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PAPER

Processing debris from destroyed and damaged buildings in Gaza: carbon emissions, time frames, and implications for rebuilding

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Abstract

Debris from destroyed buildings and infrastructure is a material representation of the human, environmental, and infrastructural devastation resulting from the destruction of Gaza. Clearing and processing debris will require a tremendous effort, calling for fleets of heavy machinery such as dump trucks and industrial jaw crushers. We estimate the carbon emissions arising from transporting debris from destroyed and damaged buildings to proposed disposal sites, and from crushing uncontaminated concrete rubble into aggregates for reuse in building blocks, roadway repair, and shoreline protection. Using open-source spatial data, we first identify the location of over 36.8 million metric tonnes of debris from buildings destroyed and damaged over the 14-month period between 7 October 2023 and 1 December 2024. Based on truck capacity and fuel consumption, we estimate that moving this debris to disposal sites for sorting and processing would require over 2.1 million dump truck loads and 29.5 million kilometres driven, which is equivalent to about 736.5 times the Earth's circumference, generating around 65 642.40 tonnes of $C0_2e$. The carbon emissions resulting from crushing uncontaminated concrete rubble and time frames required to undertake this work are highly sensitive to the type of crushers available. Assuming that 80% of the debris is viable for crushing, a fleet of 50 high-capacity industrial jaw crushers, which as far as we know are currently unavailable in Gaza, would take just over 6 months and generate around 2975.91 tonnes of $C0_2e$. With a fleet of 50 smaller crushers of the primary type used in Gaza, processing the same amount of rubble would take more than 37 years and generate around 25 148.76 tonnes of $C0_2e$. Our findings contribute to debates about the climate impacts of war and provide important insight into the time, effort and equipment required to process the immense volume of debris in preparation for the rebuilding of Gaza.

1. Introduction

Since October 2023, Palestinians in Gaza have been subjected to a campaign of violence by Israel that has killed 52 243 people, including over 18 000 children, and injured over 117 600 as of 27 April 2025, according to Palestinian Ministry of Health figures (Shurafa and Magdy 2025); when including those missing and presumed dead, the number of people killed rises to 63 243 (UN News 2025a). However, studies published in *The Lancet* project the number of people directly and indirectly killed—from injuries, lack of medical care, malnutrition, and preventable diseases—to be far greater (Khatib *et al* 2024, Jamaluddine *et al* 2025), and indicate a drastic drop in life expectancy, from 75.5 to 40 years (Guillot *et al* 2025). Exacerbating human loss and suffering is Israel's systematic targeting of essential infrastructure and services in Gaza, including hospitals, clinics, medical staff and first responders, universities and schools, water and public utilities, roads and residential buildings, and the prevention of food, humanitarian aid, medical supplies, medical

Figure 1. View of destruction in northern Gaza, February 2024. Credit: Abdullah Al-Haj / UNRWA, used with permission.

equipment, and medical personnel from entering Gaza (Asi *et al* 2024). An estimated 1.9 million people, or 90% of Gaza's inhabitants, have been internally displaced, often multiple times, due to Israeli military violence and directives (Agence France-Presse 2024). Mass forced displacement has further facilitated the controlled destruction of buildings across Gaza by Israel's military, including hospitals, universities, and residential areas (Bellingcat 2024).

The targeting of physical infrastructure has created a situation of immense destruction (see figure 1 for a visual depiction). By some estimates, 88% of infrastructure in Gaza is destroyed or damaged (Aladam 2025). According to United Nations Satellite Centre (UNOSAT) data from December 2024, the United Nations Environment Programme (UNEP) estimates there to be 50.7 million metric tonnes of debris from destroyed and damaged buildings, roads, and other infrastructure (United Nations Environment Programme (UNEP) 2024a). This staggering volume of debris poses significant challenges for reconstruction when Palestinians are free from bombardment and military occupation and able to rebuild. In this study, we focus on the tremendous task of processing debris from destroyed and damaged buildings in Gaza along with their associated carbon emissions. By doing so, we aim to contribute to debates about the climate impacts of war and provide insight into some of the substantial logistical challenges of clearing and processing building debris in preparation for Gaza's reconstruction. Specifically, we estimate carbon emissions arising from transporting building debris to UNEP-proposed disposal sites, and from crushing uncontaminated concrete rubble into aggregates to be reused in building blocks, for road repair, or for shoreline protection.

Using open-source spatial data, we first identified the location of over 36.8 million tonnes of debris from damaged and destroyed buildings. Based on truck capacity and fuel consumption, we estimate that moving this debris to disposal sites for sorting and processing would require over 2.1 million dump truck loads and 29.5 million kilometres driven, which is equivalent to about 736.5 times the Earth's circumference, generating around 65 642.40 tonnes of C02e. Processing debris at disposal sites requires machinery and labour, and the resulting carbon emissions, work and time frames required are highly sensitive to the type of crusher available. Assuming 80% of the debris is uncontaminated and viable for crushing, a fleet of 50 high-capacity industrial jaw crushers, which as far as we are aware are not currently available in Gaza, would take just over 6 months and generate around 2975.91 tonnes of C02e. With a fleet of 50 smaller crushers, which are the primary type used in Gaza, processing the rubble would take more than 37 years and generate around 25 148.76 tonnes of C02e.

Of course, we recognise carbon emission estimates to be oversimplified proxies for understanding the complex, multi-faceted, and enduring climate and environmental impacts of war and reconstruction

(Neimark *et al* 2024). Yet our findings do underscore the importance of considering debris removal and processing, which thus far has been an underexplored area in the calculation of military emissions (de Klerk *et al* 2024). Moreover, our approach seeks to overcome challenges associated with quantifying climate impacts of war when direct data collection is not possible by utilising novel estimation methods (Zhang *et al* 2023, Meaza *et al* 2024). Our study thus adds to the growing scientific and policy interest in military-emissions, climate reparations, and reconstruction (Pereira *et al* 2022, Cifuentes-Faura 2023, Bun *et al* 2024). Most importantly, we hope our study is useful for the policymakers, urban planners, civil engineers, and workers who will ultimately be responsible for planning, coordinating, and undertaking the work of rebuilding Gaza.

1.1. Environmental impacts of war and military emissions

There exists a significant body of literature examining the environmental devastation of war and its long-lasting impacts on people and the planet (e.g., radioactive fallout of nuclear bombs dropped on Japan; Okajima *et al* 1978). More recent scholarship builds on data collected in the aftermath of US-led wars on Afghanistan (2001–2021) and Iraq, specifically, the Second Gulf War (2003–2011), and from multiple Israeli bombardments of Gaza (since 2008) (Griffiths and Rubaii 2025, Neimark *et al* 2024, Specht *et al* 2025). Understandably, a key focus area of this work is environmental contamination from weapons containing toxic heavy metals and/or radioactive materials, such as uranium, and their health consequences, such as birth defects (Rubaii 2020). Scholars have also sought to theorise and investigate the wider impacts of war utilising approaches that resemble lifecycle and supply-chain analyses. These approaches emphasise that to fully appreciate the environmental and human devastation of war requires looking beyond consequences to war's 'beforemath,' including the extractive and exploitative processes of mining minerals used in weaponry (e.g., mining metals for weapons manufacturing; Griffiths and Rubaii 2025), the supply-chain in the specific enactment or war, including structures such as bases and barriers (e.g., procuring, building, and deploying concrete barriers; Larbi *et al* 2025), and reconstruction or 'clean-up' efforts, for their role in masking and spreading the toxic fallout of war (e.g., moving, disposal, and storage of toxic materials; Rubaii and Griffiths 2025).

A parallel, more policy-oriented body of research focuses on articulating the environmental damage of war through the lens of carbon emissions, or war- and military-related emissions. The contribution of military activity to climate change is massive. For instance, even when not engaged in warfare, the maintenance of military bases and equipment are significant contributors to climate change and estimated to account for about 5.5% of global carbon emissions (Parkinson and Cottrell 2022). In the UK, military emissions are thought to account for upwards of 50% of total central government emissions (UK Gov 2024). While we recognise that the focus on carbon emissions is itself reductive and can never capture the totality of environmental devastation associated with military activity and war-making, especially from the perspective of victims, its simplicity as a policy instrument in terms of measurement, comparison, and monetisation (e.g., carbon offsets and climate reparations) has pushed the question of carbon emissions to the fore of global climate policy debates (Rajaeifar *et al* 2022). Of course, carbon emissions are only useful as a policy instrument if they are adequately measured and assessed in relation to emissions targets.

Given the significant contribution of military activities to global emissions, it is perhaps of little surprise that countries, especially those with large military carbon footprints, are reluctant or unwilling to publish military emissions data (Vogler 2024). This reluctance is further enabled by a lack of consensus at the level of global climate diplomacy concerning mandatory reporting of military emissions data. For instance, the question of military emissions reporting was exempt from the 1997 Kyoto Protocol and 2015 Paris Agreement, appearing in the current UN Framework Convention on Climate Change as a voluntary requirement only (Mcfarlane and Volcovici 2023, Kinney 2024). For these reasons, the question of mandatory reporting of military emissions is a point of urgency and convergence for researchers and climate advocates seeking to address this military-emissions gap. Researchers at the Conflict and Environment Observatory have advanced a military emissions reporting framework that lists activities related to military maintenance, activity, and warfare across Scope 1, 2, 3, and 3+ categories of emissions. In their framework, military emissions caused by warfare largely fall under Scope 1 and 3+ categories, with the former accounting for fuel combustion and the latter encompassing the various human, environmental, and infrastructural consequences of war, including infrastructure damage, debris management, and reconstruction of buildings destroyed by war (Conflict and Environment Observatory 2022).

The Russia–Ukraine war has boosted policy interest in accounting for war- and military-related carbon emissions and is the first context of war about which a comprehensive assessment using a military emissions framework has been undertaken (de Klerk *et al* 2024). Ukraine officials and experts have presented military emissions estimates at successive UN Climate Change Conference meetings to both communicate the scale of climate devastation resulting from the Russia–Ukraine war and as an instrument to support the case for

financial reparations (Kopytsia 2024). Researchers have since applied like frameworks to assess military carbon emissions associated with Israel's war on Gaza, with a shocking estimate of 1 898 330 tonnes of $C0_2e$ from direct military activities over the first 15 months of warfare alone, and upwards of 32 275 089 tonnes of $C0_2e$ when including estimates for pre- and post-war (re)construction activities (Neimark *et al* 2025). Our study complements this work by focusing on the carbon emissions resulting from the work of transporting and processing debris from destroyed and damaged buildings in Gaza.

1.2. Experiences and challenges of processing debris in Gaza

In Gaza, the safe removal, transportation, crushing, and recycling of building debris is complicated by the presence of victims' remains, unexploded ordnances (UXOs), asbestos, and other substances that may be hazardous. For instance, in its preliminary assessment released on 18 June 2024, the UNEP estimated that over 800 000 tons of debris were likely contaminated with asbestos and would therefore have to be transported and processed separately as hazardous waste (United Nations Environment Programme (UNEP) 2024b). Although the exact quantity and location of UXOs in Gaza is still unknown, the United Nations Mine Action Service indicates that between 5% and 10% of explosive weapons may not have detonated on impact (UN News 2025b). As of January 2025, Gaza's government media office estimated that Israel has fired or dropped over 100 000 tonnes of explosives on Gaza since October 2023 (Aladam 2025), implying between 5000 and 10 000 tonnes of UXOs[4].

As a result of prior Israeli bombardments in Gaza (i.e., 2009, 2021, 2014, and 2021), combined with military occupation and blockade of materials essential for construction, Palestinians in Gaza have developed expertise, protocols, and practices associated with debris and demolition waste management (Abu Hamed *et al* 2023). For example, after the 2021 bombings, debris processing involved several steps, beginning with on-site assessment of damaged buildings, UXO removal, and separation of hazardous waste from rubble. Next, debris was transported to several processing sites, including the Juhr Al Deek landfill in northern Gaza, the primary disposal site utilised by the UNDP. At the landfill, hazardous waste was stored separately for recycling, treatment, or disposal. Uncontaminated rubble was sorted by material type, revealing a composition of 88% concrete, 8.6% non-concrete, and 3.4% reinforced concrete. Smaller concrete pieces were crushed on-site or sold to the private sector for reuse in building blocks and road pavements, while larger reinforced concrete foundations were transported off-site for purposes such as shoreline protection and land reclamation (Abualtayef *et al* 2018). Of the 122 525 metric tonnes of rubble brought to Juhr Al Deek in 2021, upwards of 111 621 tonnes were reportedly crushed, indicating that recycling rubble could play an important role in reconstruction. Recycling debris using local machinery and labour thus enabled Palestinians in Gaza to reclaim materials that were difficult or impossible to procure because of the long-running military occupation, blockade and siege of Gaza.

As noted in the introduction, UNEP estimates there to be 50.7 million metric tonnes of debris from destroyed and damaged buildings, roads and other infrastructure (United Nations Environment Programme (UNEP) 2024a). For comparison, the debris resulting from the 2021 bombardment of Gaza was estimated to be 335 658 tonnes (Abu Hamed *et al* 2023). As these figures show, the current volume of estimated debris from destroyed infrastructure in Gaza is unprecedented in its long experience of military occupation and routine bombardment by Israel. In fact, the current volume of debris from destroyed and damaged buildings and infrastructure in Gaza is almost 17 times more than the combined sum from all other bombardments of Gaza since 2008 (United Nations Institute for Training and Research 2024). To put this into perspective, were the total amount debris from destroyed and damaged buildings since October 2023 spread over the entirety of Gaza (approximately 356 km^2), each square metre of Gaza would contain an estimated 142.4 kg of debris. The work of clearing and processing this debris poses immense coordination and physical challenges and will lead to enduring environmental and health risks.

Removing and processing this huge volume of debris could take years or even decades, and lead to additional waves of displacement as structurally unsound buildings are demolished or repaired (Akram *et al* 2024). It also means that the toxic fallout from the destruction of Gaza and associated environmental and health risks from the existence and processing of debris is likely to last generations (Rubaii and Griffiths 2025). Debris is repeatedly unsettled as survivors search for loved ones, or when searching for wood to burn or other usable materials. Contaminated materials, soil, and dust will also be disturbed and inevitably spread during efforts to identify and dispose of UXOs and hazardous materials, and during the work of clearing and

[4] As a comparison, the atomic bombs dropped on Hiroshima and Nagasaki by the US were roughly equivalent to 15 000 and 21 000 tonnes of explosive power, respectively (Atomic Heritage Foundation 2014), and the 2020 Beirut port explosion was roughly 2,750 tonnes of explosive power (Hernandez and Scarr 2020). This means that the explosive power of weaponry fired on Gaza is almost three times the explosive power of Hiroshima and Nagasaki combined, and the amount of UXOs in Gaza equals 12–24 times the explosive power of the Beirut port explosion.

processing debris at disposal sites (Siebielec and Chaney 2012). Moreover, in addition to carbon, various toxic pollutants are released from the combustion of diesel fuel for operating heavy trucks and crushers. There are also toxins and carbon embodied in materials that are consumed during the debris management process, such as polythene sheets and tyres, and in depreciating equipment. While these factors will have far-reaching consequences for public health, safety, and the environment, we do not account for them in our analysis.

2. Method

We began by constructing a spatial map of building debris across Gaza using open-source satellite data, with the goal of identifying the location of destroyed and damaged buildings and estimating the quantity of debris at each site. The debris map draws from a variety of spatial datasets that differ slightly in their representation of building sites (e.g., as polygons vs. points), in the exact location they assign to a site, or in the date ranges during which the data was collected. For instance, the dataset used to quantify the extent of damage to building sites is based on satellite imagery taken on 1 December 2025, and how these images compare to previous observations between May 2023–September 2024 (UNOSAT 2024a). In contrast, one of the datasets we used to estimate the height of buildings—an important factor in the quantity of possible debris—originates from responses to the Palestinian Central Bureau of Statistics'(PCBS) 2017 census (Palestinian Central Bureau of Statistics (PCBS) 2021). In our analysis, we assume that physical building characteristics, such as height or surface area, vary more slowly over time than damage and destruction to buildings since October 2023, and are therefore still useful for estimating debris when combined with timely estimates of damage.

To unify datasets into a consistent map of debris across Gaza, we matched them to a map of building footprints (surface areas represented as polygons) from Microsoft's Global Building Footprints Dataset (ao68 2022), based on satellite imagery collected between 2014 and 2024. These building footprints, identifying both building location and surface area prior to any destruction since October 2023, serve as a common reference point for matching features from other spatial datasets. To identify which buildings have been destroyed or damaged since October 2023, we obtained building damage classifications from UNOSAT's Comprehensive Damage Assessment, which classifies damage at each building site (represented as a point) with labels such as 'moderately damaged,' 'severely damaged,' or 'destroyed,' based on changes in satellite imagery between May 2023 and December 2024 (UNOSAT 2024a). We matched each building footprint to the single nearest damage classification point within a radius of 4 m. If a footprint was within 4 m of several damage classifications, it would inherit the highest level of damage. For example, a footprint near both 'destroyed' and 'moderately damaged' points was classified as destroyed. Footprints of more than 4 m from any damage classification point were assumed to be intact. The cut-off of 4 m was chosen to allow a greater number of footprints to be matched with damage classifications that are slightly misaligned, without overclassifying the number of destroyed or damaged buildings. Figure 2 illustrates the matching of damage classification points to building footprints near the centre of Khan Younis. Most footprints are matched to a single point where they overlap, but some deviate by a few metres, and others contain several points of differing damage classifications.

In addition to data about building location, surface area, and damage classification (intact, moderately damaged, severely damaged, or destroyed), our calculations require data about the number of storeys for each building. This is because the quantity of debris generated by the destruction of a building is closely related to its total living space, calculated by multiplying the number of storeys by its surface area. While this is similar to estimating debris by volume, using the number of storeys accounts for the fact that buildings with fewer floors are likely to generate less debris than buildings with a greater number of floors, even if their overall height is the same. Following the approach of the United Nations Environment Programme (UNEP) (2024b), we assume that each square metre of destroyed living space produces about 1 metric tonne of debris. In the spatial debris map, the quantity of debris is calculated by multiplying the surface area of each footprint classified as 'destroyed' by the number of storeys. For footprints classified as 'severely damaged' or 'moderately damaged', we replicate the same procedure, with the caveat that they likely produce a fraction of the debris generated by destroyed buildings. In the results section, we report the full emissions associated with each damage classification, as well as 'weighted' emissions that would arise if buildings with lower damage classifications produced less debris.

Since the storey count for each destroyed or damaged building is not provided in the UNOSAT damage classifications or the Microsoft building footprints, we instead utilised a dataset from the PCBS public spatial data repository with building attributes derived from the 2017 census, including the number of storeys (Palestinian Central Bureau of Statistics (PCBS) 2021). Still, some of our baseline footprints lacked nearby

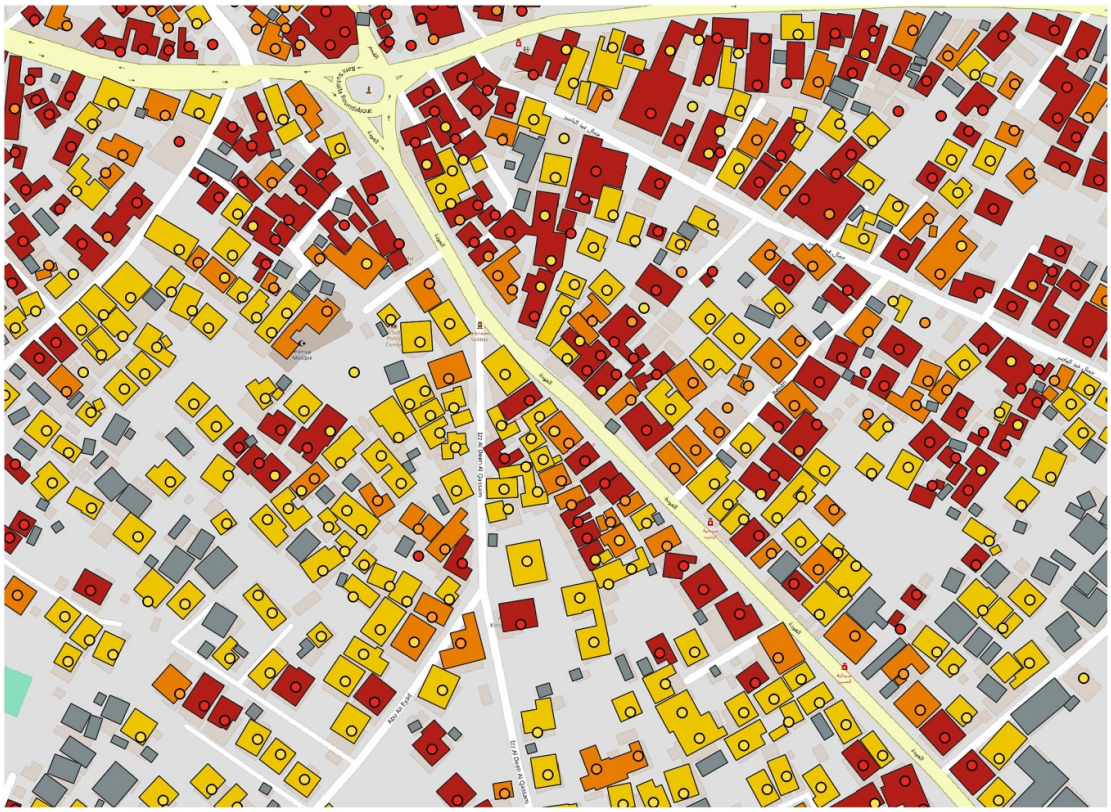

Figure 2. Matching building footprints to nearby damage classifications. Affected footprints inherit the highest damage classification of points within 4 m: moderate damage (yellow), severe damage (orange), and destroyed (red). Footprints for which there are no points within 4 m are assumed to be intact (grey). Map data from © OpenStreetMap contributors.

PCBS points, and some PCBS points had missing storey count values. To fill these gaps, we used the 'Average of Net Building Height' (ANBH) layer from Copernicus' Global Human Settlement Building Height dataset, which provides the average height in metres of built-up structures within a 100 m × 100 m grid across Gaza (Pesaresi and Politis 2023). For footprints missing a storey count, we assigned the height of the ANBH grid in which they are located. The inherited height was then converted into an approximate storey count by assuming each storey is 3 m tall and rounding to the nearest whole number. Overall, we found that about 55 000 or 19% of building footprints in the Microsoft database lacked a corresponding nearby PCBS building point, and thus required the ANBH raster to approximate storey count.

Figure 3 illustrates the matching of building footprints to nearby PCBS storey points around a street of Bureij, Deir al-Balah. Most footprints are matched to the single point they overlap; some are matched to points located within 4 m, and others are matched to multiple PCBS points where they overlap. In the case where a footprint overlaps multiple PCBS points, it inherits the average number of storeys rounded to the nearest whole number. Averages resulting in midpoint values (e.g., 0.5, 1.5, 2.5) are rounded down to prevent overestimating storey counts of buildings overlapping only two PCBS points.

Combining surface area from building footprints and story counts enabled us to create a map from which to estimate debris generated by destroyed and damaged buildings, as illustrated in figure 4. This also allows us to calculate the number of truckloads or trips required by a typical transport truck (i.e., dump truck) to clear all the debris from a given building site. The number of full truckloads is calculated by dividing the total debris at each building site by the truck maximum load capacity and rounding down to the nearest whole number. We assume that each dump truck has a maximum carrying capacity of 19 tons (≈17.24 metric tonnes) or around 12 cubic metres. This is the same capacity assumed by the UNEP to estimate the total time it may take to remove all the debris in Gaza; that is, with a fleet of 105, 19-ton capacity dump trucks operating in 8 h shifts for 30 d a month, debris removal could take up to 15 years (United Nations Environment Programme (UNEP) 2024b).

In addition to the number of truckloads, the carbon emissions arising from debris transport also depend on the distance each truckload must travel from building to the disposal sites. Although there is still some uncertainty regarding the exact location and capacities of disposal sites, we adopt the disposal site locations

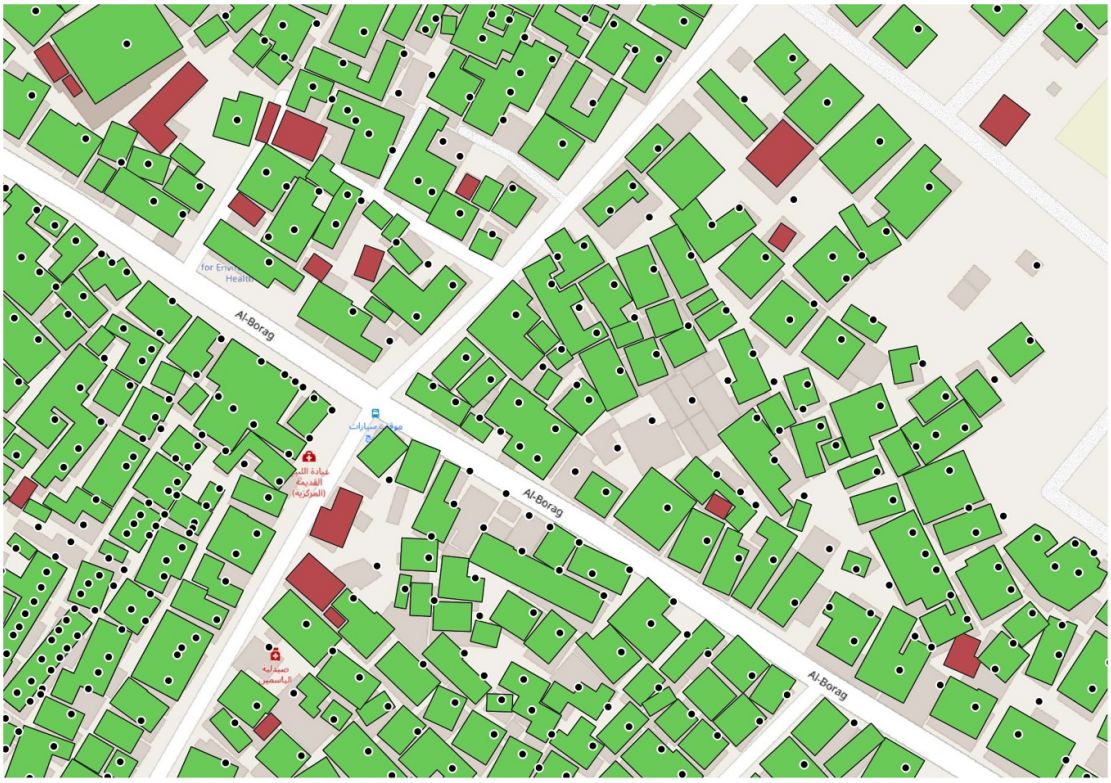

Figure 3. Matching building footprints (green if within 4 m of a PCBS point; red otherwise) to nearby PCBS points containing storey count information (black). Map data from © OpenStreetMap contributors.

proposed by the UNEP in its preliminary assessment (United Nations Environment Programme (UNEP) 2024b). We also assume trucks will travel the shortest path along Gaza's network of streets and roads between a given building site and the nearest proposed disposal site. Although the road network in Gaza has also been largely destroyed and will require both debris removal and large-scale reconstruction, for simplicity, in our calculations we assume the road network resembles Gaza's 2021 road network (United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) 2021).

As of 18 August 2024, UNOSAT estimated that approximately 31% of the road network in Gaza was moderately affected, 8.9% severely affected, and 25.4% destroyed (UNOSAT 2024b). Figure 5 highlights shortest paths calculated from 5 different destroyed buildings in Khan Younis to the nearest disposal sites. Since shortest paths must follow the topology of the roadways, this offers a more realistic distance metric than simply following a straight line to disposal sites.

The total distance driven to clear all debris from a given destroyed or damaged building site can be estimated by multiplying the number of full truckloads by the shortest distance to the nearest disposal site. The cumulative distance driven by trucks to clear the debris across Gaza is obtained by summing over the total distances from all destroyed or damaged building sites. When multiplied with an appropriate carbon emission factor, the cumulative distance yields the total carbon emissions (CO_2e) generated by the transportation of debris from buildings to disposal sites. The typical carbon emission factor for heavy transport trucks can vary significantly across vehicle model, road conditions, and geographical region, but likely ranges between 100–200 g CO_2e/tonne km. Climatiq (2024) estimates an emissions factor for medium- and heavy-duty freight trucks of 169.4 g CO_2e/ton-mile, or around 116.1 g CO_2e/tonne-km, based on the Environmental Protection Agency's GHG Emission Factors Hub. The International Council on Clean Transportation reports average emission factors for different truck types across the European Union, including 111.0 g CO_2e/tonne-km for 6 × 2-axle regional delivery trucks, 197.2 g for 4 × 2 regional delivery trucks, and up to 307.2 g for 4 × 2 urban delivery trucks (Ragon and Rodríguez 2021). Given that most of the transportation of debris in Gaza will occur in urban areas and will likely require a minimum of 3 axles to handle a 19-ton debris load, we assume a carbon emission factor of 172.1 g CO_2e/tonne-km, obtained by scaling up the 6 × 2-axle regional delivery factor to reflect the 1.55-fold increase of the 4 × 2-axle factor between regional and urban settings.

Since these carbon emission factors are normalized by carrying load, we must first multiply them by the assumed maximum capacity of the truck, before multiplying them by the cumulative transportation distance

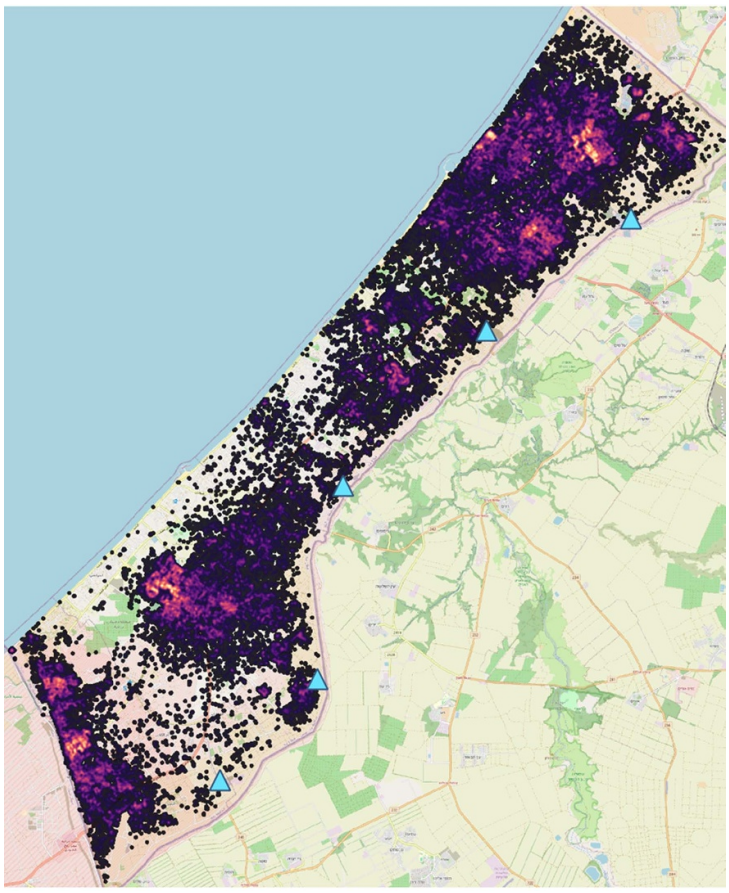

Figure 4. Heatmap of estimated debris (in tonnes) generated by destroyed buildings. Brighter areas indicate the presence of larger quantities of debris. Blue triangles indicate disposal sites proposed by the United Nations Environment Programme (UNEP) (2024a). Map data from © OpenStreetMap contributors.

to obtain total carbon emissions. However, with a limited number of trucks available, trucks will likely need to return to a building site after each disposal trip. In this case, the cumulative distance driven by all trucks could nearly double, but with a lower carbon emission factor for unloaded return trips. The impact of load on the carbon intensity of a truck is still an ongoing topic of research, but one study found that overall emissions increased on average by 34% for loaded trucks relative to their unloaded counterparts (Frey *et al* 2008). Another found that carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbon (HC) and particulate matter emissions increased by 20.4%, 23.5%, 29.0%, 11.7%, and 9.4% respectively in fully loaded trucks when compared to their unloaded counterparts (Zhang *et al* 2017). Since carbon dioxide and nitrogen oxides are the two primary pollutants in diesel engines (Reşitoğlu *et al* 2014), an increase in emissions of 20%–34% from fully loading an empty truck would imply that emissions for unloaded trucks may be between 74%–83% of their fully loaded counterparts. However, to ensure the estimate of return trip emissions remains conservative, we assume that the carbon emissions for unloaded trucks is only 50% of their loaded counterparts.

In addition to the CO_2e generated by the transportation of debris, we also estimate the carbon emissions generated by processing debris once it has arrived in landfills. In particular, we estimate the emissions associated with operating crushers to convert concrete rubble into aggregates for reuse in reconstruction. Although there is still some uncertainty regarding the exact proportion of rubble that is viable for crushing, we may be able to approximate it by deducting the quantity of contaminated debris from the total estimated with the spatial debris map, and then scaling the remaining amount by the proportion of rubble that was crushed after previous bombardments in Gaza. We assume that the proportion of debris contaminated by asbestos remains roughly equivalent to the proportion estimated by the UNEP in June 2024: 725 748 metric tonnes of asbestos-contaminated debris divided by their total estimate of 32 296 660 tonnes generated by destroyed buildings, or roughly 2.2% of total debris (United Nations Environment Programme (UNEP) 2024b). However, there are other forms of contamination besides asbestos which may require hazardous waste disposal, such as heavy metals, chemicals used in agricultural and industrial processes, and biohazardous materials. For a conservative estimate of crusher emissions, we therefore assume that

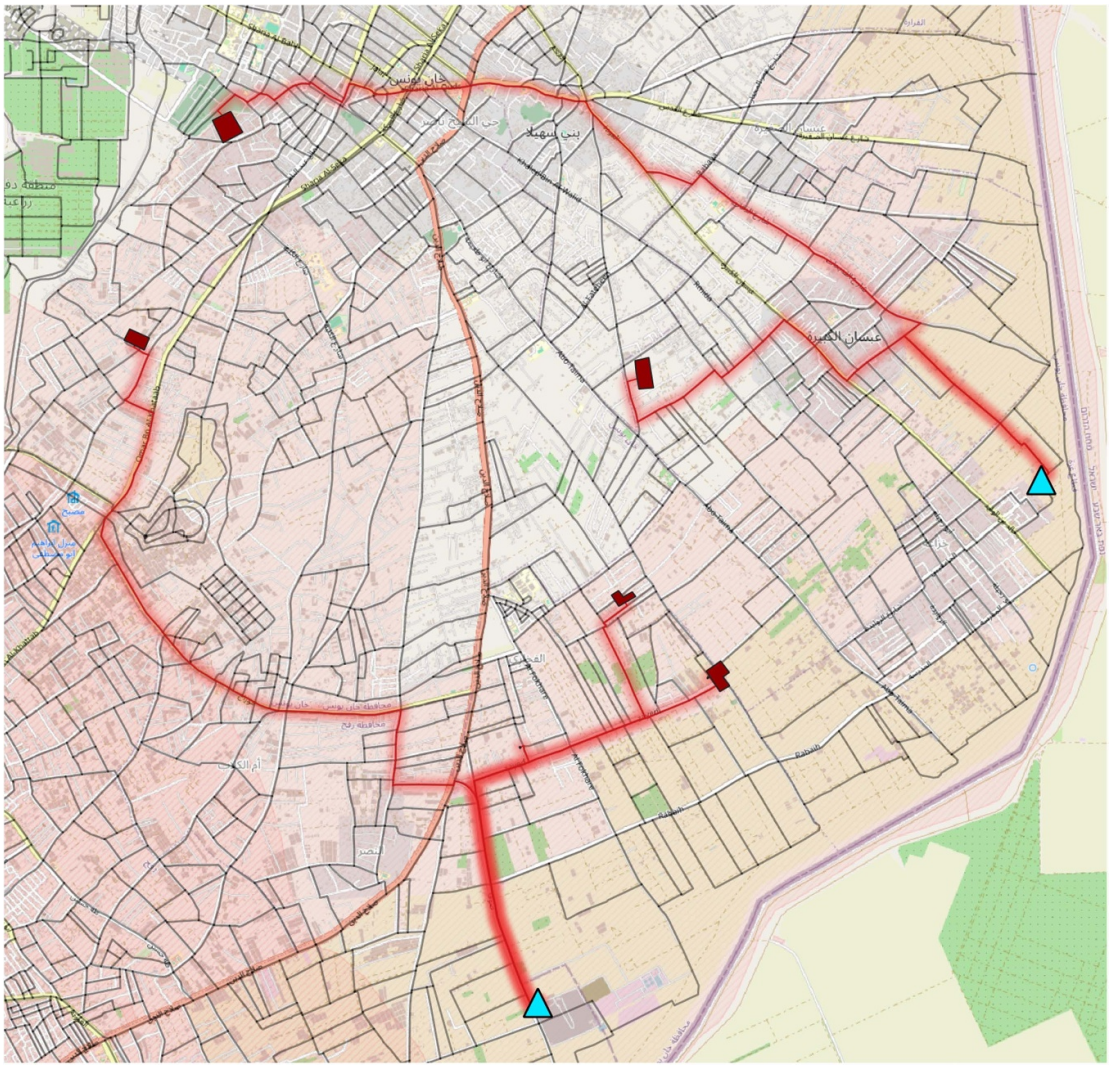

Figure 5. Shortest paths (red lines) from 5 destroyed buildings (dark red polygons, enlarged for visual emphasis) to nearest disposal sites (blue triangles) along Gaza's 2021 road network (black lines). Map data from © OpenStreetMap contributors.

potentially up to 10% of the total rubble generated could be designated as hazardous waste. We then assume that only 88% of the remaining uncontaminated rubble is composed of concrete elements which can be crushed. This proportion reflects the estimate that 88% of the total debris was composed of non-reinforced concrete elements at Juhr Al Deek in 2021 (Abu Hamed *et al* 2023) as well as the UNDP's plan to crush 300 000 out of 340 000 tons (≈88.2%) of removed rubble following the 2009 bombardment (United Nations Development Programme (UNDP) 2010). We also recognise that building debris will contain non-concrete building materials, such as steel and other metals, ceramic tile, stone, furniture, etc., all of which require separation and sorting prior to transportation and processing. We assume that these were also taken into consideration in the above mentioned case. Taking all of these assumptions together would imply that approximately 80% of the total debris transported to landfill sites may be viable for crushing.

Carbon emissions from operating crushers also depend on the type or model used at disposal sites. In 2012, the International Labour Organization reported that there were around 30–50 small crushers in Gaza, with a cost of around $3500 to $4000 US dollars per unit (Muhaisen and Ahlbäck 2012). In 2010, they had reported that the average monthly aggregates produced by recycling rubble were approximately 38 000 tons. Assuming 30 d of runtime each month, for 8 h a day, the total crushing capacity would be around 158 tons per hour, or around 3.2–5.6 tons per hour for each crusher. Capacities of this magnitude would likely fall in the range of an 8" × 12" jaw crusher, which can process around 2–6 tons per hour (Baker n.d.). Although similarly sized jaw crushers appear in a short 2010 documentary released by Al Jazeera on debris recycling in Gaza (Kauffman 2010), as well as in a photograph included in an Al Jazeera article about the 2021 recycling process (Alsaafin and Amra 2021), there is indication that these were not the only types of crushers used. In the article detailing the 2021 debris management process (Abu Hamed *et al* 2023), a photograph taken at one

crushing site shows a mobile crushing unit of a significantly larger size. Reverse image search revealed that the model of the jaw crusher in this photograph is likely related to an Apollo OM Jaw Crusher, with a maximum capacity of around 400 tonnes per hour, according to the manufacturer (Keestrack n.d.). However, given the scale and intensity of devastation across Gaza, we cannot be certain that any of these machines are still operational.

While it is difficult to estimate the exact proportion of smaller jaw crushers to larger mobile crushers in the fleet, it is likely that a substantial number of higher-capacity crushers are needed. In terms of the time spans associated with the work of crushing, with a fleet of only 50 6-ton capacity crushers operating for 8 h a day, 365 d a year, it could take over 37 years to process 36.8 million tonnes of debris, assuming 80% is viable for crushing. However, with a fleet of 50 400-tonne capacity crushers operating full-time, this figure drops down to just above 6 months. For simplicity in estimating emissions, we consider these two cases separately. In the first case, the fleet is assumed to be composed solely of smaller, 8" × 12" jaw crushers with an assumed capacity of 6 tons per hour. Fuel consumption varies by the engine that powers them, but may range between 1 to 6 l of petrol per hour (Honda n.d., Vykin n.d.). As a conservative estimate, we assume full-power processing of concrete consumes around 2 l of petrol per hour. In the second case, the fleet is assumed to be composed solely of larger mobile jaw crushers with a capacity of 400 tonnes per hour and a fuel consumption of around 15 l of diesel per hour (Ballytrain n.d.).

In both cases, we can estimate total emissions from operating the fleet by multiplying the total quantity of fuel consumed by the relevant carbon emission factors for diesel and petrol. According to the U.S. Energy Information Administration (2003), motor gasoline has a carbon dioxide emissions coefficient of 8.78 kg of CO_2 per litre, or roughly 2.32 kg of CO_2 per litre, whereas diesel has a slightly higher coefficient of 2.69 kg of CO_2 per litre. The estimate of carbon emissions from crushing follows by dividing the quantity of non-contaminated concrete rubble (assumed to be 80% of the total debris), by the capacity of crushers employed in the fleet (6 tons per hour for smaller crushers or 400 tonnes per hour for larger crushers), and multiplying the result by both an estimate of the fuel consumption (2 l of petrol per hour/15 l per hour) and the relevant carbon emission factor (2.32 kg of CO_2 per litre/2.69 kg of CO_2 per litre).

See Roy (2025) for Quantum geographic information system (QGIS) project files, spatial datasets, and images associated with the aforementioned estimations.

3. Results

In this section, we present our results pertaining to estimated emissions from transporting and crushing debris from destroyed and damaged buildings in Gaza, along with key figures derived using our outlined methodology. We begin by examining average estimations for properties of buildings, such as surface area and number of storeys, for each damage classification: moderate, severe, and destroyed. Table 1 shows that the number of moderately damaged and destroyed buildings greatly exceeds the number of severely damaged buildings, likely due to the latter's high structural instability and potential for collapse. On average, destroyed buildings are slightly smaller in terms of both surface area and number of stories. However, this does not necessarily indicate that smaller buildings are targeted more frequently, but likely reflects a degree of selection bias: smaller buildings are more likely to be destroyed or severely damaged by a bomb blast of a given radius, because the degree of destruction is assessed as a percentage of the building structure affected. According to a UNOSAT report from 2014, buildings were identified as 'destroyed' if 75%–100% of the building structure was collapsed or destroyed; 'severely damaged' if a 30%–75% of the structure was destroyed; 'moderately damaged' if 5%–30% of the structure was damaged or destroyed (UNOSAT 2014).

These percentages also have implications on how to aggregate the total quantity of debris across different damage classifications. In table 1, we report the full debris quantities for each damage classification, as if all damaged buildings would eventually be destroyed, but the actual quantity of debris present in Gaza is likely a fraction of this figure for moderately and severely damaged buildings. We thus employ the percentages of UNOSAT's description of damage classifications as weightings and assume that destroyed buildings generate 100% of their unweighted debris; severely damaged buildings, 75% of their debris; and moderately damaged buildings, 30% of their debris. This yields a weighted sum of 36 876 263 metric tonnes of debris—approximately 73% the magnitude of the United Nations Environment Programme (UNEP) (2024a) estimate of 50 773 496 tonnes for the same period (based on satellite imagery from 1 December 2024). The discrepancy between these estimates likely arises from differences in calculation methodology and datasets employed. For instance, the UNEP estimates include an additional 6705 178 tonnes of debris due to damage to and destruction of roads. It is also possible that the 0.30/0.75/1 weights we employ to aggregate debris from moderately damaged, severely damaged, and destroyed buildings are more conservative. Increasing the weight for moderately damaged buildings from 0.3 to 0.5, reflecting that many buildings with moderate damage may have to be demolished during reconstruction due to structural instability, yields a

Table 1. Estimated debris quantities.

Building damage classification	Number of buildings	Avg. Surface area (Sq. Meters)	Avg. Storey count	Avg. Quantity of debris (Tonnes)	Avg. Quantity of debris (Tonnes)	Qty. of debris - weighted[a] (Tonnes)
Moderate damage	51 147	206.93	2.44	549.24	28 092 055.26	8427 616.58
Severe damage	8555	222.15	2.31	562.22	10 432 020.40	7824 015.30
Destroyed	53 997	178.79	1.92	381.95	20 624 631.35	20 624 631.35
Total	**123 699**	—	—	—	**59 148 707.01**	**36 876 263.23**

[a] Weighted quantities represent the debris sum, scaled by damage classification: 30% for moderate damage, 75% for severe damage, and 100% for destroyed buildings.

Table 2. Estimated distances driven.

Building damage classification	Avg. Distance to nearest disposal site (Kilometres)	Avg. Number of full truckloads	Total number of full truckloads	Total number of full truckloads - weighted	Total distance[a] to nearest disposal site (Kilometres)	Total distance to nearest disposal site weighted (Kilometres)
Moderate damage	6.71	31.88	1630 360	489 108	11 405 724.38	3421 717.32
Severe Damage	6.79	32.63	605 443	454 082	4179 874.60	3134 905.95
Destroyed	6.69	22.17	1197 035	1197 035	8201 362.24	8201 362.24
Total	—	—	**3432 838**	**2140 225**	**23 786 961.22**	**14 757 985.51**

[a] Total distances represent the sum of all distances to disposal sites, taking into account the total number of truckloads required to clear the debris from each destroyed or damaged building.

total weighted estimate of 42 494 674. When the UNEP's estimate for roads is also factored in, the resulting 49 199 852 tonnes closely aligns with the UNEP's figure.

Table 2 highlights key factors for estimating the cumulative distance trucks may travel when transporting debris from destroyed or damaged buildings to UNEP-proposed disposal sites. With relatively equal average distances to the nearest disposal site, differences in cumulative distance depend largely on the quantity of debris present at building sites. For buildings classified as moderately and severely damaged, around 50% more full truck loads are required to clear the debris on average, assuming that buildings of all damage classifications would eventually be demolished. However, if we assume that moderately damaged and severely damaged buildings generate less debris than destroyed buildings, the overall cumulative distance is lower. Adopting the same percentages as before, the weighted sum of 100% of the cumulative distance for destroyed buildings, 75% of the distance for buildings classified as severely damaged, and 30% for those classified as moderately damaged yields a cumulative distance of 14 757 985.51 km. To contextualize this figure, the equatorial circumference of the Earth is around 40 075.017 km (Wikipedia n.d.), implying that the total distance driven by transport trucks to clear the current quantity of estimated debris in Gaza—assuming trucks travel only one-way with a full capacity to the nearest proposed disposal site—would wrap around Earth's equator 368.25 times. This does not account for the fact that trucks often must return to a building site with an empty load. In the case of destroyed buildings, which tend to be smaller in volume than moderately or severely destroyed ones, over 95% of the buildings require more than one full truckload, indicating that the cumulative distance driven could effectively double to 736.5 times around the Earth's equator.

Table 3 summarizes the carbon emissions associated with the transportation of debris from destroyed and damaged buildings to the nearest disposal sites (outbound), and the journey from disposal sites back to the same building site with an empty payload (inbound). It is important to note that the extent to which inbound trips contribute to total emissions is difficult to estimate for buildings requiring less than two full truckloads. However, given that a significant majority of buildings will require more than two truckloads to clear their associated debris, for instance, 95% in the case of destroyed buildings, we assume that each outbound trip is accompanied by an inbound trip of the same distance. Since emissions from empty

Table 3. Estimated transportation emissions.

Building damage classification	Outbound transport emissions[a] (Tonnes CO_2e)	Outbound transport emissions - weighted (Tonnes CO_2e)	Inbound transport emissions (Tonnes CO_2e)	Inbound transport emissions - weighted (Tonnes CO_2e)
Moderate damage	33 821.20	10 146.36	16 910.60	5073.18
Severe Damage	12 394.51	9295.88	6197.26	4647.94
Destroyed	24 319.36	24 319.36	12 159.68	12 159.68
Total	**70 535.07**	**43 761.60**	**35 267.54**	**21 880.80**

[a] Outbound emissions refer to those generated during transport of debris to disposal sites, while inbound emissions cover the return trip with an empty truck.

Table 4. Estimated crusher emissions.

Building damage classification	Qty. of Debris viable for crushing[a] (Tonnes)	Large crusher emissions (Tonnes CO_2e)	Large crusher emissions - weighted (Tonnes CO_2e)	Small crusher emissions (Tonnes CO_2e)	Small crusher emissions - weighted (Tonnes CO_2e)
Moderate damage	22 473 644.21	2267.03	680.11	19 158.13	5747.44
Severe Damage	8345 616.32	841.86	631.40	7114.40	5335.80
Destroyed	16 499 705.08	1664.41	1664.41	14 065.52	14 065.52
Total	**47 318 965.61**	**4,773.30**	**2,975.91**	**40 338.05**	**25 148.76**

[a] Assumes that 20% of total debris is contaminated by hazardous waste or composed of non-concrete and reinforced concrete elements, and therefore unsuitable for crushing.

inbound trucks were estimated to be 50% of the emissions of full outbound trucks, the overall effect of including inbound trucks scales total emissions up by 50%. As before, we estimate the weighted sum of emissions using the percentages of the building structure affected for each damage classification, resulting in a weighted total of 65 642.40 tonnes of CO_2e.

Table 4 displays the carbon emissions associated with the crushing of non-contaminated concrete rubble, which is assumed at 80% of the total debris. We further assume that the entire fleet is composed of one of the following types of crushers: (i) 50 large 400-tonne capacity mobile jaw crushers, which we are almost certain are not currently available in Gaza; or (ii), 50 smaller, 6-ton (or equivalently 5.44 tonne capacity) jaw crushers of the type previously used in Gaza. Despite motor gasoline having a slightly lower carbon emission factor than diesel, the lower capacity of the smaller crushers relative to their fuel consumption would result in significantly greater emissions. Aggregating the emissions of these cases with the UNOSAT weightings yields overall carbon emissions of 2975.91 tonnes of CO_2e for a fleet of 50 large crushers, and 25 148.76 tonnes of CO_2e for a fleet of 50 small crushers. Both emissions are significantly lower than the overall emissions associated with transporting debris. In terms of the actual time it might take to physically process the assumed 80% non-contaminated concrete rubble, we estimate that it would take just over 6 months for the fleet of 50 large crushers and more than 37 years for the fleet of small crushers. What our calculations show is that both emissions and processing time are significantly reduced with industrial-scale crushers.

Table 5 displays the quantities of debris arriving at each proposed disposal site, disaggregated by damage classification, and the approximate location of each site. This provides an overview of the quantities of debris that might be transported to each site, prior to any adjustment for contamination or crusher material suitability, if minimizing cumulative transportation distances along the road network was the only criterion used to allocate debris.

To aggregate these quantities into a more realistic estimate of current debris in Gaza, we employ the UNOSAT percentages to produce weighted sums in the final column of table 5. The weighted sums indicate that Disposal Site 5, corresponding to the proposed disposal site located between Gaza City and North Gaza, may require the greatest capacity if debris is routed in a way that minimizes distance travelled. If other allocations of debris are pursued, they will likely be associated with greater cumulative distances to transport building debris to disposal sites and thus greater carbon emissions from transportation.

Table 5. Estimated debris quantities by disposal site.

Disposal site (Index)	Approx. Location (Latitude / Longitude)	Qty. of debris nearest to site: moderate damage (Tonnes)	Qty. of debris nearest to site: severe damage (Tonnes)	Qty. of debris nearest to site: destroyed (Tonnes)	Total (Tonnes)	Total weighted (Tonnes)
1	31.269393/ 34.321974	3180 110.59	1092 496.92	3880 459.27	8153 066.79	5653 865.14
2	31.312357/ 34.368393	3743 037.23	1343 302.75	3016 404.21	8102 744.19	5146 792.44
3	31.392757/ 34.379981	2373 940.09	759 667.355	1570 993.16	4704 600.79	2852 925.85
4	31.458955/ 34.450527	5897 445.11	2482 196.32	5196 100.65	13 575 742.08	8826 981.42
5	31.504582/ 34.518419	12 897 522.24	4754 356.86	6960 674.06	24 612 553.16	14 395 698.37
Total	—	**28 092 055.26**	**10 432 020.40**	**20 624 631.35**	**59 148 707.01**	**36 876 263.23**

4. Discussion

Our study estimates the carbon emissions and possible time frames associated with two essential activities associated with clearing and processing the immense volume of debris in Gaza: the transportation of debris from the location of destroyed and damaged buildings to waste management sites, and crushing uncontaminated concrete debris for reuse. In doing so, we contribute to two areas of the literature. The first is the body of work examining war's 'aftermath' (Rubaii and Griffiths 2025), which challenges binary notions of war versus 'post-war' impacts, conceptually linking the generational fallout associated with reconstruction and clean-up activities with wider (even global) human, environmental, economic, infrastructural, and toxic legacies associated with the waging of war (Abdelnour 2023, Neimark *et al* 2024, Griffiths and Rubaii 2025, Larbi *et al* 2025). The second literature to which our study contributes is the rapidly evolving understanding of military emissions and approaches to account for the military emissions gap (Parkinson and Cottrell 2022, Neimark *et al* 2025).

The novelty of our study, in our view, is twofold. First, we direct attention to and illuminate the immense work and time required to process debris from destroyed and damaged buildings in Gaza, which we estimate at 36.8 million metric tonnes of building debris resulting from the initial 14 months of bombardment alone (from October 2023 to December 2024). This is out of an estimated 50.7 million metric tonnes of total debris according to United Nations Environment Programme (UNEP) (2024a) estimates, which unlike our study includes debris from destroyed and damaged roads and other infrastructure. Second, and importantly, we show that the resulting carbon emissions and time associated with processing building debris are dependent on the type of machinery available to undertake the work of sorting, transporting, and crushing debris. As our results show, moving building debris to disposal sites would require over 2.1 million dump truck loads, correlating to an incredible 29.5 million kilometres driven (equivalent to about 736.5 times the Earth's circumference), generating around 65 642.40 tonnes of $C0_2e$. Variance in carbon emissions and work time spans depends on the mix of crushers available. For simplicity, we calculated estimates for two scenarios: one where high-capacity industrial jaw crushers are utilised (the type not currently available in Gaza), and the other where smaller jaw crushers are utilised (the type used previously in Gaza). Based on the assumption that 80% of debris is viable for crushing, a fleet of 50 high-capacity industrial jaw crushers would take just over 6 months and generate around 2,975.91 tonnes of C02e, while a fleet of 50 smaller crushers would take more than 37 years to process the debris, generating around 25 148.76 tonnes of C02e. Hence, any scenario that prevents Palestinians in Gaza from accessing heavy machinery will add decades to the work of clearing and processing rubble, substantially delaying possibilities for rebuilding. Such a scenario will also generate an immensely greater amount of carbon emissions. Further, given that emissions associated with clearing and processing debris will be concentrated within the small and densely populated area of Gaza, it is important to recognise the potential health impacts of clearing such a large volume of debris. Further research is needed to assess the potential levels of dust, air pollutants, and noise generated by the daily movement of hundreds of trucks, and the impact this will have on Palestinians in Gaza and beyond.

While our study does not cover the toxic fallout associated with processing rubble, our results do suggest that any scenario whereby Palestinians are prevented from procuring and utilising heavy industrial-grade

machinery will both prolong and amplify the health and environmental risks of living amongst and working with contaminated and hazardous debris, and from exposure to toxins and pollutants from diesel combustion (Rubaii and Griffiths 2025). In addition to not appropriately covering the important question of toxic fallout from transporting and processing debris, our study contains some notable omissions that have important implications for civil engineers and other professionals who will plan and manage the work of debris processing. First and foremost is the sensitive and complex task of carefully recovering the remains of victims, of which an estimated 12 000 remain buried under rubble (UN News 2025a). Once debris is separated, the ability to effectively transport it will depend on the size of debris, which will require breaking larger structures and pieces into manageable sizes prior to transportation; this is both tedious and dangerous work, especially when considering the risk of exposure to toxins and contaminated debris and soil. Such work also requires equipment and fuel, which contribute to carbon emissions and the release of pollutants. We do not consider this essential step in our estimates. Nor do we address the significant challenge of road and infrastructure destruction: our modelling assumes that truck movements will follow pre-existing road networks in Gaza. In reality, much of the road network is destroyed and will require clearing. We also recognize that processing outcomes will be impacted by the quality of crushers and fuel, the size of desired aggregates (e.g. smaller pieces for use in concrete blocks versus larger pieces for shoreline protection), maintenance of machines and the availability of parts for repair when needed, and the skill and experience of operators. But perhaps the most significant question impacting our findings is our classification of building debris according to the level of destruction. Even buildings classified as 'moderately damaged' may be deemed unfit for habitation and slated for demolition and reconstruction, which would greatly increase our estimations as well as the environmental and health risks of toxins.

By undertaking an estimation of carbon emissions through the lens of the work and time spans required to clear and process debris, our study offers insights for a range of factors and purposes. For instance, researchers might utilise our estimation methods to advance a fuller understanding of the climate impacts of war and reconstruction, as well as debris management more generally. For researchers specifically interested in accounting for military emissions from war (e.g. Ukraine; de Klerk *et al* 2024) our study shows the value of engaging more deeply with the materiality of destruction (e.g. concrete, cement, steel, etc.; Larbi *et al* 2025). Aside from researchers, officials and representatives of the State of Palestine might utilise our findings to advocate for climate reparations and the necessary resources to support reconstruction efforts. Further, civil engineers and urban planners might find our approach to estimating different crushing scenarios useful for considering how to plan the immense scope of work required to clear and process rubble given the mix of equipment that is available. Finally, donors, policymakers and thinktanks advancing various 'day after' reconstruction plans might engage our methods and results to appreciate the impossibility of any serious reconstruction effort until the bombardment of Gaza ceases and the siege of Gaza is lifted. On this latter point, it is worth noting that Israel has long prevented heavy equipment and parts to repair machinery from entering Gaza (Gisha 2016, Anadolu 2025) and has specifically targeted heavy equipment used for digging and clearing debris, including those recently allowed in during the temporary cessation of violence (Al Mezan 2025). In short, any serious effort to rebuild is unlikely without a comprehensive settlement that ultimately ends the structural conditions of violence that govern the lives of Palestinians (i.e. military occupation).

By the time a cessation of further destruction is secured, the data and assumptions upon which our findings are based are likely to change. We sought to present our approach and method in sufficient detail so that other researchers could follow its underlying logic and adjust components as necessary. Although our study narrowly focuses on only two phases of a much larger reconstruction process, we hope that some of the methods and datasets discussed may be relevant for addressing other gaps in military emissions, both in Gaza and elsewhere. For instance, spatially aggregating building footprints and other properties—such as storey count and building function from OpenStreetMap labels—may enable researchers to estimate the total carbon embodied in reconstructed buildings with higher fidelity than assuming a prototypical building structure and extrapolating by the number of destroyed structures. Emissions from the delivery of humanitarian aid and supplies may be quantifiable in a similar manner as the transportation of debris: by calculating the shortest distances to distribution points along intact roadways, and estimating emissions associated with the delivery trucks' combustion of fuel. We invite researchers to identify gaps and explore the utility of our method, and to develop a more comprehensive understanding of both the immediate and generational impacts the destruction of Gaza has had on its people, infrastructure, and environment.

5. Concluding remarks

We feel it important to conclude by stating the obvious, which is that any serious effort to rebuild requires an urgent and permament end to the genocide, and to the military occupation and siege of Gaza. Moreover, while our contribution is one of estimations, some losses are unmeasurable and irrecoverable: the immense

loss of life and erasure of entire families; physical afflictions and psychological traumas that will require lifetimes and generations of care; the destruction of homes, historical sites and cultural heritage; and devistation of the natural environment and harm to the climate.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/NetworkGestalt/Gaza-Debris-Emissions.

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