A review of studies on mass-movements on the Moon

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The study of the lunar surface is a significant field in exploring the Moon. As a non-negligible geological process shaping the lunar surface, however, the mass movements on the Moon have not been deeply studied regarding all available datasets. In this paper, we report the results of the literature review and quantitative analysis of 965 articles retrieved from the Scopus, WoS, and Astrophysics Data System databases using keyword search terms between the years 1872 and 2022. The main findings show that the lunar mass movements are a lasting but recent prosperous research topic (since 2009). The top three influential journals in this area are Icarus, JGR, and P&SS. Robinson, Lucchitta, and Carr are the most three productive authors. California Institute of Technology, Arizona State University, and Johns Hopkins University are active institutions leading the lunar mass movements research, and the related institutions are mainly located in the United States, Russia, and China. Articles are primarily published in journals specializing in the fields of astronomy and physics. The index analysis of citation indicates the growth of the academic impact of articles about the lunar mass movements. This article summarizes the datasets, methods, and relevant parameters of lunar mass movements to facilitate future research, as well as discussing the limitations and trends in the field. In addition, four unsolved issues are proposed, including: 1) the lack of a comprehensive global database that records all types of landslides incidents; 2) the need for definite classification indicators to quantify the classification criteria for lunar mass movements; 3) the absence of a mathematical model to explain the triggering mechanism of mass movements on the Moon; and 4) the lack of quantitative indexes to evaluate the modification effect of mass movements on the lunar surface morphology. With the support of big data, the combination of artificial intelligence and traditional GIS methods is expected to become the main approach for addressing these issues such a bibliometric analysis can inspire future researchers by exploring the overall characteristics of the published literature on lunar mass movements.

1 Introduction

Mass wasting is a material downslope movement driven by gravity. It tends to erase surface topographic differences and form gentle reliefs (Xiao et al., 2013). The processes occur widely on Earth, mainly on steep slopes, both subaerially and underwater (e.g., Wolman and Gerson, 1978; Moore et al., 1994; Deplus et al., 2001; Corsini et al., 2009; Parker et al., 2011). Different types of mass wasting processes have also been observed on several planetary and minor bodies, such as Mars (McEwen, 1989; Shaller and Komatsu, 1994; Brunetti et al., 2014), the Moon (Pike, 1971; Lindsay, 1976; Xiao et al., 2013), Mercury (Xiao and Komatsu, 2013), Venus (Waltham et al., 2008) and some icy satellites and

asteroids like Asteroid Eros, Itokawa, Lutetia, Vesta, Mathilde, Gaspra, Ida (Kereszturi, 2014; Murdoch et al., 2015) in the outer Solar System (Schenk and Bulmer, 1998).

In a terrestrial context, mass wasting represents the result of all the interactions between various geomorphological agents and processes, which act with different intensities on all types of slopes to modify the topography (Corominas et al., 2014; Pradhan and Siddique, 2019; Bhardwaj and Sam, 2022). In general, gravity is a major requirement for driving mass movements, but it is difficult to analyze the independent effects on the scales and dynamics of mass wasting by investigating terrestrial landslides alone, because of the presence of various other environmental elements on Earth, like a dense atmosphere, precipitation, and seismicity. Mass movements on other Solar System bodies share similarities. Thus, planetary studies with variable environmental conditions might help to reveal the effects of the atmosphere, subsurface fluids, precipitation, and seismicity on mass wasting, and could foster an understanding of triggering and propagation mechanisms (Sam and Bhardwaj, 2022).

As the sole natural satellite of the planet, the Moon is an important member of the inventory of planetary bodies that host mass movements. The mass movements of the Moon could bury ice and store it (Kereszturi, 2023), change the geomorphology of the lunar surface at different scales, impact the formation rate and process of lunar soil, affect the longevity of small craters, influence the dating of moderately young lunar surfaces, and record time clues about the lunar topography's evolution. Therefore, it is an important step to study the degree and mechanism of modification of the lunar surface topography by lunar mass movements to fully clarify the evolution of the lunar surface topography, which helps to understand the ancient state of the Earth, the origin, and evolution of the Solar System. Mass movements have been distributed on various terrains on the Moon, including impact craters, volcanic domes, tectonic scarps, rilles, valleys, and wrinkle ridges (Xiao et al., 2013), but most of the landslides occur on the walls of impact craters; including Fall, Slide, Slump, Creep, and Flow, five kinds of gravity erosion processes (Bickle et al., 2021), such as the creep produced so called "girlands" identified recently in deGerlache crater (Kereszturi et al., 2022). The surface gravity of the Moon is small, just one-sixth that of those on the Earth, which means that the Moon can support proportionally higher topography than the Earth for the same material strength (Melosh, 2011). Therefore, the lunar mass movements are on a grander scale usually. On the other hand, the small gravity causes less dynamic fragmentation, so the typical debris of the mass movements on the Moon is many times bigger than similar-sized terrestrial mass movements (Xiao, 2021).

Multiresolution and multisensory remote sensing datasets from lunar exploration missions are constantly improving our understanding of the Moon. Since Pike (1971) published the first paper about mass movements on the Moon using images from the Apollo 10 Mission, a variety of mass-movement features have been reported by researchers (e.g., Lindsay, 1976; Bart, 2007; Bray et al., 2010; Perumal, 2012; Xiao et al., 2013; Otto et al., 2014; Li et al., 2018). These studies provide a qualitative description of the general morphological traits of the lunar mass movements, and based on the preliminary investigation, the causes and effects of the lunar mass movements are examined, and certain classification criteria are formulated. Several approaches have been used to study the lunar mass movements, as corroborated by publications. These

approaches include image processing and remote sensing, which are employed to map the shape of mass movements. Mapping tools are utilized to generate inventory maps of mass movements, while methods for classifying lunar mass movements are also explored. Additionally, comparative planetology is employed to examine physical and mineralogical parameters that may impact mass movements. Terrain parameters are utilized to evaluate the effects of morphology modification. Furthermore, model simulation is utilized to replicate the movement process and investigate the factors that influence mass movements.

Xiao. (2021) exhaustively summarized the patterns, causes, and effects of lunar mass movements based on the geological background of the Moon. Despite this, there is a lack of systematic analysis of mass movement studies on the Moon. To evaluate the research status of lunar mass movements, this review examines available literature on mass movements on the Moon. We conducted a quantitative analysis of the publications, authorships, disciplines, and quotations of 965 articles to explore trends, leading scholars, research fields, and academic impact in the study of the lunar mass movements. And then we carried out discussions: 1) compiled a list of the data catalogue used for lunar mass movements studies; 2) summarized the research techniques for studying mass movements; 3) highlighted the parameters used in terrain analysis and cause-effect analysis; 4) discussed the research gaps and future research trends. The review allowed to identify data, methods, and opportunities in the research of geomorphic processes, and geological evolution of the Moon.

2 Search strategy

Our search was conducted in Scopus, Web of Science (WoS), and Astrophysics Data System (ADS), a digital library for astronomy and astrophysics researchers. The created database spans 151 years (from 1 January 1872 to 18 May 2022) and provides an overview of contemporary research trends. Ten key phrases were used to search articles about lunar mass movements: lunar landslide, lunar mass movements, lunar mass wasting, lunar granular flow, lunar debris avalanche, lunar rock slide, lunar debris slide, lunar rock avalanche, lunar rockfalls, lunar boulder falls. We separated the keywords with quote marks and joined them with the OR logic operator. We examined each database (Scopus, WoS, and ADS) to find duplicate articles, and articles identified in two datasets are deleted, leaving just one version of the duplicated article. The results are primarily from ADS, complemented with Scopus and Wos search results. Abstracts, patents, and news releases did not contribute to the content of this review, since they did not provide a detailed description of the lunar mass movements study.

3 Statistical analysis

In this section, we aim to employ bibliometric analysis to uncover the diverse research aspects within the domain of lunar mass movements research. Based on the literature database, we investigate the overall research pattern by analyzing the annual publication count, and highlight publications that are usually available to acquire articles related to the lunar mass movements

through the distribution analysis of affiliated publications. The analysis of the author network and affiliated institutions can help researchers find the prominent scholars and reliable institutions in the field of lunar mass movements, and the research topics and latest research advances of their respective research groups. The objective of discipline analysis is to find the research trends of lunar mass movements across different disciplines, to identify the current hot research fields, and to comprehend the inter-disciplinary application. Lastly, the citation analysis unveils the trend of influence in lunar mass movements research, while co-citation analysis aids in identifying additional points of intersection for mass movements research.

3.1 Publications

There were 1,742 literature retrieved from the 10 keywords, of which 237 were in Scopus, 425 were in WoS, and 1,080 were in ADS. Using the deduplication rule, the final articles database contained 965 items (Figure 1) including 867 unduplicated articles (those found in only one database) and 98 duplicated articles (those found in several databases).

The number of published papers has grown exponentially since the first article about lunar mass movements appeared in 1872. (R^2 = 0.7064) (Figure 2) Taking 1973 and 2009 as key growth nodes, it can be divided into three development periods, with an average number of articles of 0.44, 14, and 29. Taking 10 years as the interval, the total number of articles in each period is calculated, which highlights the boom years of lunar mass movements research (See Figure 2). Researchers have only begun to do a lot of research on the mass movements of the Moon in the last 60 years, and 98 percent of the publications have been published in that time. 53.4 percent of all papers were published in the last 20 years (2003–2022). The high production years (2012, 2016, 2017, 2018, 2019, and 2020) were concentrated over this period, with values that were higher than the production mean (21 articles) reported for the last 30 years (1993–2022).

The articles were published in 175 publications and classified into three categories: Journal article, Conference contributions (talks and posters), and Book chapter, while the majority of them (55.6 percent) were concentrated in 32 publications. The journals with the highest number of publications were Icarus with 96 (9.9%), Journal of Geophysical Research (JGR) with 78 (8.1 percent), Planetary and Space Science (P&SS) with 30 (3.1 percent), Acta Astronautica (AcAau) with 24 (2.5 percent), Advances in Space Research (AdSpR) with 23 (2.4 percent). In addition, some Ph.D. T (Ph.D. thesis) is of great reference value with 27 (2.8 percent) (Figure 3A). The remaining papers (44.4%) were published in 143 different publications. From the data above, we could figure out which journals are usually available to acquire articles related to lunar mass movements.

3.2 Authorship

The 965 articles examined included a total of 2,622 authors. We create an author network by taking the top 200 most often appearing writers in the database and measuring the frequency of collaboration

between all authors (Figure 4). According to the frequency of collaboration, the authors were split into eight groups, and the lines indicated some collaboration with authors in other groups. The analysis shows that authors in group 1 focused on the erosion of the surface by ejecta on different planets. The second group studied the characteristics, distribution, and age of valleys and landslides on Mars, and the topic of group 3 is geological structures and process on different planets. Group 4 studied the lunar regolith based on image processing. The fifth group investigated the evolution of the planetary surface. Group 6 focuses on the evolution of craters on the Moon, and group 7 is about the thermodynamics of planets. The rest were grouped into the "other" group.

Over time, the research activeness of each group varies. The first group persisted in their research related to lunar mass movements and produced publications on the subject throughout time. Furthermore, group 4 has continued to conduct relevant research in recent years, and added fresh research findings to the database this year. For the past 4 years, groups 2, 3, and 5 have been without a new article about the subject, and group 7 has not published a new research output for approximately 15 years. Finally, the researchers of the sixth group have not updated their articles anymore since 1997.

The affiliations of the authors of the articles were dispersed among 450 institutions, including universities, research institutes, and centers. The country distribution of the articles was counted based on the affiliated institutions of the first author, as shown in Figure 5, which are mainly distributed in the United States (33.49%), Russia (14.10%), China (13.13%), Germany (6.99%), and Italy (6.27%). Coincidentally, among these countries, the United States has successfully launched 30 lunar exploration missions, Russia has successfully launched 27, China has launched 7, and the European Space Agency has launched 1. More than half of the published articles (54.2 percent) were concentrated in 15 institutions, California Institute of Technology (6.9 percent), Arizona State University (4.9 percent), Johns Hopkins University, and Russian Academy Of Sciences (4.6 percent each), NASA Goddard Space Flight Center and United States Geological Survey (4.1 percent each), Planetary Science Institute (3.7 percent), Max Planck Society (3.4 percent), Brown University (3.3 percent), National Aeronautics and Space Administration (3.3 percent) (Figure 3B).

3.3 Interdisciplinarity

The papers in the database involve 35 disciplines, with Astronomy accounting for 686 (57 percent), Physics for 221 (18 percent), Engineering for 92 (8 percent), Earth and Planetary Sciences for 77 (6 percent), Geochemistry Geophysics for 32 (3 percent), and Geology for 29 (2 percent). (Figure 6).

The changing trend of several disciplines (including a large proportion of articles) from the time dimension was further analyzed. In the direction of physics from 1915 to 1970, a total of 209 publications (94.6 percent) were published, with an average of four papers a year. Papers in Astronomy surged beginning in 1966 and have remained at a high level, averaging 12 publications annually, whereas previously relevant articles were published occasionally. Engineering studies focused mostly on the design and application of spacecraft; the first relevant article we searched was published in
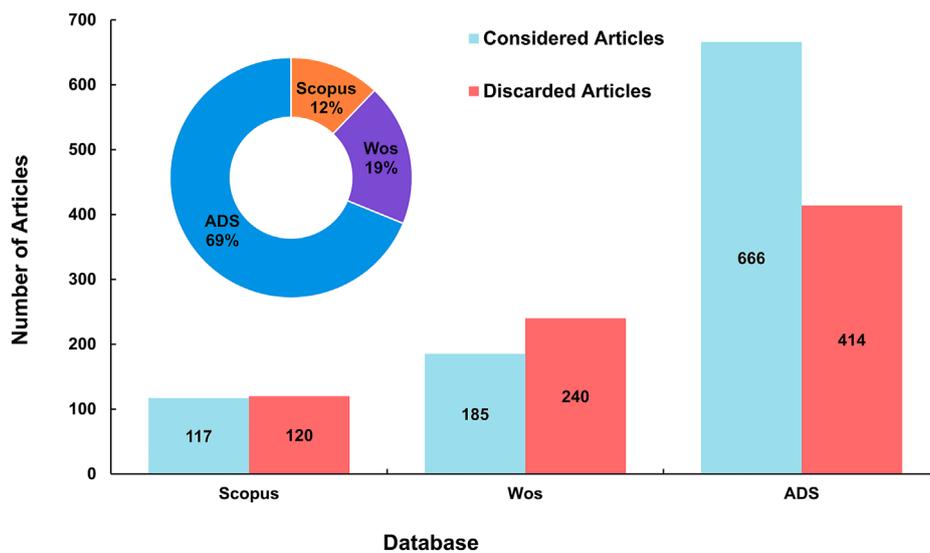
FIGURE 1
Related articles are distributed in three online databases including original search results and deduplicated results.
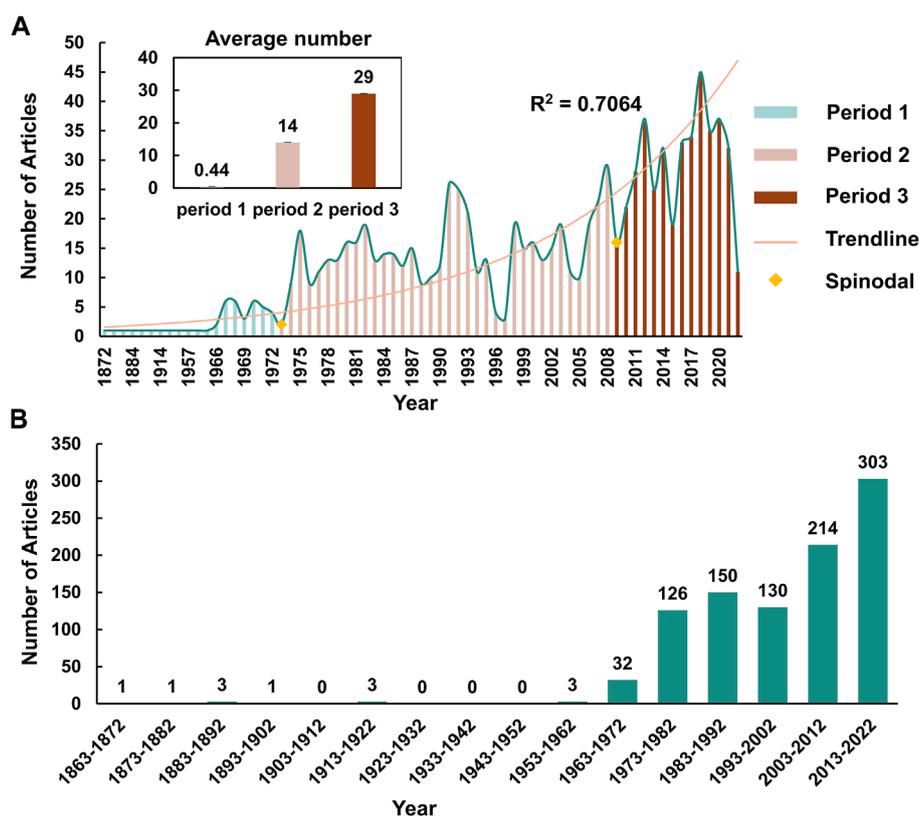
FIGURE 2
Characteristics of annual lunar mass movements literature: **(A)** Number of publications from 1872−2022 increases exponentially (R^2 = 0.7064, remove the years with no publication). The number of articles over years indicates that the evolution of lunar mass movements research could be divided into three stages (1973 and 2009 are the turning points). **(B)** Numbers of publications each decade. Most publications (98%) related to the lunar mass movements have been published in the recent 60 years.
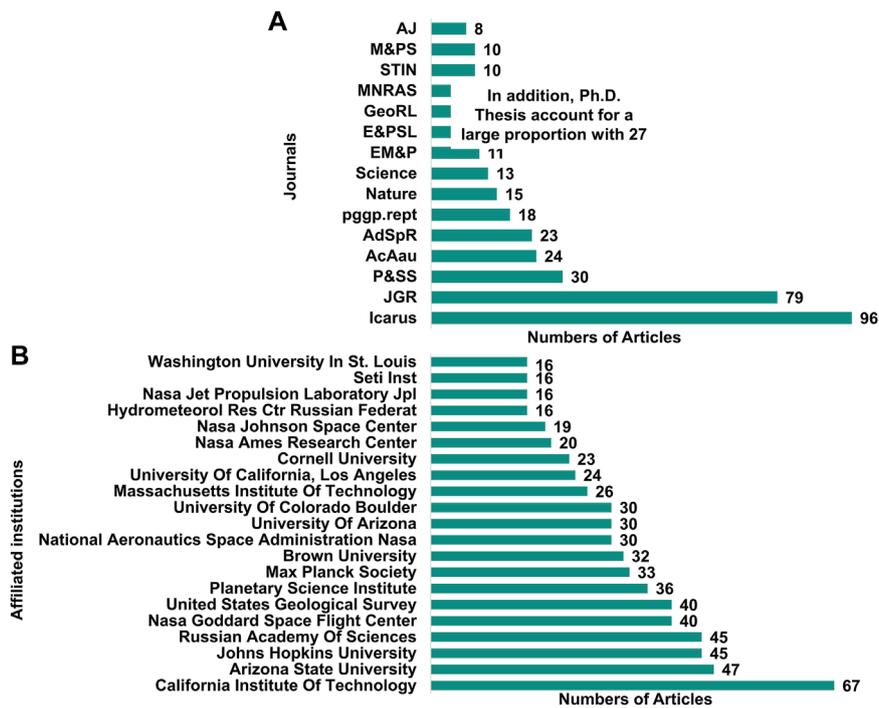
FIGURE 3
Statistics on the sources of literature on lunar mass movements: **(A)** The 15 productive journals in lunar mass movements research. **(B)** The 20 productive institutions in lunar mass movements research.
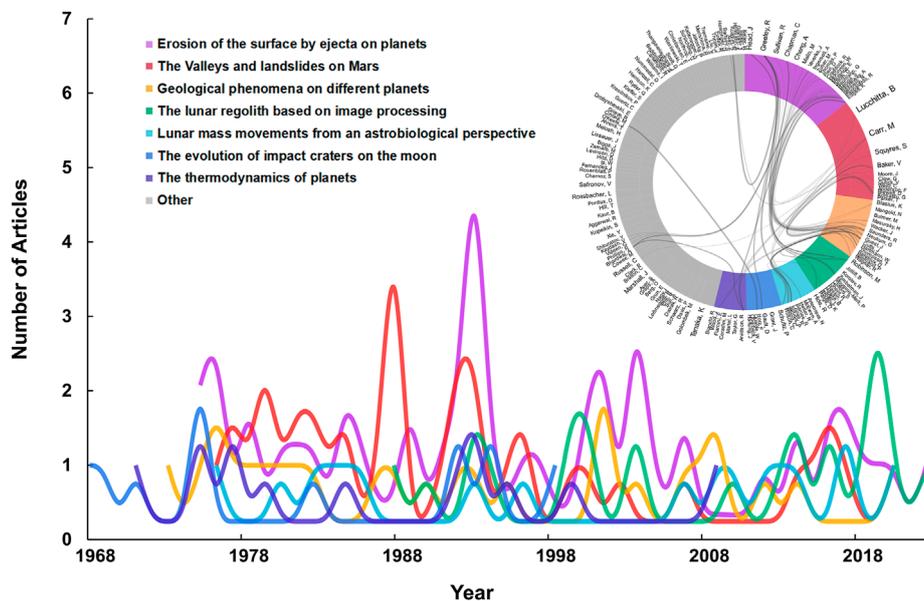
FIGURE 4
Cooperative relationship network of authors. The pie chart displays the authors grouped by the cooperation frequency and named each group by the common research fields, and lines indicate the other collaboration between authors. The line chart reflects the timeline view of the research group activity.
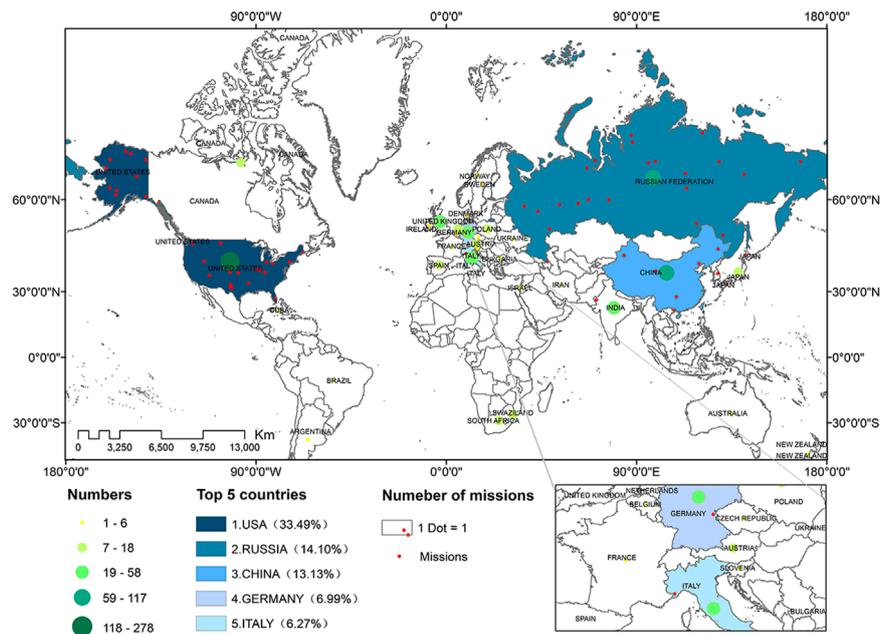
FIGURE 5
Geographical distribution of lunar mass movements publication volume level (Counted based on the affiliated institutions of the first author). The top 5 productive countries in lunar mass movements research are highlighted, the number of scatter points indicates the number of the lunar exploration missions each country launched.

1972, and after that, an increasing number of related publications were published, with an average of six articles per year for nearly 10 years. Earth and Planetary Sciences has been studied since 1969 and has been booming in recent years, with 75.3 percent of publications published in nearly 10 years, averaging 5.8. (See Figure 6).

The retrieved articles are from multiple scientific directions suggesting that the study of lunar mass movements is valuable in different scientific fields. An analysis from the time dimension reveals the development trend of several key disciplines in lunar mass movements research. Most of the articles are in the field of Astronomy, which is partly due to the absence of geology-focused journals in the past, but it can also indicate that the current research on lunar mass movements is mainly focused on this direction The rapid expansion of Earth and Planetary Sciences and many space missions in recent years validates the extensive application of comparative planetary methods in the study of lunar mass movements.

3.4 Quotation

The 965 papers in the database have been cited a total of 20,747 times between 1 January 1964, and 18 May 2022, including 409 self-citations. Each article was cited 21 times on average. Figure 7A demonstrates that the number of citations increases linearly over time. The total number of reads of these publications since 1996 was 109,094, with an average of 113 reads per publication, according to data collected by the system from ADS, Wos, and Scopus about the rate at which articles have been accessed. And 36,959

downloads were made in total, with a 38.3 download average. The data mentioned above illustrates the expansion of the impact of research on lunar mass movements, which is logical given the trend of synchronous rise in the number of articles.

We utilize six indexes, including the h-index[1], g-index[2], i10-Index[3], i100-Index, tori-Index[4], and read10-Index[5], to provide a summary of the citations, usage, and derived indicators of these articles. Because of author disambiguation issues, the result does not remove self-citations based on the author's name but instead uses a list-based removal of self-citations. Since 1962, the tori-index has increased rapidly, eventually peaking at 354.9, indicating that as time goes on, the research on the mass movements of the Moon and the contribution of earlier work to subsequent research grows. Additionally, the maximum values of the i10-index and i100-index

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1 Hirsch's h-index is the largest number H such that H publications have at least H citations. It attempts to measure the productivity and impact of a researcher in a single number.

2 Given a set of articles ranked in decreasing order of the number of citations that they received, the g-index is the (unique) largest number such that the top g articles received (together) at least g^2 citations.

3 The iN-index is the number of publications with at least N citations.

4 The total research impact of a scholar (tori) is calculated using the reference lists of the citing papers, where self-citations are removed. The contribution of each citing paper is then normalized by the number of remaining references in the citing papers and the number of authors in the cited paper. The tori-index is defined as the amount of work that others have devoted to his/her research, measured in research papers.

5 The Read-10 index represents the present readership rate for an individual's papers published within the last 10 years, normalized according to the number of authors.
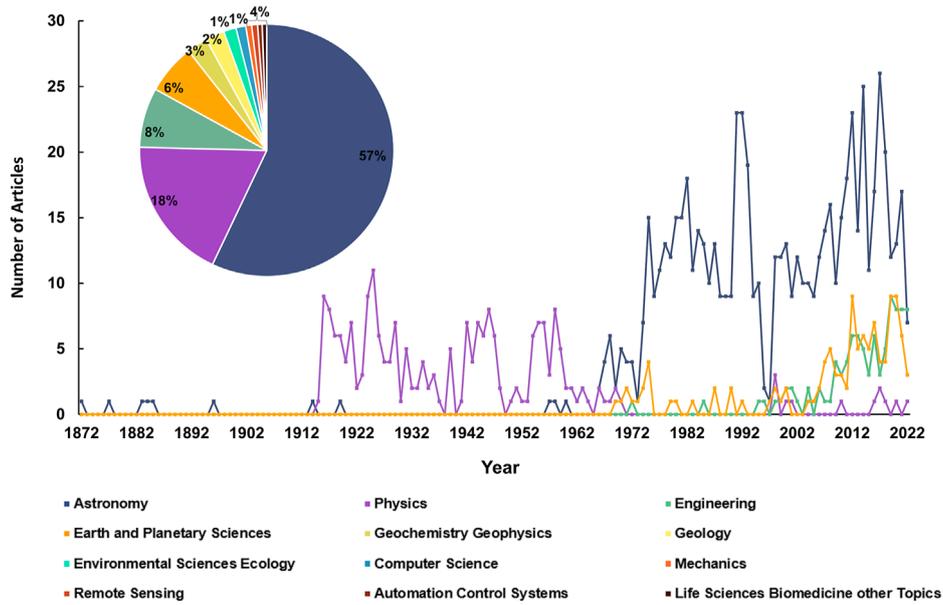
FIGURE 6
Disciplines involved in the research on lunar mass movements. The pie chart is characteristic of the discipline resulting from publication analysis. The line chart is the characteristics of the annual publication of different disciplines.
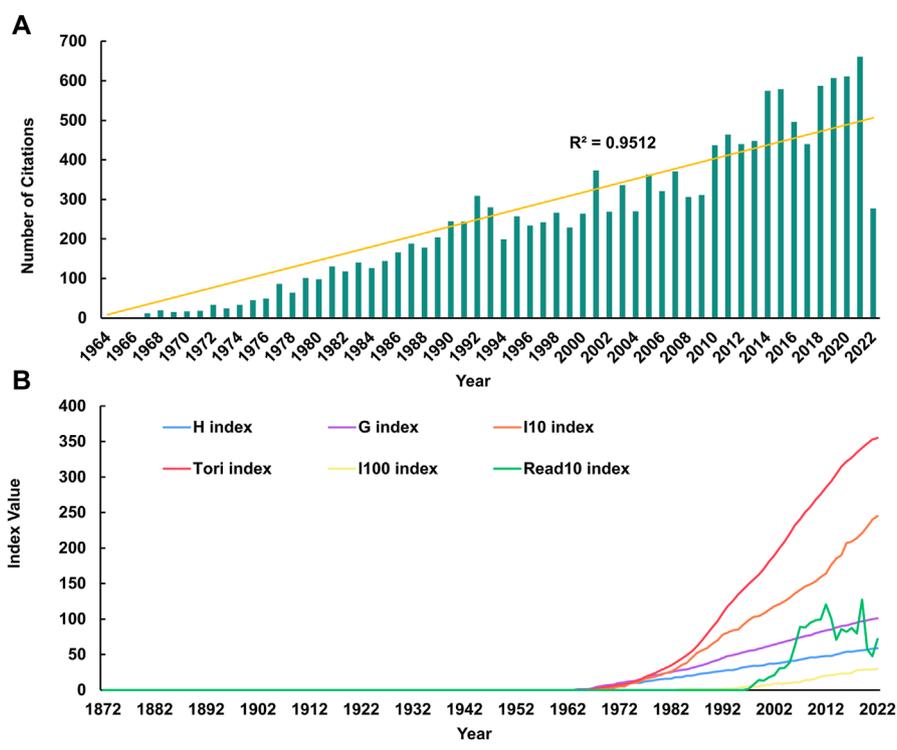
FIGURE 7
Overview of the citation of the literature on lunar mass movements: **(A)** The citation of related articles increases linearly over time (R^2 = 0.9512). **(B)** Characteristics of the index of citation per year.

FIGURE 8
Cooperative relationship network of citation.
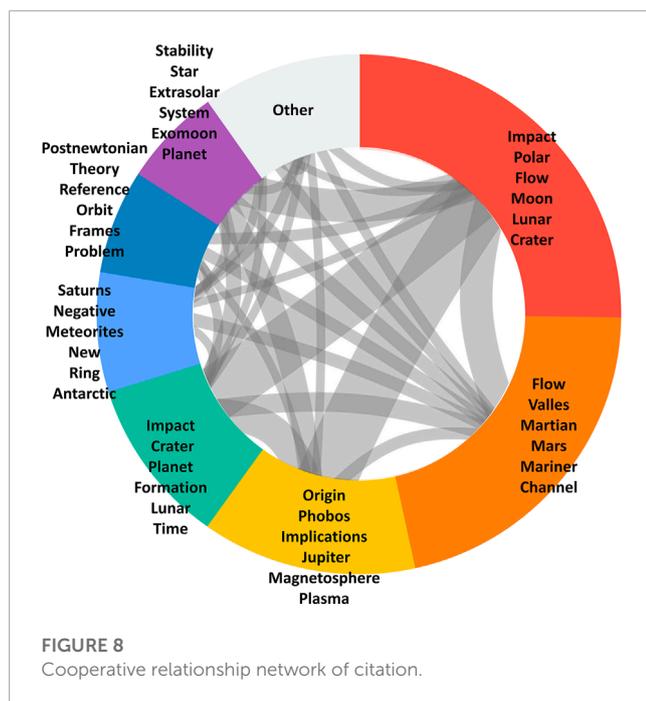
were each 245, while the maximum values of the h-index and g-index, with maximum values of 59 and 101, respectively, indicated a steadily ascending trend. The trend indicates that the number of articles with a high citation rate is increasing, implying growth of the academic impact of articles about the lunar mass movements. The Read10-index has fluctuated since 2005, indicating that the author's research on the mass movements of the Moon was volatile during the period. The statistics "0" in the chart are due to a data shortage (Figure 7B).

The co-citation network groups articles based on shared references across all publications and names them by searching for common, unique words in their titles. And the lines indicated shared references with papers from other groups, the size of the line reflects the frequency of co-citation (Figure 8). As shown, articles relating to the lunar impact crater and the Martian valley are frequently cited within the same article, implying that lunar mass movements research is commonly carried out by comparing the mass movements of Mars and the Moon. It can also be investigated by comparing the mass movements of other planets. Additionally, surface erosion, slope stability, and magnetosphere effect are some other directions that are researched frequently.

4 Discussion

4.1 Data for lunar mass movements research

The statistical analysis results of publication years and country distribution indicate that as lunar exploration technology matures, there is an increasing number of articles focused on studying lunar mass movements. This observation highlights the necessity of lunar exploration missions in providing fundamental lunar data

for conducting research on lunar mass movements. At present, three ongoing lunar missions must be mentioned: the Lunar Reconnaissance Orbiter (LRO) by the National Aeronautics and Space Administrations (NASA, United States), the SELenological and ENgineering Explorer (SELENE-KAGUYA) by the Japan Aerospace Exploration Agency (JAXA, Japan), and the Chang'E missions by the Chinese National Space Administration (CNSA, China) (Scaioni et al., 2018) (Table 1).

The open-source Java Mission Planning and Analysis for Remote Sensing (JMARS) software, a WEB-GIS platform developed by the Arizona State University (Burris et al., 2022), allows for handling planetary remote-sensing datasets. The USGS's Integrated Software for Imagers and Spectrometers (ISIS; https://isis.astrogeology.usgs.gov//) could use to perform a standard calibration procedure for Lunar Reconnaissance Orbiter Camera (LORC) images (Chin et al., 2007).

The first lunar landslides the researchers encountered were several landslides around the Tsiolkovskiy crater (Boyce et al., 2020). This landslide is the only large, long-runout landslide on the Moon, this makes the Tsiolkovskiy landslide an excellent end-member for the study of the mechanics and conditions that control the emplacement of such rapid natural mass flows and their runout distance. Over the years, the topographic parameters, morphological characteristics, formation mechanism, and surrounding areas of regolith, ejecta, geological age, and rock abundance of the landslides in the Tsiolkovskiy crater have been well studied (Guest and Murray, 1969; Wu et al., 1972; Schultz, 1976b; Greenhagen et al., 2016; Morse et al., 2018; Boyce et al., 2020). Since then, numerous mass wasting features on a local scale have been noticed and reported based on a variety of lunar image data and terrain data (Table 2).

Even though various slope failure types have been examined on the Moon, there is still a lack of a comprehensive inventory of lunar landslides on a global scale. Table 3 lists the existing inventory of mass movements on the moon on a global scale.

From the list of mass movements, we found that researchers have used several morphological characteristic factors to describe the shape of the mass movements quantitatively (see Table 2). Moreover, Brunetti et al. (2015) compiled the inventory of 60 rock slides in the simple crater and using the planimetric area of the mapped failures calculated the probability density distribution of the landslide area. The measuring methods in detail list in Table 4 Below.

4.2 Methods used in lunar mass movements research

Three approaches are most commonly used to study mass movements on the Moon: 1) Image recognition, which is used to extract the boundary information of mass movements, thus studying their morphological, evolutionary, formational, distributional, and erosional characteristics; 2) Model simulation; physical models are usually constructed to simulate the lunar environment to study the development process and formation causes of mass movements; 3) Comparative planetology, by comparing the similar characteristics of different planets, the characteristics, influencing factors and classification standard of lunar mass movements can be well interpreted.

TABLE 1 Data access to lunar mass movements research.

Lunar missions	Instrument		Spatial resolution	Access
LRO	Lunar Reconnaissance Orbiter Camera (LORC)	Narrow-Angle Camera (NAC)	~0.5 m/pixel	http://target.lroc.asu.edu/q3/
		Wide-Angle Camera (WAC)	~100 m/pixel	
	Lunar Orbiter Laser Altimeter (LOLA)		~57 m vertical resolution: ~0.1 m	http://denali.gsfc.nasa.gov/
SELENE-KAGUYA	Lunar Imager/Spectrometer (LISM)	Terrain Camera (TC)	10 m	http://l2db.selene.darts.isas.jaxa.jp/
		Multi band Imager (MI)	VIS: 20 m	
			NIR 62 m	
		Spectral Profiler (SP)	562 × 400 m	
	Laser Altimeter (LALT)		5 m	
Chang'E missions	Three-line Array Charge Coupled Device Stereo Camera (CCD)		~1m–7 m	https://moon.bao.cn/
	Laser Altimeter (LAM)		5 m	

TABLE 2 Available data catalogue of lunar mass movements in region.

Author	Location	Data	Characterization	Factors
Bray et al. (2010)	Crater Thales, Giordano Bruno	High-resolution (~0.5–2.0 m/pixel) images from the LOR-NAC	Melt deposits on the floors of complex craters are comprised of a mixture of melt and clastic debris, giving the majority of deposits a hummocky appearance	
Perumal. (2012)	Shrodinger basin	High-resolution images from the Chandrayaan-1 terrain mapping camera (TMC) and Lunar Reconnaissance Orbiter (LRO) images	Run-out flows induced seismic shaking as responsible for the down-slope mass movements. Crater counting dating provides a minimum age of landslides to be around 30 Ma	Slope
Otto et al. (2014)	The Tycho crater	The Low Altitude Mapping Orbit (LAMO) data from the NASA Dawn mission (~20 m/pixel) LOR-WAC (~100 m/pixel)	Distributed along the entire crater wall, flow-like features are observed, which are slides of low friction or liquid behavior developing striations	
Kumar et al. (2016)	Schrödinger basin	Chandrayaan-1 Terrain Mapping Camera (TMC) images, LOR-NAC&WAC, and the LOLA data set	Rim-crest is relatively smooth compared to hummocky	Length
				Slope
				Width
Li et al. (2018)	LaLande crater	LRO NAC mosaic and WAC mosaic	There are sweeping flows on the eastern crater wall	Area
Kokelaar et al. (2017)	Crater Kepler, Gambart B, Bessel, Censorinus, Riccioli CA, Virtanen F, Tralles A	High-resolution images (0.42–1.3 m/pixel) from the LORC, the LOLA, and "Kaguya Terrain Camera DEM Merge 60N60S 512 ppd"	Three types of dry-debris flow deposits are recognized: 1) multiple channel-and-lobe type, 2) single-surge polylobate type, 3) multiple-ribbon type	Length
				Slope
				Area
				Thickness
				Volume
Boyce et al. (2020)	The western rim of the Tsiolkovskiy crater	LROC images (NAC, WAC), Kaguya, and LOLA topographic data	The only giant landslide on the Moon with a lobate flow feature. The landslide components (i.e., north, south, west, and middle slides) formed almost simultaneously	Length Thickness
				Area
				Volume Mobility (i.e., L/H, H/L, L/V)

TABLE 3 Available data catalogue of lunar mass movements in globe.

Type	Number	Data	Method	Characterization
Falls, Slides, Flows, Creeps Xiao et al. (2013)	300	LOR-NAC (~0.5 m/pixel)	Visual interpretation	See Table 6
		The LOLA global elevation data (1,024 pixel/degree ~30 m/pixel in the equator)		
Rock slides Brunetti et al. (2015)	60	LOR-WAC (~100 m/pixel); Global WAC digital terrain model	Visual interpretation	The upper parts of the scarp areas of the landslides are visible on the crater rims or walls, and most of the displaced materials are deposited on the crater floors
		(~100 m/pixel)		
Rockfall Bickel et al. (2020)	136,610	LOR-NAC (~0.5 m/pixel)	RetinaNet	1) A boulder that usually has a higher albedo than the surrounding regolith
				2) A shadow that is cast by the boulder and appears right next to its parent boulder
				3) A nearly linear boulder track with light shadows at its deepest point and potentially along its rims
Granular Flows Bickel et al. (2022)	28,101	LOR-NAC (~0.5 m/pixel)	RetinaNet	The deposits of lunar flows usually form fans, fingers, rays, and/or lobes and represent distinct features that can be recognized from orbit, both morphologically and radiometrically, despite their small size

As research advances, image recognition techniques are gradually becoming semiautomatic or automatic from the manual. There are three main approaches: visual interpretation incorporating expert knowledge; recognition based on morphological features; and recognition based on machine learning or deep learning methods (Table 5). The primary method is visual interpretation with expert knowledge at present due to the diversity of types and complex morphological characteristics, which is slow and laborious. Technology for automatic identification is evolving, whereas the method is only capable of detecting a single type of mass movement at present. And recognition methods based on machine learning or deep learning lack sample libraries containing multi-scale morphological information of lunar mass movements. Therefore, more comprehensive automatic recognition methods need to be developed in combination with artificial intelligence technology in the future.

Physical model simulation compensates for the fact that researchers could not contact the lunar surface, helps us to imitate the process of movements, and explore the factors that influence mass movements and the effects on geomorphic evolution. By the discrete element method, Bui et al. (2009) introduce the self-locking ability between particles into the particle contact model to study the slope collapse of lunar soil. Since then, the discrete element method has become a common method for simulating lunar soil landslides, analyzing landslide processes and landslide mechanisms, and evaluating the engineering disaster index (Liao et al., 2018; Liever et al., 2018; Wu et al., 2020). To investigate the influence

of the low gravity environment on particle fluidity, Huang and Mao (2013) used the drop tower to design a system to simulate a low gravity environment, which captured the configurations and variability in the flow materials by drop-tower tests. Zheng and Huang (2015) used silicon carbide as a lunar regolith simulant to study the flow patterns of lunar regolith by capturing configurations of the flow and calculating the engineering strains under the action of different chute angles.

As mentioned in the introduction, the mass movement process is widely distributed on Earth, Moon, Mars, Mercury, Venus, and some icy satellites and asteroids in the outer Solar System, with some of the same or similar characteristics, meaning that their forming may have similar properties. As a result, when studying the classification, formation, and influencing factors of mass movements on the Moon, researchers frequently refer to mass movements on other planets (Hargitai and Kereszturi, 2015). For example, an alcove, a channel, and a deposition apron are characteristics shared by lunar crater-wall landslides and Martian gullies. Fine granular material without liquid water collapsing results in the formation of Martian gullies. Also, on the Moon, there is no atmosphere and water, these observations suggest that dry landslides can form recess-channel-apron morphology on the planets (Bart, 2007). Mass-wasting such as slumps, slides, and flow-like features are both found in the Rheasilvia crater on Vesta and the Tycho crater on the Moon. Analyzing the similarities and differences of mass-wasting features on the Moon and asteroid Vesta concerning their gravity shows that slumping is triggered when gravity forms a torque on the

TABLE 4 Factors for measuring lunar mass movements morphology and mobility.

Factor		Description	Method	Role
Slope		The local slope angle nearby of the landslide scarps	Slope angles are tangents measured on the slope plots	Explore the relationship between slope instability and slope
Geometry	Area	Areas of the plan view of deposits	Measured using an ArcMap outline tool	Understand size, origin, emplacement, as well as the relationship with other terrains in the immediate vicinity
	Length	The maximum length from the rim	Measured the distance using the ruler in ArcMap	
	Width	The maximum width from the rim		
	Thickness	The thickness of the deposits	Derive thickness approximately from shadow lengths	
	Volume	The volume of the deposits	Segment on-slope areas and thicknesses were coupled to determine the segment volumes and these were then summed to find a total	
	Drop height	The difference in elevation between the source area and the deposit extreme tip	Measured by elevation difference based on altitude data using ArcMap	
Mobility	L/H	The ratio of length to drop height	Calculate the ratio of length to drop height	The H/L ratio is widely regarded as a proxy for the dynamic friction angle of the landslide. Study the mobility dependence on volume
	L/V	The ratio of length to volume	Calculate the ratio of length to volume	
	H/V	The ratio of drop height to volume	Calculate the ratio of drop height to volume	

TABLE 5 Methods for lunar mass movements identification.

Method	Author	Description
Visual interpretation	Schultz. (1976a)	Lunar surface features were interpreted by visual interpretation based on lunar orbiter photographs, accompanied by explanatory text
	Xiao and Komatsu. (2013)	Collecting over 300 typical mass wasting features by observed mass wasting features in LORC NAC images.
	Brunetti et al. (2015)	Mapped 60 rockfalls in simple impact craters, with scarps and deposits, have been distinguished, and some tracks, blocks, and cracks in the bodies have been mapped
	Kumar et al. (2016)	Found Boulder falls in the Schrödinger basin and mapped >1,500 boulders associated with trails and bouncing marks
	Kokelaar et al. (2017)	Seven lunar crater sites of granular avalanches are studied utilizing high-resolution images, for the first time, extensive remobilization of coarse talus by inundation with finer debris
Morphology	Craddock and Howard. (2000); Simon and Bruyn. (2007)	Using inequalities to fit crater boundaries to identify landslide locations and profiles
	Mahanti et al. (2014)	Chebyshev polynomial function is used to describe the crater shape in a quantitative and repeatable way
	Yordanov et al. (2016)	Based on the Chebyshev polynomial method to match the cross sections of impact craters, identified landslides by associating the asymmetry of the cross-section with the landslides
	Scaioni et al. (2018)	Based on the classification of morphological parameters by Chebyshev polynomials, fixing empirical absolute thresholding and statistical adaptive thresholding are adopted to identify slumps in simple impact craters
Deep learning	Bickel et al. (2020)	Analyzing an archive of more than 2 million high-resolution images from LORC using a fifth-generation Convolutional Neural Network (CNN M5), created the first global map of 136.610 lunar rockfall events

TABLE 6 Characteristics of different types of lunar mass movements [Modified from Xiao et al. (2013)]

Type		Definition	Distribution	Characterization	Example images Xiao et al. (2013)
Falls		Abrupt downslope movements by which rocks or regolith detach from steep slopes Highland and Bobrowsky, (2008)	A subhorizontal stratum along the rim of the rilles	Traces of rolling boulders are also typical indicators of recent rock falls	
Slides	Rock slides	Mass downslope movements along ruptures or relatively thin zones of intense shear strain, separate the sliding material from the more stable underlying planar Highland and Bobrowsky, (2008)	Most slides occur in Eratosthenes and Copernican-aged craters	The volume of displaced material gradually enlarges from the sliding front. Sub-parallel fractures grow in impact melt sheets due to gravitational dragging; the shattered rocks slide along slopes forming talus deposits at the foot of the slopes. Cruden and Varnes. (1996)	
	Debris slides			Debris slides displace material that has smaller grain sizes than rock slides	
Slumps		Sudden mass movements of large amounts of rocks and/or fine material for short distances Ritter et al. (2006)	Craters, tectonic scarps, and volcanic rilles	The movement is characterized by sliding along a concave-upward or planar surface, the displaced material in slumps usually has a larger volume Cruden and Varnes. (1996)	
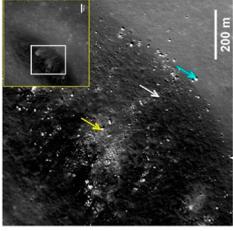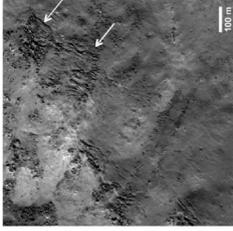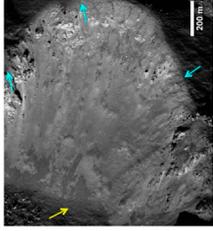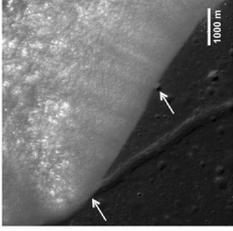
TABLE 6 (*Continued*) Characteristics of different types of lunar mass movements [Modified from Xiao et al. (2013)]

Type		Definition	Distribution	Characterization	Example images Xiao et al. (2013)
Flows	Channeled flows	A form of continuous mass movement in which a combination of loose soil and rock fragments move downslope Highland and Bobrowsky, (2008)	Flow features are only observed in impact craters	Channeled flows on the Moon have a morphology of flow feature, usually composes of a gully/alcove in the source region. Malin and Edgett. (2000)	
	Sweeping flows			Have a morphology of flow feature, but does not form any channels	
Creeps		Creep is imperceptibly slow, steady, downward movement of soil and/or rocks Highland and Bobrowsky, (2008)	Almost all lunar surfaces	Form the lunar regolith ripples, appear convex in downslope directions, and are sub-parallel with each other. Adjacent ripples are about 20 m apart	
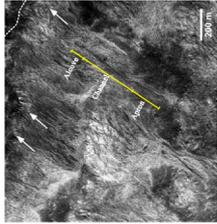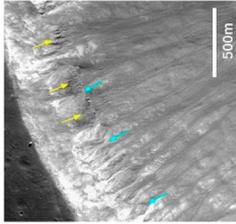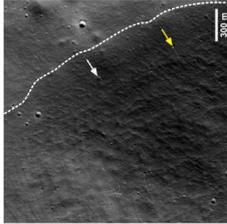
slumping body which exceeds the frictional forces and slumping develops more efficiently on bodies with higher gravity (Otto et al., 2014). Rock slides on the Moon are, on average, more massive than analogous rock slides on Mercury, according to a comparison of the size of landslides on the simple impact crater-wall on the Moon and Mercury (Brunetti et al., 2015). Therefore, it is hypothesized that authors a result of the properties of the rock material or possibly a result of the lunar surface gravity, which is weaker than those of Mercury's (Brunetti et al., 2015). Furthermore, the lunar mass movements classification system was updated from the Varnes (1978) classification system for terrestrial landslides based on movement characteristics and material properties (Cruden and Varnes, 1996).

4.3 Parameters of morphological and triggering analysis

As mentioned above, several variables were employed to quantify the morphological characteristics of mass movements including geometric parameters such as length, width, surface area, volume, and average thickness; mobility parameters such as L/H, L/V, and H/V; and other factors such as slope angle, which were typically determined using ArcMap software (Table 4). These morphometric parameters serve as indicators that reflect the effects of mass movements on topographic modification of the lunar surface. They are integrated into topographic analysis for quantitative comparison to highlight the difference of mass wasting within various environments, thus revealing the triggers and modification effects on the terrain of the lunar mass movements. For example, slope angles measurement for the host terrains of the mass wasting features aids in detecting the minimum slopes on which mass wasting can initiate. This provides insights into the slope evolution of lunar surface terrains under the influence of mass wasting (Xiao et al., 2013). Furthermore, comparing the details of topographic features on mass wasting in different craters enables exploration of whether mass wasting in mare settings differs significantly from that in highlands. Comparisons with terrestrial counterparts could also aid in understanding lunar surface processes (Kokelaar et al., 2017).

The modification of the surface topography by lunar mass movements focuses on two aspects: the modification of the sloping topography and the modification of the deposit topography. The lunar gravity gradually changed the slope height difference to a flatter topography by moving the slope material toward a region with a gentler topography. Therefore, mass movements generally occur preferentially over slopes forming lately, with a steeper slope angle (Xiao et al., 2013). Thus, the distribution of mass movements could provide a reference for relative age estimates in lunar topographic units, which was shown in Bickel et al. (2020) using the quantitative of rockfalls. In addition, the type and velocity of mass movements are different on the different side slopes. For example, older surfaces on the Moon generally have slopes much less than the angle of repose of lunar materials, where creeping of regolith is the dominate landslides (Xiao et al., 2013), and the speed at which the debris moves increases with slope steepness (Soderblom, 1970).

Compared to the same volume of landslides on the Earth, the lunar landslide has a much larger scale of mass wasting, resulting in a spectacular accumulation of landforms (Xiao et al., 2013). It is due to the Moon having a sixth gravity of the Earth, which means the material formed is less fragmented under the small gravity force of the Moon for the same material strength. Additionally, the weathered lunar regolith on the Moon's surface can lubricate coarse particles and reduce sliding friction, lengthening, extending the path of mass movements (Riller and Lieger, 2008), and giving the accumulation landform a slender appearance, as well as the regolith would damp the impact of individual particles, reducing fragmentation (Kokelaar et al., 2014). The density of lunar soil on the lunar slope is lower than that on the flat surface, and the bedrock erosion rate is higher than that on the flat surface because large-scale movement exposes the bedrock by clearing debris on the slope (Lin et al., 2020). In conclusion, the combined effect of small-scale microscopic gardening and mass movements will lessen the slope's fluctuation while burying the downhill and making it flat or fluctuate gently.

Studying the triggering of mass movements is inextricably linked to investigating its morphological features and spatial distribution traits. On the Moon, endogenic dynamic processes (such as volcanism, tectonism, tides, and body shrinkage) and seismic activity induced by impact cratering, as well as thermal stresses raised by diurnal temperature changes, are among the forces that could result in deformation and failure in slope materials (Watters et al., 2019; Head et al., 2020) (Figure 9).

Impact cratering includes asteroid impact, meteorite impact, etc. Different sized impact bodies have various impact effects, and seismic activity caused by impacts can have an impact on a much larger areas than the original impact craters [(Schultz, 1976a). The impact destroys the composition material's structure and original topography. The impact destabilizes the slope by causing a mass movement and changing its morphological characteristics, makes the slopes gentler and the surface regolith layer thicker and results in degraded craters (Bickel et al., 2022; Ikeda et al., 2022; Chandnani and Herrick, 2023)]. The impact of micrometeorites (0.1–2 mm) can also degrade the surface of the rock and possibly cause the granule on the surface to separate triggered debris flow and gardening produced agglutinate formation and related cohesion increase (Soderblom, 1970; Hörz et al., 1971; Basilevsky et al., 2013; Bandfield et al., 2014; Bickel et al., 2021; Bickel et al., 2022; Ikeda et al., 2022). Impact-related seismicity is shallow seismic, and tectonic activity can also be the cause of shallow seismic. Boulder falls are not caused by shallow moonquakes along lobate scarps but by ground shaking due to meteorite impacts (Ikeda et al., 2022).

The rate of diurnal temperature change is less than 2 K/min on the Moon ((Molaro and Byrne, 2012), but grain-scale stresses induced by diurnal temperature changes are on the order of 100 MPa (Molaro et al., 2015). This magnitude of stress is comparable to the typical strength of lunar rocks. Thus, the temperature changes lead to the grain reorientation caused by the differential expansion of the matter to induce mass movements. The strength of thermal weathering depends on the size of the rock mass's particles and albedo and thermal inertia, and some research has found that the thin regolith cover would prevent the initiation of thermal fracturing (Molaro et al., 2017; Ruesch et al., 2020). Besides thermal fracturing, thermal moonquakes, which happen only in extremely dry sand with a smooth surface may be another mechanism driving lunar landslides (Linasay, 1976; Bickel et al., 2021).

FIGURE 9
Triggering factors for mass movements on the Moon [Modified from Xiao. (2021)].
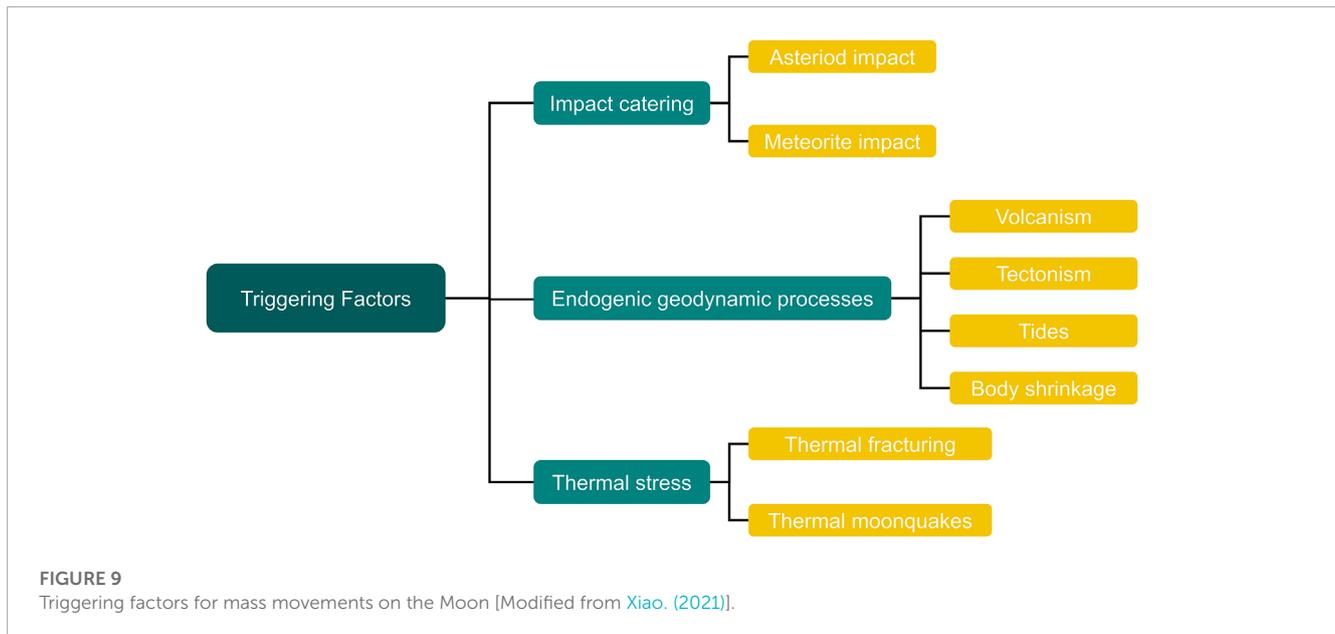
There are no affect factors like rainfall, melting snow, and frequent human activities of mass movements on the Moon compared to the mass movements on the Earth. Other factors, such as material composition, terrain conditions, lunar exploration and land missions, and space weathering, may play an important role in the formation and development of the lunar mass movements. In addition, whether the lunar soil contains water ice, what form of water storage, and how much water is still controversial, which will also have an important impact on the cause of the mass movements (Bart, 2007; McCubbin et al., 2015). At the same time, the mechanical properties of the rock composition material will affect the stability of the slope and the formation and development of the mass movements.

As lunar exploration engineering technology, such as the Artemis project (Barzilla et al., 2021) continues to advance, an increasing number of lunar orbiters and manned landers are impacting the lunar surface environment. According to recent news reports, scientists have found an orbiter component that has fallen into a fresh impact crater on the far side of the Moon. This intriguing finding has led us to speculate that external impact events of a similar nature could generate varying degrees of vibration across different scales of lunar surface regions. Such vibrations may potentially contribute to the occurrence of mass movements.

4.4 Future research direction

The research in this field describes a higher increase in the last 14 years (2009–2022), which has benefited from the dozens of successful manned and unmanned exploration Missions. In light of ongoing advancements in lunar exploration technology and an abundance of lunar exploration data, lunar mass movements have attracted the attention of an increasing number of researchers as an ideal window to study the transformation effects of internal and external forces on the morphology of the Moon's surface. However, the following problems still need to be solved.

At present, the recognition and mapping of mass movements still rely on visual interpretation of integrated expert knowledge, which is a time-consuming task (Nass et al., 2018), while suffering from artificial and technological limitations and biases. This contributes to the lack of catalogs on a global scale including all kinds of mass movements, and the lack of knowledge about the spatial distribution and density of mass movements. Research by Bickel et al. (2021), Bickel et al. (2022) used a machine learning-driven approach to solve this major limitation of human-driven, mapped 28,101 flow features and 136,610 boulder tracks between 60°N and S. These works opened the door to a statistically sound, global-scale analysis of the spatial distribution, density, and drivers of rockfalls and granular flows. However, a comprehensive inventory of other types of mass movements is still lacking. A morphological information sample database of multi-scale mass movements needs to be constructed to complete the global-scale database of mass movements, and machine learning or deep learning methods for identifying more types of lunar mass movements need to be experimented with. Then, a global-scale analysis of the spatial distribution, and density of all kinds of mass movements could be carried out.

Existing classification schemes for mass movements have unclear classification metrics. The current classification of the mass movements modified the classification system adopted by Varnes's (1978) for terrestrial landslides, which is classified by three indicators: movement process, slope morphology, and deposition characteristics (Kokelaar et al., 2017). Classifying lunar landslides based on the characteristics of terrestrial landslides would be incomprehensible. There are a series of problems, such as environmental simulation costs being high, explaining characteristic differences being difficult, and reference standards being inconsistent. It is urgent to establish a classification index system combining morphology, slip materials, and movement mode according to mass movements' morphology and spatial distribution characteristics. Rajaneesh et al. (2022) defined 15 critical parameters of the Martian landslide inventory viz., length (L), width (W),

relative relief (RR), area, L/W ratio, RR/L ratio, TI of landslide (mean, minimum, and maximum), and slope statistics (mean, minimum, and maximum), TI of the scarp, the slope of the scarp, and geology, which were analyzed using multiple discriminant analysis (MDA), it turns out that the parameters RR/L, L/W, and RR were suggested to be the parameters that primarily discriminates the Martian landslides. And then machine learning algorithms were used to evaluate the classification of landslides. This study demonstrates the potential of using machine learning models to classify extra-terrestrial landslides. Therefore, the main research direction of lunar landslide classification in the future is using machine learning algorithms to design a data-driven classification parameter system based on the spatial distribution characteristics and the morphological characteristics, integrating the environmental and geological information.

Triggers of the mass movements discussed above were short of compelling statistical evidence at present. This is partly limited by the lack of a comprehensive global-scale inventory. With the available data, only one or a few factors of a single type of mass movement could be conducted a quantitative assessment on a small scale by researchers, which cannot meet the demands of multi-scale big data analysis. The differences in the morphological characteristics and spatial distribution of mass movements were significant because its formation process is always influenced by the interaction of environmental and geological factors. In the study of terrestrial landslides, the landslide susceptibility model is usually constructed by multiple discriminant analysis of triggers such as terrain, hydrology, and human activities through algorithm models such as logistic model tree, random forest, support vector machine, and Bayesian (Chen et al., 2017; Pham et al., 2019; Sun et al., 2020; Xie et al., 2021). Thus, driven by machine learning and big data technology, there is a need to construct the mathematical model to illustrate the intersecting response mechanism of triggers for lunar landslides based on the multiple discriminant analysis of environmental, geological, and geomorphic on a multi-scale.

The study on the modification effect of mass movement on the lunar surface morphology is mostly a qualitative analysis, and without quantitative indicators and universality, as discussed above. In future studies, comparing the transformation scale under various types, terrain conditions, composition materials, space environment, and other conditions could be considered to develop a systematic evaluation index system, and to provide parameters for revealing the evolution process and mechanism of the lunar surface morphology.

It is anticipated that the study of lunar mass movements will advance significantly based on novel data sets acquired in the new era of lunar exploration, evolving computational methods, and GIS big data capabilities as a result of growing recognition of the significance of lunar mass movements research and the development of unmanned and manned lunar exploration projects.

5 Conclusion

The paper generates a database of articles about the lunar mass movements that reflects general information (e.g., data, tool, and method) related to the research of lunar mass movements and highlights the recent advances and the interest areas.

This study shows that the main and frontier research topics of lunar mass movements include the erosion of the surface by ejecta, geological phenomena, the lunar regolith, the evolution of planetary surface, the evolution of lunar impact craters, and thermodynamics. Icarus, JGR, and P&SS are the top three productive publishing journals. And research on lunar mass movements is dominated by a few countries, institutions, and scholars. California Institute of Technology, Arizona State University, and Johns Hopkins University are active institutions leading the lunar mass movements research, and the related institutions are mainly located in the United States, Russia, and China, considering their successful launch of lunar exploration missions as well as investments in research and development, it is not surprising. Frequent collaboration is carried out between scholars on the same or similar subjects to promote the development of research on the lunar mass movements.

Astronomy and physics are the primary disciplines, with research on the modification effect and degree of mass movements on the lunar surface being crucial to the exploration of the geological structure and evolution of the Moon. The citation index analysis indicates the growth of the academic impact of articles about the lunar mass movements. Moreover, co-citation network analysis, which provides important information about the research direction, revealed that comparative planetology was commonly used in the research on the characterization of lunar mass movements, and surface erosion, slope stability, and magnetosphere effects are some directions that are researched frequently.

Reviewing existing studies of lunar mass movements, we propose four unsolved issues. 1) The comprehensive database of lunar mass movements that records all types of landslides incidents on a global-scale has not been compiled. 2) The classification indicators to quantify the classification criteria for the lunar mass movement have not been definite. 3) The mathematical model to explain the triggering mechanism of mass movements on the Moon has not been built. 4) The quantitative indexes to evaluate the modification effect of mass movements on the lunar surface morphology have not been identified. Under the background of continuous innovation in lunar exploration technology and continuous enrichment of lunar exploration data, more types of mass movements should be identified and mapped on a global-scale with artificial intelligence technology to expand lunar landslide database, Multiple discriminant analysis and machine learning tools could be used to construct a lunar landslide classification system, and combined with feature datasets like crater size-frequency distribution, moonquake, impact flux, and topographic, driven by lunar landslide database, the causes and modification effects of mass movements could be clarified finally.

To sum up, this review provides a longitudinal survey of the published literature about the lunar mass movement in the last 151 years. It is hoped that these studies can inspire researchers from the field of lunar surface processes, especially new researchers, to understand the lunar mass movements.

Author contributions

JW conceived the idea of the study. KL wrote the paper. KL and JW interpreted the results. YS analyzed the data. All

authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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