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Particulate Matter (PM₁₀ and PM_{2.5}) and Greenhouse Gas Emissions of UAV Delivery Systems on Metropolitan Subway Tracks

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Abstract: This study examines UAV (unmanned aerial vehicle) delivery services using metropolitan subway tracks in South Korea. The aim of the study is to enhance the usefulness of UAV delivery services in urban areas, evaluating what kinds of UAVs are more environment friendly than freight trains, with regard to particulate matter emissions and global warming potential. Under evaluation conditions, freight train delivery was a significantly better alternative in terms of particulate matter emissions, regardless of the size and energy source of the UAVs. However, despite freight trains being a well-known eco-friendly mode of transportation, it can be seen from this study that small UAVs satisfied a few conditions that could potentially provide a good transportation alternative, with low global warming potential. This paper provides important insights into the comparison of UAVs and freight trains with regard to carbon and particulate matter emissions, highlighting the implications that, in some situations, UAVs can be a feasible alternative for policymakers who prepare policy measures of an activation plan for UAM (urban air mobility).

Keywords: UAV; freight train; particulate matter; greenhouse gas emissions; urban delivery



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1. Introduction

UAVs (unmanned aerial vehicles) have garnered worldwide attention as a sustainable alternative to delivery services using traditional transportation modes. Many global companies, such as Amazon, Google, UPS, DHL, and Alibaba are testing, or piloting, UAV delivery services because of its numerous advantages over traditional delivery services. However, such testing has been limited to rural areas; dense urban areas were excluded as there are various regulations concerning drone mass, population density, altitude, and use, although cases varied substantially from country to country [1–5]. In addition, UAV delivery services are not yet suitable for precise urban deliveries in terms of safety, energy consumption, infrastructure requirements, aerial congestion, privacy, and noise for a city [6–8]. Due to the various issues raised, the potential of UAV delivery services has not been witnessed in urban areas but rather in rural areas with poor infrastructure of isolated populations [9].

To address these problems, this study proposes a new way to use UAV delivery services in cities. It could be described as a shipping UAV that travels on a subway track. Under the premise that rail-related regulations allow this delivery method, delivery UAVs using subway tracks have a number of advantages. There are no people on subway tracks, so there are no privacy concerns. It will also not create noise problems within residential areas. It is extremely unlikely that a UAV will fall and cause personal injury, or cause traffic jams or environmental problems on a rail track.

However, this delivery system loses the biggest advantage of UAV, which is the last-mile delivery. In addition, subway trains can transport to city centers using huge cargo compartments, and is well known as an environment-friendly transportation mode [10].

Therefore, this study was initiated to evaluate which UAVs and freight trains are most environment-friendly in terms of particulate matter and greenhouse gas emissions, a great concern to the urban environment. Consequentially, the present research focused on the environmental impact assessments of UAVs and freight trains and compared them using life cycle assessment (LCA). The aim was to determine what kind of UAVs and cargo types are relatively more beneficial to the environment, in terms of lower carbon emissions and particulate matter, compared to freight trains.

Studies on UAVs' LCA has been undertaken by many previous researchers [11]. The UAVs' environmental performance has mainly been compared to last-mile delivery modes, such as trucks [6,12], motorcycles [13], and existing distribution systems [14]; however, there is no research comparing it with freight trains. Likewise, studies on environmental assessment of freight trains have also been undertaken by many previous researchers [15–19], but there is no study comparing it with UAVs.

This paper is organized as follows. The methodology section describes the goal and scope, inventory, and impact assessment of this study. The result and discussion section present and discuss what kinds of UAVs are more environment friendly than freight trains, with regard to particulate matter emissions and global warming potential. Based on the results, the conclusions, implications, and limitations of this study are presented.

2. Methodology

In this study, the Publicly Available Specification 2050 [20] was applied to the analysis and the principles and guidelines of ISO14040:2006, ISO14044:2006 and ISO14067:2013 were followed [21–23].

2.1. Goal and Scope

The goal of this study is to evaluate and compare the carbon footprint and particulate matter emissions of the UAV delivery system on subway tracks and traditional freight trains, using the LCA method. The scope of this study includes transportation by UAVs and freight trains based on metropolitan subway tracks in South Korea.

2.1.1. Functional Units and System Boundaries

The system boundary is shown in Figure 1. To begin, electricity production was considered, comparing coal electricity and nuclear electricity. The energy supply and emissions of both delivery systems were analyzed. The returning and disposal step should then be considered; however, it was not in this study due to a lack of data and operating system.

The functional units consisted of two types: considering drone payload, and performance of the battery. The first comprises 1000 boxes (1 kg/box) carrying 16 stations. The second type consists of 100 boxes (10 kg/box) carrying 5 stations. The total weight for delivery is equal to 1 ton, and the transportable stations depend on the performance of the UAVs battery. The allowable stations were decided by total delivery distance, as shown in the assumptions section below.

2.1.2. Assumptions and Limitations

- For both delivery modes, only the transportation processes were considered, and consequently the manufacturing and disposal processes of UAVs and freight trains were excluded.
- The maximum transportation distance of UAVs assumed 50% consumption of its battery capacity.
- The distance between subway stations assumed 1 km.
- The durability of each delivery mode was ignored.

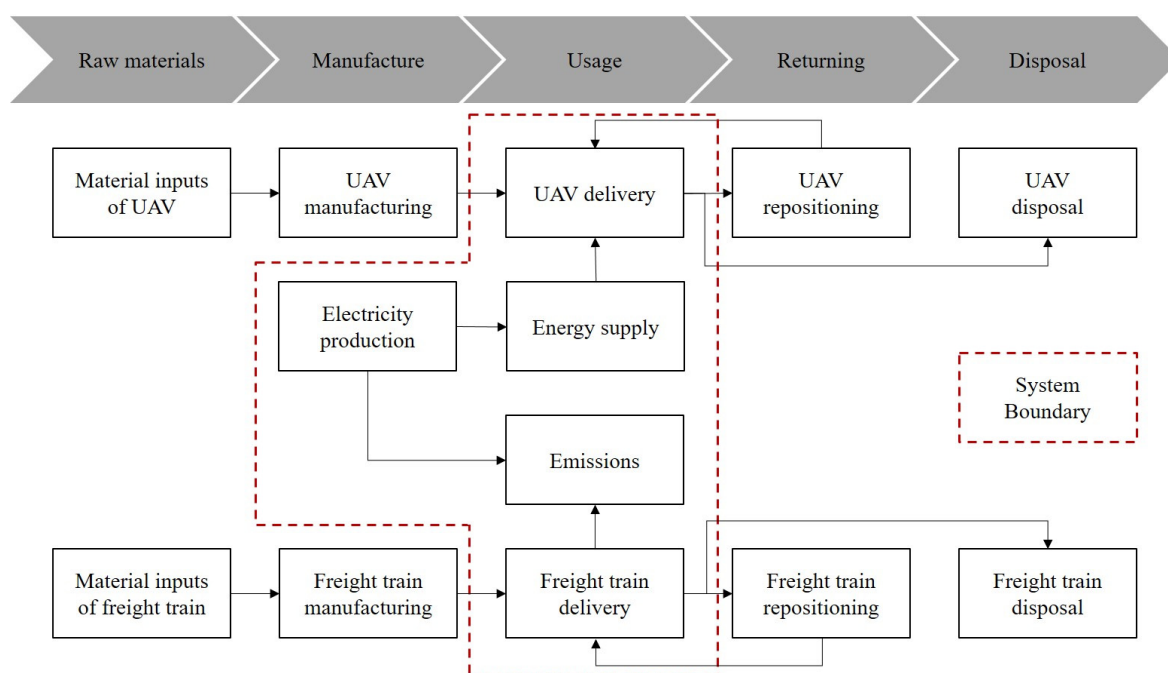


Figure 1. System boundary and the scope of this study.

2.2. Life Cycle Inventory

This study used a LCA with the energy data of UAVs and freight trains obtained from the Ecoinvent 3 and Agri-footprint databases, contained in SimaPro 8.2.0 software (PRé Sustainability B.V., Amersfoort, The Netherlands). The data for the energy of UAVs were taken from coal and nuclear electricity from the Ecoinvent database. For freight train operations, electricity freight train data from the Agri-footprint database were applied as shown in Table 1.

Table 1. Life cycle inventory and selected database.

Inventory	Selected Database
Coal electricity high voltage	Ecoinvent 3
Nuclear electricity high voltage	Ecoinvent 3
Electricity freight train	Agri-footprint

2.3. System Scenarios

This study comprised two types of UAVs, categorized as small and large according to transport weight and distance. Each UAV was further categorized based on the form of energy used by a coal-based battery (UAV-C), or a nuclear-powered battery (UAV-N). These power sources account for the highest shares (71.4%) of national power in South Korea [13]. The models chosen were MD4-1000 (Microdrones GmbH: Siegen, Germany) for small UAVs, and MG-1S (DJI: Beijing, China) for large UAVs, as the stability and consistency of the two models have been proven over a long period of time. The two models also had similar battery capacity. The MD4-1000 uses a 22.2 V, 13,000 mAh battery, has an average flight time of 45 min, a flight speed of 12 m/s, and can cover 16 subway stations. The MG-1S uses a 22.2 V 12,000 mAh battery, has an average flight time of 25 min, a flight speed of 12 m/s, but can cover only 5 subway stations. The characteristics of the two UAVs are presented in Table 2.

Table 2. Specification of UAVs.

	Manufacturer (Model)	Battery Type	Payload (kg)	Flight Time (min)	Flight Speed (m/s)	Station Coverage
Small UAV	Microdrones (MD4-1000)	22.2 V, 13,000 mAh	1	45	12	16
Large UAV	DJI (MG-1S)	22.2 V, 12,000 mAh	10	25	12	5

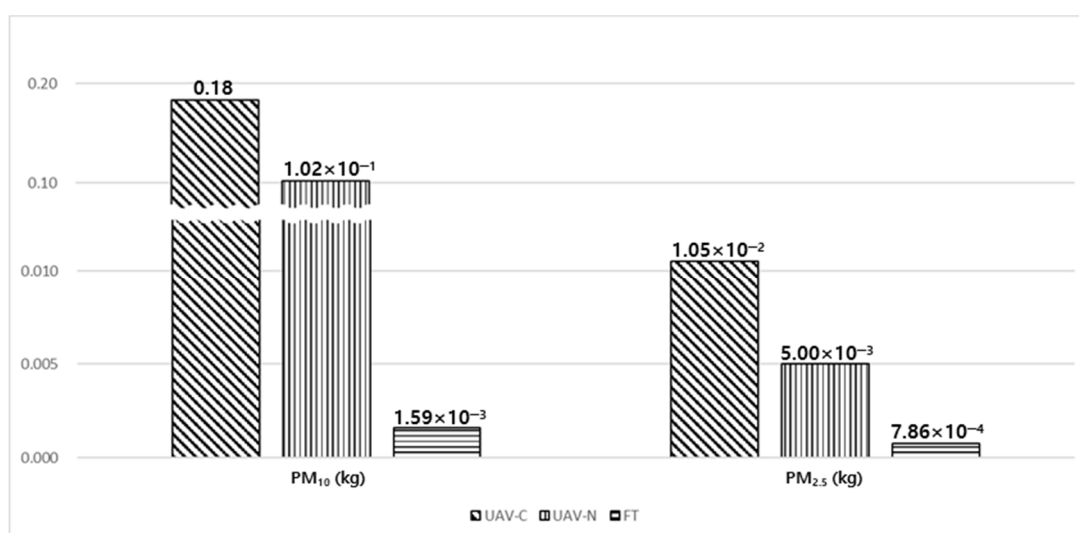
2.4. Life Cycle Impact Assessment

Life cycle impact analysis (LCIA) was carried out based on ReCiPe midpoint, IMPACT 2002+ and CML methods using SimaPro 8.2.0 software. The PM₁₀, PM_{2.5} and GWP were applied ReCiPe midpoint [24], IMPACT 2002+ [25], and CML [26] methods, respectively.

3. Results and Discussion

3.1. Comparison of Particulate Matter Emissions between Small UAVs and Freight Trains

Particulate matter emissions (PM₁₀ and PM_{2.5}) for 16 km (or 16 stations) of delivery by small UAVs and freight trains were calculated using the SimaPro 8.2.0 software, as shown in Figure 2. The PM₁₀ for cargo transported by small UAVs were 0.18 (UAV-C) and 1.02×10^{-1} (UAV-N) kg. The PM₁₀ for cargo transported by freight train was 1.59×10^{-3} kg. The PM_{2.5} for cargo transported by small UAVs were 1.05×10^{-2} (UAV-C) and 5.00×10^{-3} (UAV-N) kg. The PM_{2.5} for cargo transported by freight train was 7.86×10^{-4} kg.

**Figure 2.** Particulate matter emissions between small UAVs and freight trains.

In short, small UAVs emitted significantly more particulate matter than freight trains, regardless of their energy source. Especially with regard to PM₁₀, small UAVs had at least 64 times higher particulate matter emission than freight trains, even with nuclear-powered energy. These results show that in terms of reducing particulate matter emissions, freight trains are already sufficiently environment-friendly, and are unlikely to be replaced by small UAVs. It also suggests that small UAVs carrying more than 1000 light cargoes may repeatedly be more disadvantageous to the environment than traditional transportation modes carrying a large number of light cargoes at the same time.

3.2. Comparison of Global Warming Potential (GWP) between Small UAVs and Freight Trains

The GWP for 16 km (or 16 stations) of delivery by small UAVs and freight trains were calculated as shown in Figure 3. The GWP of goods transported by UAVs was 171.56 (UAV-C), and 2.24 (UAV-N) kg CO₂eq. The GWP of goods transported by freight train was 0.76 kg CO₂eq.

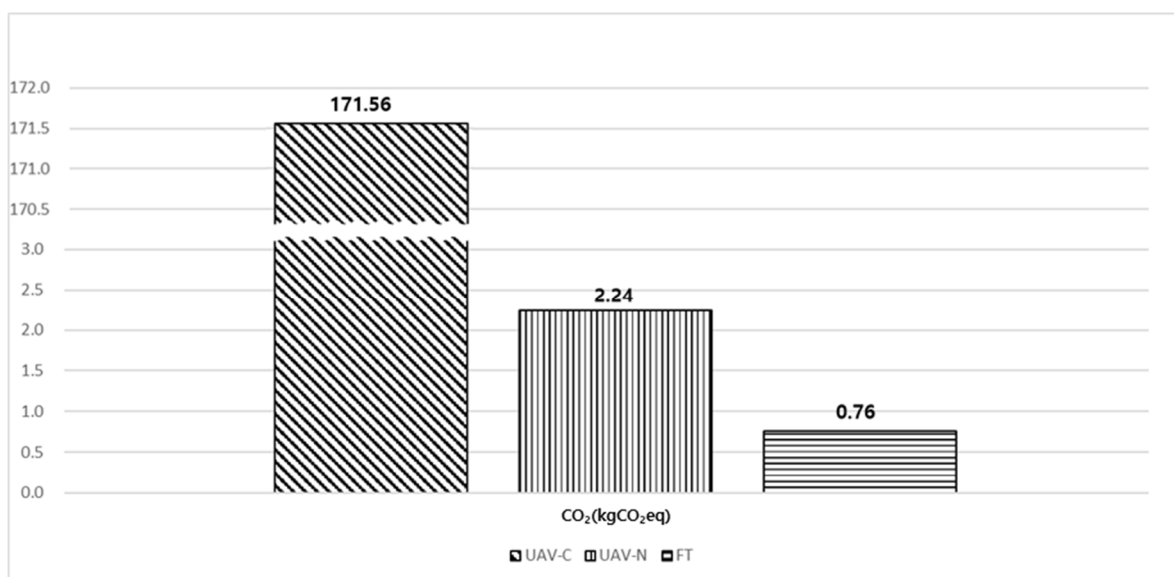


Figure 3. GWP between small UAVs and freight trains.

Unlike particulate matter emissions, small UAVs have a higher replacement potential in terms of GWP, but still have at least three times higher emissions than freight trains. Interestingly, the GWP values had a difference of 76 times, depending on which energy source was used to power the battery within the small UAVs. These results show that the type of power generation is much more sensitive in the case of GWP than particulate matter emission, as has been observed in previous studies [27]. In consideration of environmental factors such as global warming, the implication with regard to drone delivery is that it is more effective to use environmentally friendly sources, such as nuclear power, for lower carbon emissions.

3.3. Comparison of Particulate Matter Emissions between Large UAVs and Freight Trains

Figure 4 shows the particulate matter emission (PM₁₀ and PM_{2.5}) for 5 km (or 5 stations) of delivery by large UAVs and freight train. The PM₁₀ of cargo transported by large UAVs was 0.017 (UAV-C), and 9.43×10^{-3} (UAV-N) kg. The PM₁₀ of cargo transported by freight train was 4.96×10^{-4} kg. The PM_{2.5} of cargo transported by large UAVs was 9.69×10^{-4} (UAV-C), and 4.65×10^{-4} (UAV-N) kg. The PM_{2.5} of cargo transported by freight train was 2.46×10^{-4} kg.

The main difference between large and small drones is that the number of deliveries is reduced to one-tenth when carrying the same weight of cargo. This substantial reduction in the number of deliveries shows higher potential at PM_{2.5} than at PM₁₀. The PM_{2.5} emissions of large UAVs were only 1.9 times higher than a freight train, suggesting that a further reduction in the number of deliveries by UAV could achieve a better environmental performance than freight trains.

3.4. Comparison of Global Warming Potential (GWP) between Large UAVs and Freight Trains

Finally, the GWP for 5 km (or 5 stations) of delivery by large UAVs and freight trains is presented in Figure 5. The GWP of goods transported by large UAVs was 15.84 (UAV-C), and 0.21 (UAV-N) kg CO₂eq, and that of cargo transported by freight train was 0.24 kg CO₂eq.

The results show that in terms of carbon emissions reduction, UAVs can be an effective alternative to freight trains, a leading eco-friendly transportation mode. When they transported the same weight of cargo over the same distance, large UAVs using nuclear power as an energy source had lower carbon emissions than freight trains.

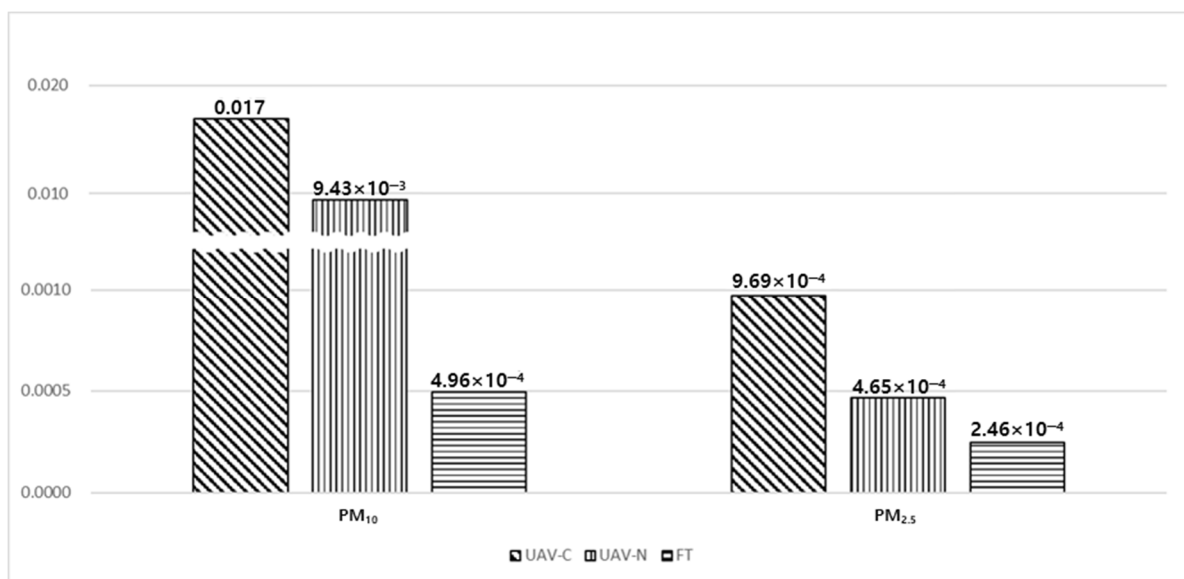


Figure 4. Particulate matter emissions between large UAVs and freight trains.

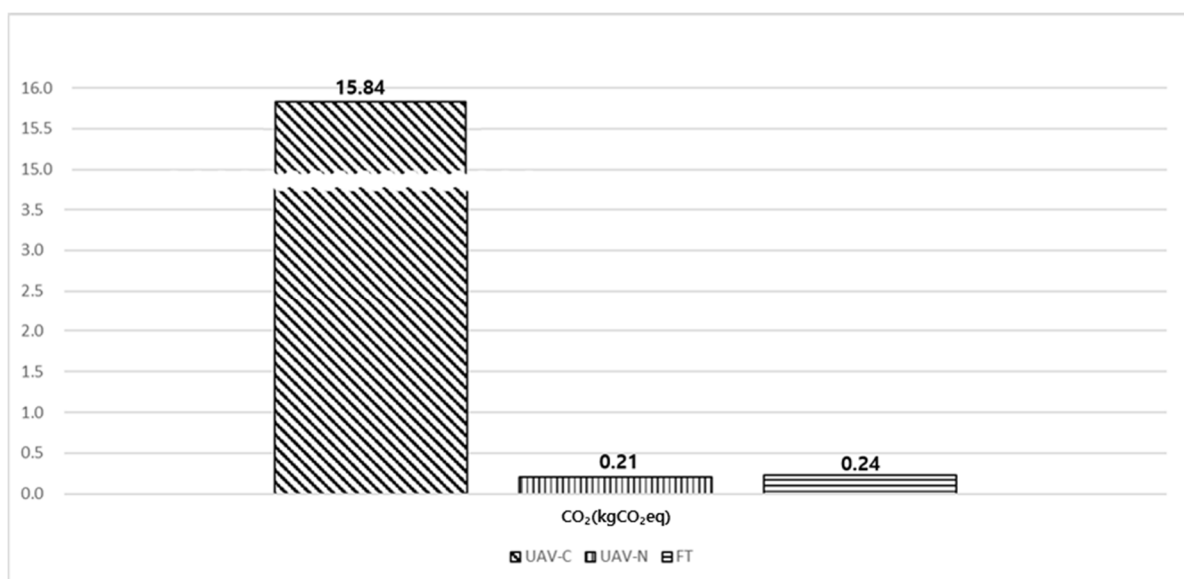


Figure 5. GWP between large UAVs and freight trains.

These results reveal several trends: Firstly, within the transportable range of UAVs, the environmental performance of a drone has a comparative advantage over freight trains depending on how much it can reduce the number of deliveries it carries, but increase the maximum weight it can carry. Therefore, UAV operation on the path of subway tracks, in non-regular short-haul transport within a city, can be helpful to the environment. Secondly, since the energy of UAVs is entirely battery-dependent, battery power source can determine its environment friendliness. In this study, two of the most-used energy sources in South Korea were compared; however, there is a need to study more environmentally friendly power generation methods, such as solar energy and wind power, which may suggest other implications.

4. Conclusions

This research consisted of system scenarios of UAV delivery services using metropolitan subway tracks in South Korea. The aim was to enhance the usefulness of UAV delivery

services in urban areas, and evaluate what kind of UAVs are more environment-friendly than freight trains, with regard to particulate matter emissions and GWP.

Under the evaluation conditions, freight train delivery was a significantly better alternative in terms of particulate matter emissions, regardless of the size and energy source of the UAV. Especially with regard to PM₁₀ emissions, freight trains are at least 113 times lower than small UAVs with coal-powered energy, when carrying 1 ton of cargo. Even with large UAVs based on nuclear power generation, freight trains were 19 and 1.8 times lower for PM₁₀ and PM_{2.5} emissions, respectively.

On the other hand, despite freight trains being well known as an eco-friendly mode of transportation, it can be seen from this study that the small UAV was the best alternative with respect to GWP. However, small UAVs have to satisfy the following conditions: use a relatively eco-friendly power generation-based battery, such as nuclear power; cover short distances (or stations); and have 10 kg or more payload when carrying 1 ton of cargo. Nevertheless, this paper provides important comparative insights into carbon and particulate matter emission between UAVs and freight trains, highlighting the benefits that UAVs can provide in some situations. Moreover, considering the growing importance of urban UAV use, carbon emissions provided by this study could be helpful in decision-making for delivery services operators and their stakeholders, offering practical contributions such as the possibility that subway tracks can be turned into the UAV's expressway.

Our theoretical contribution is that this paper is pioneering research to suggest a practical alternative for the use of UAV-based urban delivery services without noise, danger, or privacy problems. To address this problem, we focused on the advantage of using drones underground, in terms of being environment friendly; this advantage may be a possible link to future studies.

The limitations of this study are as follows: Firstly, although UAVs cannot fly over cities due to various problems, UAVs traveling on subway tracks is only one alternative, which may cause unexpected problems in terms of safety. In addition, it may need an autonomous mobility system, such as a navigation system without GPS [28]. It is necessary, therefore, to secure safety first, after sufficient research on UAV transportation services. In the future, technology development may enable UAVs for urban logistics. If a UAV is developed that is noiseless, fall-resistant, and weather agnostic, there is no need to restrict the use of UAV delivery services to subway lines. Secondly, due to limitations in data collection, LCA could not be performed for the entire process from the cradle to the grave. Future studies in this area, therefore, need to collect the database of UAV production and disposal. Based on this, a cradle-to-grave LCA perspective should be acquired, to understand the overall environmental load.

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