, while the ERP series defines the principal manufacturing allocation. Figure 1 differentiates directly recorded manufacturing activity from the modeled supply-chain pathways.

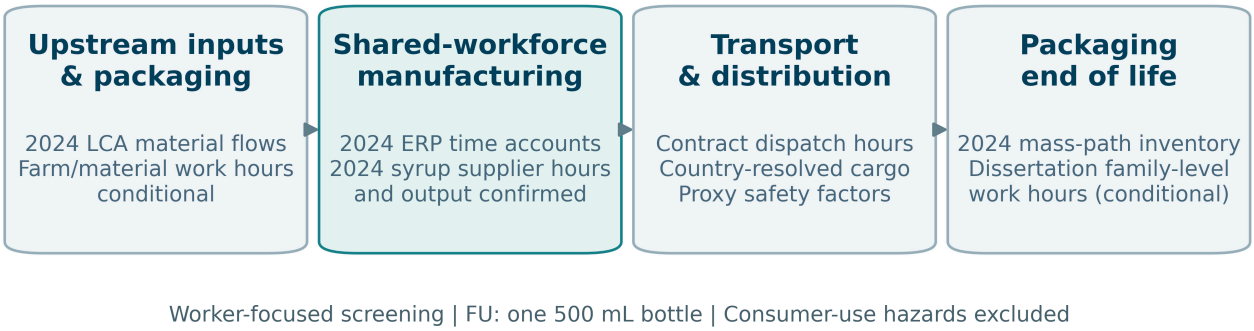



**Figure 1.** Intended worker-centered life-cycle boundary and present inventory evidence.

The intended boundary and the numerically characterized subset must be distinguished. Inclusion of a process in the goal-and-scope diagram does not imply that its actual workforce or severity reporting definition was directly measured. Table 1 identifies the source data, reporting vintage, activity units, ownership and limits on independent validation.

**Table 1.** Inventory source provenance, reporting years, activity units and validation status.

| Source/Responsible Holder | Year or Vintage | Reporting Unit/Role | Source Treatment and Reporting Scope |
|---|---|---|---|
| PET ERP manufacturing accounts (company) | 2024; 72 line–month records | Recorded actual line-assigned productive working hours and PET bottle counts | Actual line-assigned productive working time; SKU hours attributed by production share. |
| Syrup supplier contract-time summary (supplier) | 2024 | 60,347.5 contracted operating h/year | 2024 supplier-wide contractual operating-time input; source retained by data owner. |
| Syrup supplier total output (supplier, author attestation) | 2024 (data-owner confirmed) | 118,392,431 kg complete supplier output | 2024 supplier-wide production denominator; time-correspondence confirmed by data owner. |
| Background physical environmental LCA (source company) | 2024 (data-owner confirmed) | kg/1 L normalized once to 500 mL | Physical inputs normalized once from 1 L to the 500 mL functional unit. |
| Dissertation [23] (published research source) | 2026 thesis; national rate datasets 2023/2024 | Crop labor: h/kg cane (p. 92); OHS CF: cases/h (Table 22 of Ref. [23]) | Crop coefficient source equation (p. 92); country–sector CF Table 22 of Ref. [23]; defined scenario tests. |
| Dispatch and waste material records (company/prior LCA) | 2024 dispatch; author-designated 2024 K-PCR waste routing | Dispatch-equivalent h, material-family kg and h | Dispatch hours not cargo-specific exposure; disposal route mass is not route-specific workforce time. |

The 2024 ERP six-line monthly working-time and production records were checked directly at the 72 line–month level. The 2024 K-PCR product format records were examined for a separate within-series count-versus-volume allocation test. The contractual syrup supplier time is identified as a supplier-wide operating-activity coefficient, rather than employee clock time. Source years, coverage and measurement units for country–sector occupational factors are identified in Section 2.7 and Table 2. The national reporting and working-time sources comprise the Korean Ministry of Employment and Labor [24], Safe Work Australia [25], Thailand's National Statistical Office (using Social Security Office statistics) [26], ILOSTAT [27], and the Australian Bureau of Statistics [28]. The original dissertation ([23], p. 92) establishes the cane-mass labor-coefficient equation used for the principal agricultural scenario.

**Table 2.** Country–sector injury and fatality screening factors (cases/h); source-year checks and worker-population limitations.

| Country/Sector Proxy | Injury Factor (Cases/h) | Fatality Factor (Cases/h) | Source Reference and Reporting Coverage |
|---|---|---|---|
| Australia agriculture | $1.05 \times 10^{-5}$ | $4.62 \times 10^{-8}$ | ILOSTAT 2023; ABS work hours [27,28]. Serious claims and traumatic fatalities differ [25]. Population mismatch remains. |
| Thailand agriculture | $5.45 \times 10^{-6}$ | $1.56 \times 10^{-7}$ | ILOSTAT 2024: 35.53 h/week; rounded CFs reproduced [27]. SSO-based reporting may miss informal farming [26]. |
| Republic of Korea manufacturing | $3.89 \times 10^{-6}$ | $5.75 \times 10^{-8}$ | Thesis [23], Table 22; 2024 MoEL comparison close, not exact [24]. Population not matched to ERP. |
| Republic of Korea transport | $6.20 \times 10^{-6}$ | $8.20 \times 10^{-8}$ | Thesis [23], Table 22; 2024 MoEL comparison close, not exact [24]; >=4-day treatment basis. |

**Table 2.** *Cont.*

| Country/Sector Proxy | Injury Factor (Cases/h) | Fatality Factor (Cases/h) | Source Reference and Reporting Coverage |
|---|---|---|---|
| Thailand transport/warehousing | $2.39 \times 10^{-6}$ | $6.49 \times 10^{-8}$ | ILOSTAT 2024: 47.33 h/week; rounded CFs reproduced [27]. Cargo-origin proxy, not crew exposure. |
| Australia transport/warehousing | $9.29 \times 10^{-6}$ | $3.80 \times 10^{-8}$ | ILOSTAT 2023; ABS hours; approximate CF match [27,28]. Cargo origin, not seafarer workforce. |
| Republic of Korea waste | $7.03 \times 10^{-7}$ | $3.79 \times 10^{-8}$ | Dissertation [23], Table 22; Korean waste-sector generic characterization proxy. |

### *2.2. Source Data, Working-Time Definition and Privacy*

The analysis covers three anonymized manufacturing facilities (A, B and C), six PET lines and 12 months of 2024 (72 line–month observations). Productive(Hr) represents the actual productive working hours of workers assigned to the respective production lines, compiled from working-time and shift records according to the confirmed ERP data definition. Recorded variables also include all-PET-line bottle counts and the outputs of three studied 500 mL SKUs (S1–S3). Totals are 785,659 productive working hours and 482,450,260 PET bottles, of which 171,696,216 belong to the study cohort. Non-negative entries and usable denominators were checked; line-specific hours are not direct observations of time spent on each SKU.

Employees were assigned to their respective PET production lines, and each line's recorded Productive(Hr) represents the actual productive working time of its assigned workforce derived from work time and shift information. This is a worker-activity measure rather than a machine-running-time proxy. Within-line attribution to the studied SKUs is modeled using their respective shares of product output. The national injury factors are applied only to the defined case-equivalent screening calculation, separately from the organization's observed incident records. The allocated quantity is recorded worker-hour activity, not a proportional share of the company's observed occupational injury cases.

Plant–month pooling hypothetically combines productive working hours and all-product counts over a plant–month, while line–month preserves the documented separation of personnel assigned to individual lines. The studied S1–S3 SKUs all have the same 500 mL nominal volume. The 2024 K-PCR format inventory documents other PET bottle sizes on some of these lines; those sizes are considered solely as components of the complete production-denominator test, not as additional assessed functional units. The separate K-PCR format-mix sensitivity compares within-series bottle-count and beverage-volume shares; the principal ERP-based allocation remains the reference analysis.

### *2.3. Activity Variables Versus Organizational Social Aspects*

In this product-oriented S-LCA screening, worker hours are an activity variable that connects process activity to the functional unit of one finished 500 mL bottle. The organizational origin of a record does not make the model an organization-level social assessment: recorded productive hours from separately assigned production-line workforces enter the product inventory only after application of an explicit SKU-allocation rule. Company-wide injury cases, occupational safety policies, audits and management practices are instead organizational contexts used to describe the provenance and interpretation of the evidence. Such records are not treated as product-level social impacts, allocated to SKUs or used as numerical inputs to the modeled injury and fatality burdens. ISO 14075:2024 is used as a conceptual and methodological reference for the product functional unit, life-cycle

inventory and interpretation, not as an authority to assign organization-level outcomes to products [1,19].

Production-share rules attribute line-level work activity to products; they do not distribute organization-level observed injury cases. The four boundaries are modeling choices, not alternative official observations of workforce assignment. The confirmed distinct line workforces make line–month attribution more consistent with the recorded organizational structure, while SKU-level exposure still requires further product-run reconciliation. Plant–month and plant–year scenarios illustrate pooling sensitivity rather than a statistically validated improvement in accuracy.

### *2.4. Process-Activity-Based Inventory Design and Database Exclusion*

Physical activity inputs include sugar and packaging mass (kg/500 mL), imported freight (ton-km/500 mL), supplier contracted operating hours divided by full-supplier output (h/kg), dispatch-hour proxies (h/500 mL), recorded line-specific productive working hours allocated to the studied SKUs (h/500 mL), and secondary treatment work coefficients. Author-designated 2024 production format/mass references are distinguished from 2024 ERP time and production logs and from published 2023/2024 national-sector CF statistics. The former sources do not directly measure worker hours for individual sugar farms, ships, waste facilities or specific finished-product SKUs.

Neither PSILCA nor the Social Hotspots Database (SHDB) supplies the inventory coefficients or the injury/fatality characterization factors applied in this case study. This is a fit-for-purpose inventory decision, separate from the limitations of each database's own social-risk assessment. SHDB offers country–sector worker-hour estimates linked to economic input–output data; PSILCA likewise contains sector-level worker-hour information and, in relevant implementations, raw social inventory indicators [16,17]. These are potentially useful inventory sources, but they do not identify the joint 2024 facility, production-line, month and SKU observations or separately assigned line workforces that are indispensable for testing Equations (1) and (2). For the background pathways, this study links measured or documented physical quantities (e.g., kg and ton-km per 500 mL) to explicitly defined, unit-matched worker-hour coefficients. Substituting general country–sector intensities would require additional sector and unit conversion, boundary matching and checks against double counting, producing a different hybrid inventory rather than a direct substitute for the process-specific inputs used here. Therefore, the ERP and specified physical-coefficient sources were selected for the stated research question; the social databases are neither regarded as invalid inventory sources nor excluded solely because monetary risk-screening results may depend on prices [16,17].

Source background material quantities per liter are multiplied by 0.5 once for the 500 mL functional unit. The original dissertation [23] reports crop labor coefficients as labor input per hectare divided by harvested crop yield per hectare (p. 92); these have units of h/kg harvested crop or h/kg sugarcane here. A separate sugar-conversion formula divides by the recovery fraction. Dissertation Table 20 reports stage-level labor results, whereas Table 22 reports country–sector characterization factors. The later dissertation example (pp. 119–120) applied the reported agricultural coefficient directly to sugar mass; the present study instead uses dimensionally consistent Scenario A and retains that direct application only as a counterfactual Scenario B.

### *2.5. Four Labor-Time Accounting Boundaries*

For plant p, PET line l, month m and SKU s, H_plm is defined as the actual productive working hours recorded for the workers assigned to that line, Q_s,plm as the output of

s, and Q_all,plm as total bottle output on that line–month. For positive total output, the line–month allocation of line-assigned productive working hours to SKU s is the following:

$$H_s^{\mathrm{LM}} = \sum_{p,l,m} H_{plm} \frac{Q_{s,plm}}{Q_{\mathrm{all},plm}} \quad (1)$$

For comparison, the plant–month pooling scenario combines the productive hours of distinct line-assigned workforces and all relevant bottle production within a plant–month before applying the product share. It does not assert actual interline worker sharing:

$$H_s^{\mathrm{PM}} = \sum_{p,m} \left( \sum_l H_{plm} \right) \frac{\sum_l Q_{s,plm}}{\sum_l Q_{\mathrm{all},plm}} \quad (2)$$

Line–year and plant–year allocations use the same proportional rules after pooling across the relevant months. Plant–month pooling applies one plant-wide mean productive working-hours-to-bottles ratio, whereas line–month retains line-specific ratios and the known separation of line-assigned employees. A difference arises when the studied SKU is concentrated on lines with different ratios. Physical causes such as product format, automation, work organization and speed cannot be separated by this allocation identity alone; line-level staffing should not be presumed to be shared.

For a given plant–month and SKU s, the difference between plant–month and line–month attributed hours can be written as $\Sigma_l\, Q(s,l,m)[r(p,m) - r(p,l,m)]$, where r is the corresponding ERP hours per bottle. This identity explains why differences arise from the interaction between SKU location across lines and line-specific account intensity; it does not identify the actual causal staffing mechanism.

For each SKU s and boundary b, attributed productive working-time intensity is $I(s,b) = H(s,b)/Q(s)$, expressed as allocated hours or seconds per bottle. Unit-count weighting assumes equal attributed productive hours per unit within a boundary, not equal observed SKU-specific time. All three studied SKUs have a nominal volume of 500 mL, so a volume-weighting exercise restricted to these three SKUs alone is mathematically identical to bottle-count weighting. It would not test the original allocation, whose denominators also contain other PET products. The format composition and matched run-time distribution of the entire 482,450,260-bottle PET population are not established in the available research extract. Although product-level production run-time records exist in company systems, a complete-denominator comparison has not been performed and is not represented as completed empirical validation.

### *2.6. Prospective Safety Characterization and Eligibility Gates*

For worker-hour-based characterization, the framework first links the product-specific physical quantity of each process to a supported physical worker-hour intensity. The resulting product-attributed worked hours may then be combined with a characterization factor whose denominator is the same kind of worker time:

$$H_{s,i} = Q_{s,i}^{\mathrm{phys}}\, LC_i^{\mathrm{phys}} \quad (3)$$

$$SF_{s,k} = \sum_i H_{s,i}\, CF_{i,k}^{\mathrm{OHS}} \quad (4)$$

Here, $Q(s,i)$ denotes physical activity for process i; $LC(i)$ is a worker-hour coefficient matching that physical unit, and $CF(i,k)$ is a country–sector injury or fatality characterization factor (reported cases per worker hour). Their product is a modeled case-equivalent burden for included pathways, not an observed accident probability. The reported injury or fatality cases underlying the country–sector characterization factors refer to the respective statistical populations and reporting definitions (Table 2), not to accidents observed at the three plants

studied or identified as caused by S1–S3. Applying these factors to product-attributed worker hours yields conditional modeled case equivalents; it does not assign any observed national accident to an individual product. Manufacturing H(s,i) derives from actual line-specific productive working hours, but its attribution to individual SKUs is modeled; national accident-statistics denominators can cover different working hours and worker populations. Harmonization is not demonstrated merely by expressing both quantities as hours.

The screening eligibility checks encompass the physical denominator of each activity coefficient, geography, year, activity-to-worker population matching, recordability/severity threshold, working-hour denominator, contractor and informal worker coverage, and avoidance of duplicated indirect utility work. These checks classify the model inputs; they do not demonstrate full empirical harmonization. The sea-cargo characterization uses general transport/warehousing factors assigned by cargo origin, which are only scenario proxies and do not directly measure the flag state, crew nationality or seafarer injury experience.

### *2.7. Occupational Injury Statistics and Consistency Rules*

The source statistics differ in event coverage and at-risk populations even when expressed as cases/h. Korean statutory industrial-accident tables concern insurance-recognized cases requiring at least four days of treatment and, if overall accident totals are used, may include occupational diseases rather than traumatic injuries alone [24]. Australian nonfatal serious-claim reporting generally concerns accepted compensation claims with at least a working week of absence, whereas traumatic-injury fatalities have a different reporting system [25]. Thailand's Social Security Office (SSO) occupational injury/disease statistics include compensated cases with absences of up to three days as a separate category [26]. The Thai 2024 agricultural injury-rate numerator is linked to a registered/insured worker population; the mean weekly actual hours from ILOSTAT describe the wider industry, so exact numerator–exposure-population identity cannot be assumed [26,27]. These definitional differences are a limitation of the model's country–sector proxy characterization, not evidence that the underlying ERP work hours are invalid.

Table 2 lists the seven country–sector injury/fatality CF pairs from dissertation Table 22 [23], together with source-year and event-coverage checks against ILOSTAT, ABS and relevant national statistics [24–28]. For Thailand agriculture (2024), nonfatal and fatal rates of 1006.26 and 28.86 per 100,000, respectively, divided by 35.53 actual h/week × 52 weeks, yield $5.446 \times 10^{-6}$ and $1.562 \times 10^{-7}$ cases/h, reproducing the model's rounded factors. For Thailand transport (2024), corresponding rates 587.93/15.97 with 47.33 h/week reproduce $2.39 \times 10^{-6}$ and $6.49 \times 10^{-8}$ cases/h. Australia 2023 and Korea 2024 are described using their respective national reporting categories and hours data. The Korean waste stage retains the generic country–sector factor reported in dissertation Table 22.

### *2.8. Data-Quality Checks and Sensitivity Design*

For the 2024 ERP source, each of the 72 site line–month entries was checked for productive worker hours, all-PET output, and outputs of the three studied 500 mL SKUs. The original reported annual totals and four count-based manufacturing boundaries are reproduced from these entries. The format-mix test separately calculates count-weighted and beverage-volume-weighted shares within the 2024 K-PCR product series for the same six analyzed lines. These are reported as distinct specified allocation scenarios. Uncertainty calculations are deterministic changes in defined model parameters and boundaries; they are not statistical confidence bounds.

### *2.9. Supplier-Contract Hours and Transportation Activity*

The 2024 syrup supplier aggregate comprises 60,347.5 contractual operating hours across all supplier production and 118,392,431 kg total syrup output in the same calendar year, as confirmed by the authors. The ratio is 0.0005097243 h/kg. This is not a timecard measure for the studied bottles. A separate supplier-signed aggregate provenance statement has not been supplied or represented as independently verified. This study also reports 19,478.5 preform contractual hours and, for syrup delivery, 3824 annual dispatches and 32,982 driving-equivalent dispatch hours; these are not individually observed SKU driver exposure hours.

### *2.10. Physical Background Materials and Freight Boundary*

The three 2024 K-PCR plant datasheets provide physical material and packaging reference flows expressed per liter, together with monthly product format output. Material inputs per liter are multiplied by 0.5 once to define the 500 mL functional unit. The separately documented product format series supplies the within-series count-versus-beverage-volume allocation comparison; the ERP line–month entries remain the principal manufacturing time and production reference. The 2024 syrup-processing labor coefficient is 60,347.5 contractual h/118,392,431 kg total supplier output = 0.0005097243 h/kg, with the two annual inputs confirmed for the same year by the source-data owner. The preform-processing labor coefficient of 0.0045484 h/kg is applied with the reference PET mass as a separately documented supplier activity proxy.

Imported sugar in syrup input is modeled using the physical mass of sugar per 500 mL, 60% Australian origin and 40% Thai origin. Modeled routes use Brisbane–Busan (7300 km) and Laem Chabang–Busan (3700 km), with 0.00008 h/ton-km as a dissertation-derived shipping work intensity. The generic transport-sector characterization factors for Australia and Thailand are used only as cargo-origin scenario proxies, not as measured injury rates among the ship crews involved. Crew nationality, vessel flag and matched seafaring worker exposure remain unavailable.

Packaging end-of-life mass is assigned to source-reported two-stage recycling, energy-recovery and landfill routes, with material conservation checked for PET, PE, other plastics and paper in all three sites. Occupational treatment workload, however, uses material-family worker-hour values from Ref. [23] and Korean waste-sector proxy factors, not verified worker hours separately observed at each disposal technology. Thus, route mass shares must not be interpreted as observed route-specific injury burdens.

### *2.11. Record Provenance, Eligibility and Statistical Definitions*

The 2024 supplier contractual operating hours (60,347.5 h) and total supplier output (118,392,431 kg) are defined for the same calendar-year reporting period as confirmed by the source-data owner. The 2024 K-PCR plant production/material records supply physical inputs and product format observations for the same general study year. ERP production/working-time activity is the source for the principal 72 line–month attribution, while the product format records support the separate count-versus-volume weighting sensitivity. Data-owner access controls apply to the underlying commercial records.

The dissertation [23] provides the national reporting-criteria comparison in its Table 8 and the seven country–sector CF values in its Table 22. Table 2 of the present paper states the relevant injury-event definition, covered worker group, reference year and available time denominator for interpreting each application. In particular, Thailand agricultural compensation statistics describe a registered/insured sector population and are interpreted accordingly; the modeled results are cross-country case-equivalent screening indicators rather than pooled incidence estimates for an identical worker cohort.

### *2.12. Country-Resolved Characterization and Coefficient Unit Scenarios*

For country c, let m_sugar denote refined sugar input (kg/500 mL), s_c the sugar origin share, LC_cane,c the documented agricultural work intensity (h/kg harvested sugarcane) and R_c the proxy mass fraction of recovered sugar from cane. The dissertation ([23], p. 92) defines LC_crop,c = LH_ha,c/Y_c, with LH_ha,c in h/ha and Y_c in kg harvested crop/ha, and separately LC_sugar,c = LC_cane,c/R_c. Principal Scenario A therefore calculates H_c,A = m_sugar × s_c × LC_cane,c/R_c, applying recovery exactly once. After calculating these country-specific hours, each is multiplied by its country–sector injury/fatality CF, and the results are summed. This is a unit-consistent screening calculation, not a fitted estimate of previous injury totals.

The dissertation reports cane-basis agricultural labor coefficients of 0.001875 h/kg for Australia and 0.024 h/kg for Thailand, defined from labor input (h/ha) divided by harvested sugarcane yield (kg/ha) ([23], p. 92). Its illustrative later application uses the same numerical coefficients directly with sugar-mass input (pp. 119–120); the present study specifies Scenario A as the dimensionally consistent cane-recovery application and retains the historical direct-sugar expression solely as Scenario B diagnostic arithmetic. Country-level recovery fractions 0.1323344 (Australia) and 0.1072167 (Thailand) are used once [29,30] and identified as national/industry proxies. An independent 2023 yield-based calculation supplies a separate labor-intensity plausibility benchmark.

For illustration, Site A uses 0.04405948 kg of imported refined sugar per bottle, with 60% Australian and 40% Thai origins. Scenario A first converts sugar inputs to cane-equivalent input using the recovery proxy and then applies the corresponding h/kg cane coefficient, equivalent to using LC_sugar,c = LC_cane,c/R_c once. Scenario B omits this step and directly multiplies sugar mass by the cane coefficient, only to show the effect of the dissertation example's inconsistent unit application. Scenario B is not an independently validated representation of agricultural worker exposure or a second empirically supported coefficient definition.

The six characterized pathway groups comprise agriculture, upstream materials/processing, inbound transport, beverage manufacturing, outbound distribution and packaging treatment. Per-liter physical material inventory inputs are normalized to 500 mL once; country-specific working time is multiplied by its country–sector injury or fatality factor before site weighting. The contribution denominator contains the modeled characterized pathway groups; separately represented material and utility activities outside the selected characterization are outside that defined denominator, without being treated as zero occupational risk.

For beverage manufacturing, the Korean sector-level proxy CF is multiplied by manufacturing productive working hours that were recorded by production line and subsequently attributed to products. The ERP variable is confirmed as actual production working time from shift and time records, but it is not demonstrated to match the national CF's total covered workforce, case definitions or exposure-hours denominator. The combined sensitivity multiplier $\gamma$ scales this modeled manufacturing component only as a hypothetical exposure-scope stress test ($\gamma$ = 1.00 or 1.25), not as an empirical correction from machine time to person hours.

The dissertation supplies the applied CF ledger but not complete independent documentation of every original statistical numerator and exposure denominator. The 2024 ERP extracts support reconstruction of all 72 line–month count-attribution observations and the resulting published aggregates; this evidence does not amount to independent individual shift-clock auditing. The site-specific background process matrix includes secondary modeled inputs that have not all been independently authenticated. Source workbooks, line–month records and newly derived company-specific tables remain confidential and

are not authorized as public Supplementary Materials unless the relevant data owners approve release.

## 3. Results

### *3.1. Inventory and SKU Composition*

The six PET lines produced 482,450,260 bottles in 785,659 recorded actual productive working hours during 2024. The studied 500 mL S1–S3 cohort comprises 171,696,216 bottles (S1: 126,340,032; S2: 19,315,344; S3: 26,040,840). Table 3 reports SKU-attributed hours using the line–month production-share rule, which respects the separation of line-assigned workers while still modeling the division of their hours among SKUs. These values are not directly clocked product-specific person hours.

**Table 3.** Source-derived SKU outputs and line–month modeled manufacturing labor-time attribution.

| SKU | Units in 2024 | Allocated Hours (h) | h/Bottle | s/Bottle |
|---|---|---|---|---|
| S1 | 126,340,032 | 191,192.63 | 0.001513318 | 5.448 |
| S2 | 19,315,344 | 27,353.35 | 0.001416146 | 5.098 |
| S3 | 26,040,840 | 46,360.34 | 0.001780294 | 6.409 |
| Total | 171,696,216 | 264,906.32 | 0.001542878 | 5.554 |

S1–S3 are anonymized internal product identifiers. Table 4 compares line/plant–month/year allocation boundaries using the same annual hours and production counts.

**Table 4.** Impact of alternative manufacturing accounting boundaries on selected product activity.

| Accounting Boundary | Attributed Productive Hours (h) | Change vs. Line–Month | s/Bottle |
|---|---|---|---|
| Line–month | 264,906.32 | Reference | 5.554 |
| Line–year | 265,176.38 | +0.10% | 5.560 |
| Plant–month | 278,268.55 | +5.04% | 5.835 |
| Plant–year | 278,352.44 | +5.08% | 5.836 |

### *3.2. Labor-Allocation Boundary Sensitivity*

The percentage changes shown in Table 4 are deterministic responses to an allocation specification, not confidence intervals or estimates of true error.

Line–year attribution changes the selected-cohort hours by +0.10% relative to line–month, while plant–month yields 278,268.55 h (+5.04%) and plant–year yields 278,352.44 h (+5.08%). Line–month preserves the source-defined workforce assignment boundary; plant–month pooling is a hypothetical aggregation scenario for comparison. The sensitivity arises when an SKU is disproportionately produced on lines with distinct productive working hours per bottle, rather than from an assumption that personnel physically transfer across lines. Figure 2 illustrates the changes in SKU-level productive working-time intensities and the associated ranking reversal between line–month and counterfactual plant–month allocation.

Table 5 reports each SKU's productive-time intensity under line–month and counterfactual plant–month attribution. Seconds per bottle are allocated worker time, not processing cycle duration or a measured injury risk.

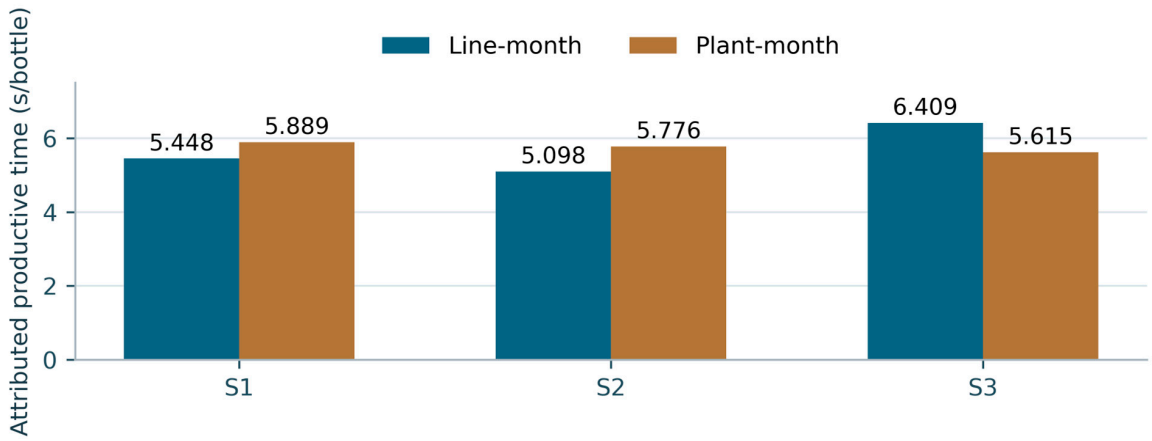



**Figure 2.** Differences and rank reversal in SKU modeled labor-time intensity under line–month and plant–month pooling.

**Table 5.** SKU-wise attributed productive-time sensitivity to line–month and hypothetical plant–month pooling.

| SKU | Line–Month (s/Bottle) | Plant–Month (s/Bottle) | Change in Attributed h |
|---|---|---|---|
| S1 | 5.448 | 5.889 | +8.09% |
| S2 | 5.098 | 5.776 | +13.30% |
| S3 | 6.409 | 5.615 | −12.39% |

### *3.3. SKU Rank Reversal and Plant Contribution*

Under line–month attribution, descending SKU intensity is S3 > S1 > S2, whereas counterfactual plant–month pooling yields S1 > S2 > S3 (Table 5). These represent allocated productive working-time rankings, not individual injury-risk rankings. The divergence is consistent with distinct line workforces and varying line-specific productive-hour intensity; it does not demonstrate staff interchange between lines.

As a manufacturing-only characterized comparison, each SKU's allocated productive hours per bottle are multiplied by the same Korean manufacturing injury and fatality factors. Consequently, the manufacturing case-equivalent ordering follows the relative working-hour intensities. Section 3.7 subsequently examines how these rankings translate to a controlled modeled life-cycle comparison when nonmanufacturing pathway burdens per 500 mL are held constant across the three SKUs.

Table 6 presents the plant-level decomposition of the difference in attributed productive working hours between plant–month and line–month allocation.

**Table 6.** Plant-level decomposition of the plant–month minus line–month difference.

| Plant | Line–Month h | Plant–Month h | Change | Share of Total Shift |
|---|---|---|---|---|
| A | 141,274.86 | 154,503.92 | +9.36% | 99.00% |
| B | 44,054.12 | 44,054.12 | +0.00% | 0.00% |
| C | 79,577.34 | 79,710.51 | +0.17% | 1.00% |
| Total | 264,906.32 | 278,268.55 | +5.04% | 100.00% |

Plant A includes three analyzed PET lines, Plant B one, and Plant C two. Plant A accounts for 99.00% of the total plant–month minus line–month attributable-hour difference,

consistent with the study-SKU distribution across lines having different productive hours per bottle. Separate line staffing is documented by the ERP data definition. The 2024 K-PCR production format datasets identify additional bottle volumes on some of the six lines, which means bottle-count shares do not need equal beverage-volume shares. Neither this observation nor any volume sensitivity demonstrates that workers were actually shared across lines or that workers spent time on each SKU in exact proportion to beverage volume.

A 2024 product format sensitivity analysis was conducted for the same six PET lines across 72 site line–month periods. Within the K-PCR production format inventory, the studied 500 mL SKU outputs are expressed both as bottle-count shares and as beverage-volume shares of each line–month's complete product mix. Each share is separately applied to that line–month's recorded productive worker hours. The within-inventory bottle-count and volume-weighted scenarios attribute 279,779.01 and 215,156.55 h, respectively, a −23.10% change relative to the count-weighted comparator. This is a controlled test of output-denominator choice alongside the principal ERP manufacturing-boundary analysis. The other container sizes enter the allocation denominator only; their life-cycle impacts are outside the specified 500 mL functional unit.

The manufacturing allocation boundaries generate a documented SKU ranking sensitivity. To examine its implication for characterized life-cycle results without changing product composition or supply-chain assumptions, Section 3.6 applies one common non-manufacturing characterized burden per 500 mL to all three studied SKUs and varies only each SKU's manufacturing productive-hours attribution. The resulting controlled scenario for both modeled injury and fatality indicators is presented in Section 3.7.

### *3.4. Evidence Boundaries for Characterized Pathways*

The ERP productive working-time records, supplier contractual operating schedules and background physical material flows have different provenance and coverage from the secondary country–sector factors. The screening model combines a specific physical activity and a compatible labor coefficient wherever documented. Table 7 separates author-confirmed real line-level productive hours, modeled product attribution, national CF proxies and organization-level accident information, without equating them.

**Table 7.** Evidence tiers for ERP attribution, source activities and modeled occupational impacts.

| Evidence Component | Supported Result | Interpretation Boundary |
| --- | --- | --- |
| Foreground hours | Recorded line-specific productive worker hours allocated to S1–S3 under four modeled attribution boundaries; no observed company injury cases are distributed. | Hours are observed by line and allocated to SKUs, not directly clocked for individual products; contractor and national-statistics populations are defined separately. |
| Organizational OHS context | Company-wide occupational incident and safety-management records provide contextual information; they are not product-level inventory flows or modeled burden inputs. | No organizational S-LCA is conducted. Company injury cases are not allocated to SKUs or used to derive CFs; these factors represent separate country–sector reporting populations, not observed accidents caused by the studied products. |
| Background process hours | 2024 syrup output, K-PCR material inputs per 500 mL, end-of-life mass/routing assumptions and supplier contractual activities are documented. | Supplier work activity, maritime transport work and end-of-life workload are represented by separately identified allocation assumptions or secondary factors. |

**Table 7.** *Cont.*

| Evidence Component | Supported Result | Interpretation Boundary |
| --- | --- | --- |
| Country–sector OHS proxy | Seven injury/fatality factor pairs traced to dissertation Table 22; Table 2 documents selected international reporting differences. | Country reporting scope and severity thresholds differ; cargo-origin transport CFs represent screening proxies rather than measured ship-crew risk. |
| Characterized modeled pathways | 19 source-traced modeled process entries for each of three sites; injury and fatality indicator results with explicit scenario control. | These are modeled indicators for the defined pathways, not a census of workplace injuries or a complete inventory of all indirect activities. |

The 2024 internal safety request reports four employee injury cases and one contractor injury case under its stated reporting scope; one employee injury is identified as a company sporting-event case. Hence, the previous five-case aggregate refers to employees plus a contractor, whereas the three-case subgroup refers to employees after excluding that sporting event case. Neither count is population- and exposure-matched to the published national-sector CFs, and neither enters the modeled case-equivalent results. No enterprise injury case was classified as caused by an assessed SKU, used to derive a country–sector CF, or allocated to S1-S3. Likewise, the national industry cases represented in those CFs are not assumed to have occurred during production of the studied bottles.

The 2024 source contractual dispatch schedules identify 2151, 717 and 956 annual syrup deliveries to facilities A, B and C, respectively; nominal truck capacity does not establish actual payload. Material mass used for syrup and packaging pathways is based on the author-designated 2024 plant inventory with 500 mL functional-unit normalization, while dispatch activity is a separate contractual operation-time proxy. Sugar-import sea-freight intensity depends on assumed routes, ton-kilometers and secondary crew-hour intensity rather than direct ship-worker records.

### *3.5. Supplier and Transport Activity Attribution*

The model draws on the dissertation [23] for the agricultural coefficient's original harvested-cane definition (p. 92), its earlier direct-sugar illustrative application (pp. 119–120) and country–sector CF ledger (Table 22). The model also uses the 2024 line-level ERP production and productive-working-time records, supplier contractual activity summaries and author-designated 2024 K-PCR background material quantities normalized once to 500 mL. Table 8 distinguishes the activity meanings, units and reporting populations. No existing injury rate was inverted to invent source activity measurements.

**Table 8.** Source-linked physical activities, units and interpretation scope used in the conditional screening calculation.

| Physically Traced Activity | Source Activity and Reporting Year | Interpretation for the 500 mL Product |
| --- | --- | --- |
| Syrup supplier full-production contractual workforce | 60,347.5 h/year; author-confirmed 2024 supplier output 118,392,431 kg | Same-year 2024 syrup supplier intensity 0.000509724 h/kg is calculated from contract activity and whole-supplier output; not a timecard or SKU-specific worker-hour observation. |
| Preform processing workforce | 19,478.5 annual contract h (2024), with published 0.0045484 h/kg preform process coefficient | The study coefficient is applied to the documented PET mass per bottle as a supplier activity proxy, rather than measured SKU-specific working time. |

**Table 8.** *Cont.*

| Physically Traced Activity | Source Activity and Reporting Year | Interpretation for the 500 mL Product |
|---|---|---|
| Inbound syrup distribution | 3824 trips, 32,982 annual truck dispatch operating h (2024) | The reference scenario uses the full PET-site production denominator; a selected-SKU denominator is examined separately as a defined sensitivity. |
| Manufacturing, selected SKUs | 278,268.55 h of actual production working time attributed to study SKUs under hypothetical plant–month pooling | Workers were assigned by line. Plant–month pooling is a counterfactual; the share attributed to each SKU is modeled from bottle production, with national CF coverage treated separately. |
| End-of-life treatment | Twelve physically conserved plastic/paper two-stage pathways, normalized to 500 mL | Dissertation Table 20 material-family worker-hour estimates are combined with Korean waste factors from Table 22; the individual disposal-route worker hours are not asserted to be directly measured. |

The site A source LCA supplies 0.04405948 kg of sugar per 500 mL, corresponding to Australia/Thailand origin portions of 0.0264357/0.0176238 kg. The imported sugar cargo gives approximately $2.066 \times 10^{-5}$ modeled sea-work hours per bottle under the original 0.00008 h/(ton-km) proxy. This is a transport work-intensity scenario and cannot be equated to observed crew working time.

The 2024 K-PCR packaging inventory provides 23.974 g PET per 500 mL for Site A. In the modeled two-stage routing, 20.004 g is assigned to recycling, 2.973 g to energy recovery and 0.997 g to landfill. Comparable mass-conservation calculations are applied to the other materials and sites in Table 9. These material-flow scenarios are distinct from observations of worker-time exposure in individual treatment facilities.

**Table 9.** Modeled PET end-of-life material routing per 500 mL bottle—physical mass, not measured worker exposure.

| Plant | PET Total g/Bottle | Recycling g/Bottle | Energy Recovery g/Bottle | Landfill g/Bottle |
|---|---|---|---|---|
| A | 23.974 | 20.004 | 2.973 | 0.997 |
| B | 23.926 | 19.964 | 2.967 | 0.995 |
| C | 23.912 | 19.952 | 2.965 | 0.995 |

These physical masses are an LCA scenario with two-stage treatment routing, not field-measured 2024 end-of-life destinations. The occupational treatment impact is modeled at the original dissertation plastic/paper material-family labor-hour level and is not allocated to individual treatment routes using a back-calculated h/kg intensity.

### *3.6. Agricultural Coefficient Dimensional Audit*

The dissertation ([23], p. 92) defines the crop coefficient as labor input per hectare divided by harvested crop yield per hectare, establishing the Australian 0.001875 h/kg and Thai 0.024 h/kg coefficients on a harvested-sugarcane-mass basis. Table 10 reports Scenario A with one country-specific cane-to-sugar recovery conversion (13.2334% Australia; 10.7217% Thailand). The source illustration on pp. 119–120 applied the coefficients directly to sugar input, which is retained as a diagnostic Scenario B for comparison. The main results follow the dimensionally consistent cane calculation.

**Table 10.** Country-origin sugar input and conditional Scenario A agricultural work activity per 500 mL.

| Site | Imported Sugar kg/500 mL | AU Sugar kg/500 mL | TH Sugar kg/500 mL | AU Cane Work h/500 mL | TH Cane Work h/500 mL |
|---|---|---|---|---|---|
| A | 0.0440595 | 0.0264357 | 0.0176238 | $3.7455794 \times 10^{-4}$ | $3.9450086 \times 10^{-3}$ |
| B | 0.0438818 | 0.0263291 | 0.0175527 | $3.7304753 \times 10^{-4}$ | $3.9291004 \times 10^{-3}$ |
| C | 0.0440964 | 0.0264578 | 0.0176385 | $3.7487140 \times 10^{-4}$ | $3.9483102 \times 10^{-3}$ |

As an external yield-based plausibility check requested by the reviewer, 2023 Australian industry data report 29.76 million tons of harvested cane across 341,084 ha, or approximately 87,251 kg/ha [29]. Thailand's official 2023 agricultural statistics report 9927 kg per rai (1 ha = 6.25 rai), or approximately 62,044 kg/ha [31]. Multiplying these independently published yields by the existing cane-mass labor coefficients implies approximately 164 h/ha for Australia and 1489 h/ha for Thailand. These are back-calculated implied values using 2023 yields, not the source labor-input observations originally used to construct the coefficients; they provide a dimensional plausibility scale only and were not substituted into any reported footprint or sensitivity result.

Country-specific cane-basis hours are multiplied by their respective country–sector injury and fatality factors before aggregation. Scenario A is the principal unit-consistent calculation; Scenario B is the historical direct-sugar application represented solely as a diagnostic calculation. The external 2023 national-yield crosscheck provides implied labor-input scales for dimensional interpretation and does not modify the model's source activity coefficients.

### *3.7. Conditional Life-Cycle Screening and Combined Sensitivity*

The screening model has 19 characterized process entries for each of three anonymized sites (57 site-process entries). Each process's worker-hour activity is multiplied by a country–sector factor, and the included site burdens are weighted by 2024 selected bottle counts. Principal Scenario A applies a single, country-specific sugar recovery conversion to the documented cane-basis coefficients. Diagnostic Scenario B applies those coefficients directly to refined sugar input, mirroring the dimensionally inconsistent dissertation illustration. All non-agricultural inputs and the established numerical results are preserved.

Under principal cane-basis Scenario A, the bottle-weighted case-equivalent indicator is $3.356 \times 10^{-8}$ modeled injuries and $7.501 \times 10^{-10}$ modeled fatalities per 500 mL. Within the six characterized pathways, agriculture contributes 75.75% of modeled injuries and 84.31% of modeled fatalities, while manufacturing contributes 18.79% and 12.42%, respectively (Table 11). These are shares of the defined characterized pathway sum and are interpreted as modeled occupational safety screening burdens. Figure 3 visualizes the Scenario A distribution of these modeled injury and fatality burdens across the six characterized pathways.

**Table 11.** Scenario A-characterized pathway modeled burdens and contributions per 500 mL bottle (conditional cane-mass basis).

| Life-Cycle Stage | Modeled Injuries/500 mL | Injury Contribution | Modeled Fatalities/500 mL | Fatal Contribution |
|---|---|---|---|---|
| Upstream agriculture | $2.542 \times 10^{-8}$ | 75.75% | $6.324 \times 10^{-10}$ | 84.31% |
| Upstream materials | $6.668 \times 10^{-10}$ | 1.99% | $9.857 \times 10^{-12}$ | 1.31% |
| Inbound transport | $6.778 \times 10^{-10}$ | 2.02% | $7.829 \times 10^{-12}$ | 1.04% |
| Beverage manufacturing | $6.305 \times 10^{-9}$ | 18.79% | $9.319 \times 10^{-11}$ | 12.42% |
| Outbound distribution | $4.795 \times 10^{-10}$ | 1.43% | $6.341 \times 10^{-12}$ | 0.85% |

**Table 11.** *Cont.*

| Life-Cycle Stage | Modeled Injuries/500 mL | Injury Contribution | Modeled Fatalities/500 mL | Fatal Contribution |
|---|---|---|---|---|
| Packaging EOL | $9.154 \times 10^{-12}$ | 0.03% | $4.935 \times 10^{-13}$ | 0.07% |
| WEIGHTED TOTAL | $3.356 \times 10^{-8}$ | 100.00% | $7.501 \times 10^{-10}$ | 100.00% |

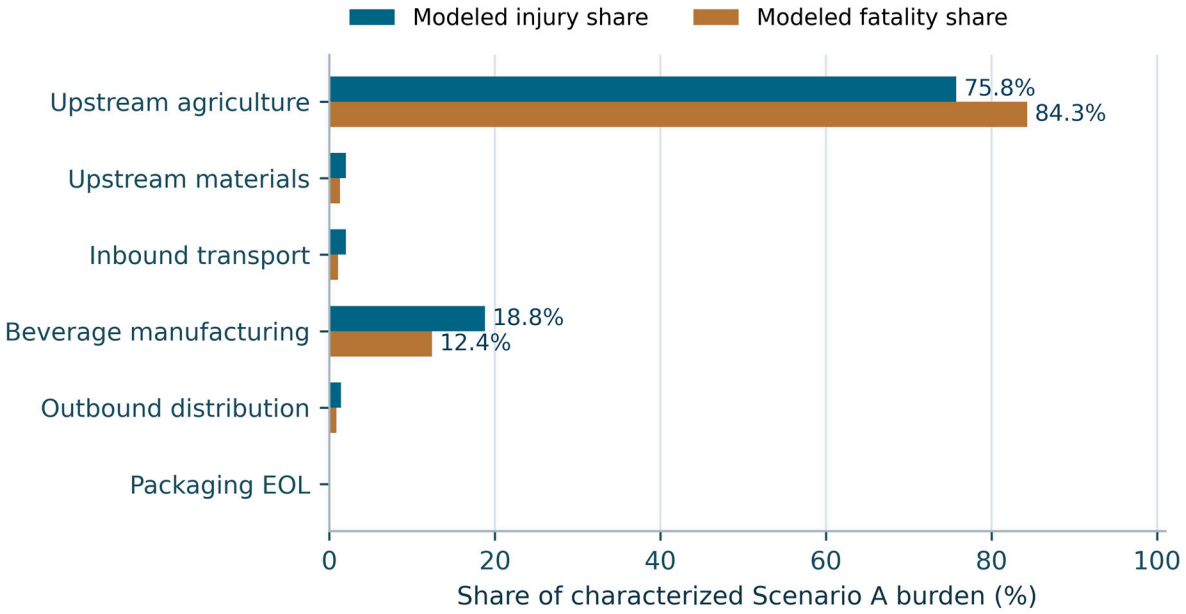



**Figure 3.** Scenario A distribution of modeled injury and fatality burdens among characterized pathways; the figure does not display observed occupational accident shares.

Diagnostic Scenario B yields $1.096 \times 10^{-8}$ modeled injuries and $1.859 \times 10^{-10}$ modeled fatalities per bottle. Recalculating shares over exactly the same characterized pathways gives agriculture 25.76% of injury and 36.70% of fatality indicator totals, compared with manufacturing 57.51% and 50.12% (Table 12). The strong change in relative contributions illustrates the consequence of a dimensionally inconsistent direct sugar application, not legitimate uncertainty over the documented physical unit. Neither scenario measures observed injuries or a confidence interval.

**Table 12.** Characterized pathway shares under principal cane-basis Scenario A and diagnostic direct-sugar-application Scenario B (counterfactual; not separately validated).

| Characterized Pathway | Scenario A Injury | Scenario B Injury | Scenario A Fatality | Scenario B Fatality |
|---|---|---|---|---|
| Agriculture | 75.75% | 25.76% | 84.31% | 36.70% |
| Upstream materials | 1.99% | 6.08% | 1.31% | 5.30% |
| Inbound freight | 2.02% | 6.18% | 1.04% | 4.21% |
| Manufacturing | 18.79% | 57.51% | 12.42% | 50.12% |
| Outbound freight | 1.43% | 4.37% | 0.85% | 3.41% |
| End of life | 0.03% | 0.08% | 0.07% | 0.27% |
| Characterized pathways only | 100.00% | 100.00% | 100.00% | 100.00% |

Table 13 presents model-defined one-factor sensitivities, including the previously reported agricultural-stage labor-hour comparator and assumptions for dispatch, sea transport and waste processing; none is an independently measured uncertainty range. Table 14 combines principal/diagnostic agricultural calculation A/B, a hypothetical $\gamma = 1.00/1.25$ multiplier on the manufacturing modeled workload, and sea-labor intensity ×1/×10. Because the ERP input is already actual productive work time, $\gamma$ is not a correction from machine hours to person hours. Neither multiplier validates worker exposure nor harmonizes national injury statistics.

**Table 13.** One-factor screening sensitivity results (cases modeled per 500 mL); values are not confidence limits.

| Alternative Calculation | Modeled Injury/500 mL | Modeled Fatalities/500 mL | Injury Change | Fatal Change |
|---|---|---|---|---|
| Scenario A: principal cane-basis with one recovery conversion | $3.356 \times 10^{-8}$ | $7.501 \times 10^{-10}$ | +0.00% | +0.00% |
| Scenario B: diagnostic direct sugar-mass use of cane coefficient | $1.096 \times 10^{-8}$ | $1.859 \times 10^{-10}$ | −67.33% | −75.21% |
| Dissertation Table 20 agricultural-stage hours comparator (source mapping unverified) | $4.424 \times 10^{-8}$ | $9.901 \times 10^{-10}$ | +31.85% | +32.00% |
| All syrup dispatch hours dedicated to the studied SKU cohort | $3.433 \times 10^{-8}$ | $7.603 \times 10^{-10}$ | +2.30% | +1.36% |
| Korean general transport CF for sugar sea cargo | $3.353 \times 10^{-8}$ | $7.509 \times 10^{-10}$ | −0.08% | +0.10% |
| Sea shipping labor intensity ×10 | $3.496 \times 10^{-8}$ | $7.584 \times 10^{-10}$ | +4.18% | +1.11% |
| Waste family labor h ×2 | $3.357 \times 10^{-8}$ | $7.506 \times 10^{-10}$ | +0.03% | +0.07% |

**Table 14.** Combined model-definition and hypothetical exposure sensitivities; no matched worker-hour validation or probability distribution is implied.

| Agric. Calculation | γ Hypothetical Manufacturing Multiplier | Sea Labor Factor | Modeled Injury/FU | Modeled Fatality/FU |
|---|---|---|---|---|
| A | 1.00 | 1× | $3.3557 \times 10^{-8}$ | $7.5009 \times 10^{-10}$ |
| A | 1.00 | 10× | $3.4959 \times 10^{-8}$ | $7.5841 \times 10^{-10}$ |
| A | 1.25 | 1× | $3.5133 \times 10^{-8}$ | $7.7339 \times 10^{-10}$ |
| A | 1.25 | 10× | $3.6535 \times 10^{-8}$ | $7.8171 \times 10^{-10}$ |
| B | 1.00 | 1× | $1.0962 \times 10^{-8}$ | $1.8595 \times 10^{-10}$ |
| B | 1.00 | 10× | $1.2364 \times 10^{-8}$ | $1.9427 \times 10^{-10}$ |
| B | 1.25 | 1× | $1.2538 \times 10^{-8}$ | $2.0924 \times 10^{-10}$ |
| B | 1.25 | 10× | $1.3940 \times 10^{-8}$ | $2.1757 \times 10^{-10}$ |

Holding other characterized pathways fixed, substituting line–month (264,906.32 h) for plant–month (278,268.55 h) attribution reduces Scenario A modeled injuries by 0.90% to $3.3254 \times 10^{-8}$/FU and modeled fatalities by 0.60% to $7.4562 \times 10^{-10}$/FU. Neither reduction equals the 5.04% manufacturing hours difference. This is not a run-time allocation test or a validated SKU-specific life-cycle comparison.

The combined entries are deterministic arithmetic stress tests with all other pathway terms held fixed. $\gamma = 1.25$ is a hypothetical manufacturing activity coverage perturbation,

not a finding that recorded Productive(Hr) fails to represent actual working time. Sea ×10 has no directly observed vessel–crew–hour basis. The model outputs therefore cannot rank actual worker injury risks across suppliers or countries.

For Scenario B, the analogous modeled total reductions under the alternative manufacturing pooling boundary are 2.76% for injuries and 2.41% for fatalities. These percentages are controlled accounting-boundary sensitivities. The subsequent SKU-level Scenario A table provides a separate standardized five-pathway reference for examining the rank consequence of line–month and plant–month productive-hour attribution.

To assess SKU-level characterized ranking under a controlled life-cycle reference, the five nonmanufacturing characterized pathways are assigned the same Scenario A case-equivalent intensity per 500 mL to each of the three studied SKUs. Only each SKU's manufacturing productive worker-hour intensity changes between the source ERP line–month and counterfactual plant–month boundaries. Each result equals the common nonmanufacturing Scenario A contribution plus the SKU-specific worker hours/500 mL multiplied by the Korean manufacturing CF. The bottle-weighted totals reproduce the original plant–month Scenario A and its line–month sensitivity; Table 15 reports both endpoints for each SKU. These standardized modeled rankings isolate the workforce-attribution effect under a common 500 mL supply-chain background.

**Table 15.** Controlled SKU-level Scenario A-characterized burdens (cases per 500 mL), using a common nonmanufacturing reference and alternative manufacturing allocation boundaries.

| SKU | Line–Month Injury | Plant–Month Injury | Line–Month Fatality | Plant–Month Fatality |
|---|---|---|---|---|
| S1 | $3.314 \times 10^{-8}$ | $3.362 \times 10^{-8}$ | $7.439 \times 10^{-10}$ | $7.510 \times 10^{-10}$ |
| S2 | $3.276 \times 10^{-8}$ | $3.349 \times 10^{-8}$ | $7.383 \times 10^{-10}$ | $7.492 \times 10^{-10}$ |
| S3 | $3.418 \times 10^{-8}$ | $3.332 \times 10^{-8}$ | $7.593 \times 10^{-10}$ | $7.466 \times 10^{-10}$ |

## 4. Discussion

### *4.1. Contribution Relative to Occupational Health LCA Literature*

Occupational health impacts have long been addressed within LCA and integrated product policy. Hofstetter and Norris examined occupational consequences in product policy [20]; Kijko et al. modeled labor-hour-based chemical-exposure effects and subsequently traced them through whole product life cycles [21,22]. Their exposure-based endpoints are not numerically interchangeable with this study's national injury case-equivalent proxies. The present contribution is the four-boundary allocation analysis of documented line-specific productive working hours and its effects on SKU attributions, not the invention of worker-hour characterization or an assumption of actual shared line staff.

Other antecedents include Scanlon et al.'s work-environment DALY indicators, Huang et al.'s industry-based occupational health factors, and Tsalidis' worked-hour or expenditure-based screening [11–14]. These prior contributions mean neither worker-hour characterization itself nor country-by-country summation should be presented as novel to this study. The observational novelty is the transparent four-boundary comparison and SKU rank reversal in the available 2024 ERP production cohort.

Plant–month pooling is counterfactual, since workers were separately assigned by line in the source records. The +5.04% manufacturing-hours change produces only a 0.90% injury and 0.60% fatality reduction in Scenario A when line–month replaces plant–month and other modeled pathways are fixed. The effects are accounting sensitivities, not observed changes in occupational risk.

### *4.2. Rationale and Limitations of Nonmonetary Supply-Chain Scaling*

Two methodological choices are distinguished. First, this study does not adopt the default social-risk scoring pathways of PSILCA or SHDB. Second, it does not extract their country–sector worker-hour intensities as substitutes for the case-specific inventory. The second choice is not a logical consequence of the first: both databases contain potentially useful social-inventory information, independently of the risk scores. For the present research question, however, country–sector labor intensity does not reconstruct recorded hours assigned to a specific PET line in a specific month or the corresponding SKU counts. Likewise, attaching broad sector estimates to the background physical flows would require an explicit mapping of monetary or sector output units to the observed mass and transport activity, with matched scope and no double counting [16,17].

The physical-inventory design records material masses per 500 mL, transport activity per 500 mL, supplier contractual-hour coefficients and the 2024 productive worker time attributed to bottles on the six PET lines. The format-share sensitivity uses one 2024 product format inventory consistently for both the bottle-count and beverage-volume denominators. The main manufacturing allocation continues to use the original ERP source, so each comparison retains its explicitly defined source cohort and attribution rule.

Financial valuation and price changes can influence worker-hour attribution when economic input–output pathways are used for scaling; this is an additional modeling consideration and does not by itself invalidate database inventory variables. The present inventory instead combines observed 2024 ERP line-specific productive hours with documented material, supplier-operation and transport activity variables to isolate a defined manufacturing allocation-boundary question. PSILCA or SHDB inventory estimates could be evaluated in a separately specified hybrid or comparative model, but such substitution is not necessary to answer the current line-versus-plant attribution question and was not performed in the reported calculations [16,17,19].

### *4.3. The Distinction Between Activity Variables and Social Aspects*

The product functional unit is one finished 500 mL beverage. The connection to the production organization is confined to data provenance and the resolution of the activity inventory: line-specific productive working hours are recorded by the company and then allocated to that product reference flow using the stated output shares. An observed organization-wide injury count or safety-management practice has a different scope, population and meaning. Such information can contextualize the product study but is not a process-specific work-hour flow, an allocated company accident count or a second organization-level impact result. Table 7 now explicitly identifies these corporate records as context only. Accordingly, this manuscript does not extend the product indicator to a social assessment of the organization [1,19]. Accordingly, two operations are distinguished: the inventory step attributes recorded line-specific worker hours to the products, whereas the characterization step combines product-linked worker hours with separately sourced country–sector CFs. Neither operation apportions the enterprise's observed injury cases nor treats national cases as accidents attributable to the assessed SKUs.

ISO 14075:2024 establishes principles and a framework for the S-LCA of products [1]. Its role in this study is expressly conceptual and methodological: it informs the product functional unit, scope, activity-based inventory structure and transparent interpretation of characterized pathways. It is not invoked as a normative authorization to allocate corporate injury cases or organization-wide social aspects to products, nor as evidence that a separate organizational S-LCA was undertaken. The analysis is described as ISO 14075-informed, without claiming ISO 14075 certification or demonstrating full conformity. The modeled case-equivalent results arise from the specified process inventory and independently stated

country–sector screening factors rather than from a social-aspect allocation prescribed by the standard.

### *4.4. Boundary Coverage and the Level of Validation*

Included model stages comprise agriculture, upstream materials, inbound freight, line-specific beverage production, outbound freight and packaging end of life. Each requires an activity-to-work mapping and injury/fatality factor. Their evidentiary status differs: manufacturing includes actual line-assigned productive working hours followed by modeled SKU allocation; supplier hours are contractual operation; the K-PCR material records are author-designated 2024 references with residual template labels and source-count reconciliation limits; and CFs are secondary country–sector proxies. Since national worker coverage and all upstream activities are not comprehensively observed, the characterized pathway total is a conditional screening indicator, not a validated whole-supply-chain accident measure.

Packaging recovery and disposal remain in the chosen life-cycle boundary and are modeled with source-reported aggregate plastic/paper work coefficients; not every treatment route has a separately validated occupational denominator. Consumer safety during beverage consumption is outside the Workers stakeholder endpoint. Accordingly, the manuscript reports a conditional screening indicator for multiple life-cycle pathways and a separately supported 2024 manufacturing ERP allocation analysis; these two outputs have different levels of empirical validation.

The syrup supplier coefficient is derived from source-data-owner-confirmed 2024 contractual hours and supplier-wide output, with both values and their units displayed in the Materials and Methods Section. The 2024 K-PCR materials and production format data are used for the stipulated physical-activity reference and stand-alone denominator sensitivity, respectively. These applications do not change the verified manufacturing ERP allocation totals.

### *4.5. Interpretation for Product and Industrial Safety Decisions*

The proposed indicator addresses the worker-safety dimension of social sustainability associated with United Nations Sustainable Development Goal target 8.8, which calls for safe and secure working environments and is monitored in part through occupational injury indicators [32]. It does not measure national SDG progress or certify supplier working conditions. Its contribution is to connect product-attributed physical activities with explicitly identified worker-safety endpoints and to disclose scenario uncertainty for supply-chain decisions.

Principal Scenario A follows the original harvested-cane mass denominator and identifies agriculture as the largest modeled injury pathway within the characterized process scope. The independent national-yield calculation provides a dimensional plausibility benchmark, and the country-specific factor ledger identifies the relevant worker populations. Line–month manufacturing attribution preserves distinct recorded production-line workforces; the within-format-inventory count-versus-volume analysis quantifies an additional product-output denominator sensitivity.

Additional injury-related data should not be invented to create a complete footprint. Surveillance research shows that even routinely published injury statistics can be incomplete or dependent on classification practices [33–35]. Likewise, organizational safety practices and worker characteristics influence hazard and injury likelihood beyond exposure activity [36,37]. A higher h/bottle is therefore neither automatically safer nor less safe; it indicates more modeled attributed productive activity under a specified allocation, not a

causal safety verdict. Longer shifts and overtime are also occupational determinants [38] and cannot be inferred from the Productive(Hr) field alone.

### *4.6. Limitations and Conditions for Transferability*

The modeled burdens are case-equivalent occupational safety screening proxies rather than observed product-specific injury probabilities. The national factors describe distinct event and covered-population definitions: Korean recognized cases may include occupational diseases, Australian serious claims and traumatic fatalities have separate reporting conventions, and Thailand agricultural factors reflect registered/insured-sector reporting [24–27]. Productive(Hr) is actual productive working time for line-assigned employees, while the country factors have their own reference hours and covered populations. The agricultural coefficient is h/kg harvested cane ([23], p. 92), and external 2023 yields are used only as a dimensional check. Reported life-cycle percentages refer to the six characterized pathways; the count-versus-volume allocation is a separate defined sensitivity.

The reported scenario comparisons are deterministic changes in specified model assumptions, with all other characterized inputs controlled. Transfer to other production systems calls for a defined functional unit, output-denominator data, staff-assignment boundaries and country–sector factors labeled by statistical event coverage and time units. The observed line-assignment structure supports line–month as the personnel-consistent accounting boundary, while plant–month and format-volume weighting are separate modeled allocation tests.

### *4.7. Country-Specific Multiplication and Aggregation*

For each physical process and source country c, activity-linked worker hours are multiplied by the factor for country c before summing the modeled burdens. This follows ordinary process-based LCA bookkeeping and avoids mismatched cross-country weighted means. It is an implementation rule in this model, not a newly introduced life-cycle impact characterization method.

For every modeled source country, process worker hours are multiplied by that country–sector's factor before summation, following ordinary process-based LCA accounting. Thailand 2024 agriculture and transport factors are reproduced arithmetically from the published injury/fatality rates and actual weekly hours. The remaining factors are used as reported in dissertation Table 22 with their source-year, sector and reporting-scope identifiers in Table 2. Interpretation of differences between country–sector screening indicators follows the source-specific event definitions and worker coverage.

## 5. Conclusions

This article reports two distinct outcomes for one 500 mL beverage: (i) a four-boundary comparison of 2024 ERP productive working-hour attribution and (ii) conditional modeled occupational injury and fatality burdens for characterized life-cycle pathways. The 72 line–month records describe actual working time in production derived from shift and time data for distinct line-assigned employees, but the product-by-product allocation is not a direct timecard measure, and national CFs may use different worker populations.

Plant–month pooling yields 278,268.55 of the 785,659 recorded productive hours for 171,696,216 study bottles, 5.04% more than line–month; this is a hypothetical pooling boundary rather than a documented staff-sharing mechanism. Under the principal cane-basis Scenario A, characterized pathways yield $3.356 \times 10^{-8}$ modeled injuries and $7.501 \times 10^{-10}$ modeled fatalities per bottle, with agriculture contributing 75.75% of included-pathway injuries. Diagnostic Scenario B, which applies the cane coefficients directly to sugar input contrary to their original units, yields $1.096 \times 10^{-8}$ and $1.859 \times 10^{-10}$ and a 25.76% agricul-

tural injury share. The difference reflects an intentionally counterfactual unit application, not two equally supported source definitions.

The main empirically supported finding is the sensitivity of 2024 production-line productive-hour attribution to the selected line/plant accounting boundary. A separate count-versus-beverage-volume test on the 2024 product format inventory demonstrates sensitivity to the choice of complete line-output denominator. Under a common nonmanufacturing characterized burden per 500 mL, the modeled SKU-level Scenario A ranking changes from S3 > S1 > S2 under line–month to S1 > S2 > S3 under plant–month, as shown in Table 15. This standardized calculation does not change the functional unit or describe realized product-attributable accidents. The country-specific cane-based labor coefficients and included pathway definitions support the consistent conditional life-cycle screening interpretation.

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