

# Trends, Advancements, and Future Directions of Unmanned Aerial Vehicle Technology-Based Stockpile Volume Estimation: A Systematic Review

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## Abstract

*Advancements in Unmanned Aerial Vehicles (UAVs) have revolutionized geospatial data acquisition by offering rapid, precise, and cost-effective alternatives to conventional surveying techniques. Accordingly, UAVs have emerged as a transformative tool for gathering data to estimate the volume in various industries. This study aims to investigate recent trends, advancements, and future directions of UAV technology in Stockpile Volume Estimation (SVE). The literature on UAV-based SVE was systematically reviewed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Relevant documents published from 2020 to February 20, 2025, were identified on the Web of Science and Scopus databases. These documents were screened via the Covidence platform, and 61 studies were included in this review. The results of this study demonstrate the current state of UAV adoption for quantifying bulk pile volume, while highlighting emerging trends and potential prospective developments in this field. In particular, the analysis of the reviewed documents revealed 8 emerging key trends and 8 future directions concerning UAV-based stockpile volume computation. Overall, the insights from this review highlight critical knowledge gaps and future research priorities, thereby guiding the development of more robust, accurate, efficient, and cost-effective approaches to estimating stockpile volume in various industries.*

**Keywords:** AI, LiDAR, Stockpile, UAV, Volume

## 1. Introduction

Photogrammetry is an emerging technology with a deep historical foundation for obtaining reliable geospatial data through a mathematical process of visual assets [1]. This is a scientific and technological discipline of collecting accurate information about objects and the environment by capturing, measuring, and analyzing photographs without touching them [2] and [3]. Initially, it was performed using terrestrial photographs [4]. After the invention of the airplane, aerial photography has played a pivotal role in advancing the field of photogrammetry [5]. The recent emergence of UAS (Unmanned Aircraft/Aerial System[s]) has revolutionized photogrammetry by allowing fast, accurate, high-resolution images [5] and [6] and

processing them through Structure-from-Motion (SfM) techniques to generate detailed 3D models [7]. With this advancement, UAS-based photogrammetry has received significant attention in various fields, including construction, agriculture, forestry, and disaster management [8]. Specifically, it has emerged as a widely adopted technique for stockpile monitoring across multiple sectors [9]. Although UASs are referred to by various terms, including 'Unmanned Aerial Vehicles' (UAVs), 'Remotely Piloted Aerial Systems' (RPAS), and 'drones' and Autonomous Aerial Vehicles (AAV) in the literature [10], only the term 'UAV' is used throughout this paper for simplicity.

A stockpile typically refers to a large, accumulated bulk of materials [11] such as sand [12], gravel [13], soil [11], coal [14], salt [15], wood chips [16], and waste [17], usually stored in the form of heaps [18]. They are maintained in various industries, particularly construction, mining, waste management [18], and quarry [19] for either future usage, mitigating the impact of material shortages, or transporting outside the working zone [11] and [20]. Accurate volume estimation of bulk materials is essential in these industries for proper inventory management [21], estimating reliable costs [22], effective resource planning [23], enhancing profitability, minimizing waste [24], and many more. Conventionally, stockpile volumes have been estimated using various technologies like eyeballing, walking wheel, counting buckets, or truckloads [25], and manually surveying with measuring tapes [19], Total Stations (TS), Global Navigation Satellite System (GNSS) [26], and Terrestrial Laser Scan (TLS) [15]. These techniques are often tedious, labor-intensive, and time-consuming [27] for irregular piles and expansive coverage areas [28], and pose significant safety risks [29]. Therefore, in recent years, UAV-based methods have gained popularity for Stockpile Volume Estimation (SVE) to complement the limitations of conventional methods [9] and [30].

In the last few years, UAV technology has emerged as an effective alternative for SVE [9]. UAV-based photogrammetry has demonstrated significant advantages in stockpile volume quantification by providing enhanced accuracy, reducing data acquisition time, and increasing operational convenience compared to traditional methods [31]. However, UAV photogrammetry is limited in dark, dusty, and confined areas, especially due to the usage of vision cameras [32][33] and [34]. In contrast, LiDAR sensors are more capable of penetrating smoke, dust, and darkness compared to optical imaging sensors, such as vision cameras [33]. Therefore, recent studies have increasingly focused on utilizing UAV-mounted LiDAR systems for volume estimation. In addition, numerous studies have recently been conducted to enhance the accuracy and efficiency of volumetric estimation of heaps and stockpiles across various industries [13]. Therefore, reviewing recent studies is essential to identify current trends, advancements, and future directions in UAV-based SVE.

There are a few review studies relating to UAV-based SVE in the literature. Methods for estimating the porosity and volume of wood jams were compared and reviewed in one of them [35]. Although this paper is not directly related to the SVE, it has discussed methods of estimating the volume of

wood jams. A comprehensive review was conducted on the applications of UAV technology in the mining industry [36]. Even though this review extensively covers UAV technologies and their diverse mining applications, it has not comprehensively focused on stockpile volume calculation. The accuracy of unmanned aerial systems photogrammetry and structure from motion in surveying and mapping, based on the studies from 2009 to 2020, was reviewed in another study [37]. Although this review broadly discusses UAV and structure-from-motion applications with emphasis on achieved accuracy, coverage of UAV-based SVE is very limited. In a review paper, UAV technology usage in municipal solid waste management and landfilling was comprehensively reviewed [38]. They have analyzed publications relating to waste management and landfills from 2010–2021 and highlighted the usage of UAVs for waste volume estimation as a part of the review.

SVE in open and confined environments was reviewed in another study [9]. They have focused on UAV and LiDAR technologies used for SVE, compared to GNSS and TLS Surveys. While all indoor mission SVE studies have been considered, only outdoor mission-related studies from 2020 to 2023 have been included. However, they have not focused on identifying trends or advancements in UAV-based SVE, including UAV data fusion, the use of artificial intelligence (AI) for SVE, volume calculation methods, and software usage. In addition, this paper has not focused on identifying future directions of UAV-based SVE. The current development in non-contact detection technologies for bulk material piles was reviewed in another review paper [39]. However, they have not mainly focused on UAV technology-based volume calculations of bulk material piles. Overall, existing reviews related to UAV-based SVEs have not been conducted to identify current trends, advancements, and future directions in UAV-based SVE, particularly in areas such as artificial intelligence, UAV data fusion, volume calculation methods, modern software, etc. In addition, these reviews cannot be considered fully systematic literature reviews, as they have not completely adhered to standardized systematic review protocols such as the PRISMA guidelines.

To the best of our knowledge, there is a lack of studies focusing on a systematic review to analyze the latest trends, advancements, as well as future directions of UAV technology for SVE. Therefore, this study sought to fill this gap by conducting a systematic review of the academic literature relating to the UAV-based SVE and seeking to answer the following research questions:

- RQ1: What is the status of UAV technology usage in the context of SVE?
- RQ2: What are the recent trends and advancements in UAV-based stockpile volume quantification?
- RQ3: What are the future directions of UAV technology for computing the volume of stockpiles?

The goals of each research question mentioned above are as follows. The first research question aims to investigate the status of published documents based on publication year, document type (journal articles or conference proceedings), publisher, and geographical distribution. The second research question aims to identify and categorize the recent trends and advancements of UAV technology applied to SVE. The final research question explores potential future developments of UAV technology for advancing the stockpile volume calculation.

In this study, a systematic literature review of UAV-based stockpile volume estimation was conducted to synthesize existing workflows, validation strategies, accuracy levels, and application domains, and to identify knowledge gaps and future research needs. Following PRISMA 2020 guidelines for systematic reviews [40] and [41], relevant articles were searched in major bibliographic databases (Scopus and Web of Science) using combinations of keywords related to UAV, stockpile, and volume estimation. Although 1459 articles were initially identified, after removing duplicates and applying predefined inclusion and exclusion criteria at the title and abstract, and full text levels, 61 studies were retained for detailed analysis. For each study, information was extracted on UAV sensors and platforms, application domain, software, volume computation methods, usage of AI and data fusion, as well as accuracy assessment strategies. The methodological steps of the review, including the search strategy, screening procedure, and data extraction process, are described in detail under the methodology section. Further, this systematic review is structured in the following order. Section 2 presents the methodology adopted for identifying and selecting relevant documents from academic literature. Section 3 presents the study findings, organized into three subsections, each corresponding to one of the three research questions (RQ1–RQ3). Section 4 discusses the findings of the review and concludes in Section 5.

## 2. Methodology

This systematic literature review was conducted in accordance with the PRISMA 2020 guidelines. The methodology was applied to answer research

questions RQ1, RQ2, and RQ3. Figure 1 presents the PRISMA-based flowchart outlining the review process.

### 2.1 Inclusion/Exclusion Criteria

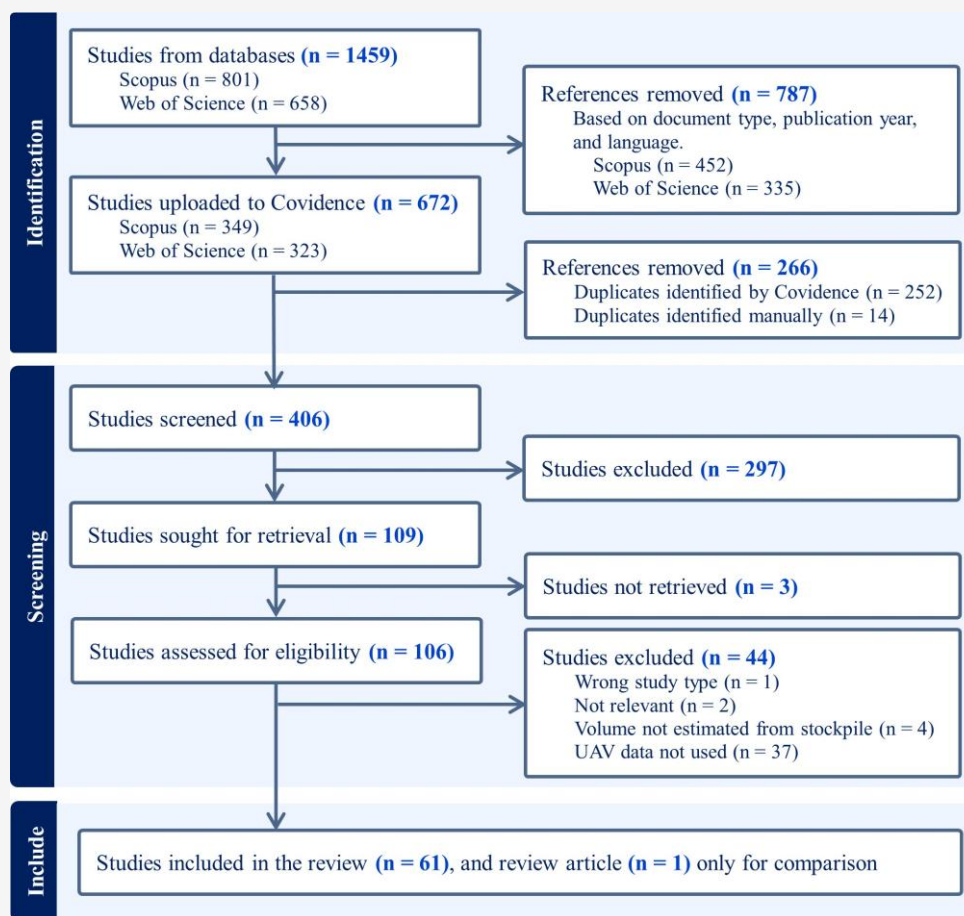
This review aimed to select all studies that utilized UAV technology for quantifying the volume of a stockpile or a similar bulk material pile. Studies were excluded if they did not utilize UAVs for data collection, even though they employed LiDAR technology. Document types of articles, proceedings papers, and reviews were only included for this review. However, review articles were included only for comparison. Other document types, such as data papers, book chapters, and notes, were excluded. The document search was limited to publications released from 2020 to the date on which the databases were searched on February 20, 2025. Finally, only documents written in English were selected for this review.

### 2.2 Information Source and Search Strategy

First, key concepts and terminology related to UAV-based SVE were reviewed. Then, the primary keywords associated with the defined research questions, along with their corresponding synonyms, acronyms, and related terms, were identified and shown in Table 1. During the paper identification stage, the Scopus and Web of Science (Clarivate Analytics) databases were searched on February 20, 2025, to identify relevant academic papers. The specific search string was applied to the title, abstract, and keywords of the literature to select academic papers. The 'AND' operator combined major keywords, while the 'OR' operator linked each keyword with its synonyms, acronyms, and related terms. According to the Table 1, the Boolean strings for searching academic papers on Web of Science: TS = ("uav\*" OR ... OR "laser scan\*") AND TS = ("stockpile\*" OR ... OR "storage\*") AND TS = ("volume\* estimat\*" OR ... OR "evaluat\* volume\*"). The Boolean strings for the Scopus database: (TITLE-ABS-KEY ("uav\*" OR ... OR "laser scan\*")) AND (TITLE-ABS-KEY ("stockpile\*" OR ... OR "storage\*")) AND (TITLE-ABS-KEY ("volume\* estimat\*" OR ... OR "evaluat\* volume\*")).

### 2.3 Selection Process

The PRISMA methodology consists of three main stages: identification, screening, and inclusion [41] and [40]. At the initial identification stage, the search results showed that the Scopus and Web of Science databases contained 801 and 658 relevant academic publications, respectively.



**Figure 1:** PRISMA-based flowchart

**Table 1:** The search terms

Major keywords	Synonyms, acronyms, and related terms					
UAV	uav* drone* uas* SfM ALS lidar	unmanned aerial* unmanned aircraft* automated aircraft* autonomous aerial* aerial surveillance* unoccupied aerial*	remotely piloted aircraft* remote-controlled aircraft* structure from motion airborne laser scan* light detection and ranging laser scan*			
Stockpile	stockpile* material* inventor* aggregat* earthwork*	pile* quarr* gravel landfill* storage*	stock* heap* asphalt mound	salt sand coal cut	bulk soil waste fill	
Volume Estimation	volume* estimat* volume* measur* volume* analy* volume* evaluat* comput* volume* assess* volume* predict* volume*	volume* calculat* volume* quantif* volume* determin* estimat* volume* measur* volume* determin* volume* evaluat* volume*		volume* comput* volume* assess* volume* predict* calculat* volume* quantif* volume* analy* volume*		

After applying the exclusion criteria: document type, publication year, and language, the number of search results of the Scopus database was reduced to 349, and the Web of Science database was reduced to 323 documents. Then, a total of 672 documents were uploaded into the Covidence platform for the remaining process. The Covidence platform automatically detected 252 documents as duplicates, and they were removed from further processing. Next, 14 duplicate documents were identified manually, and they were also removed from further processing. After removing duplicate documents, 406 documents remained for the next screening stage. During the screening stage, the titles and abstracts of all 406 documents were systematically evaluated. 297 studies were irrelevant and excluded from further processing as they did not pertain to UAV data or SVE. Consequently, 109 documents

were retained for further analysis. These documents were assessed for full-text availability, and three (03) lacking full texts were subsequently excluded from the review. After a thorough full-text review of the 106 downloaded documents, 44 were excluded as they did not meet the inclusion criteria. The reasons for exclusion: wrong study type ( $n = 1$ ), not relevant ( $n = 2$ ), volume has not been estimated based on stockpiles ( $n = 4$ ), and UAV data has not been applied ( $n = 37$ ). Inclusion and exclusion decisions were reached through consensus, resulting in the selection of 61 documents for this comprehensive systematic literature review, including one review article only for comparison. Details of all included articles are presented in Table 2. All included articles were categorized based on the UAV sensor type and stockpile environment.

**Table 2:** Details of included articles

ID	Author/s	Year	UAV Platform	Number of Stockpiles	Software	Volume calculation method	Usage of Fusion	Usage of AI	Ref.
<b>UAV Sensor: RGB (Photogrammetry); Environment of stockpile: Open</b>									
1	Son et al.	2020	MR	1	S3	SG	Yes	-	[42]
2	Liu et al.	2020	-	2	-	SG	Yes	Yes	[43]
3	Eker & Aydin	2020	MR	5	S2	Tri	-	-	[44]
4	Cho et al.	2020	HB, MR	1	S1	SG, CS	-	-	[45]
5	He et al.	2020	MR	10	-	SG	-	-	[46]
6	Kokamägi et al.	2020	MR	2	S1, S4, S6	SG	-	-	[47]
7	Ajayi et al.	2020	MR	1	S3	SG, Con	-	-	[48]
8	Mora et al.	2020	MR	3	S4, S5, S12	SG	-	-	[49]
9	Šádek & Struhár	2020	MR	1	S1	SG	-	-	[50]
10	Stalin et al.	2020	MR	2	S1, S5	SG	-	-	[51]
11	Puripanda et al.	2020	FW, MR	1	-	SG	-	-	[52]
12	Kavaliauskas et al.	2021	MR	16	S5, S7, S14	Tri	-	-	[7]
13	Ostrovskiy et al.	2021	MR	1	S1, S4	SG	-	-	[53]
14	Seong et al.	2021	HB, MR	1	S2	SG, CS	-	-	[54]
15	Ajayi & Ajulo	2021	MR	2	S2	SG	-	-	[20]
16	Carvalho et al.	2021	MR	8	S2	Tri	-	-	[29]
17	Fotheringham et al.	2021	MR	1	S3, S6	SG	Yes	-	[6]
18	Brezani et al.	2021	-	12	S3, S15	SG	-	Yes	[55]
19	Chapman	2021	FW	2	-	SG	-	-	[2]
20	Stalin & Kumar	2021	FW	1	S1	SG	-	-	[27]
21	Filkin et al.	2022	MR	1	S2, S10	SG	-	-	[56]
22	Lee & Lee	2022	MR	1	S2	SG	Yes	-	[57]
23	Matsimbe et al.	2022	MR	1	S3	SG	-	-	[19]
24	Mello et al.	2022	MR	1	S2	SG	-	-	[3]
25	Lee et al.	2022	FW	1	S3, S5	CS	-	-	[58]
26	Heraki et al.	2022	MR	1	S2	Tri	-	-	[59]
27	Villalobos et al.	2022	MR	1	S3, S6	CS	-	-	[1]
28	Harvey	2022	MR	1	S2	Tri	-	-	[60]
29	Kim et al.	2022	-	1	-	SG, CS	-	-	[61]
30	Han et al.	2022	MR	2	S2, S3, S4	SG	Yes	Yes	[62]
31	Spreitzer et al.	2022	MR	6	S3	SG, Tri	-	-	[63]
32	Jiang et al.	2022	MR	1	S4	SG	-	Yes	[64]

**Table 2:** Details of included articles (cont.)

ID	Author/s	Year	UAV Platform	Number of Stockpile	Software	Volume calculation method	Usage of Fusion	Usage of AI	Ref.
<b>UAV Sensor: RGB (Photogrammetry); Environment of stockpile: Open</b>									
33	Halim et al.	2023	MR	1	S2, S3, S13	SG	-	-	[65]
34	Künnapu et al.	2023	MR	2	S9	Tri	-	-	[66]
35	Chonpatathip et al.	2023	MR	1	S3	SG	-	-	[67]
36	Kuinkel et al.	2023	MR	2	S3	SG	-	-	[28]
37	Huang et al.	2023	MR	1	S3	Tri	-	-	[14]
38	Rachmawati et al.	2023	-	3	-	SG	-	-	[68]
39	Ellinger et al.	2023	-	17	-	SG	Yes	Yes	[18]
40	Hulanová et al.	2023	MR	11	S11, S7	SG	-	-	[23]
41	Gejdoš et al.	2024	MR	1	S1, S8	Tri	-	-	[16]
42	Perera et al.	2024	MR	2	S3	SG	-	-	[15]
43	Li et al.	2024	-	1	-	Tri	-	-	[69]
44	Wang et al.	2024	MR	1	-	Tri	-	-	[12]
45	Sánchez et al.	2024	MR	1	S15	Tri	-	Yes	[70]
46	Kuinkel et al.	2024	MR	1	S3	SG	-	-	[31]
47	Muhammed & Abed	2024	MR	1	S2	Tri	-	-	[11]
48	Saepudin et al.	2024	MR	1	-	Tri	-	-	[17]
49	Wallner et al.	2024	MR	6	S3	Tri	-	-	[13]
50	Iqbal et al.	2025	MR	3	S2, S4, S16	SG, Tri	-	Yes	[30]
<b>UAV Sensor: LiDAR; Environment of stockpile: Both open and confined</b>									
51	Alsayed et al.	2021	MR	2	S17	SG	Yes	-	[24]
52	Alsayed et al.	2021	MR	2	S17	SI	Yes	-	[25]
<b>UAV Sensor: LiDAR; Environment of stockpile: Confined</b>									
53	Ahmad et al.	2021	MR	2	S17	SG	Yes	-	[32]
54	Gago et al.	2021	MR	4	-	SG	Yes	-	[71]
55	Alsayed et al.	2022	MR	1	S17	SG	-	-	[34]
56	Alsayed & Nabawy	2022	MR	2	S17	SG	Yes	-	[33]
<b>UAV Sensor: LiDAR; Environment of stockpile: Open</b>									
57	Meng et al.	2023	MR	17	-	CS	-	-	[72]
58	Chen et al.	2024	MR	2	S19, S20	M	Yes	-	[73]
59	Molina et al.	2024	MR	1	S18	Tri	Yes	-	[22]
60	Zhu et al.	2024	H	1	S19	Tri	-	-	[74]
<b>UAV Sensor: Both RGB (Photogrammetry) and LiDAR; Environment of stockpile: Open</b>									
61	Jafari & Dorafshan	2025	MR	P: 6; L: 2	S3, S17	SG	-	Yes	[21]

**Abbreviation:**

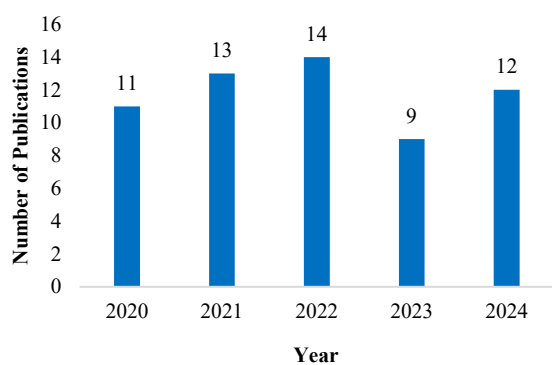
MR: Multi-rotor	S3: Pix4Dmapper	S10: DroneDeploy	S19: CloudCompare
FW: Fixed wing	S4: Autodesk ReCap	S11: Pix4Dcloud	S20: Open 3D
HB: Hybrid	Photo	S12: PixElement	SG: Square Grid
H: Helicopter	S5: Bentley	S13: SimActive	Tri: Triangulation
P: Photogrammetry	ContextCapture	Correlator3D	CS: Cross-sectional
L: LiDAR	S6: Trimble Business	S14: Trimble Stratus	Con: Contour
S1: Agisoft PhotoScan Professional	Center	S15: OpenDroneMap	SI: Surface integration
S2: Agisoft Metashape Professional	S7: Propeller	S16: WebODM	M: Manual
	S8: 3D Survey	S17: MATLAB	
	S9: ArcGIS Drone2Map	S18: Autodesk ReCap Pro	

**3. Results****3.1 Publication Status of the Included Documents (RQ1)**

A bibliometric analysis of all included articles was conducted to illustrate the status of UAV-based SVE,

focusing on annual publication trends, types of publications (conference and journal), publishers, and contributing countries. The publication year of each article is included in Table 2. As shown in

Figure 2, the annual distribution of publications was as follows: 11 articles in 2020, 13 in 2021, 14 in 2022, 9 in 2023, and 12 in 2024. As of 20 February 2025, two articles have been published in 2025. However, they were not included in the figure because the year 2025 is not yet complete, and including it in the annual publication trend would be misleading. According to the graph, it can be concluded that an average of 12 papers per year have been published annually relating to the UAV-based SVE over the past five years.



**Figure 2:** Annual publications from 2020 to 2025

The 61 included documents in this review consist of 37 journal articles and 24 proceeding papers. Journal articles (12) have been published by MDPI, followed by Elsevier (4), Springer (3), Korean Society of Surveying, Geodesy, Photogrammetry and Cartography (JKSGPC) (2), Taylor & Francis (2), and other (14) journal articles by different publishers. Proceedings papers (5) have been published by IEEE, followed by American Society of Civil Engineers (ASCE) (4), American Institute of Aeronautics and Astronautics (AIAA) (3), IOP Publishing (2), IOS Press (2), and other (8) proceedings papers by different publishers. The comparison of publisher percentages for the reviewed articles is depicted in Figure 3.

The map shown in Figure 4 provides a visual summary of geographic trends in academic literature on UAV-based SVE from 2020 to February 20, 2025. The proportional blue dots represent the number of publications from different countries among the included studies in this review. The geographical distribution of publications highlights the global diversity in studies on UAV-based SVE over the last five years. The USA has published the highest number of articles (9), followed closely by China (8) and South Korea (7), indicating a high level of UAV-based SVE research activity in these countries. The United Kingdom (5), Brazil (4), and Slovakia (3) have also given notable contributions to such publications. Moderate contributions have been

given from the Czech Republic, India, and Nigeria, each with 2 publications. A wide range of other countries, including Australia, Germany, Indonesia, Pakistan, Russia, Sri Lanka, and Turkey, have published one research paper each, reflecting the global interest in UAV applications for SVE. This distribution highlights the increasing adoption of UAV technology for SVE in both developed and developing regions

### 3.2 Trends and Advancements in UAV-Based Stockpile Volume Estimation (RQ2)

Trends and advancements in UAV-based SVE over the last five years can be categorized into several key areas: (1) UAV sensors, (2) UAV platforms, (3) application domain, (4) accuracy assessment and validation, (5) software usage, (6) volume calculation methods, (7) UAV data fusion and system integration, and (8) AI and automation.

#### 3.2.1 UAV sensors

Recent UAVs are equipped with advanced miniaturized sensors [70]. All included articles were categorized based on the UAV sensor type and stockpile environment, as shown in Table 2. Usage of UAV sensors for SVE has been illustrated in Figure 5. Most of the studies, 50 out of 61 (as a percentage 82%), have relied solely on UAV-based photogrammetry techniques, typically using Red Green Blue (RGB) sensors to create 3D models via SfM and Multi-View Stereo (MVS) for SVE. As a smaller portion, 10 out of 61 (as a percentage of 16%), of studies have used UAV-mounted LiDAR systems, which provide direct 3D point cloud data to create a 3D model and estimate the volume. One study has analyzed data collected by UAV photogrammetry and UAV LiDAR while comparing their SVE [21]. Accordingly, only one study (as a percentage of 2%) has used both UAV Photogrammetry and UAV LiDAR technologies for estimating stockpile volume comparatively. However, this paper has not provided more details regarding UAV LiDAR observation, including the details of the UAV utilized for the observation. Besides, UAV LiDAR-based SVE showed a 4.4% difference in volume compared to visual data-based estimates generated using Pix4D software.

The distribution of usage of the UAV sensors highlights that UAV photogrammetry remains the dominant method in the literature for SVE, likely due to its reduced equipment costs [53], accessibility [73], lower operational cost, and flexibility [21] compared to LiDAR. Nevertheless, UAV LiDAR has more advantages compared to UAV photogrammetry [9]. When estimating the volume of a stockpile using UAV LiDAR, it can obtain accurate data on stockpile

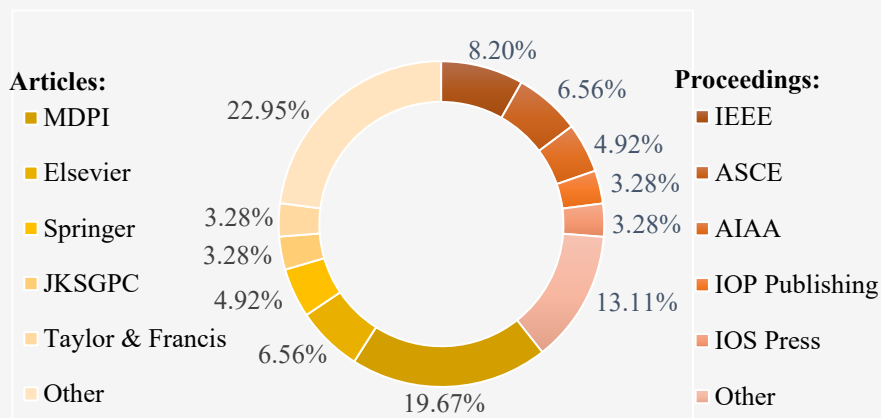


Figure 3: Publishers of the articles and proceedings

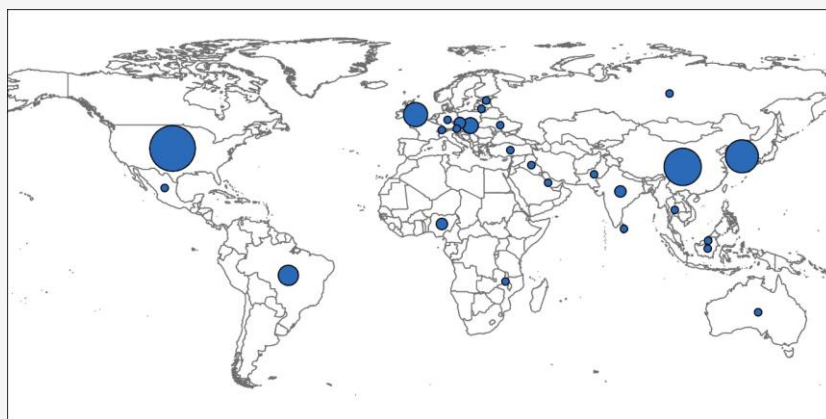


Figure 4: Geographical distribution of included publications

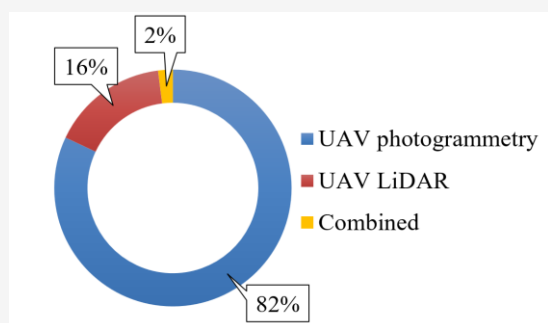


Figure 5: UAV sensor usage for SVE

without the need for Ground Control Points (GCPs). UAV LiDAR can be applied to estimate the volume of a complex stockpile under the vegetation cover, as LiDAR pulses can penetrate gaps between leaves and branches to reach the stockpile surface, providing more accurate data compared to UAV photogrammetry [9]. Further, LiDAR sensors perform better in low-light and dusty environments according to their active sensing technology, which

operates independently of external lighting conditions. UAV LiDAR is more effective than UAV photogrammetry when the accuracy is regarded as essential [9]. Overall, UAV LiDAR-based SVE studies are limited, and comparative studies with UAV photogrammetry are rare. Therefore, comparative UAV LiDAR and UAV Photogrammetry-based SVE studies should be given priority in future studies.

### 3.2.2 UAV platforms

Different UAV platforms are increasingly utilized as remote sensing platforms for the various near-ground applications [75]. As shown in Figure 6, the commonly used UAV platforms are multi-rotor, fixed-wing, hybrid, as well as unmanned helicopters. The type of UAV platform used in each included article is presented in Table 2. The summary of usage of different types of platforms for SVE during the study period is depicted in Figure 7, categorized by sensing technology: photogrammetry and LiDAR. The graph was prepared using information provided in each study. Some studies did not specify the UAV

platforms used, while others reported the use of multiple platforms with relevant details.

Multi-rotor UAVs generate lift through multiple rotating propellers, which are powered by brushless motors. These UAVs are not particularly power-efficient, and their flight duration tends to be relatively short [75]. However, multi-rotor UAVs can hover and fly in any direction, making them well-suited for indoor missions [33]. In addition, the advantages of multirotor UAS include vertical take-off and landing, stationary flight for capturing vertical and overhanging features, and the ability to fly along facades [26]. Therefore, among the UAV platforms, multi-rotor UAVs are the most employed platform for SVE in both UAV photogrammetry, with over 40 publications, and UAV LiDAR, with nearly 10 publications.

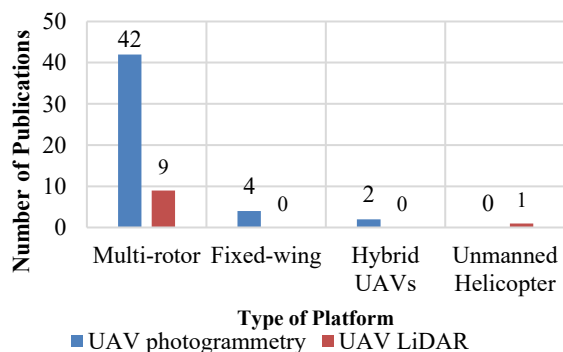
Fixed-wing UAVs and hybrid UAVs have been utilized occasionally in photogrammetry-based SVE, while their usage in UAV LiDAR-based studies is negligible or absent. Fixed-wing UAVs, resembling conventional aircraft, generate lift through the difference in air pressure between the upper and lower surfaces of their fixed wings as they move forward [75]. These UAVs are less suited for capturing images of vertical features, and they require a minimum flight altitude for safe operation

[26]. In addition, fixed-wing UAVs require a runway for takeoff and landing, and their landing process is more difficult to control compared to that of multi-rotor UAVs [75]. However, these UAVs have longer flight times and can cover more ground compared to multi-rotor UAVs [2]. Hybrid UAVs, also referred to as vertical take-off and landing (VTOL) UAVs, integrate the characteristics of both multi-rotor and fixed-wing UAVs [75]. These UAVs take off and land in multi-rotor mode, then transition to fixed-wing mode for flight, offering the benefits of easy control during takeoff and landing, along with improved energy efficiency during flight [75].

The unmanned helicopter is the least utilized platform in SVE, with only one UAV LiDAR-based study. Unmanned helicopters, resembling traditional helicopters, use a large rotor for lift and a tail rotor to control direction [75]. These UAVs offer excellent power efficiency and flight duration, but their complex mechanical blade structure results in high vibrations and increased costs [75]. Therefore, the reviewed literature reports limited research on the use of unmanned helicopters as a UAV platform. Overall, there is a trend of using multi-rotor UAVs for SVE in both UAV photogrammetry and UAV LiDAR.



**Figure 6:** UAV platforms: (a) Multi-rotor UAV [2] (b) Fixed-wing UAV [52] (c) Hybrid UAV [75] and (d) Unmanned Helicopter [74]

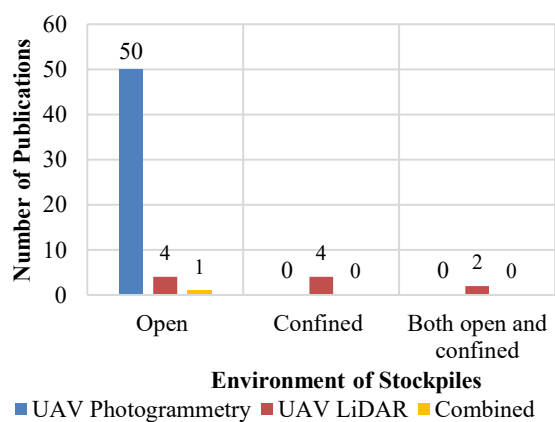


**Figure 7:** Types of UAV platforms used in SVE studies

### 3.2.3 Application domain

In many industries, stockpiles are stored in various environments, such as outdoors in open areas or indoors in confined spaces. All included articles were categorized by considering the environment of the stockpile also and presented in Table 2. The graph in Figure 8 illustrates the summary of the distribution of UAV-based SVE studies across stockpiles stored in different environments: open, confined, and both, concerning the sensor types used: UAV photogrammetry, UAV LiDAR, and both. The data clearly show that all UAV photogrammetry-based SVE studies have predominantly been conducted in open environments, with 50 publications. In contrast, UAV LiDAR has been employed in a small number of studies across all environments, with slightly

higher representation in confined and open spaces. Only two studies have been applied in both open and confined spaces simultaneously. The use of both UAV photogrammetry and UAV LiDAR simultaneously in a study has been limited to an open environment. These findings reveal a strong research emphasis on UAV photogrammetry in open settings, while confined or mixed environments remain underexplored, particularly with integrated sensor approaches. All UAV LiDAR-based SVE studies in confined spaces have been conducted by Alsayed et al. [24][25][32][33] and [34] except one study [71], during the study period. Several studies have been conducted to develop and assess cost-effective UAV-based solutions for SVE in confined indoor spaces, enhancing safety, accuracy, and affordability by using low-cost UAVs equipped with actuated 1D LiDAR sensors and using multiple UAVs by Alsayed et al.



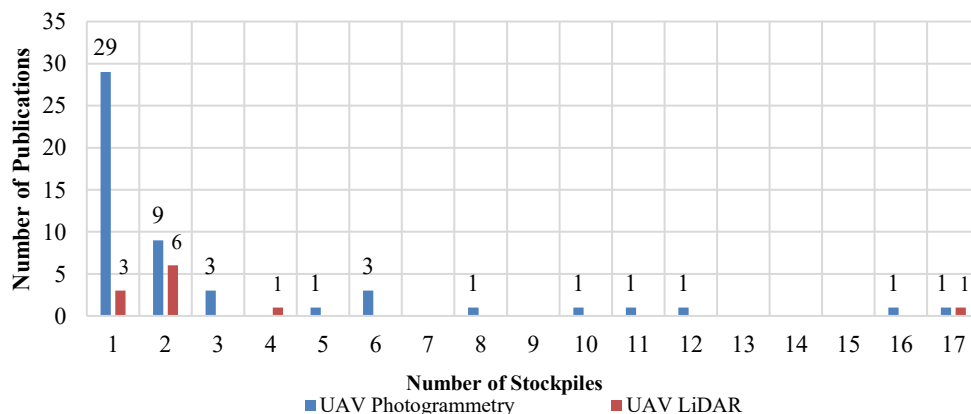
**Figure 8:** The environment of the stockpiles in the experiment

When proposing an SVE method, testing it on multiple stockpiles is essential to reduce bias [73]. The number of stockpiles that each study has tested

the proposed method, is presented in Table 2. Accordingly, the graph depicted in Figure 9 illustrates the summary of usage of the number of stockpiles in UAV-based SVE studies, differentiated by the type of sensor used: UAV photogrammetry or UAV LiDAR. UAV photogrammetry dominates the literature, with most studies (29 publications) focusing on single-stockpile scenarios. The number of publications conducted for UAV-based SVE studies decreases sharply as the number of stockpiles increases, with very few studies analyzing more than six stockpiles. In contrast, UAV LiDAR-based studies are significantly fewer across all categories, with most focusing on one or two stockpiles when testing their methods. This trend highlights that numerous studies have focused on simpler, single-stockpile use cases, especially with UAV photogrammetry, and many studies should be focused on multi-stockpile analysis, especially in UAV-LiDAR-based future SVE studies.

### 3.2.4 Accuracy assessment and validation

Accurate estimation of stockpile volumes is essential in various fields [9], and it plays a critical role in financial estimation and assessing stock levels in many industries [76]. Figure 10 presents boxplots of the distribution of relative error (%) across different UAV photogrammetry-based SVE studies, while Figure 11 presents similar results of UAV LiDAR-based SVE studies, with each box corresponding to a unique combination of paper ID, scenario number, and number of stockpiles used in validation. Each study has tested various methods, software, and flight parameters for UAV-based SVE, with each instance considered as a distinct scenario in this analysis. Each box represents the interquartile range (IQR), with whiskers indicating the spread of the data, 'X' markers denoting the mean relative error, and 'O' markers representing the outlier of each study. Only



**Figure 9:** Number of experimented stockpiles in SVE studies

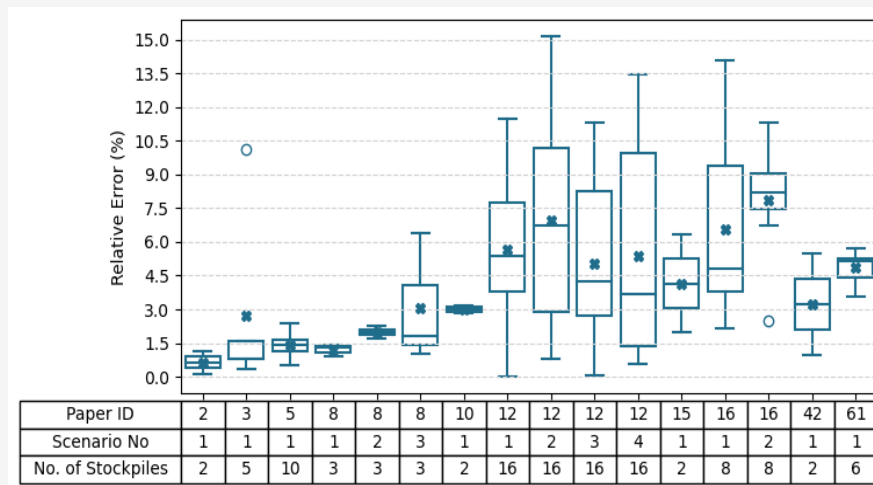
studies that used multiple stockpiles under the same scenario were included, as multiple observations are essential to reduce the bias associated with single-stockpile error [73]. Further, studies lacking the presentation of relative error with a validation method have been excluded from this analysis.

The boxplot results clearly show that although certain UAV photogrammetry-based SVE studies have achieved low minimum relative errors within the same scenario, the high variation that is evident from the wide interquartile ranges and extended whiskers in the boxplot indicates inconsistent performance, thereby reducing overall reliability. Despite a few studies in both UAV photogrammetry and UAV LiDAR-based SVE having achieved low average relative errors under the same scenario with low variation, they have been validated only for a limited number of stockpiles, except Papers ID 5 and 57. Therefore, enhancing accuracy should be a key priority for future research in UAV-based SVE. However, future UAV-based SVE studies should aim not only to improve mean accuracy but also to minimize internal variability, ensuring more

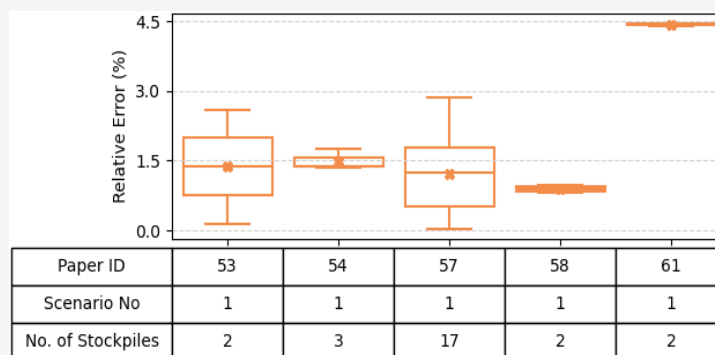
consistent and dependable results. Besides, these studies should focus on validating methodologies using multiple stockpiles under the same scenario.

### 3.2.5 Software usage

Advancements in UAV technology and automated photogrammetric software have greatly enhanced the efficiency and cost-effectiveness of geospatial data acquisition [67]. Most modern photogrammetric software employs the SfM technique, which reconstructs a 3D scene or object from multiple 2D images obtained at different angles, generating a point cloud like that produced by LiDAR [7]. These photogrammetry software can process UAV images and generate a wide range of output products, including point clouds, 3D textured mesh, orthomosaic, contour map, Reflectance Maps, Thermal Maps, Index Maps, Digital Elevation Models (DEMs), Digital Surface Models (DSMs), and Digital Terrain Models (DTMs) [28]. A diverse range of photogrammetry software is currently employed to process UAV images [28]. In contrast,

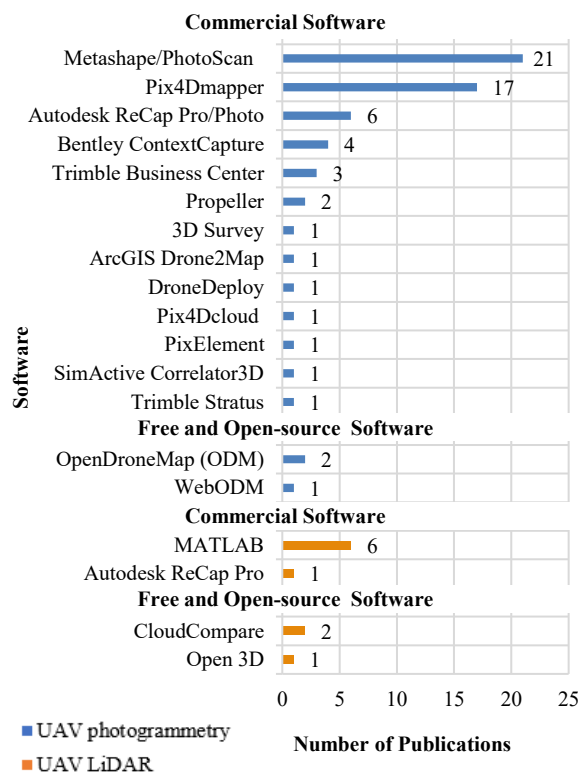


**Figure 10:** Relative error variation in UAV-photogrammetry-based SVE



**Figure 11:** Relative error variation in UAV-LiDAR-based SVE

only a few different software programs are available for processing UAV LiDAR data. The software used by each study is presented in Table 2. Figure 12 illustrates the frequency of software usage in UAV-based SVE studies, categorized by studies based on photogrammetry and LiDAR processing, and further divided into commercial and free, open-source software.



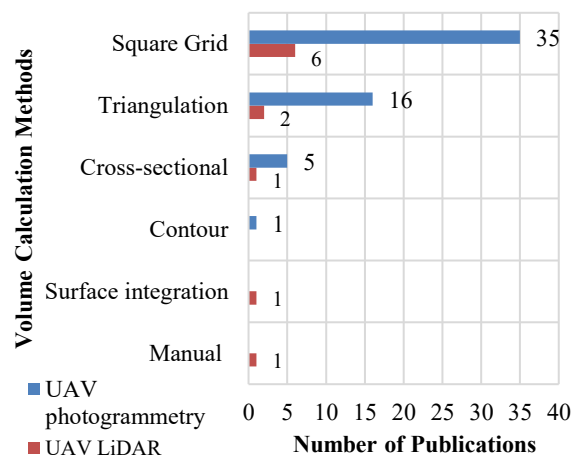
**Figure 12:** Software usage for SVE

Among commercial photogrammetry software, Agisoft Metashape Professional, that previously known as Agisoft Photoscan [65], and Pix4Dmapper are the most widely used, appearing in 21 and 17 publications, respectively. Other commercial tools like Autodesk Recap, Bentley ContextCapture, Trimble Business Center, and Propeller have been moderately utilized. Comparatively, the usage of free and open-source photogrammetry software, such as OpenDroneMap (ODM) and WebODM, shows limited adoption. However, these free and open-source tools can be used to transform UAV-captured aerial images into precise photogrammetry products [30], without the need for significant investment in purchasing commercial software. In addition, WebODM specializes in volume calculations, including earthwork volume estimates, stockpile measurements, and excavation evaluations [30].

For UAV-LiDAR data processing, MATLAB dominates among commercial tools, while CloudCompare and Open 3D are the primary open-source alternatives. Although these free open-source software provide sophisticated tools for processing, visualizing, and comparing LiDAR datasets [30], each open-source software has been used in a few SVE studies. Overall, the distribution highlights a strong reliance on commercial software for both UAV photogrammetry and UAV LiDAR data usage in SVE, in contrast to the relatively limited use of free and open-source software. Accordingly, this emphasizes the need for future studies on SVE that utilize free and open-source tools for minimizing the cost of projects and getting maximum benefits.

### 3.2.6 Volume calculation methods

Several volume calculation methods have been applied in SVE during the study period, including the grid method [45][51] and [69], triangulation [45] and [51], cross-section method [11] and [69] and contour [45]. Further, point cloud-based volume calculation methods can be classified into three categories: slice-based, voxel-based, and convex hull-based methods [77]. Volume calculation methods used by each study have been included in Table 2. The summary of the distribution of publications employing various volume calculation methods for UAV-based SVE during the study period has been illustrated in Figure 13.



**Figure 13:** Volume calculation methods applied in SVE studies

Among these volume calculation methods, the square grid-based approach is the most used in both UAV photogrammetry-based studies and UAV LiDAR-based studies, appearing in 35 and 6 publications, respectively.

DEMs are commonly structured as square grids, where each cell represents a specific elevation value. These elevation values can be used as the basis for generating contour lines, visualizing slope gradients, analyzing terrain features, and performing volume calculations [67]. The square grid-based volume calculation is one of the most used calculation methods in surveying and mapping [12]. A UAV survey generates a non-uniform spacing point cloud. Then the point cloud is converted into a DEM in the form of a grid with regular intervals to generate an orthogonal image. Since the DEM grid produced from the UAV survey matches the Ground Sampling Distance (GSD) of the captured imagery, the area of each grid cell can be calculated directly if the GSD is known. In addition, because each DEM grid cell has 3D coordinates, applying the height to the area of each cell allows it to be represented as a square column, as shown in Figure 14, enabling volume calculation [45]. The volume of each grid cell is calculated using Equation 2, derived from Equation 1. Finally, the overall volume can be calculated by summing the volume of all individual grid cells [51]. The volume of each grid cell can be calculated using Equation 1 [45].

$$V_i = L_i \times W_i \times H_i \quad \text{Equation 1}$$

Where:

$V_i$	= Volume of $i^{\text{th}}$ grid cell
$L_i$	= Length of $i^{\text{th}}$ grid cell
$W_i$	= Width of $i^{\text{th}}$ grid cell
$H_i$	= Height of $i^{\text{th}}$ grid cell

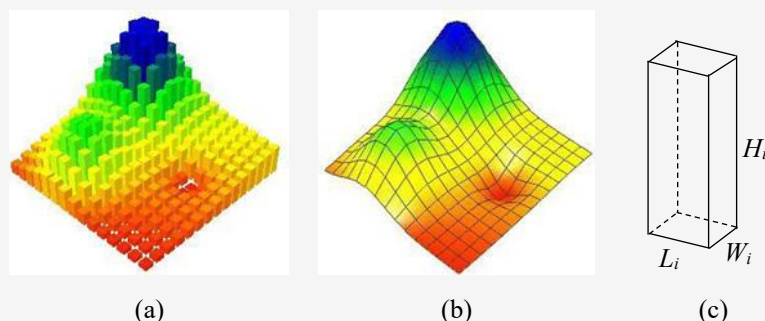
When,  $Z_i$  is the altitude of the center of cell  $i$  of the 3D terrain,  $Z_b$  is the altitude of the center of cell  $i$  from the base surface, and  $GSD$  is the Ground Sample distance [27][45][51] and [65],  $L_i = W_i = GSD$  and  $H_i = Z_i - Z_b$ . Then, Equation 2 [27] can be derived from Equation 1.

$$V_i = GSD^2(Z_i - Z_b) \quad \text{Equation 2}$$

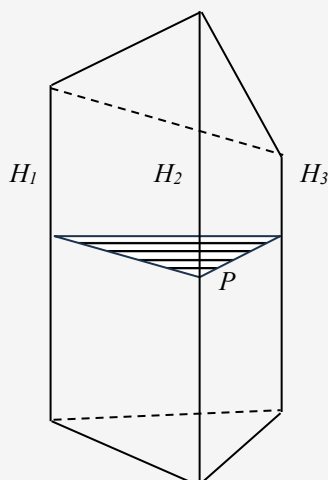
The grid-based volume calculation method is the most reliable and highly accurate for volume calculation for UAV-based data [27]. Besides, this method has been widely applied in most image processing programs due to its simplicity and faster computation compared to the triangular approach [54]. However, interpolating point clouds into grids can cause volume errors due to the irregular, non-smooth surfaces of large bodies [72].

The Second majority among the reviewed studies has used the triangulation-based volume calculation method for estimating the volume of stockpiles. This method has been applied in 16 photogrammetry-based studies and two LiDAR-based studies. The volume of a stockpile can be calculated by using the obtained point cloud data from the UAV observations. Before calculating the volume of a stockpile, it is necessary to reconstruct its three-dimensional shape [14]. A triangular mesh or TIN can be generated using UAV data to reconstruct the 3D shape of the stockpile. Then, three principles should be considered when forming each triangle in a TIN. Each triangle should be as close as possible to an isosceles triangle; the vertices used to form the triangle should be the closest; and the triangulated network must be uniquely defined [66]. Therefore, the Delaunay triangulation is widely used to create a TIN. The Delaunay triangulation is unique [66], and no other points exist within the circumcircle defined by the triangle's vertices [70].

The volume of the stockpile reconstructed as a triangulated mesh or TIN can be computed using the triangular prism method. The element of a triangular prism is shown in Figure 15. The prism method uses two surfaces created from 3D data: one is the actual top surface, and the other is the bottom reference surface, for calculating the volume [78]. The total volume of the bulk pile can be obtained by accumulating and summing the volume of all individual triangular prisms [14]. According to Figure 15, the volume of each triangular prism can be computed using Equation 3 [78].



**Figure 14:** (a) and (b) 3D structures of DEM, and (c) Square column of a DEM cell [45]



**Figure 15:** Triangular prism [78]

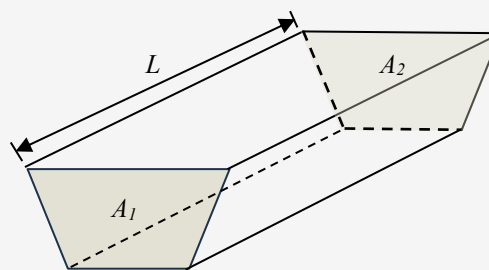
$$V_i = \frac{P}{3} \sum_{i=1}^3 H_i \quad \text{Equation 3}$$

Where:

- $V_i$  = Volume of the triangular prism
- $P$  = Planimetric (base) area of the triangle
- $H_i$  = Vertical distance (height) between the two surfaces at each triangle vertex

The triangular network method enhances earthwork volume accuracy by effectively representing topographic features, and this is suitable for complex terrain calculations [12]. Specifically, the triangular network is constructed directly from the original data points, unless simplified or interpolated later, with each point serving as a vertex of a triangle [78]. Besides, a more accurate volume calculation can be achieved with a higher number of triangular prisms [14]. However, similar earthwork volume results can be obtained by processing the point cloud through TIN or DEM from the same high-resolution UAV data [54].

As the third method, the cross-sectional method has been used to calculate the volume of the stockpile in five photogrammetry-based studies and one LiDAR-based study. This method is commonly applied to relatively regular solids and calculates volume by measuring the area between two consecutive cross-sections and multiplying it by the distance between them [78]. The object for which volume is to be calculated is divided into segments, referred to as slices, typically oriented either horizontally or vertically. In Figure 16, two vertical cross-sections have been illustrated.



**Figure 16:** Volume determination from cross-sections [45]

Most cross-sectional volume calculation studies involving linearly oriented stockpiles or earthworks, including roads, railways, canals, and sewage works, have employed vertical slicing methods, while conically shaped stockpiles have applied horizontal slicing methods. Further, the computation method of cross cross-sectional method may vary based on the properties of the solid object [78] and required accuracy, using different mathematical formulas such as average end-area, conic approximation [11], etc.

According to Figure 16, the cross-sectional-based volume is determined using the average end-area method using Equation 4 [11][58] and [61], whereas the conic approximation method is used to calculate the volume based on Equation 5 [11].

$$V = L \left( \frac{A_1 + A_2}{2} \right) \quad \text{Equation 4}$$

$$V = \frac{L}{3} (A_1 + A_2 + \sqrt{A_1 A_2}) \quad \text{Equation 5}$$

Where:

- $V$  = Volume between the two cross sections 1 and 2
- $L$  = Distance between the two cross sections 1 and 2
- $A_1$  = Area of 1<sup>st</sup> cross section
- $A_2$  = Area of 2<sup>nd</sup> cross section

The accuracy of the cross-section-based volume calculation depends on the distance between the cross-sections [27], especially in irregular-shaped sections [45]. Two similar studies have been conducted to validate UAV-based DEM as an accurate method for estimating earthwork volume compared to the officially accepted cross-section method [45] and [54]. According to the results achieved, with around 1% accuracy, they have mentioned that DEM-based volume calculation can

be applied instead of the existing cross-section method in BIM design and construction. Another study examined the applicability of UAV-based volume calculation using the average end-area and DSM methods in earthworks [61]. The results of this study have indicated that shorter chain intervals in earth cut sections improve accuracy in UAV-based earthwork volume calculations by producing volume estimates that more closely align with those derived from the DSM method. A study was conducted to assess the accuracy of earthwork volume estimation using UAV photogrammetry under real construction site conditions, compared to the traditional survey method [58]. Averaging cross-section-based volume calculation was applied to both methods, and the results revealed that the volume estimated using UAV photogrammetry was only 2.36–2.51% higher than the traditional surveying method.

In the selected academic papers, only one study has been conducted for SVE using the horizontal slicing approach under the fundamentals of the cross-section method and UAV LiDAR data. Accordingly, an enhanced point cloud slicing method was proposed to improve the accuracy of volume estimation of large irregular bodies, where traditional methods struggle with multiple contours and uneven point density [72]. This method combined Euclidean clustering as well as the concave hull algorithm to extract multi-contour boundaries from point clouds and compute the volume using Equation 6 [72]. This enhanced point cloud slicing method has achieved an average relative error of 1.17%, compared to the volume obtained by the modelling method.

$$V = \sum_{i=0}^{m-1} A_i h$$

Equation 6

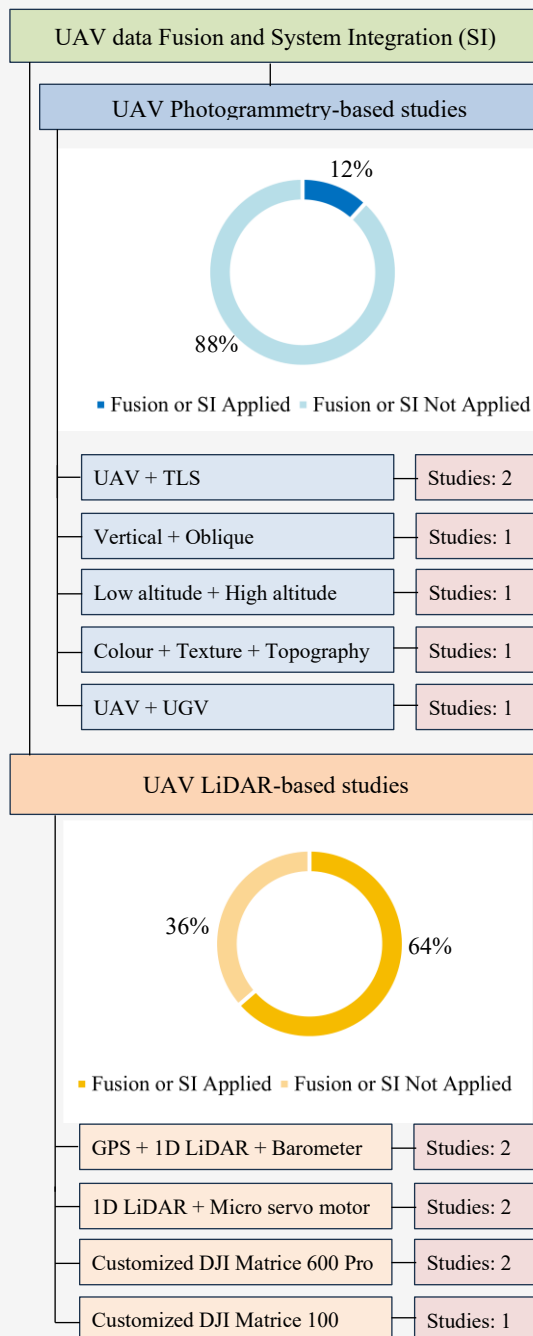
Where:

- $V$  = Overall volume of the point cloud
- $A_i$  = Area of the slice
- $h$  = Slice spacing
- $i$  = Number of the point cloud slice
- $m$  = Number of point cloud slices

### 3.2.7 UAV data fusion and system integration

A single sensor is frequently insufficient to survey the condition of a stockpile completely and accurately, especially in dynamic or complex environments [39]. The combination of multiple sensors substantially enhances the accuracy of the stockpile survey [39]. Furthermore, UAVs can be integrated with additional sensors, enabling the collection of diverse measurements within a single flight mission [25]. In addition, while individual technologies possess distinct advantages and

limitations, integrating multiple technologies in SVE can help mitigate these limitations and enhance the overall accuracy and reliability of the results [42]. However, only six studies, as a percentage of 12%, have applied data fusion and system integration methods to enhance the SVE among the reviewed UAV photogrammetry-based studies, as illustrated in Figure 17. In contrast, a notable trend is observed among LiDAR-based SVE studies, with 64% (7 studies) employing fusion and system integration.



**Figure 17:** Classification of studies that applied UAV data fusion or system integration for SVE

One study compared and integrated UAV and TLS technologies to determine an optimal method for accurate and efficient waste stockpile volume computation [42]. All three techniques: UAV, TLS, and fusion of UAV and TLS, were well suited to producing highly accurate point clouds with RMSE 0.032, 0.202, and 0.030 m, respectively, while all three techniques produced similar volume estimates. However, the UAV-based method was the most time-efficient, while the fusion approach offered the highest accuracy. Another study integrated UAV and TLS technologies to assess the accuracy and effectiveness of volume calculations in mining operations [6]. They observed that the combination of UAV and TLS datasets has improved surface model accuracy, reduced data shadows, and enhanced volumetric calculations. The fusion model offers a practical solution to overcome the limitations of both UAV and TLS methods. Nevertheless, it is generally less efficient compared to the UAV-only strategy [42].

Earthwork volume calculations and 3D model generations by fusing vertical (90°) UAV images and different high oblique (45°, 60°, 75°) UAV images at two different flight heights (50 m and 100 m) were evaluated [57]. Most accurate results for 3D model generation and earthwork volume calculation were achieved when combining vertical and 45° oblique images at a flight altitude of 50 m, with the lowest RMSE values  $\pm 0.05$  m. The results of this study revealed that fusing vertical and oblique images at angles of 40°–50° is suitable for obtaining a 3D model for earthwork volume calculations.

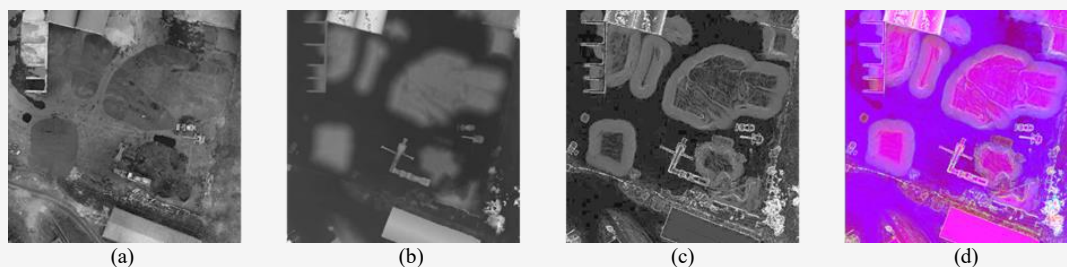
A method named the Fast Pixel Grid/group Matching and Elevation Determination (Fast-PGMED) algorithm for a fast and cost-effective elevation determination method in earthwork operations using UAVs and deep learning was developed [62]. Two top-view images at different altitudes at low and high flight heights were fused into a 2:1 scaled image pair to obtain a virtual elevation model for the proposed method. The developed Fast-PGMED method, combining UAV-

based low-high orthoimage pairs and deep learning, enables fast, dense, and accurate elevation mapping for earthwork volume estimation with significantly reduced processing time compared to traditional photogrammetry.

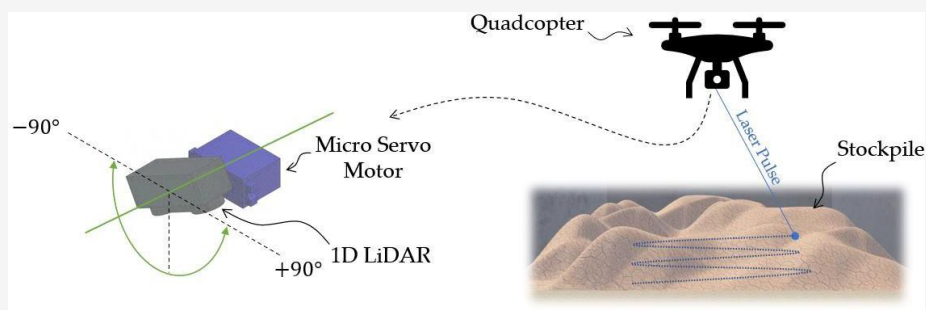
Another method was developed to automate the segmentation and volume calculation of stockpiles using a pretrained deep learning model that integrates color, texture, and topographic information [18]. The study designed a pipeline including the combination of RGB orthomosaics, elevation, and slope maps into a 3-channel input, as shown in Figure 18, for Mask-RCNN instance segmentation. The method achieved an average F1 score of 0.70 for object detection and 0.90 for pixel-wise segmentation, with 0.92 average volumetric accuracy.

A collaborative UAV and Unmanned Ground Vehicle (UGV) framework was proposed to improve the accuracy and efficiency of pile volume estimation [43]. During their study, aerial (UAV) and ground (UGV) image data were fused to overcome the limitations of single-viewpoint reconstruction, and they are integrated into a Simultaneous Localization and Mapping (SLAM) based system, using tag-based pose optimization to align and merge sparse 3D maps, followed by ground segmentation for heightmap-based volume estimation. The proposed method demonstrated high accuracy and significantly reduced processing time compared to dense reconstruction approaches, proving its suitability for SVE.

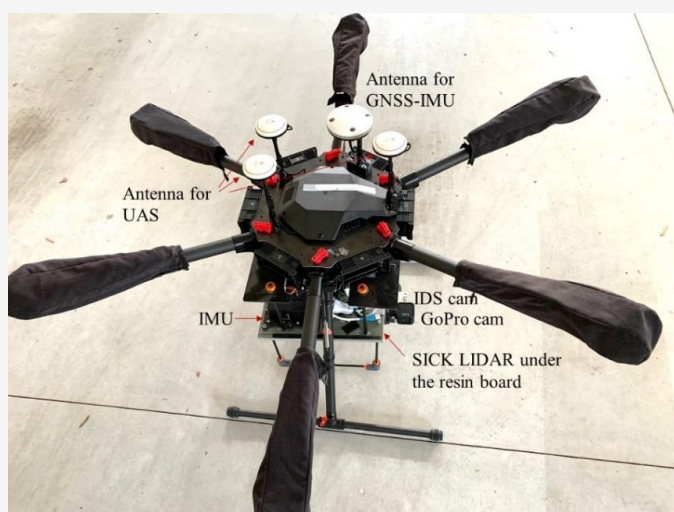
Seven UAV LiDAR-based studies have used UAV data fusion or system integration for advancing SVE. Accordingly, two similar studies have been conducted to explore UAV-assisted solutions for indoor and outdoor SVE with a focus on safety, cost-efficiency, and accuracy [24] and [25]. They have combined multiple sensor data streams during the real-world assessment in their two studies. The UAV has been equipped with GPS for localization, while a 1D LiDAR and a barometer have been used to estimate stockpile height. Although visual inspection has been conducted only for the outdoor experiment,



**Figure 18:** (a) Grayscale derived from the RGB orthomosaic, (b) adjusted relative heights visualized as grayscale, (c) local slope as greyscale, and (d) stacked all these three layers as RGB false color [18]



**Figure 19:** The developed actuated 1D LiDAR method for scanning and estimating stockpile volumes [33]



**Figure 20:** Customized design of UAV-based LiDAR system [73]

the same method has been applied in the semi-confined space, and its accuracy was validated, obtaining an error of just 2.4%.

Two similar studies have developed a low-cost and accurate UAV-based method using an actuated 1D LiDAR for indoor SVE. A 1D LiDAR sensor has been attached to a small UAV using a micro servo motor, as depicted in Figure 19. The servo motor shaft oscillates  $\pm 90^\circ$  in a plane perpendicular to the UAV's forward direction by offering 3D maps from a 1D LiDAR. The first study reported an absolute mean error ranging from 0.14% to 2.6% [32], while the second study achieved an average error of  $0.8 \pm 1.1\%$  [33] using the developed 1D LiDAR method in stockpile volume calculations in confined environments.

Another two UAV LiDAR-based studies have employed a similarly customized UAV-based LiDAR system for studying the accuracy of bulk pile volume measurement, as shown in Figure 20. The DJI Matrice 600 Pro UAV has been customized with the attachment of different sensors such as an IDS uEye industrial image camera, GoPro Hero 5 video

camera, SICK LD-MRS LIDAR sensor, three Raspberry Pi III-embedded computers, NovAtel SPAN GNSS-IMU with an antenna, and three UAS flight navigation antennas [22]. The first study evaluated the accuracy and efficiency of this UAV-based LiDAR system on a bulk aggregate pile compared to GPS-derived volume [22]. The volume has been calculated for both the point cloud, which has been extracted for the GPS points, and the full point cloud. The extracted point cloud-based volume was accurate with 1% error compared with the GPS-derived volume, while the full point cloud-based volume had an error of 17%. The second study evaluated bulk pile volume calculation using this system for two small targets and achieved accuracy with around 1% error compared to the manually calculated volume [73].

A UAV LiDAR-based aerial robotic system was developed and evaluated the system for the smart inventory of stockpile warehouses [71]. This integrated system includes the DJI Matrice 100 quadrotor platform, DJI Guidance navigation system, Velodyne VLP 16 Puck Lite, UDOO x86 on-board

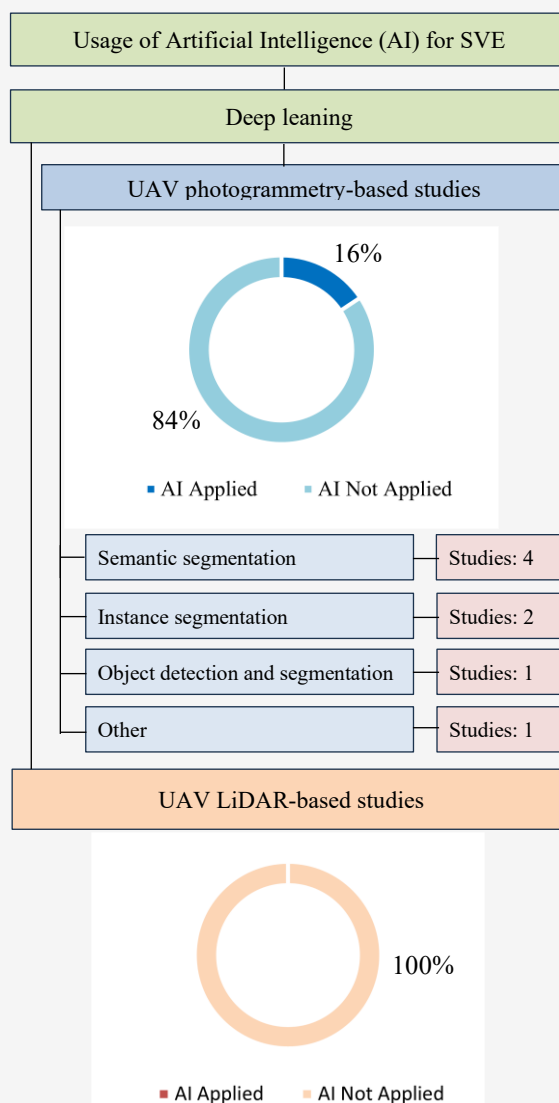
computer, DJI N1 video encoder, and DJI remote controller. The study has concluded that this UAV LiDAR system is a viable alternative to manual stockpile inventory, with an achieved accuracy of 98%.

### 3.2.8 Artificial intelligence and automation

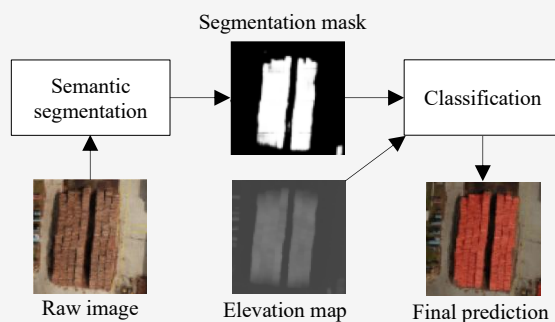
According to the academic literature, AI, including deep learning techniques such as Convolutional Neural Networks (CNN) and Generative Adversarial Networks (GAN), has significantly contributed to image segmentation, object detection, and 3D reconstruction [39]. However, among the reviewed UAV photogrammetry-based studies, only eight studies, as a percentage of 16%, have employed intelligent algorithms in the process of bulk pile volume estimation. In contrast, none of the reviewed LiDAR-based studies incorporated such AI methods to enhance bulk pile volume calculation. Specifically, deep learning techniques have been applied to separate stockpiles in the UAV images during the stockpile volume computation. Accordingly, as illustrated in Figure 21, four UAV photogrammetry-based studies have employed deep learning for semantic segmentation, followed by two studies for instance segmentation, while one study has been used for object detection and segmentation. In contrast, one study has utilized deep learning techniques to perform patch-based pixel matching between low-high orthoimage pairs.

In the previously mentioned collaborative UAV-UGV framework study [43], a lightweight CNN has been trained for semantic segmentation to separate ground and stockpile from the point cloud. This network has seven layers, including five convolutional layers (Conv2D) and two transposed convolutional layers (Deconv2D). Although pile volume has not been calculated directly using AI, the actual volume calculation is done geometrically, using classical 3D reconstruction and mathematical integration over a heightmap.

An automated system using UAVs and deep learning was developed to monitor and estimate wood stockpile volumes [55]. In the developed method, manual steps were reduced by using deep neural networks (DNNs) for semantic segmentation while identifying and delineating woodpile areas in UAV images. In the experiment, different architectures such as U-Net, PSPNet, and FPN with ResNet-18 and VGG-16 backbones have been tested. Although the extents of woodpile areas were calculated and evaluated, volume calculation has not yet been fully implemented or evaluated. The automated AI-based workflow for volume estimation has been mentioned for a possible future study, as illustrated in Figure 22.



**Figure 21:** Classification of studies based on the purpose of using AI for SVE



**Figure 22:** The proposed improvement in semantic segmentation [55]

UAV photogrammetry and deep learning were integrated to automate the identification and volume

estimation of construction and demolition (C&D) debris [64]. UAV images were captured with both nadir (90°) and oblique (45°) camera angles to ensure comprehensive coverage of debris stockpiles, processed using SfM techniques in Autodesk ReCap Photo to generate 3D point clouds, and the Pointcloud2Orthoimage (P2O) tool was used to create the orthoimage and elevation images automatically. Then, orthographic RGB images were used to train Fully Convolutional Neural Networks (FCNs), including U-Net and a custom encoder-decoder model, for the semantic segmentation to identify concrete debris. The segmented label images were overlaid on the elevation image, and debris contours were extracted to compute volume based on elevation and area data. U-Net showed higher performance with a concrete debris “Intersection over Union” value of 0.9 in testing data sets. However, volume calculation accuracy has not been evaluated against other traditional surveying methods.

The effect of different GSDs on stockpile volume measurement accuracy was analyzed, and UAS visual-based volume estimation was compared with UAS LiDAR and deep learning-based approaches [21]. A 1D CNN model has been developed to automatically classify the 3D point cloud obtained by Pix4D, to identify and extract stockpiles from the background. The study has found a strong correlation ( $R^2 = 99\%$ ) between Pix4D volume measurements and manual GSD calculations. The maximum volume difference between Pix4D and MATLAB outputs was 6%, while flights at 100 ft and 200 ft differed by less than 3%. Compared to UAV LiDAR, Pix4D has shown an average volume difference of under 4.4%, and the average difference with deep learning-based point cloud classification was below 5.5%.

In the previously stated study [18], it has designed a pipeline including the combination of RGB orthomosaics, elevation, and slope maps into a 3-channel input for Mask-RCNN instance segmentation. Pretrained Mask-RCNN with a ResNet-50 backbone on the COCO dataset has been used in this study. The method achieved an average F1 score of 0.70 for object detection and 0.90 for pixel-wise segmentation, with 0.92 average volumetric accuracy.

A cost-effective and repeatable solution was developed for estimating the volume of scrap piles in metal industry terrains using UAVs and open-source software [70]. UAV images have been processed using ODM to generate DEM, point cloud, and orthophotos. As a part of the proposed method, the pretrained Meta's Segment Anything Model (SAM), trained on 11 million images and 1 billion masks, has

been used for instance segmentation to identify individual scrap piles based on both DEM and RGB images. For each pixel within a segmentation mask, the interpolated ground height has been subtracted from the surface height extracted from the DEM to obtain the local pile height. These height differences have been summed across all pixels in the mask to compute the total pile volume. This method has achieved more accuracy in volume calculation with an error of 2.6%, while the QGIS method achieved an accuracy with an error of 3.02%.

The application of the YOLOv11-seg model for detecting and segmenting road layers: subgrade, asphalt, and aggregate base was presented [30]. Further, this study analyzed the volume calculation of these layers by four software programs: Agisoft Metashape, CloudCompare, Civil 3D, and WebODM. During the experiment, the model achieved high classification accuracy, with 95% for asphalt and aggregate base, and 83% for subgrade. It reached a maximum precision of 1.0, an F1 score of 0.92 at a confidence threshold of 0.779, and maintained a recall of 0.96 at lower confidence levels. In the volumetric analysis, WebODM has proved to be the most accurate among the four software tools evaluated, with volume accuracies of 99.85% for subgrade and asphalt, and 99.9% for aggregate base.

The aforementioned Fast-PGMED algorithm development study [62], they integrated UAV images with deep learning to enable fast and accurate elevation determination for earthwork volume estimation. An FCN called DeepMatchNet was trained to perform patch-based pixel matching between low-high orthoimage pairs. Next, a Fast-PGMED algorithm has been developed to quickly match pixels and determine elevation values for preparing an elevation map. Although deep learning was not used directly for volume calculation in this study, deep learning was used to estimate this dense elevation map, which was then used for volume calculations using conventional geometric methods

### *3.3 Future Directions for UAV-Based Stockpile Volume Estimations (RQ3)*

The determination of SVE is essential in various fields for planning, budgeting, scheduling, inventory management, financial estimation, operational continuity, improving storage space utilization, and many more. UAVs have emerged as pivotal tools in enhancing the accuracy and efficiency of bulk pile volume estimation. Considering the current trends, advancements, and capabilities of UAVs in stockpile volume calculation, as well as the current state of research, this study proposes several directions for

future research in advancing volume estimation of bulk piles.

### 3.3.1 Utilization of UAV LiDAR technology

Even though UAV LiDAR is more expensive than UAV photogrammetry, LiDAR sensors have superior capability in penetrating through smoke, darkness, and dust compared to visible light sensors [33]. In addition, UAV LiDAR is more effective than UAV photogrammetry when the accuracy is regarded as essential [9]. However, UAV LiDAR-based bulk pile volume estimation studies are relatively limited, and comparative studies with UAV photogrammetry are rare. This seems to demonstrate that comparative UAV LiDAR-based studies for volume estimation should be conducted in the future [42].

### 3.3.2 Usage of multiple types of UAV platforms

The results of this review reflect that most studies have employed the same type of UAV platform in estimating the stockpile volume. Therefore, future research can be conducted on investigating different types of UAVs for comparative analysis of quantifying the stockpile volume [19] and [31] and analyzing their impact on the accuracy of generating 3D models [66]. In addition, future research could focus on investigating the source and categories of errors resulting from each type [28] and [31].

### 3.3.3 Complexity of stockpiles and environment

Stockpiles of various materials are commonly stored in both open environments and confined or limited-access spaces [32]. Some stockpiles have irregular, complex shapes and are often stored in large, dusty areas [21]. Estimating the volume of these stockpiles can be challenging due to factors such as excessive dust, limited visibility, and the irregularity of their shapes [32]. Limited research has been conducted on UAVs for estimating the volume of irregularly shaped objects in such challenging environments [21]. Further, current studies are limited to volumetric computations conducted during daylight hours [19]. Future research should explore UAV technology for quantifying the volume of bulk piles in various shapes and materials under different environmental conditions [28], in both day and nighttime.

### 3.3.4 Enhancing accuracy and efficiency

Fast and accurate volume computation of bulk materials is crucial in various industries to create reliable cost estimates [22], proper inventory management, and increased operational efficiency [13]. Even though various studies have been undertaken to enhance the accuracy and efficiency of

estimating the pile volume [13], only a few studies have been tested on multiple stockpiles. Some of these studies have observed that obtaining high accuracy usually requires an expensive and time-consuming method [16]. Besides, only a limited number of studies have achieved considerable accuracy in earthwork volume estimation [57]. Accordingly, future studies can focus on developing accurate, rapid, and cost-effective methods for SVE, with validation across multiple stockpiles [19].

### 3.3.5 Adoption of open-source software

Open-source software provides advanced capabilities for processing, visualizing, and comparing datasets derived from techniques such as photogrammetry and LiDAR [30]. In addition, UAV images can be processed directly using open-source software like WebODM to generate detailed 3D models, including orthophotos and point clouds [30]. Furthermore, this software offers an effective and accurate solution for volume estimation, excelling in applications such as earthwork, stockpile measurement, and excavation assessment [30]. However, open-source software-based studies for estimating bulk pile volume are limited. Accordingly, free and open-source software-based comparative research can enhance cost-efficiency in volumetric estimation in the future.

### 3.3.6 GNSS for reducing the requirement of GCPs

GCPs provide accurate geospatial references, substantially enhancing the precision and reliability of volumetric estimations [30]. However, manufacturers have argued that ground controls are unnecessary when using RTK-enabled UAVs [2]. Accordingly, future research can focus on assessing the performance of advanced GNSS-integrated UAV platforms [3], such as those equipped with RTK capabilities [57], to eliminate the need for traditional GCPs in bulk volume estimation. Further studies can employ UAVs equipped with PPK GNSS technology to eliminate the requirement for manual GCP surveys, thereby enhancing accuracy and operational efficiency [58].

### 3.3.7 Intelligent algorithms and automation

Deep learning techniques have been employed in segmenting and detecting stockpiles on both UAV images and derived photogrammetric point clouds. However, the application of deep learning in UAV LiDAR-based bulk pile volume estimation remains comparatively underexplored. In addition, intelligent algorithms have been used primarily for segmentation and stockpile detection, but not directly for volume estimation. Accordingly, future research can focus on employing various intelligent

algorithms, including deep learning, comparatively [21] for UAV LiDAR-based studies to automate the estimation of the bulk volume. Furthermore, the application of AI techniques for classifying 3D point clouds has received growing attention [21]. Therefore, future studies could focus on integrating AI-based classification methods into the SVE process.

### 3.3.8 System integrations and multi-sensor fusion

A single sensor system may be insufficient to comprehensively capture the condition of a stockpile, particularly in complex environments [39]. To address this limitation, different sensors such as high-resolution cameras, LiDAR, ultrasonic sensors [39], thermal cameras, and air quality monitors can be attached to the UAVs [25]. The fusion of high-resolution visual data with advanced sensing technologies enhances the UAV's capacity to perform sophisticated tasks, such as accurate pile volume estimation [73]. Although studies integrating UAV visual data with UAV-based LiDAR for bulk volume estimation are scarce in the literature, this fusion may enhance the accuracy of bulk volume computations in future studies.

## 4. Discussion

The included review article [9] discussed UAV and LiDAR technologies for SVE, contrasting them with GNSS and TLS survey methods. However, it has not focused on identifying trends or advancements in UAV-based SVE, including UAV data fusion, the use of AI for SVE, volume calculation methods, and software usage. In contrast, our review yields several key insights that reflect the trend, advancement, and future developments of SVE using UAV technology. Firstly, this review reflects that there has been a consistent average annual research interest in the use of UAV technology for SVE. However, the included review article [9] has plotted the annual publication from 1990 to 2022, and they have observed that the number of studies has increased since 2012. Further, our study observed that although related publications are globally spread, a significant concentration is observed in the United States, China, and South Korea, indicating these countries as major contributors to the field. Even though the included review article [9] has mentioned the country of each study, the geographical distribution of the included publications has not been identified.

Secondly, several key trends or advancements in UAV technology-based SVE were observed: **(1)** Both our study and the included review article [9] observed that most SVE studies are based on UAV Photogrammetry compared to UAV LiDAR, due to their reduced equipment costs [53], accessibility

[73], lower operational cost, and flexibility [21]. However, UAV LiDAR technology is more applicable for complex stockpiles under the vegetation cover [9], low-light, and dusty environments [33], and accuracy is regarded as essential [9]. **(2)** Many studies of both approaches have utilized multi-rotor UAVs due to their superior stability, maneuverability, and ease of use in complex environments [33]. In addition, multi-rotor UAVs offer enhanced safety during take-off and landing [26], and eliminate the need for large airports or runways [75]. **(3)** All UAV photogrammetry studies, and half of the UAV LiDAR studies, have been conducted in open environments, while other UAV LiDAR studies were carried out in confined environments. UAV photogrammetry is limited in dark, dusty, and confined areas, especially due to the usage of vision cameras [32] [33] and [34], while UAV LiDAR can perform well in low-light and dusty areas [33]. Therefore, UAV photogrammetry studies have mainly focused on open spaces, whereas most UAV LiDAR studies have concentrated on confined environments. In addition, our study observed that the proposed method by each study has only been tested on one stockpile in most of the UAV Photogrammetry studies. In contrast, many of the UAV LiDAR studies have tested their method on multiple stockpiles. **(4)** Only three UAV photogrammetry studies in our review have reported accuracies with less than 3% error for all multiple tests, while four LiDAR studies have reported similar accuracy. Although some studies achieved considerable accuracy, they have not been proven with multiple stockpiles. However, multiple observations are essential to reduce the bias associated with a single observation [73]. Therefore, future SVE studies should be conducted on multiple stockpiles. **(5)** Many studies of both approaches have utilized commercial software such as Agisoft Metashape/PhotScan Professional (Most photogrammetry processing) and MATLAB (Most LiDAR processing), rather than free and open-source alternatives. However, free and open-source solutions provide advanced capabilities for processing, visualizing, and comparing datasets derived from techniques such as photogrammetry and LiDAR, as well as offer an effective and accurate solution for volume estimation [30]. In addition, this software provides low-cost, transparent, customizable, and interoperable workflows. Therefore, future studies can focus on applying these solutions for UAV-based SVE. **(6)** The square grid method has been employed for volume calculations in most studies of both types. This method has been widely applied in SVE due to its simplicity and faster computation compared to other approaches [54].

Although the grid-based volume calculation method is the most reliable and highly accurate for volume calculation [27], interpolating point clouds into grids can cause volume errors due to the irregular, non-smooth surfaces of large bodies [72]. **(7)** A relatively small number of UAV photogrammetry-based SVE studies (~12%) have incorporated fusion or system integration. Mainly, fusions between UAV and TLS data [42] and [6], vertical and oblique images [57], low and high-altitude data [62], color, texture, and topography [18], and UAV-UGV data [43] have been used in UAV photogrammetry-based SVE studies. In contrast, a significantly higher number of UAV LiDAR-based studies (~64%) have applied fusion techniques. Especially, the fusion of GPS, 1D LiDAR, and a Barometer [24] and [25], and 1D LiDAR with a Micro servo motor [32] and [33] has been utilized in UAV LiDAR-based SVE studies. In addition, the DJI Matrice 600 Pro [22] and [73] and the DJI Matrice 100 [71] have been customized by integrating different sensors. Nevertheless, the integration of UAV photogrammetry and UAV LiDAR in SVE studies remains rare in the literature. **(8)** Only a limited number of UAV photogrammetry studies (~16%) have employed deep learning methods during the SVE process. In contrast, such techniques have not been applied in any UAV LiDAR-based studies. However, these AI concepts have been used in UAV photogrammetry-based SVE studies only for segmentation and object detection. Therefore, this can be further advanced in future studies through the incorporation of AI for 3D segmentation, 3D point cloud classification, and volume estimation. Finally, this review highlighted eight potential directions for future research and development in UAV technology-based SVE, as mentioned in Section 3.3.

Additionally, our review synthesizes different limitations and suggestions regarding the usage of UAV data, software, and volume calculation methods as follows. Compared to traditional surveying methods such as TS, GNSS, and TLS, both UAV photogrammetric and UAV LiDAR methods can capture the full geometry of stockpile surfaces for SVE [9]. However, GCPs are needed to get an accurate output in the UAV photogrammetry approach [9]. In contrast, GCPs are not necessary for UAV LiDAR-based SVE to achieve accurate data [9]. Further, UAV photogrammetry is limited in dark, dusty, and confined areas, especially due to the usage of vision cameras [32] [33] and [34]. Conversely, UAV LiDAR is better for surveying complex stockpiles with vegetation cover, because LiDAR pulses can pass through gaps between leaves and branches, reaching the ground surface [9]. However, both photogrammetry and LiDAR-related

software are essential aspects for SVE. A wide range of photogrammetry software, including Agisoft Photoscan, Pix4Dmapper, and WebODM, is currently used to process UAV images. Orthomosaics generated with Pix4Dmapper were brighter than those produced with Agisoft Photoscan, and Pix4Dmapper also produced a more visually appealing DSM than Agisoft Photoscan and 3DSurvey. In addition, its use of GCPs enables point-cloud generation with a precision of approximately 5–20 cm [48]. Although commercial software is widely used in SVE, UAV images can be processed directly using open-source software like WebODM to generate detailed 3D models, including orthophotos and point clouds [30]. Especially, WebODM is better for volume calculations in various industries, including construction [30]. However, the accuracy of SVE is greatly affected by the volume calculation method, such as the grid method, triangulation, and the cross-section method. Nevertheless, the grid-based method estimates elevations at grid corners by interpolating measured data, which can deviate from the true terrain. As a result, this square-grid approach has notable shortcomings for calculating earthwork volumes in complex terrain [12]. Conversely, the triangular network method more accurately represents terrain within the survey area, thereby improving earthwork volume estimates, and it can incorporate topographic map data, making it broadly applicable for complex terrain [12]. In contrast, the accuracy of the cross-section method depends strongly on section spacing, especially for irregularly shaped profiles [45].

## 5. Conclusion

This systematic literature review was conducted in accordance with the PRISMA 2020 guidelines to identify current trends, advancements, and future developments in UAV technology-based SVE. Relevant articles were screened via the Covidence platform, and 61 studies were included in this review. The research articles included in this study were systematically analyzed to answer three research questions, thereby reviewing the trends, advancements, and future developments of UAV technology in SVE. Firstly, a bibliometric analysis was performed on the selected documents to evaluate the status of using UAV technology in bulk pile volume quantification. Secondly, the recent trends and advancements in this field were reviewed in eight categories for better understanding. Thirdly, prospective development trends in estimating stockpile volume using UAVs were investigated, and eight potential areas for further studies in UAV-based SVE were identified. Finally, different limitations and suggestions regarding the usage of

UAV data, software, and volume calculation methods were synthesized.

However, the findings of this review are subject to multiple limitations. First, the Web of Science and Scopus databases were only searched to identify relevant documents. Secondly, this review was limited to papers published only from 2020 to the date (February 20, 2025) that databases were searched, as the primary objective was to capture current research trends in UAV technology for estimating stockpile volume. As the third, the document types of journal articles and proceedings papers were only considered, and non-English and other types of documents were excluded from this review. Nevertheless, only one review article was included for comparison. Finally, publications that neither utilized UAV-based methods nor specifically addressed SVE were omitted from the analysis.

Overall, this review recommends future research on SVE in incorporating UAV LiDAR, system integration, multisensory fusions, AI, open-source software, GNSS techniques such as UAV RTK and PPK, and multiple types of UAV platforms. In addition, future research should prioritize the influence of stockpile geometry and environmental complexity to advance SVE, focusing on enhancing accuracy, efficiency, and cost optimization.

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