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Embodied Transboundary Greenhouse Gas Emissions and Mitigation Opportunities of over 700 Belt and Road Initiative Projects

Lingli Hou,* Tomer Fishman, Stefano Merciai, Takuma Watari, Yanan Liang, Ester van der Voet, Asaf Tzachor, Heming Wang, Peng Wang, Jun Bi, and Ranran Wang*

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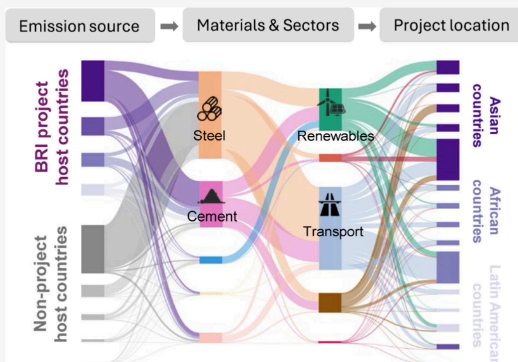
ABSTRACT: The Belt and Road Initiative (BRI), the world's largest ongoing infrastructure endeavor, tackles urgent development needs in underserved regions. However, its construction phase, especially material extraction and processing, may have far-reaching climate implications that remain poorly known. Here, we present the first global, project-level assessment of greenhouse gas (GHG) emissions embodied in the construction of over 700 individual BRI projects (2008−2024) across 105 countries. By integrating a detailed project data set with a physically grounded global supply chain model that captures material-specific sourcing patterns, we estimate 134 Mt of CO_2 equiv emissions, around half of which occur outside the project host countries. This reveals the previously unquantified global supply chain reach of the BRI. Depending on operational performance, BRI renewable energy projects may achieve emission reductions comparable in scale to the construction-phase emissions within 2 years. Our results underscore the need and opportunity to embed cleaner material sourcing and sustainability assessment into BRI and other transnational infrastructure efforts.



KEYWORDS: *infrastructure, embodied environmental impacts, climate change mitigation, global supply chain*

1. INTRODUCTION

Infrastructure is foundational to economic growth and societal quality of life, enabling access to essential services, like energy, transport, and water.[1] In low- and middle-income countries, infrastructure deficits have long been recognized as a key bottleneck to achieving development goals.[2,3] However, infrastructure construction is inherently material-intensive and contributes substantially to global greenhouse gas (GHG) emissions through the extraction, processing, and transport of construction materials.[4−6] As climate commitments intensify globally, reconciling the urgent need to close infrastructure gaps in underserved regions with the imperative of environmental sustainability emerges as a defining challenge.

The Belt and Road Initiative (BRI), launched by China in 2013, is the largest transnational infrastructure endeavor in history.[7,8] With projects spanning over 150 countries, mainly in low- and middle-income countries, the BRI channels large-scale investments into roads, railways, energy systems, and industrial facilities.[9] While early discussions focused on geopolitical,[10] economic,[11] and policy[12] dimensions, recent studies have highlighted the BRI's environmental implications,[13−17] such as deforestation, biodiversity loss, and climate impacts.[8,18]

However, much of the existing literature evaluates the initiative at an aggregated, economy-wide level. These studies typically examine carbon implications through macroeconomic channels such as foreign direct investment (FDI), trade-embodied emissions, structural decomposition analysis, or demand-driven carbon footprints.[19−23] While such approaches provide valuable insights into emission flows associated with trade, investment, and economic growth, they primarily assess annual territorial or consumption-based emissions at the national or regional scale. This framing, although important, can obscure how the initiative is implemented in practice, i.e., through physical infrastructure projects on the ground, and makes it difficult to distinguish BRI's specific contributions from those of broader development efforts.[24] These macro-level analyses may also mask the diversity of physical infrastructure types and scales, limiting the assessments of both environmental footprints and mitigation priorities. In

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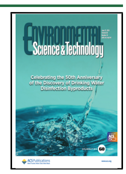

addition, renewable energy projects developed under the BRI hold mitigation potential that could support global climate goals.[25,26] However, project-level assessments of the BRI's climate effects remain scarce, largely due to the lack of consistent project data[24] and an analytical framework capable of linking physical infrastructure characteristics to supply chain emissions across countries.[27]

Furthermore, while the emission impacts of global supply chains have been highlighted in many sectors, understanding of the magnitude, spatial distribution, and key drivers, such as infrastructure types and material sourcing patterns, of the transboundary emissions associated with infrastructure projects remains limited. Many BRI projects rely on carbon-intensive construction materials, such as steel and copper,[22] which are often produced outside the project host countries where the infrastructure is physically constructed. This creates a spatial disconnect between where infrastructure services are delivered and where the associated carbon emissions, particularly from construction material extraction and processing, are incurred, often spanning multiple international jurisdictions. Without this understanding, public and private infrastructure decision-makers lack the evidence needed to identify emissions hotspots, target material-related mitigation opportunities, and design climate-compatible infrastructure systems that reflect transboundary supply chain impacts.[24,28−30]

In this study, we address these critical gaps by providing the first global, project-level estimates of GHG emissions embodied in the construction of BRI infrastructure projects. The embodied emissions include both on-site emissions and upstream emissions from material extraction, processing, and transport. To achieve this, we compile a data set detailing the physical characteristics of over 700 BRI projects built from 2008 to 2024, spanning 28 infrastructure types and 4 main infrastructure service sectors (transport, electricity, building, and water) across 105 countries. We integrate this data set with a newly developed multiregional input−output (MRIO) framework that traces global commodity flows in hybrid physical−monetary units and links them to production-based emissions, enabling consistent attribution of embodied emissions to specific materials and producing countries. This methodological approach, combining detailed project-level data with comprehensive global supply chain tracing, allows us to capture both the heterogeneity of infrastructure development and the transboundary nature of embodied emissions, connecting emissions from project host countries to the geographic origins of those materials. Finally, we assess the emission reduction potential of BRI renewable energy projects by estimating the magnitude of operational-phase emission reduction under four performance scenarios reflecting a wide range of technology and capacity factor assumptions. Together, these analyses offer a comprehensive and spatially explicit assessment of BRI's climate impacts, providing new evidence and an integrated methodological approach to inform more sustainable infrastructure planning and equitable global climate governance.

2. METHODOLOGY

We estimate GHG emissions embodied in the construction of over 700 BRI infrastructure projects from 2008 to 2024, covering the life cycle from raw material extraction to the end of construction (i.e., upfront embodied emissions). The accounting framework consists of four main steps: (1) project compilation and material quantification, (2) estimation of embodied emissions from material provisioning and on-site construction, (3) transboundary supply chain attribution, and (4) estimation of operational emission-reduction potential from renewable projects.

2.1. Compiling the BRI Project Data Set and Estimating Material Use

We build on and extend our existing method[24] to compile a data set of BRI infrastructure projects constructed from 2008 to 2024. All project-level information was sourced from BRI's official Web site[31] supplemented through data from related construction companies. We initially identified 800 BRI projects across 108 countries. Of these, 706 projects contained sufficiently detailed information on physical quantities and infrastructure characteristics to allow material and emissions accounting; the remaining 94 projects lacked essential information (e.g., missing dimensions and unclear construction scope) and were therefore documented but excluded from quantitative analysis. Several of the 706 projects comprise multiple infrastructure components (e.g., airport terminals and runways), which we treat as separate project units for material and emissions estimation. After this disaggregation, the final analysis includes 735 project components in 105 countries. We categorized these components into 28 infrastructure types and four main infrastructure service sectors: transport, electricity, buildings, and water.

Following established material stock accounting methods,[32,33] we estimate the material use associate with each project based on its physical dimensions and infrastructure type. Specifically, we quantify 12 types of construction materials and group them into five categories for presentation: steel, cement, Cu and Al (copper and aluminum), aggregates (sand and stone), and other construction materials (bitumen, ceramics, bricks, plastics, wood, and glass). To calculate the material stock (MS) of material i of a project in infrastructure type p constructed in country j, we apply the corresponding accounting unit (AU), e.g., km for railway and m^2 for buildings, and material intensity coefficients (MICs) as in eq 1. All subsequent scalar multiplication is denoted by "×", while matrix multiplication is denoted by "·".

$$MS_{i,p,j} = AU_{p,j} \times MIC_{i,p} \tag{1}$$

We largely adopt the same archetype classifications and MICs as our previous work, with minor adjustments based on updated data sources (detailed in Table S1 of the Supporting Information). For aggregates, we assume a simplified allocation by splitting the total quantity evenly between stone and sand to enable material-specific emission tracing. A sensitivity analysis varying the stone and sand split changes total supply chain embodied emissions by negligible share (Table S2), confirming its limited influence on aggregate results.

2.2. Estimating Embodied Emissions from Material Provisioning and On-Site Construction

We estimate the GHG emissions embodied in the construction of BRI infrastructure projects by quantifying two components: (1) emissions from material provisioning, and (2) emissions from on-site construction activities. Material provisioning emissions represent cradle-to-gate impacts associated with upstream extraction, processing, and supply chain inputs of construction materials, while on-site emissions arise from project-level construction activities occurring after material delivery. These two components therefore correspond to

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sequential and non-overlapping stages of the construction life cycle.

2.2.1. Emissions from Material Provisioning. We quantify the global supply chain-wide emissions embodied in construction materials by applying country-specific, market-weighted emission factors to the material stock quantities obtained above

$$\text{GHG\_material}_{i,p,j} = \text{MS}_{i,p,j} \times \text{EF\_market}_{i,j} \quad (2)$$

The market-weighted emission factors, expressed in kilograms of CO_2 equivalent per kilogram of material and denoted as $\text{EF\_market}_{i,j}$, represent the average cradle-to-market emission intensity of material i used in project host country j based on year 2016.

To construct these factors, we follow a two-step procedure using production and trade matrices obtained from the BONSAI,[34] a newly developed global hybrid Supply−Use Table-based Multi-Regional Input−Output (SUT−MRIO) database which covers footprint for over 1200 products in 50 regions/countries based on European Classification of Products by Activity. First, we match the material types in our project database to BONSAI's material definitions and match the countries according to BONSAI classification (Tables S3 and S4). For each material i, we derive a production matrix (P_i), which captures 50 regions' contributions to the upstream GHG emissions embodied in 1 kg of material produced in each producing country. This includes both direct and indirect emissions along global supply chains (e.g., steel produced in China may include coke from Brazil, chemical inputs from Russia, and machinery from South Korea). Second, we obtain a market matrix (M_i), which represents the sourcing composition of material i used in 50 BONSAI region, i.e., the share of imports from each producing country. Multiplying the production and market matrices yields a supply chain emission matrix (S_i) (eq 3), indicating the contribution of each of the 50 regions of GHG emissions associated with 1 kg of material i used in each BONSAI region.

$$S_i = P_i \cdot M_i \quad (3)$$

As we have 105 BRI economies in our scope of projects, we assign the according column from S_i based on how BONSAI categorizes these countries. For instance, Nigeria and Angola are not in the BONSAI country/region list, so we assign the column for "Rest of Africa" to them; Brazil has its own column in S_i, then we can directly use this column. By doing so, we get the consumption contribution matrix for all BRI economies, S_BRI_i (50 × 105), which details the contribution of 50 world's regions/countries to 1 kg of material consumed in each project country. The sum of jth column in S_BRI_i results in the market emission factor of material i in project host country j ($\text{EF\_market}_{i,j}$). These cradle-to-gate emission factors obtained from the BONSAI SUT−MRIO framework cover emissions from material extraction, production, upstream supply chain inputs, and trade-related transport embodied in the material supply chains, but do not explicitly model project-specific domestic delivery to construction sites. Emissions associated with the final usage of the materials and other on-site production activities are modeled separately as explained below.

While BONSAI is a relatively new MRIO framework, its construction follows established principles of supply use balancing and physically defined product systems rather than monetary sector averages. It offers globally consistent, regionally differentiated emission factors in physical units, which is particularly relevant for infrastructure-related assessments where physical material flows dominate environmental impacts. Detailed BONSAI methodological documentation is fully transparent and available in its official platform[35] and developers' page.[36]

2.2.2. Emissions from On-Site Construction. We estimate the emissions from on-site construction activities (e.g., earthworks, machinery use, and energy use) based on infrastructure-specific accounting units (e.g., buildings and roads measured in m^2 of area, railway measured in km of length). The on-site emission factors (EF_onsite_p) are drawn from Ecoinvent database[37] and supplemented by estimates from the literature (see Table S5). On-site construction emissions represent A5-stage[38] project-level activities during infrastructure assembly, including machinery operation, on-site energy use, and construction fuel combustion occurring after material delivery.. The on-site construction emissions for infrastructure type p located in project host country j are calculated as

$$\text{GHG\_onsite}_{p,j} = \text{AU}_{p,j} \times \text{EF\_onsite}_p \quad (4)$$

2.2.3. Total Embodied Emissions. We sum the GHG emissions from material provisioning and on-site construction to obtain the total embodied emissions for infrastructure type p located in each project host country j.

$$\text{GHG\_total}_{p,j} = \sum_i \text{GHG\_material}_{i,p,j} + \text{GHG\_onsite}_{p,j} \quad (5)$$

The GHG emissions can be further aggregated by infrastructure type (GHG_total_p), project host country (GHG_total_j), and main infrastructure service sector (GHG_total_s), to enable analysis by geography, infrastructure type, and service provision.

2.3. Tracing the Geographic Origins of Embodied Emissions

2.3.1. Emission Sources of Each Material. First, we organize the material stocks we calculated into material bills listing the total weight of each material in the 105 project countries. For material i, we have the material bill as a vector (V_i), dimension of which is 105 × 1. We calculate the contribution (V_m_i) of all 50 world regions/countries for material i used in project countries as follows:

$$V\_\text{m}_i = S\_\text{BRI}_i \cdot V_i \quad (6)$$

V_m_i is a 50 × 1 vector specifying the contribution of 50 countries/regions for material i consumed in all project countries. The sum of this vector means the total emission from providing material i in all BRI projects. We can further get the matrix of source country's contribution to material (C_m) to by stacking V_m_i horizontally as follows:

$$C\_\text{m} = [V\_\text{m}_1 V\_\text{m}_2 V\_\text{m}_{12}] \quad (7)$$

C_m is a 50 × 12 matrix, and each row column stands for a source country/region's contribution for 12 materials.

2.3.2. Emission Source of Each Project Country. To trace the country-to-country emission source, we need to distinguish each source region/country's contribution in each material in 105 project countries. We calculate the contribution for material i (C_i) as follows:

$$C_i = S\_\text{BRI}_i \cdot \text{diag}(V_i) \quad (8)$$

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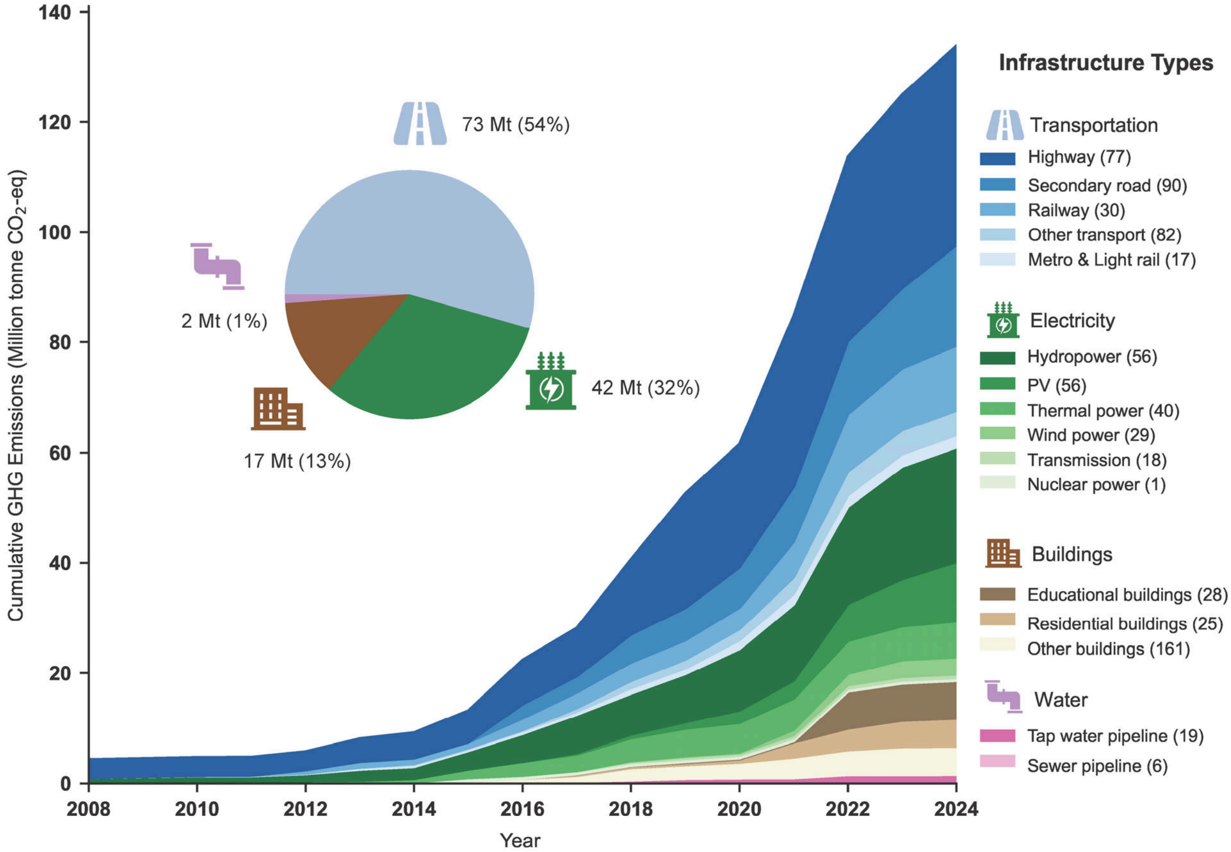

Figure 1. Cumulative GHG emissions embodied in the construction of 706 BRI infrastructure projects between 2008 and 2024. Emissions include those from on-site construction activities and those from material extraction, processing, and transport. The numbers in the legend indicate the number of BRI projects per infrastructure type by 2024. The pie chart shows the sectoral breakdown of cumulative emissions across the four infrastructure service sectors.

C_i is a 50 × 105 matrix, each column in C_i stands for contribution of 50 countries/regions for providing material i in one project country. The diag(V_i) is converting V_i into a 105 × 105 diagonal matrix. Then aggregating the detailed contribution bill results in the total contribution of one source country to one project country as in eq 9.

$$C\_c = \sum_i C_i \tag{9}$$

C_c is a 50 × 105 matrix, and the element of C_c in rth row, jth column specifies the total contribution of source country/region r to project country j. The tracing framework is presented in the Figure S1.

2.4. Estimating Operational Emission Reduction Potential

To assess the emission reduction potential of BRI, we estimate the annual emissions that could be avoided by renewable energy projects within the BRI. We compile 143 renewable energy projects in 58 project host countries, detailing each project's location, technology type (e.g., solar PV, off-shore wind, and hydro), and installed capacity.

First, for renewable energy project type p in project host country j, we calculate its possible electricity generation per year (Electricity_gen$_{p,j}$) as

$$\text{Electricity\_gen}_{p,j} = \text{Capacity}_{p,j} \times 365 \times 24 \times \text{Cap\_factor}_p \tag{10}$$

where Capacity$_{p,j}$ is installed capacity (kW) and Cap_factor$_p$ is the type-specific capacity factor, capturing a range of real-world operational efficiency[39,40] (Table S6). The use of average grid emission intensity reflects an attributional displacement assumption and does not attempt to model marginal generation responses or future demand growth. Capacity factors are specified as technology-level ranges derived from internationally reported operating data (e.g., IRENA[39]). While not location-specific to individual projects, the selected low—high bounds span commonly reported performance ranges for renewable technologies[41] and capture geographic variability across diverse operating contexts, including many BRI host countries.

Next, following an existing method,[26] we estimate the annual GHG emissions reduction from these renewable energy projects by comparing the average emission intensity of operating existing power mix in country j (EF_j; see Table S7) with that of operating renewable type p ($EF_{p,j}$).

$$\text{GHG\_reduction}_{p,j} = \text{Electricity\_gen}_{p,j} \times (EF_j - EF_{p,j}) \tag{11}$$

Both emission factors are in kg of CO_2 equiv per kWh. For each renewable project type p, we consider a range of potential estimates for $EF_{p,j}$ (Table S6). Given the multicountry scope of the BRI portfolio and the absence of consistent marginal generation data sets across host countries, an attributional approach based on average grid intensity provides a harmonized and transparent reference framework for comparative assessment.

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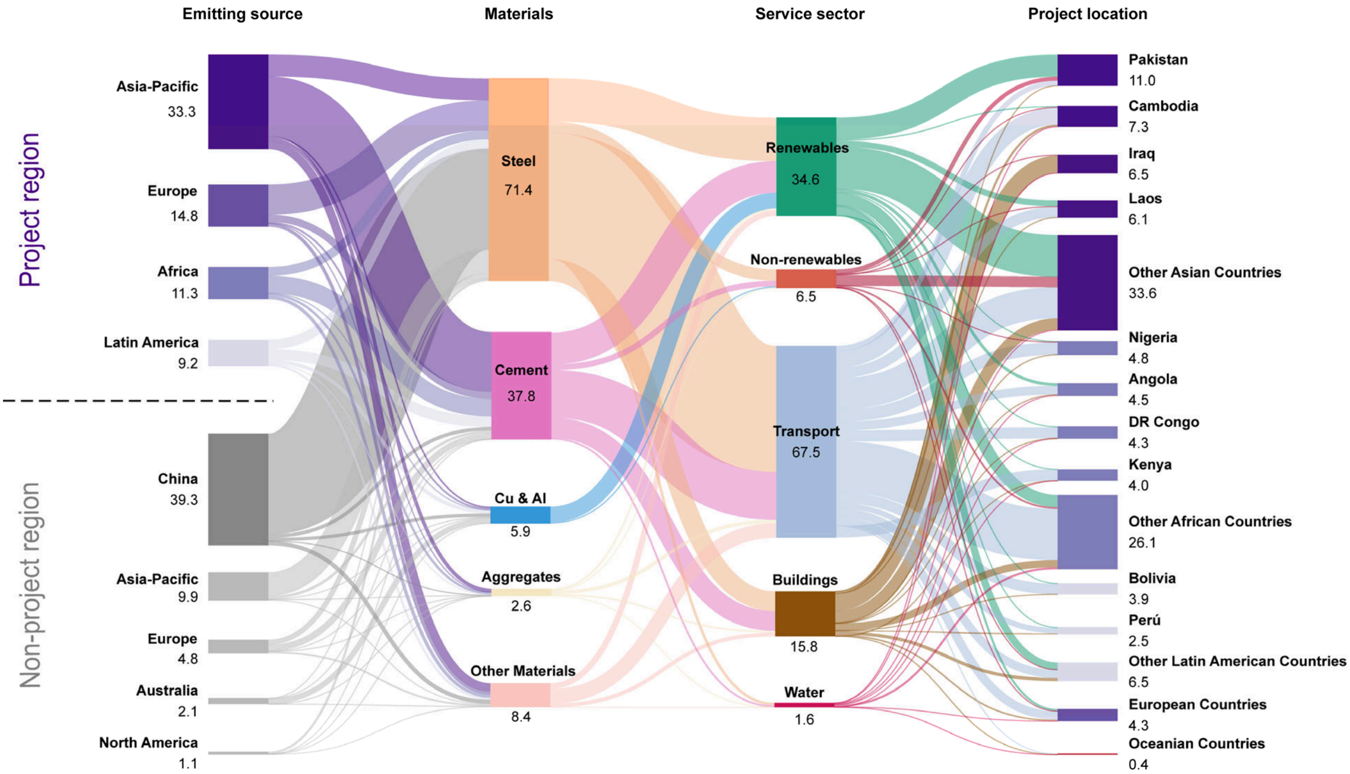

Figure 2. Sankey diagram of transboundary GHG emissions (Mt of CO_2 equiv) embodied in the construction of 706 BRI projects, linking emitting countries/regions (left) to infrastructure systems, characterized by their in-use material stocks, service sectors, and host countries (right). "Project regions" (in varying shades of purple) refer to countries that host BRI projects, while "non-project regions" (in gray; China in dark gray) are those without any such projects, typically excluded from conventional BRI analyses. Due to the resolution of the underlying supply chain data set, when tracing to emission sources, some non-project countries (e.g., Bhutan and Togo) are aggregated with project countries (e.g., Pakistan) into regional clusters (e.g., Rest of Asia and Pacific; see Table S4) and treated as project regions (e.g., Project region and Asia-Pacific). This treatment renders our estimates of BRI's global supply chain outreach conservative, as some emissions from non-project countries are attributed to project regions. Flows in the diagram are color-coded to reflect the emission drivers on the left-hand side. For example, emissions embodied in Pakistan's BRI projects primarily stem from renewable energy development, and emissions embodied in renewable energy projects largely originate from steel and cement. For presentation purposes, the Sankey diagram aggregates regions, infrastructure types, and materials ("Other materials" include bitumen, ceramics, bricks, plastics, wood, and glass).

We then sum the annual emission reduction across all renewable projects to estimate the total emission potential reduction (eq 12).

$$\text{GHG\_reduction} = \sum_{p,j} \text{GHG\_reduction}_{p,j} \tag{12}$$

To assess uncertainty and variability, we define scenario frameworks for material sourcing pathways and four operational performance settings.

2.5. Scenario Assumptions

To assess uncertainty and structural variability, we construct alternative scenarios for material sourcing and renewable operation. Each scenario modifies specific model parameters while holding other components constant, allowing us to isolate the influence of individual assumptions on total embodied emissions and transboundary attribution.

2.5.1. Material Sourcing Scenarios. Material sourcing scenarios explore how alternative sourcing patterns affect embodied emissions while keeping total material demand constant. These scenarios modify the emission intensities associated with material production to represent sourcing from lower or higher intensity producers, or exclusively from domestic production.

In the min-sourcing scenario, materials are hypothetically sourced from the lowest emission producers among the 50 BONSAI regions. In the max-sourcing scenario, materials are sourced from the highest-emission producers. In the locally produced scenario, materials are assumed to be produced domestically in the project host country; if no domestic production exists for a given material, the global average production intensity is applied as a proxy.

2.5.2. Operational Performance Scenarios. Operational performance scenarios modify two parameters in eqs 10 and 11: the capacity factor (Cap_factor_p) and the emission intensity of renewable generation ($EF_{p,j}$), while keeping installed capacity constant.

LowTech−LowCapacity: Upper-bound emission intensity with lower-bound capacity factor.

LowTech−HighCapacity: Upper-bound emission intensity with upper-bound capacity factor.

HighTech−LowCapacity: Lower-bound emission intensity with lower-bound capacity factor.

HighTech−HighCapacity: Lower-bound emission intensity with upper-bound capacity factor.

The capacity factor and emission intensity bounds are derived from literature ranges (Table S6). These scenarios provide a structured range of plausible operational outcomes

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without altering installed capacity or project portfolio composition.

3. RESULTS

3.1. Total and Pattern of Embodied GHG Emissions of BRI

Constructing the 706 BRI projects included in the accounting data set from 2008 to 2024 has led to 134 million tonnes (Mt) of CO_2 equiv GHG emissions (Figure 1). This includes both emissions from producing construction materials along the supply chain and those from on-site construction for 165 km^2 of roads, 13 thousand kilometers of railway, and 84 GW of energy production infrastructure along with other infrastructure such as buildings and water systems constructed globally. Before 2013, the official launch of the BRI, the cumulative emissions increased slowly as only a handful of projects were added each year. Following the official launch, the cumulative emissions grew significantly faster over the next decade. For example, embodied emissions reached approximately 22 Mt of CO_2 equiv in 2016 (78 cumulative projects), but nearly tripled to 62 Mt of CO_2 equiv by 2020 (317 cumulative projects) (Table S8). Within the subsequent three years, the cumulative emissions further doubled to around 125 Mt of CO_2 equiv by 2023, corresponding to 656 cumulative projects. Although emissions appeared to slightly slow down from 2022 onward, this should not be interpreted as a slowdown of BRI. The surge in 2021−2022 partly reflects projects that were delayed during the pandemic and subsequently concentrated into those two years, and the milder growth after 2022 aligns with the policy shift toward "small yet smart" projects[42] rather than a reduction in overall activity.

The construction of transport infrastructure is the dominant source. By 2024, it contributed approximately 54% of the total cumulative emissions (73 Mt of CO_2 equiv). Within this sector, 74% of the emissions (54 Mt of CO_2 equiv) were for road construction, including highways and secondary roads. Railways were the second-largest source within transport, responsible for about 12 Mt of CO_2 equiv Urban rail systems, including metro and light rail, and other types of transport infrastructure, such as bridges and airport runways, together had a relatively small share, contributing around 7 Mt of CO_2 equiv in total (Figure S2).

Electricity infrastructure, which accounts for 27% of BRI projects by number, has also been a major source of the cumulative embodied emissions (32% or 42 Mt of CO_2 equiv). Notably, 83% of these emissions are attributable to renewable energy projects, mainly hydropower (21 Mt of CO_2 equiv), solar PV (11 Mt of CO_2 equiv), and onshore wind (3 Mt of CO_2 equiv) (Figure S2). Construction of thermal power plants was responsible for approximately 6 Mt of CO_2 equiv. In comparison, buildings and water systems contribute a smaller share due to their relatively limited scale, totaling 19 Mt of CO_2 equiv, primarily from schools (7 Mt of CO_2 equiv) and residential buildings (5 Mt of CO_2 equiv).

3.2. Transboundary Supply Chain Emissions of BRI Infrastructure

Most of the embodied emissions (126 Mt of CO_2 equiv, 94%) are associated with the extraction, processing, and transport of construction materials, with the remaining 6% arising from on-site construction activities. Tracing these emissions from project host countries through infrastructure service sectors, their in-use material stocks, and upstream material supply chains reveals that around half of the emissions originated outside the project host countries, underscoring the globalized nature of BRI infrastructure (Figure 2). That is, BRI exerts substantial indirect economic and environmental impacts that reach beyond the conventionally recognized host countries. Among the non-project countries, China stands out, both as the BRI's principal proponent and a key material supplier due to its geographic proximity to many major host countries, contributing around 31% of the total embodied emissions. A further 15% of emissions came from other non-project countries across the world, including those without any formal BRI engagement. This global reach is broader than generally acknowledged, and is likely still underestimated. The supply chain data set groups smaller countries, including both project and non-project countries, into regional clusters, which we treat as project regions when accounting for emission sources. Nonetheless, this should have minimal impact on the results, as the aggregated non-project countries are small economies.

Since these emissions are tied to material use, their geographic distribution reflects the local availability of construction materials and the types of infrastructures being built. By material type, approximately 60% of the production-related emissions from metals, specifically steel, aluminum, and copper, occurred outside the project countries (Figure 2 and Figure S3). For steel, China was the dominant source, accounting for roughly half of its associated emissions. Consequently, China is the primary emission source country for most project countries. In the case of copper and aluminum, Australia, formally a non-project country, contributes one-third of the emissions associated with the material provision. For example, much of the emissions were traced from mining activities in Australia to solar PV projects in the United Arab Emirates as copper and aluminum are key components of renewable energy technologies. In contrast, only 15% of cement-related emissions are outsourced, since cement is typically sourced within a country.

Regional patterns in GHG emissions of BRI projects also reveal how infrastructure construction reflects local development priorities. In Asia and the Middle East, where energy access remains a key concern, renewable energy projects contributed to around 40% of total emissions, reflecting a regional emphasis on energy infrastructure. By contrast, over two-thirds of emissions from projects in Africa and Latin America originated from the construction of transport infrastructure, aligning with a need to enhance physical connectivity. These differences highlight that the BRI does not follow a uniform investment model, but rather adapts to regional contexts by supporting the types of infrastructure most needed in each location. Hence, their associated emissions and emission sources, and potential reduction strategies, must reflect this.

3.3. Modeled Emission Reduction Potential of BRI Renewable Energy Projects

To assess the potential contributions of BRI renewable energy projects to the global emission reduction effort, we estimate the annual operational-phase emission reduction by those projects under a range of operational scenarios (Figure 3). Depending on assumptions such as capacity factor and technology type, the potential emission reductions range from 75 to 148 Mt of CO_2 equiv per year. When contextualized against the total embodied emissions of all 706 projects, these potential annual reductions approach or

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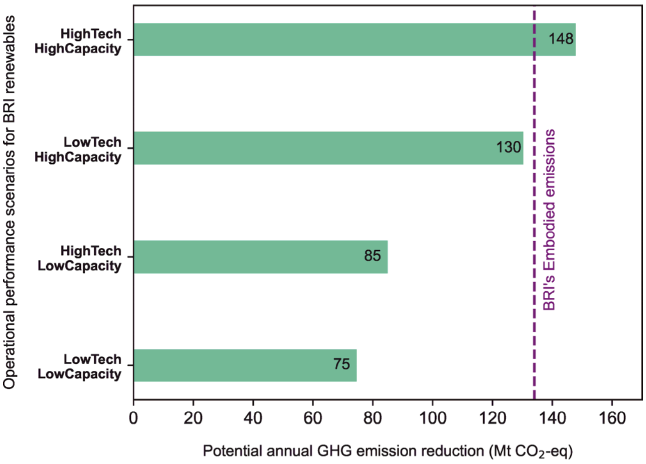

Figure 3. Modeled annual GHG emission reduction (Mt of CO_2 equiv) from BRI renewable energy projects under four operational performance scenarios combining technological efficiency and capacity utilization. The vertical dashed line offers a reference GHG emission level, the total embodied emissions from constructing 706 BRI projects. This reference illustrates the potential climate relevance of BRI renewables, rather than representing direct offsets.

exceed the construction-related emissions within two years. These estimates assume displacement of the average grid emission intensity in each host country, consistent with an attributional accounting approach. They therefore represent modeled potential reductions rather than realized or consequential outcomes, which would depend on marginal generation dynamics and power system evolution. Accordingly, the results should be interpreted as illustrative portfolio-level estimates rather than project-specific or decision-grade projections.

The modeled annual GHG emission reduction of BRI renewable energy projects vary substantially across the four operational scenarios, which differ only in capacity factor and renewable emission intensity parameters while holding installed capacity constant. Of the two performance parameters we examined, capacity factor, which measures the fraction of electricity actually generated relative to a plant's maximum output, has the greater influence. Under high-capacity conditions, annual emission reductions reach 148 Mt of CO_2 equiv for HighTech systems, compared to 85 Mt of CO_2 equiv under low-capacity conditions (a 74% increase). In contrast, the choice of technology type (HighTech vs LowTech), which reflects differences in emissions intensity within each renewable energy technology type, has a smaller effect. Switching from HighTech to LowTech results in a 12% reduction in such potential reduction at both high capacity (148−130 Mt of CO_2 equiv) and low capacity (85−75 Mt of CO_2 equiv).

The potential annual emission reduction by BRI renewable projects also vary considerably across regions (Table S9). In the Asia-Pacific and Middle East region, potential reduction reaches up to 119 Mt of CO_2 equiv under the HighTech−HighCapacity scenario, and remain above 61 Mt of CO_2 equiv even in the LowTech−LowCapacity case. Africa follows, with potential emission reduction ranging from 11 to 22 Mt of CO_2 equiv per year. In contrast, Europe and Latin America show much lower potentials, at only 1−2 and 2−5 Mt of CO_2 equiv per year, respectively. Oceania has no such potential emission reduction, as no BRI renewable energy projects were identified in the data set for this region.

4. DISCUSSION

4.1. Climate Significance of Emissions Embodied in BRI Construction

Our study provides the first global, project-level estimate of GHG emissions embodied in the BRI infrastructure projects. We find that the construction of the 706 BRI projects between 2008 and 2024 resulted in 134 Mt of CO_2 equiv, accounting for about 0.02% of cumulative global GHG emissions over the same period. While modest in aggregate terms,[43] these embodied emissions represent one-time emissions associated with infrastructure construction accumulated over multiple years. Therefore, their relevance lies in their close link to infrastructure capital formation in hard-to-abate sectors such as cement and steel and in their distinct transboundary supply chain characteristics.

These emissions embodied in BRI are estimated based on a market-weighted emission factors that reflect prevailing global production and trade structures. Sensitivity analysis exploring contrasting material sourcing patterns further shows that the embodied emissions could vary substantially, from 49 Mt of CO_2 equiv under a low-carbon sourcing scenario to 214 Mt of CO_2 equiv when materials are sourced from carbon-intensive suppliers (Figure S4). This range highlights the critical role of cleaner material sourcing in reducing infrastructure-related emissions. In addition, intensity-adjustment scenarios for major emitting regions show that although total embodied emissions shift in magnitude, the relative transboundary attribution patterns remain broadly consistent under these tested bounds (see the Supporting Information and Table S10). Together, these sensitivity analyses indicate that while absolute emission levels are sensitive to sourcing and production intensity assumptions, the structural distribution of emissions across regions remains comparatively robust. The relatively small contribution of on-site emissions (6%) is consistent with previous LCA studies[44−47] indicating that the majority of embodied emissions in infrastructure systems arise from material production rather than construction activities. These results emphasize that decarbonization efforts in infrastructure systems must primarily address upstream material production rather than focusing solely on on-site construction activities.

Moreover, the BRI's long-term emission implications will extend beyond the construction phase. Transport infrastructure, the dominant contributor to embodied emissions assessed in our study, is a core focus of the BRI.[9] While designed to improve connectivity of underserved locations, expanding transport network is likely to increase freight and passenger volumes, resulting in higher operational emissions.[48,49] Although the majority of infrastructure-related life cycle emissions often occur during construction,[6] additional system-wide emissions arise from vehicle manufacturing and ongoing energy use to operate the transport systems. A similar dynamic applies to buildings and energy infrastructure, where emissions continue throughout the operational phase. Many of the assessed projects have only recently been built, and useful information on their usage patterns is still unavailable. Once these become clearer, future assessments could incorporate a more comprehensive set of emission sources including those from infrastructure operation, maintenance, and end-of-life stages.

To situate these findings within the broader BRI carbon literature, it is important to distinguish between emissions

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embodied in infrastructure capital formation and economy-wide emission flows associated with trade and final demand. Many existing studies focus on national territorial emissions or economy-wide emission footprints using macroeconomic or structural decomposition frameworks. In contrast, our estimate captures the one-time carbon cost embedded in physical infrastructure construction and traces its transboundary supply chain attribution. Differences in reported magnitudes across studies therefore reflect variations in system boundaries and analytical scale rather than contradictory conclusions. These embodied emissions should not be interpreted against a zero-development baseline. In many host regions, infrastructure expansion reflects broader development trajectories, and alternative financing or domestic investment could plausibly have resulted in similar construction activities under different sourcing configurations. The relevant counterfactual is therefore not the absence of infrastructure, but alternative development pathways with potentially different material intensities and supply chain structures. By focusing on construction-phase embodied emissions at the project level and tracing their transboundary supply chains, our study complements existing macro-level assessments of BRI-related emissions.

4.2. Accounting and Attribution of Transboundary Emissions in BRI Supply Chains

The BRI relies heavily on international production and supply chains, extending well beyond the geographical boundaries of formal participation. Our emission tracing analysis shows the material foundation of BRI is enabled not only by China and BRI host countries, but also by a broad network of global suppliers. Countries not formally involved in the BRI, such as Australia, Japan, and the United States, are integral to the global supply chain, supporting key materials such as copper used in renewable energy projects. These findings highlight the inherently transboundary nature of BRI-related embodied emissions.

Under the United Nations Framework Convention on Climate Change (UNFCCC) framework, upstream supply chain emissions are regulated as territorial emissions of producing countries.[50] As such, countries exporting construction materials, like Australia, are formally accountable for the emissions generated during production, despite the absence of formal BRI project involvement. However, through their industrial, environmental, and trade policies, these countries can influence the carbon intensity of exported materials, thereby shaping the emissions profile of BRI infrastructure far beyond their borders.

Our project-level supply chain tracing helps clarify the geographic distribution of emissions associated with BRI infrastructure. By combining bottom-up project data with global supply chain modeling, we link infrastructure demand to upstream production emissions and identify where these emissions occur across the international material supply network. Without such tracing, emission estimates risk masking the contributions of countries not formally participating in the BRI, thereby complicating efforts to design equitable and effective mitigation strategies.

Greater transparency in supply chain attribution also creates opportunities for mitigation through procurement decisions, industrial policy, and international cooperation. Given China's central role in BRI financing and coordination, it holds significant leverage over supply chain structures and associated emissions practices. Existing international and BRI-related initiatives[51,52] may serve as channels for strengthening attribution transparency and mitigation standards across participating countries. In this context, clearer attribution of embodied emissions is a prerequisite for aligning large-scale infrastructure development with global climate governance objectives.

4.3. From Modeled Potential to Real-World Mitigation

Emissions from BRI electricity infrastructure construction are predominantly associated with renewable energy projects, reflecting the growing emphasis on clean energy among China and BRI participating countries.[9] Our finding suggests that the potential emission reduction from BRI renewables could be considerable and highlights the opportunity for infrastructure to serve both development and climate mitigation goals. Beyond climate mitigation, these infrastructure investments are also associated with broader economic and social objectives, including improved connectivity, energy access, and industrial development, which should be considered when interpreting their overall sustainability implications.

At the same time, the potential operational emission reductions from BRI renewable energy projects do not diminish the importance of addressing emissions arising from construction. As the global energy system decarbonizes, the marginal mitigation benefits of new renewable capacity are expected to decline. Durable climate outcomes therefore request addressing emissions at their source, particularly in material production. Considering the key contributions of steel and cement in BRI emissions and in infrastructure emissions globally, demand-side policies, such as public procurement, quotas, or targeted subsidies, to drive adoption of low-carbon alternatives could play an important role.[53]

Additionally, well-established material efficiency strategies can be applied to BRI infrastructure to further reduce its GHG emissions, including structural specifications and design codes that support longer service life, reduce material intensity, and incorporate recycled materials like scrap steel and recycled aggregate.[54−56] Another pathway toward reducing emissions at the source is through host country−led planning, supported by inclusive consultation. National governments identify priority infrastructure types that reflect development strategies and local needs, while balancing feasibility under material and resource constraints. Aligning BRI infrastructure projects with local urban forms can prevent overexpansion and lower material demand.[56] Our analytical framework provides a basis to assess the emission impact of these interventions and to support more data-driven decision-making in sustainable infrastructure planning.

4.4. Limitations

Despite the strengths of our project-level approach, several limitations arise from data availability and methodological assumptions. First, although the BRI project data set compiled from the official portal represents the most systematic and transparent source currently accessible, omissions are still possible,[24] including projects not publicly disclosed and uncertainties in attributes such as project start years or design parameters (e.g., road width when unreported). All assumptions and data sources are documented in the Supporting Information to support cross-checking and reproducibility.

Second, the material intensity coefficients rely on archetypal values for each infrastructure type, which may not fully capture regional or temporal variations in engineering practices. The

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use of archetypes is a standard approach in large-scale bottom-up material assessments[57,58] and reflects current data constraints. Chinese standards are prioritized given the dominant involvement of Chinese firms in BRI project design. However, construction practices may vary across host countries. In regions with lower material efficiency or higher waste rates, applying archetypal coefficients based on Chinese standards may underestimate material demand. Conversely, in projects with simplified design specifications or lower structural redundancy, material use may be lower than archetypal assumptions, potentially leading to overestimation. These directional uncertainties primarily affect absolute magnitudes rather than the relative importance of major material categories or the broader transboundary attribution patterns.

Third, market-based emission factors are derived using the BONSAI hybrid SUT-MRIO framework, whose current release has a reference year of 2016. Applying a single reference year to projects spanning 2008−2024 does not capture temporal changes in trade structures or technological efficiency. Although sensitivity tests suggest that the core attribution patterns are relatively stable, the use of a single reference year cannot fully capture dynamic trade reconfigurations or technological transitions. Future updates of MRIO databases with time-varying structures would enable more temporally resolved assessments.

Finally, estimates of operational-phase emission reductions from BRI renewables represent modeled potential rather than realized outcomes. Actual reductions depend on factors such as project completion rates, grid integration, and the counterfactual generation mix displaced. These uncertainties may shift the numerical values but are not expected to alter the overall order of magnitude or the relative differences across technologies and regions. Comprehensive consequential assessments remain difficult due to limited and uneven project-level data availability across BRI regions.

4.5. Broadening the Sustainability Assessment of the BRI

Infrastructure underpins development but is deeply carbon-intensive, and the scale and reach of the Belt and Road Initiative entail both its benefits and its environmental risks. By quantifying construction-phase emissions at the project level and tracing their transboundary supply chains, this study provides a basis for evaluating the climate implications of infrastructure expansion. While renewable energy projects within the BRI portfolio may generate operational mitigation benefits, addressing emissions embedded in material production remains essential for achieving durable climate gains.

To address the overarching question of BRI's sustainability, future assessments must go beyond GHG emissions to account for a broader range of environmental pressures, such as local pollution, land use changes, and resource depletion, particularly in material-producing countries. Meanwhile, further work is needed to assess the scalability of material efficiency strategies and the viability of clean supply chains across diverse regional contexts. This is especially important given the wide range of countries involved in the BRI, each with distinct development priorities, regulatory frameworks, and institutional capacities. In this context, aligning infrastructure planning with local development needs and environmental constraints will be essential to advancing a more sustainable and equitable BRI.

■ ASSOCIATED CONTENT

Data Availability Statement

The BRI project list was compiled from weekly reports published on the official Belt and Road Initiative (BRI) website (https://www.yidaiyilu.gov.cn/list/w/xmzb), covering the reporting period from February 2021 to 2024. The compiled BRI project data set will be available on the Zenodo repository (https://zenodo.org/records/20528963) upon publication of the article. Greenhouse gas (GHG) emission intensity and material market composition data were obtained from the developers of the BONSAI Climate Footprint Analyzer (https://bonsai.uno/download-data/). Additional data sources are detailed in the Methodology section and the Supporting Information.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c17941.

Supplement figures and tables for results and parts of the data, e.g., material intensities and grid emission intensities (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Lingli Hou − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands;* orcid.org/0000-0003-1642-6340; Email: l.hou@cml.leidenuniv.nl

Ranran Wang − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands; State Key Laboratory of Water Pollution Control and Green Resource Recycling, School of the Environment, Nanjing University, Nanjing 210023, China; Institute for the Environment and Health, Nanjing University Suzhou Campus, Suzhou 215163, China;* Email: ranran.wang@nju.edu.cn

Authors

Tomer Fishman − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands*

Stefano Merciai − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands; 2.-0 LCA Consultants, Aalborg 9000, Denmark*

Takuma Watari − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands; Material Cycles Division, National Institute for Environmental Studies, Tsukuba 305-8506, Japan;* orcid.org/0000-0002-6072-3679

Yanan Liang − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands;* orcid.org/0000-0003-1862-2927

Ester van der Voet − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, Netherlands;* orcid.org/0000-0003-0788-9570

Asaf Tzachor − *School of Sustainability, Reichman University, Herzliya 4610101, Israel; Centre for the Study of Existential Risk (CSER), University of Cambridge, Cambridge CB2 1TN, United Kingdom*

Heming Wang − *State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang 110004, China; Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australian Capital Territory 2601, Australia*

Peng Wang − *State Key Laboratory for Ecological Security of Regions and Cities, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; University of Chinese Academy of Sciences, Beijing 100049, China;* orcid.org/0009-0001-1145-9605

Jun Bi − *State Key Laboratory of Water Pollution Control and Green Resource Recycling, School of the Environment, Nanjing University, Nanjing 210023, China; Institute for the Environment and Health, Nanjing University Suzhou Campus, Suzhou 215163, China*

Complete contact information is available at:
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Author Contributions

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Notes

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