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Review

Landslide Studies in the Context of Disaster Management in Bangladesh—A Systematic Literature Review

Tanvir Hossain [1,2], Mahmud Al Noor Tushar [2], Sanzida Murshed [2], Utsav Basak [2] and Md. Ashraful Islam [2,*]

1 Geoinformation Science and Earth Observation ITC Faculty, University of Twente, Hallenweg 8, 7522 NH Enschede, The Netherlands; t.hossain@student.utwente.nl
2 Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh; mant@du.ac.bd (M.A.N.T.); sanzida.geol@du.ac.bd (S.M.); utsav-2019916958@geol.du.ac.bd (U.B.)
* Correspondence: ashrafhimel@du.ac.bd; Tel.: +880-1816522334

Abstract: Landslides and their resulting impacts on property and human life have become an ongoing challenge in the hilly regions of Bangladesh. This study aims to systematically review diverse landslide studies in Bangladesh, particularly focusing on landslide disaster management (LDM) from 2008 to 2023, encompassing the pre-disaster, syn-disaster, and post-disaster phases. Several key attributes of landslide studies were considered, including general trends, data types, study scales, contributing factors, methodologies, results, and validation approaches, to investigate challenges and subsequently identify research gaps. This study evaluated 51 research articles on LDM using a systematic literature review (SLR) technique that adhered to the Preferred Reporting Item for Systematic Reviews and Meta-Analyses (PRISMA) framework. Our finding revealed that articles on LDM were dominated by the pre-disaster (76%) and the syn-disaster phases (12%), with the post-disaster phase (12%) receiving equal attention. The SLR revealed a growing number of studies since 2020 that used data-driven methods and secondary spatial data, often focused on medium-scale analyses (district level) that, however, often lacked field-based validation. From the factors examined in various landslide studies, topographical and hydrological factors were found to be the most significant attributes in assessment. This study identified key challenges, such as insufficient landslide inventories including poor site accessibility and a lack of high-resolution geological, soil, and rainfall data. It also highlighted critical research gaps, including the need for advanced technologies in susceptibility mapping for national hazard atlas, the investigation of underexplored causative factors, effective early warning systems, detailed post-event characterization, health impact assessment, risk-sensitive land use planning, and interactive web portals for landslide prone areas. This study would thus aid researchers in understanding the depth of existing knowledge and provide insights into how landslides fit into broader disaster management frameworks, facilitating interdisciplinary approaches.

Keywords: landslide hazards; disaster management; quantitative literature review; Bangladesh

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1. Introduction

The occurrence of landslide hazards is widespread all over the world. In the last two decades (2000–2023), 14,541 lives were lost in landslide events, affecting ~4.5 million individuals and resulting in $2.72 billion worth of damages (adjusted values in $) globally [1]. In Asia, the situation is notably severe, with 10,241 fatalities and ~3.9 million people affected, leading to $1.56 (adjusted values in $) billion worth of damage. Likewise, Bangladesh, a country in South Asia, has experienced landslides almost every year, and the scenario is getting worse, with a 4% annual growth rate of landslide incidents. A total of 204 landslides were reported in Bangladesh within the period between 2000 and 2018, causing 727 deaths and 1017 injuries [2]. These figures demonstrate the urgent need for comprehensive policies aimed at lowering landside risk and enhancing disaster management, especially in Asia and other high-risk countries, in order to avoid the enormous financial and human losses associated with frequent landslide events. Bangladesh sits at the convergence of three tectonic plates: the Indian, the Eurasian, and the Burmese. This unique geographic position renders the country a geologically complex setting in the region [3]. In addition, climate change has resulted in shifts in rainfall patterns, frequently producing more intense and unpredictable rainfall events compared to previous years. This shift increases the risk of heavy precipitation over shorter durations, potentially leading to more frequent landslides, in highly fragile topographic hills having relatively softer rocks. Consequently, Bangladesh is not only susceptible to various natural disasters, but also landslides are becoming increasingly deadly in recent times [4,5]. For instance, landslides pose a serious threat to localities adjacent to hillslopes in the Chittagong hilly areas, having a complex origin due to their geographical location, but they are caused primarily by excessive rainfall during monsoons, along with a few other less common anthropogenic causes such as hill cutting, deforestation, or settlement in vulnerable spots [2,6,7]. It is anticipated that the number of landslides in this region will increase in the future, likely to lead to significant damage and loss [8].

Landslide disasters in Bangladesh's hilly regions impose substantial economic and social burdens [9]. They disrupt livelihoods, displace populations, and heighten vulnerability to poverty and health issues [10]. The destruction of infrastructure also strains local economies by limiting access to markets, education, and services, thereby impeding sustainable development [11]. In recent times, landslides have posed a significant threat to Rohinga refugees, with densely packed shelters offering little protection. Heavy rainfall triggered numerous landslides, leading to fatalities, injuries, and the destruction of homes [12]. This challenge exacerbates the already precarious living conditions in the camps, where access to essential services is limited. While it is nearly impossible to escape hazards, it is possible to minimize their impacts by implementing appropriate risk management actions [13]. Addressing landslide disasters is especially difficult in a developing country like Bangladesh, where resources are constrained and scarce, necessitating proper management strategies to mitigate such a devastating calamity.

Like any other disaster, the management cycle for landslides generally comprises four phases: mitigation, preparedness, response, and recovery, and various interventions related to each are crucial for mitigating landslide risk in Bangladesh (Figure 1).

The initial two phases are associated with the pre-disaster period, while the latter two take place after the disaster. Mitigation encompasses all efforts aimed at minimizing the potential impacts of future disasters [14]. These efforts can be categorized broadly into structural measures, involving engineering solutions for safety issues, and non-structural measures like land use planning and evacuation before landslide occurrence. Preparedness involves taking actions to lessen the impacts of forecasted disasters, including security measures like evacuating vulnerable populations [15]. While evacuation planning is considered a mitigation measure, its actual execution is a form of preparedness [16]. The response stage entails emergency measures undertaken during both the occurrence of a disaster and its immediate aftermath, with a primary focus on protecting human lives [17]. This step includes the rescue of victims and addressing the immediate needs of the survivors. Recovery involves fixing the damages, reconstruction of infrastructure, and restoration of critical services after a disaster. In the case of major catastrophes, this recovery process may extend to 25 years, although less time is typically required for lighter impacts or disasters affecting smaller areas [16]. The existing disaster management system and policies in Bangladesh reveal significant shortcomings across all phases of the disaster management cycle (DMC) [18]. These discrepancies underscore the inability of institutional arrangements to address disaster-related challenges, the dearth of effective collaboration and communication between governmental and non-governmental sectors, and the lack of concrete reconstruction and rehabilitation policies [19,20]. In response to this reality, the Government of Bangladesh has launched numerous plans and programs aimed at disaster risk reduction through enhanced disaster management. For instance, the Government of

Bangladesh initiated the Comprehensive Disaster Management Program (CDMP) project, with the overarching goal of mitigating the human, economic, and environmental costs of disasters in Bangladesh [21]. Notwithstanding these endeavors, the execution of disaster management strategies encounters hindrances that ultimately impede the attainment of favorable outcomes [19].

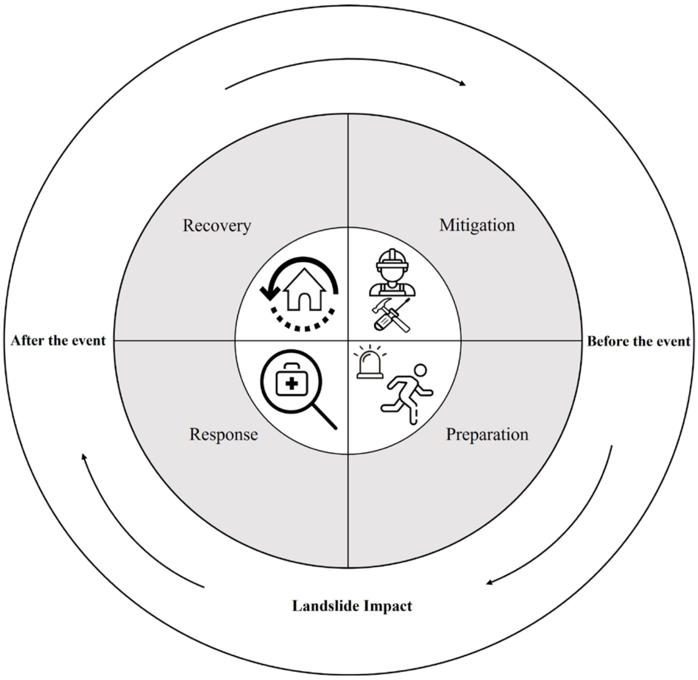

Figure 1. The cyclical phases of landslide disaster management include mitigation and preparation before the event, as well as response and recovery after the event. This process is continuous, with each phase feeding into the next to enhance future risk reduction and preparedness. (Modified after: [16]).

A substantial body of research has extensively examined landslide occurrences in Bangladesh, with a focus on assessing landslide susceptibility and vulnerability through GIS-based and statistical analyses of risk factors [22–26]. Focusing mainly on several notable review works that have also delved into this topic [27–32], we found that existing reviews discussed several aspects, such as trends in landslide susceptibility mapping in alignment with the global practices and causes and consequences of landslides and specific recommendations for addressing landslide problems in the Chittagong region. However, these studies focused on specific aspects of landslides, leaving a gap in the form of a comprehensive systematic literature review that encompasses the entire DMC.

Against this backdrop, the present research aims toward conducting a SLR of landslide research across different phases of the DMC and identifying research gaps within these phases. The significant insights derived from this study bear substantial policy implications, fostering the development of sustainable and risk-aware land use planning, particularly in the hilly regions of Bangladesh.

2. Materials and Methods

The major aim of this study was to conduct an SLR of the existing literature concerning landslide disaster management. Systematic reviews ought to be based on a protocol that clearly defines the rationale, hypothesis, and planned methodology of the review. This protocol is crucial for ensuring thorough planning and explicit documentation before commencing the review [33]. Such preparation fosters consistency within the review team, ensures accountability, upholds research integrity, and enhances the transparency of the eventual review. Moreover, having a protocol in place may diminish arbitrariness in decision making during data extraction and utilization from primary research, as planning allows the review team to anticipate and address potential issues in advance [34].

We adopted the PRISMA protocol, validating its methodological rigor and instilling confidence in the research's credibility (Figure 2). The PRISMA protocol is a widely adopted framework for conducting SLRs across various domains. It offers a methodical approach to conducting, reporting, and amalgamating evidence from multiple studies, thereby promoting transparency and rigor throughout the review process [33]. The articles were searched for systematically and subsequently evaluated based on their relevance to the set criteria and the study objectives. To meet the inclusion criteria, all authors thoroughly reviewed the selected articles (n = 51), ensuring no redundancy or bias in the findings. Key themes were identified, and similarities and differences between studies were highlighted. Where feasible, the results were presented in tabular form to enhance clarity. The detailed methodology and systematic processing steps employed in this study are outlined in the following sections.

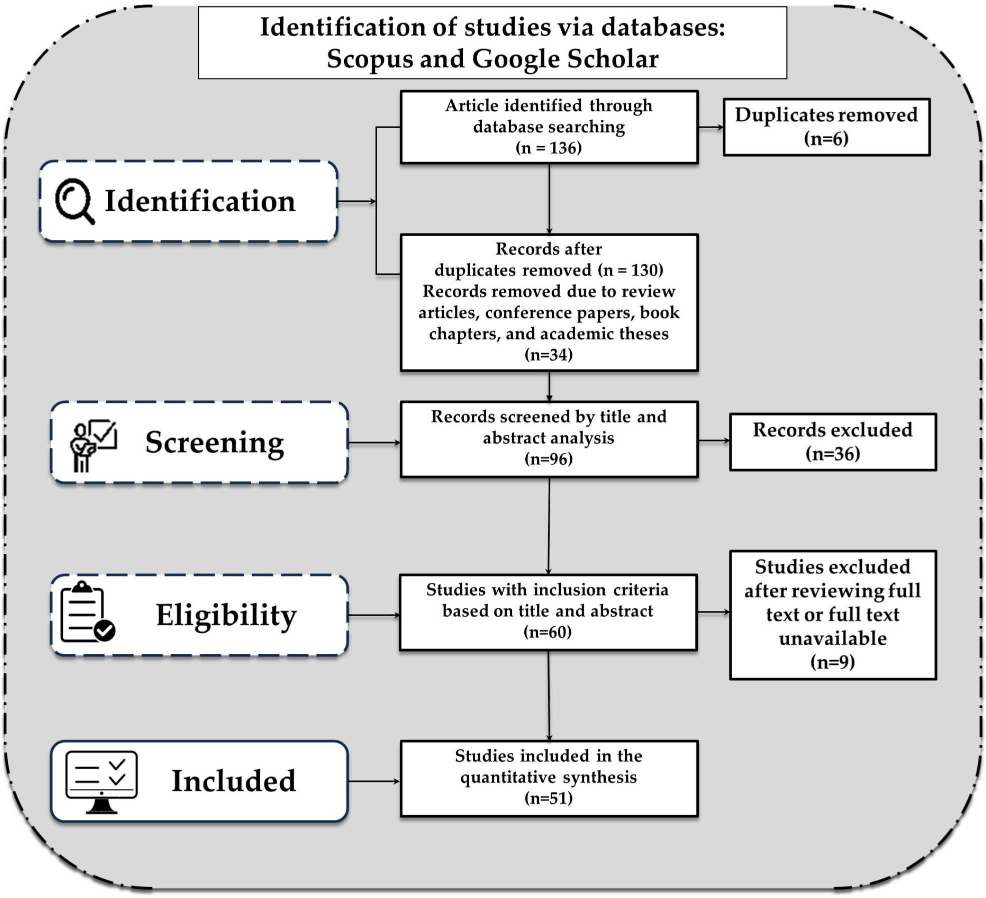

Figure 2. The workflow showing the process of the systematic literature review using PRISMA framework; n = number of research papers. Adopted from https://www.prisma-statement.org/prisma-2020-flow-diagram (accessed on 09 July 2024).

2.1. Article Selection

The initial step of the SLR was a thorough search for scholarly articles targeting the four stages of the LDMC in Bangladesh (Figure 2). We used Boolean logic to fine-tune our searches and to retrieve the relevant articles efficiently from large numbers of articles. Our search encompassed reputable electronic databases, such as Scopus (https://www.scopus.com) and Google Scholar (https://scholar.google.com) during the period from 1 November to 30 November 2023. The search utilized specific keywords including 'Landslide Susceptibility Mapping', 'Landslide Vulnerability Assessment', 'Landslide Risk Reduction', 'Landslide Risk Management', 'Landslide Preparedness', 'Landslide Prevention', 'Landslide Mitigation', 'Landslide Response', 'Landslide Recovery', 'Landslide Measures', 'Slope Stability Problem', and 'Seismic Induced Landslide'. We found a total of 136 articles by searching with these keywords and checking the reference lists. This study incorporated exclusively peer-reviewed research articles addressing landslides in Bangladesh that were published in scientific journals between 2008 and 2023. We excluded review papers, conference papers, book chapters, and theses. Out of 136 articles, we selected 51 based on specific exclusion criteria including redundancy (ensuring that preprints were not counted as articles), the absence of sufficient information, such as lacking detailed methodology, unclear context, or not covering even a single phase of the disaster cycle. After our careful review, we ensured that the selected articles covered all the four phases of the LDMC.

2.2. Article Categorization

The papers selected for final review were categorized according to the different phases of the LDMC: preparedness, mitigation, response, and recovery. However, categorizing each article solely based on one phase appeared to be challenging due to the interconnected nature of these phases. To avoid confusion, we grouped the selected articles into three broad disaster phases namely pre-disaster, syn-disaster, and post-disaster. In this study, the pre-disaster phase includes the preparedness and mitigation phases, the syn-disaster phase encompasses the response phase, and the post-disaster phase comprises the recovery stage.

The information from each research paper was then documented and organized into an Excel spreadsheet detailing the researchers' affiliations, year of publication, study area, study scale, data type, variables used, main objective, methodology, landslide inventory, and result validation. The study area of the reviewed articles was designated in terms of administrative boundaries, but at varying scales. We categorized the scale of the studies into 4 scales (Scale is based on a hierarchical administrative structure of Bangladesh with several layers. The country is divided into 64 districts, known as zilas, which serve as the primary administrative units. Each district is further subdivided into upazilas, which function as the second level of administrative division and typically consist of multiple unions. Unions are the third and most local level of administration), namely, small scale, medium scale, large scale, and very large scale based on the Representative Fraction (R.F.) of the study area maps. Studies encompassing divisional and district levels are classified as small- and medium-scale studies, respectively, while those encompassing the upazila and union levels were categorized as large scale and very large scale, respectively.

The data used in the studies were categorized into primary and secondary categories, further subdivided into spatial and non-spatial data. The research methodologies employed in the selected articles were categorized as either data-driven or knowledge-driven. Data-driven methodologies utilized statistical analysis and machine learning techniques, while knowledge-driven approaches employed heuristic/knowledge-based methods, questionnaire surveys, analytical hierarchy process (AHP), or fuzzy and fuzzy-AHP-based approaches.

Landslide inventories play a pivotal role in understanding landslides by documenting past occurrences and facilitating the exploration of the connection between landslide occurrences and their triggering and controlling factors [35]. The inventories utilized in the studies were based either on fieldwork with GPS or derived from earth observation data such as Google Earth images or very high spatial resolution imagery. The validation of the research findings was subsequently classified into several categories: field-based validation, statistical technique-based, equation-based, previous research-based validation, and image overlay techniques.

2.3. Data Interpretation and Analysis

We conducted a comprehensive analysis of the database that resulted from categorizing the publications examined in this review using descriptive and statistical analysis to understand the evolution of research on LDM over time. This analysis helped identify common research methods, challenges, and gaps in the existing literature. Graphical representations were generated to illustrate research trends. These visualizations were created using Python, specifically using libraries such as Matplotlib, Seaborn, and NumPy within the Google Colab integrated development environment. Additionally, we used ArcGIS 10 software to map the geographical distribution of LDM research, providing a visual overview of the regions where these studies have been conducted.

3. Results and Discussion

3.1. Landslide Research Trends in Bangladesh

3.1.1. Insights from Keywords

One of the initial steps involved identifying key attributes for determining the most frequently mentioned keywords in existing landslide research related to Bangladesh (Figure 3).

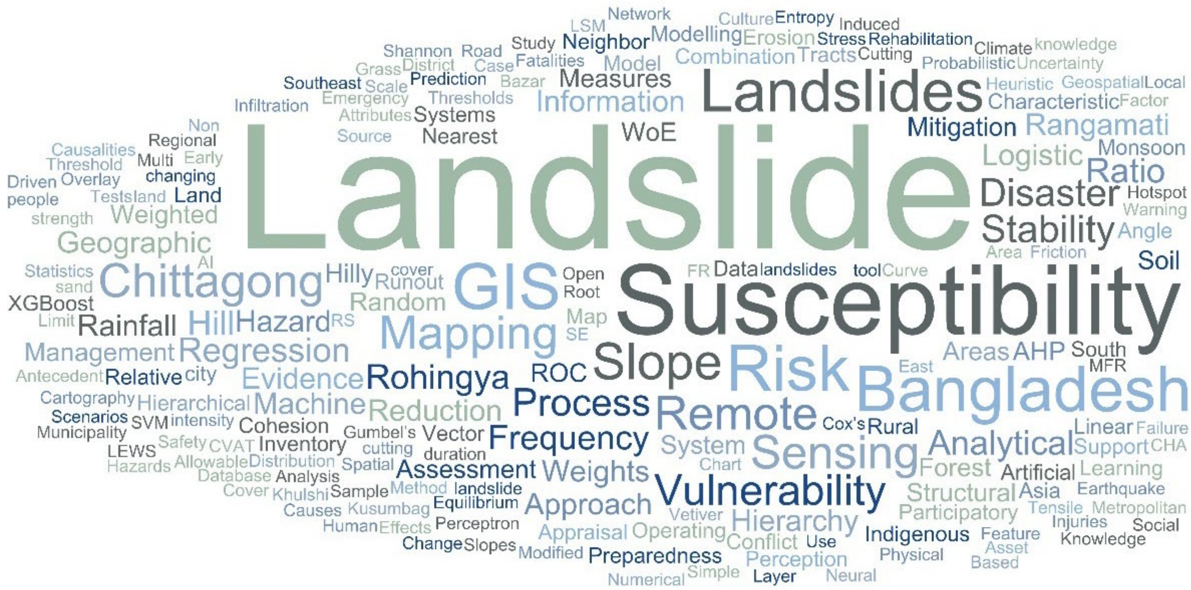

Figure 3. Word cloud of the keywords mentioned in the landslide research conducted in Bangladesh.

Our analysis revealed the most prevalent in the literature: "landslide", "susceptibility", "mapping", "GIS", "Bangladesh", "Chittagong", "risk", "vulnerability", and "remote sensing". These keywords consistently appeared across numerous publications, underscoring their centrality in the discourse on landslide research in Bangladesh. The findings also indicate a strong geographic focus in landslide research, particularly on specific sites such as Chittagong City, Chittagong Hilly Areas (CHAs), Khulsi, Kusumbag, Cox's Bazar, Rangamati, and Rohingya-inhabited regions. The recurrence of these locational keywords highlights the concentrated nature of landslide studies within these areas of Bangladesh, highlighting their significance in the broader research context [31].

Regarding model-related keywords, the most frequently mentioned included Logistic Regression (LR) [24], Analytical Hierarchy Process (AHP) [36], Weighted Linear Combination (WLC) [37], Random Forest (RF) [24] and Support Vector Machine (SVM) [38]. The resulting keywords also exposed various aspects of non-structural measures in landslide risk assessment including vulnerability, susceptibility mapping, risk mitigation, and disaster risk reduction. Non-structural measures such as human factors, local perception, social vulnerability, and indigenous knowledge, are integral to landslide research, advocating for participatory approaches and community engagement. Structural measures including retaining walls, block structures, sandbags, among others [9,39] were also discussed.

The literature also addresses the influence of environmental factors on landslide susceptibility, including the discussion of soil erosion and land cover changes [40] but had little focus on climate change scenarios affecting landslide risk.

3.1.2. Frequency of Published Articles

The temporal distribution (Figure 4) of research papers on LDM in Bangladesh reveals an increasing trend in research output over the period, emphasizing the growing emphasis on understanding and addressing LDM.

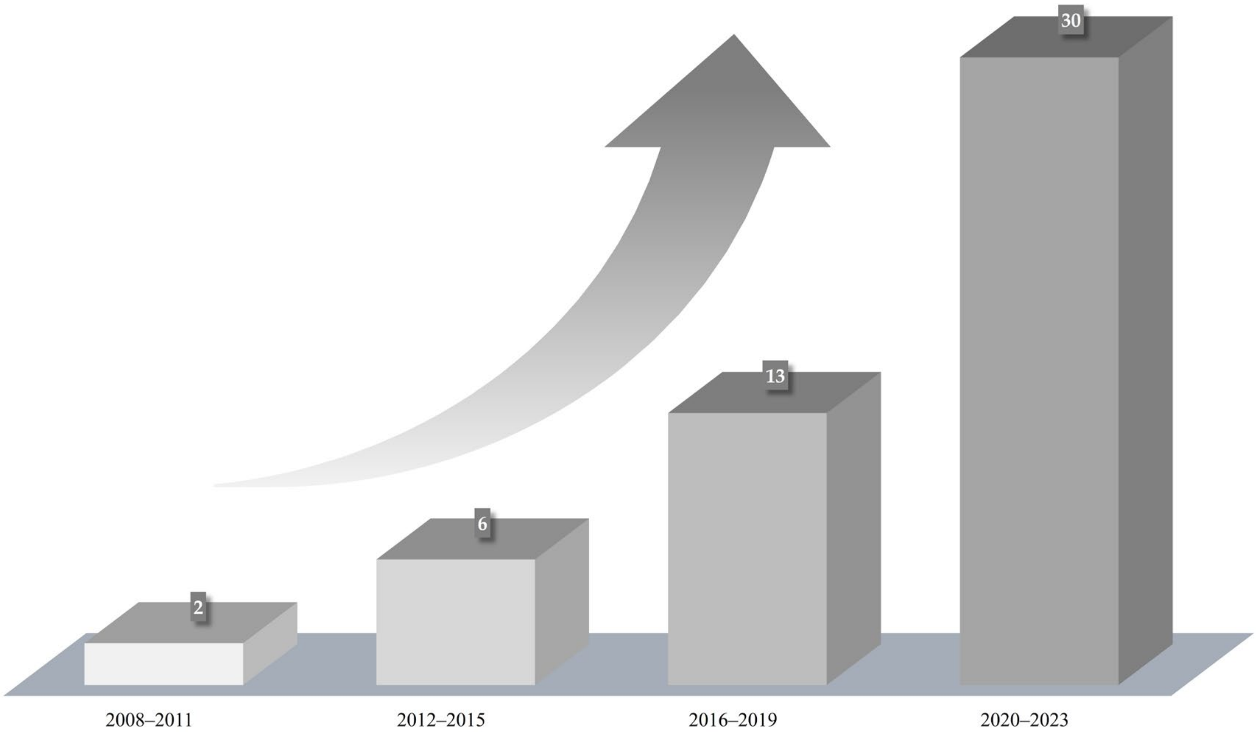

Figure 4. Temporal distribution, categorized by four-year intervals of selected articles (i.e., 51) on the LDMC.

A notable rise in publications is observed during the periods 2016–2019 and 2020–2023, which comprise 25.5% and 58.8% of the total papers, respectively. This upward trend indicates an escalated interest and focus on this critical subject matter in recent years and underscores a growing commitment to addressing the challenges of LDM in Bangladesh. Greater awareness of the impacts of landslides on communities and infrastructure, coupled with increased funding from national and international sources, has likely fueled more research initiatives.

3.1.3. Landslide Research Affiliations

The affiliations of researchers in each research paper reveal a diverse landscape of institutions and organizations involved in research activities (Figure 5).

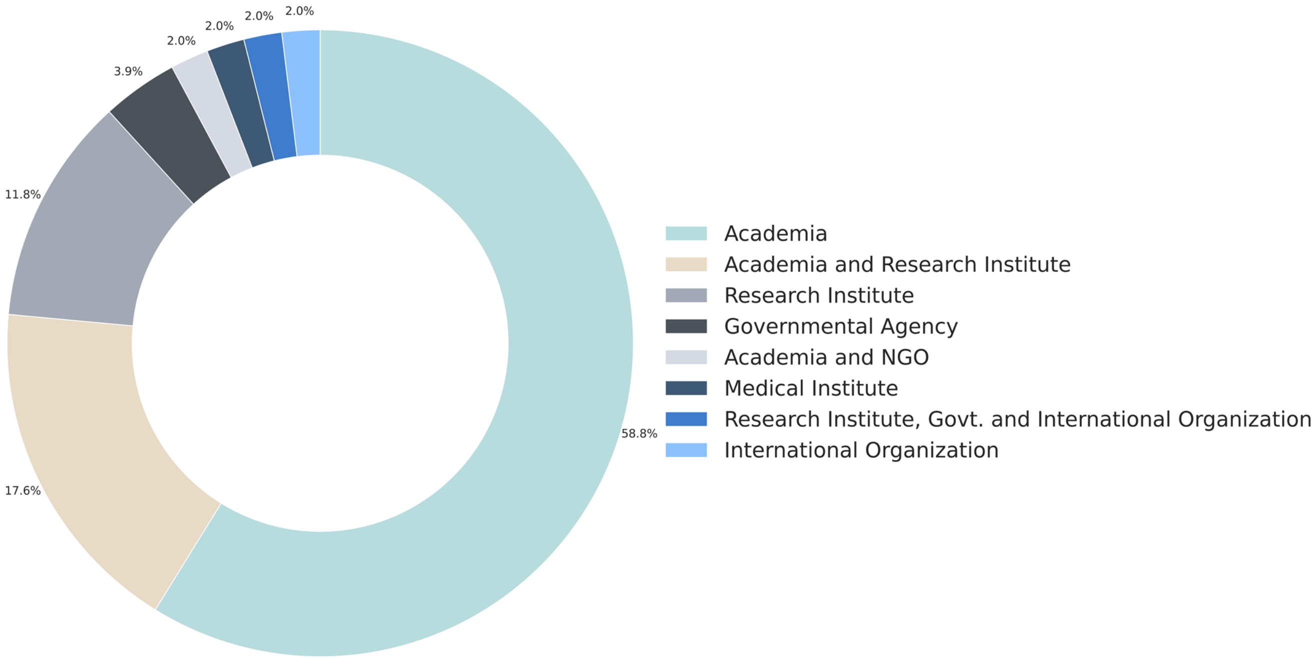

Figure 5. Pie chart showing authors affiliations in reviewed landslide studies for the current study.

Academia represents the largest group (58.8%), underscoring the pivotal role of academic institutions in knowledge generation. Collaboration between academia and research institutes (IRDR, BUET-JIDPAS, IWFM) accounts for 17.6%, highlighting interdisciplinary efforts. Individual research institutes (IRDR, BUET-JIDPAS, REACH Initiative) contribute 11.8% emphasizing specialized research endeavors. The involvement of academia with non-governmental organizations (e.g., DADO), medical institutes (e.g., BAPMR, SCISIL), US govt. agencies (e.g., NASA, GESTAR, USRA), governmental agencies (e.g., Urban Development Directorate), and international organizations (e.g., World Bank Group) indicate relatively less research activity pertaining to LDM research in Bangladesh. This distribution reflects the dominant role of academic and research institutions while pointing to the need for greater engagement from a broader spectrum of organizations in LDM research. Involving NGOs, government agencies, and international bodies can bring invaluable practical insights, as these entities for instance NGOs and government agencies often work directly with affected communities and possess firsthand experience with disaster management challenges. Moreover, they have access to empirical data that could greatly benefit landslide studies. However, considering these nonacademic entities in landslide studies might bring more insightful outputs by means of establishing formal partnerships between government bodies, NGOs, and international organizations with the academia. With the help of academia, government agencies can facilitate training workshops for NGOs and international organizations to improve coordination and knowledge sharing. Such collaborations thereby address the financial constraints often faced by academic institutions in Bangladesh while providing NGOs and government agencies with the intellectual support they may lack in scientific studies. Acknowledging individuals' contributions in landslide disaster management could also yield positive outcomes, potentially encouraging their continued participation in landslide disaster risk mitigation and prevention efforts.

3.2. Landslide Research Encompassed Disaster Management

The SLR focused primarily on categorizing selected articles into three disaster management phases. A total of 51 papers were reviewed and divided into four temporal periods: 2008–2011, 2012–2015, 2016–2019, and 2020–2023 (Figure 6).

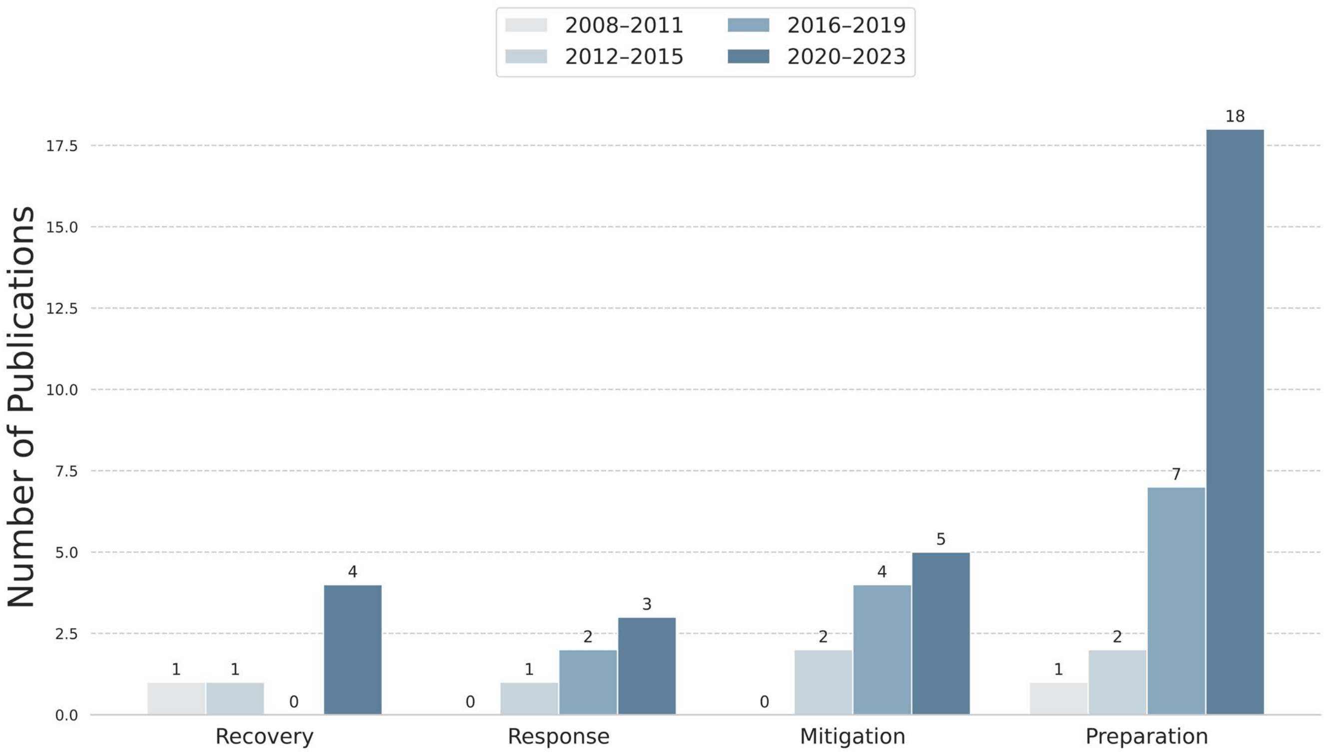

Figure 6. Year wise frequency distribution of the reviewed articles primarily focuses on the four phases of the LDMC.

Only six of the reviewed papers focused on landslide recovery, with four publications in 2020–2023 and one each in 2008–2011 and 2012–2015. Landslide response was aligned with only six of the reviewed papers, with three publications in 2020–2023, two in 2016–2019, one in 2012–2015, and none in 2008–2011. Eleven papers concentrated on landslide mitigation, with five publications in 2020–2023, four in 2016–2019, and two in 2012–2015. The majority (28) of the reviewed papers, however, related to landslide preparation, with 18 publications in 2020–2023, seven in 2016–2019, two in 2012–2015, and one in 2008–2011. Landslide preparation emerged as the most heavily studied phase in Bangladesh, as evidenced by the greater number of publications compared to other phases (Figure 6). Although all four phases of LDM—recovery, response, mitigation, and preparation—have received increased attention in scientific studies, particularly from 2020 to 2023, there has been a notably higher emphasis on landslide preparation. This finding can be attributed to government initiatives prioritizing disaster preparedness, increased interest among researchers in this domain, and advancements in technology that facilitate easy access to pre-disaster analysis. In contrast, this finding also highlights the need to prioritize research on the other phases to ensure comprehensive long-term planning and effective disaster management in Bangladesh.

3.3. Landslide Research Objectives, Spatial Trends, and Distribution

Recent publications from 2008 to 2023 emphasize landslide susceptibility or risk assessment in vulnerable areas, which is crucial for effective disaster risk reduction and spatial planning (Figure 7) [37].

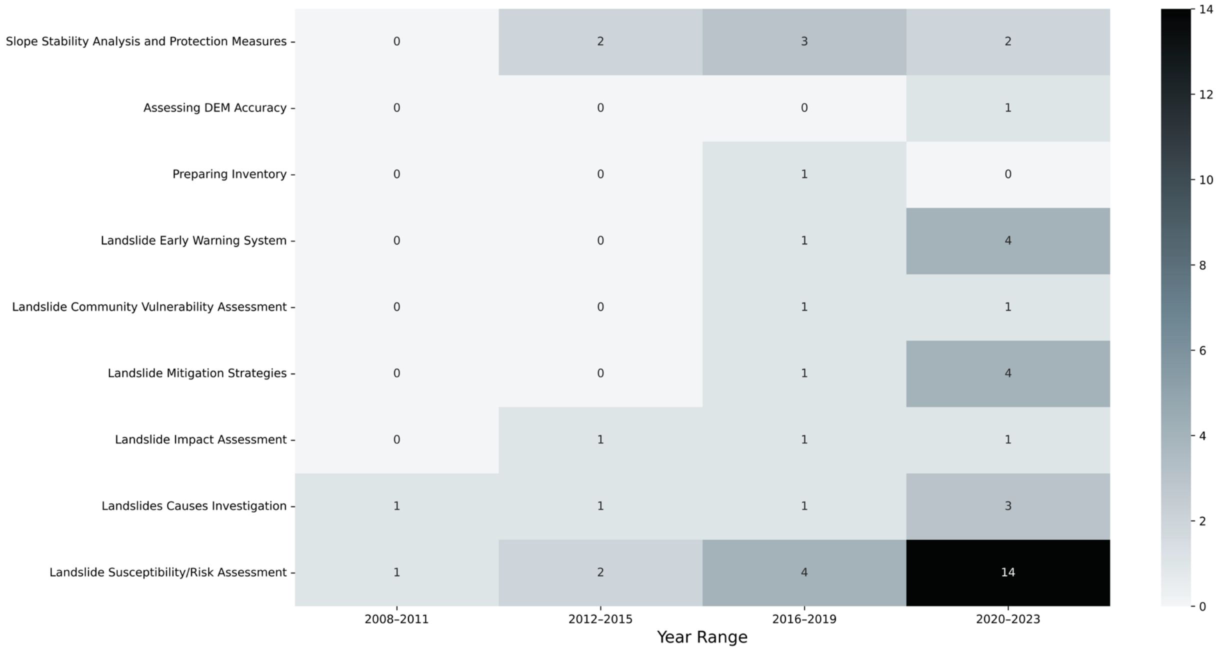

Figure 7. Distribution of articles by study objective across four publication year intervals.

Landslide research has seen a notable increase in studies related to early warning systems, mitigation strategies, causative factors, and susceptibility analysis over the studied time frame. Meanwhile, critical areas such as landslide impact assessment, community-based vulnerability evaluation, inventory preparation, and DEM accuracy assessment have received comparatively less attention (Figure 7). Research areas related to response and recovery, particularly the relocation of vulnerable communities residing in the CHA, require further investigation. Additionally, there is a lack of peer-reviewed research on community-based landslide management, which could be an effective approach for mitigating landslide impacts.

The studies reviewed utilized two primary types of data, spatial and non-spatial data. This review revealed a notable shift towards the increased utilization of spatial data in landslide studies in Bangladesh over time. Before 2019, researchers relied on both spatial and non-spatial data for their studies. However, after 2019, particularly from 2020 to 2023, there has been a significant increase in dependency on spatial data, which was less prominent before 2019 (Figure 8).

The spatial distribution of papers reveals a concentrated focus on landslide research in specific regions of Bangladesh, particularly in Chittagong City, the CHA, Khulshi, Kusumbag areas of Chittagong, Cox's Bazar district, Rangamati district, and Rohingya-inhabited areas (Figure 9).

These locations emerge as key landslide hotspots within the literature, indicating a higher prevalence of studies and heightened landslide vulnerability. While the literature recognizes the importance of studying areas with Rohingya populations and assessing landslide risks in regions inhabited by displaced communities, Bandarban and Khagrachari districts remain relatively the least explored areas, possibly due to the fewer occurrences of landslides than in Chittagong, Rangamati and Cox's Bazar districts.

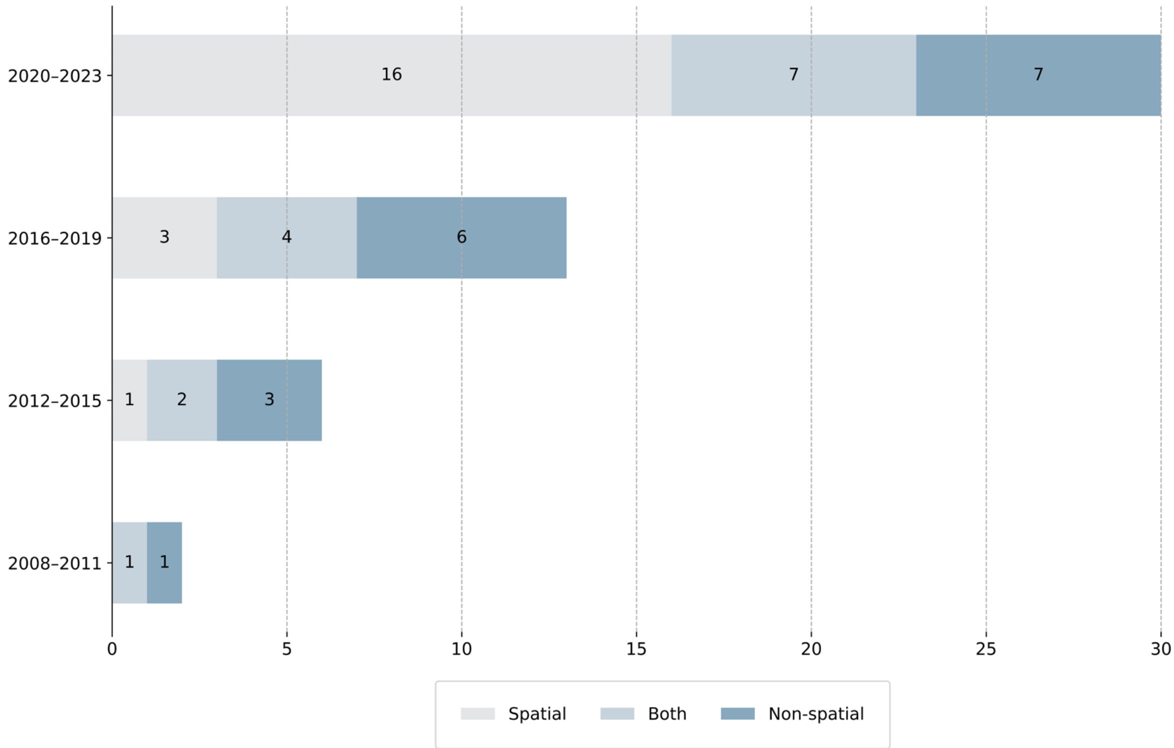

Figure 8. Temporal trend of spatial and non-spatial data used in the articles.

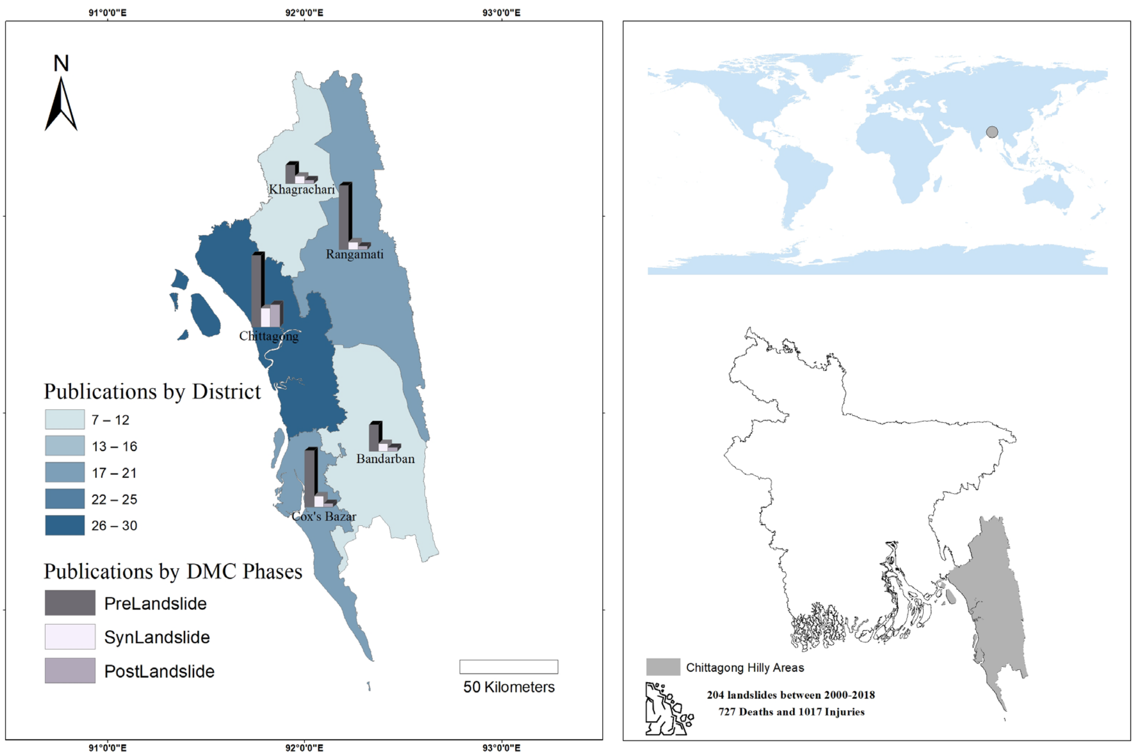

Figure 9. Spatial distribution of the articles on landslide disaster management in Bangladesh.

3.4. Methods Used in Landslide Research

The reviewed articles demonstrated two predominant methodological approaches: data-driven or knowledge-driven, whereas a limited number of studies in this research were classified under the 'other' category, focusing on probability estimation, physical process simulation, and data collection (Figure 10).

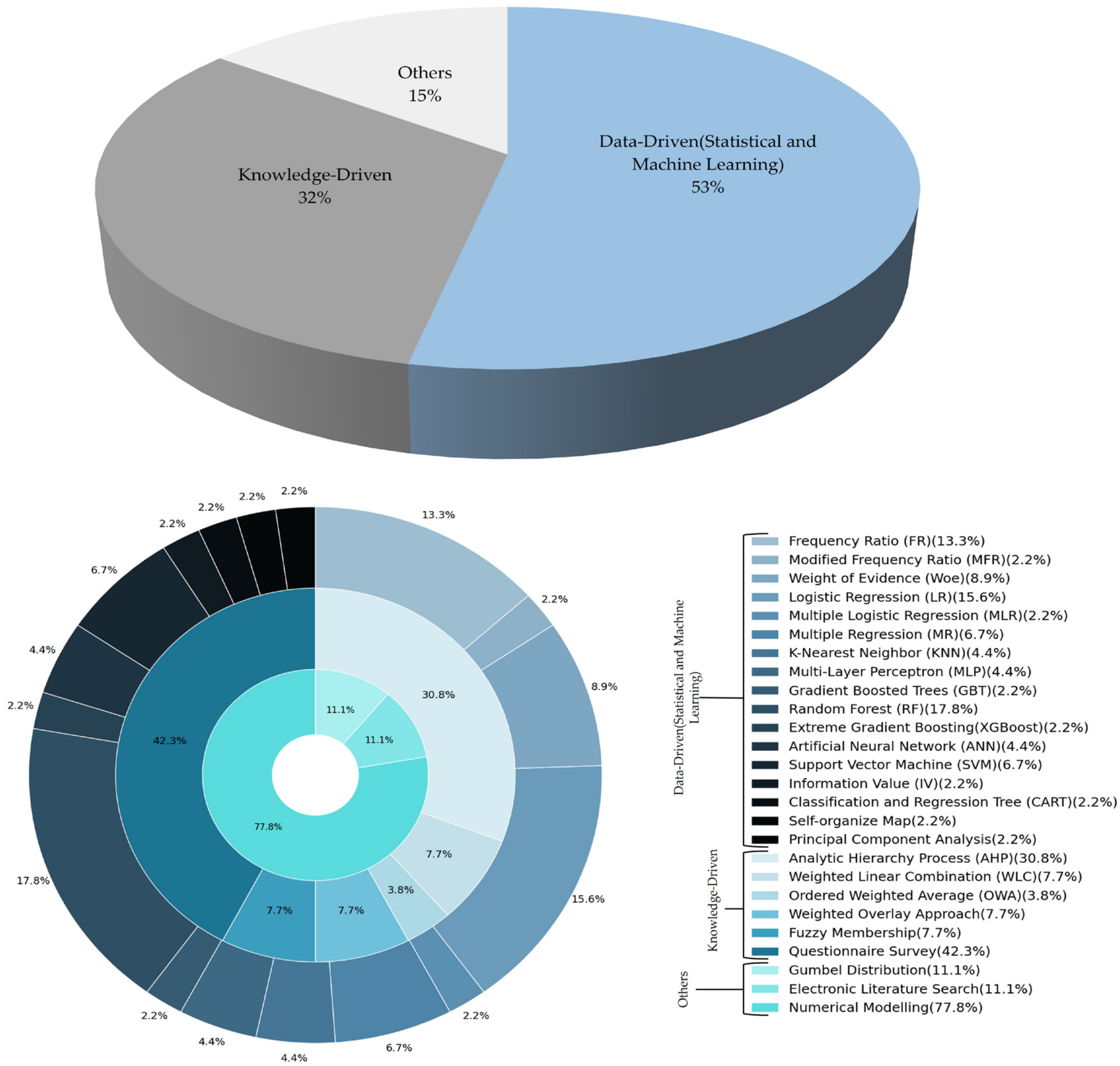

Figure 10. Diverse methodological approaches used in published landslide studies in Bangladesh.

Data-driven methodologies emphasizing quantitative analysis utilized primarily statistical and machine-learning techniques. Conversely, knowledge-driven approaches relied on multi-criteria evaluation techniques and questionnaire surveys, emphasizing a qualitative understanding. Data-driven techniques (53%) encompassed various statistical methods, such as Frequency Ratio (FR; 13.3%), Modified Frequency Ratio (MFR; 2.2%), Weight of evidence (Woe; 8.9%), Logistic regression (LR; 15.6%), Multiple Logistic regression (2.2%), or Multiple Regression (6.7%). Machine learning techniques included K-Nearest Neighbor (KNN; 4.4%), Multi-Layer Perceptron (MLP; 4.4%), Gradient Boosted Trees (GBT; 2.2%), Random Forest (RF; 17.8%), Xtreme Gradient Boosting (XGBoost; 2.2%), Artificial Neural Network (ANN; 4.4%), Support Vector Machine (SVM; 6.7%), Information Value (IV; 2.2%), Classification and Regression Tree (CART; 2.2%), self-organizing map (2.2%), and Principal Component Analysis (2.2%).

Other data-driven methods (15%) included Gumbel Distribution (11.1%), electronic literature search (11.1%), and numerical modeling (e.g., Finite Element Model (FEM), Limit Equilibrium Model (LEM), Bishop's Simplified Method, and Seismic loading) (77.8%).

Numerical modeling techniques focused primarily on slope stability analysis and critical rainfall conditions associated with landslides, while statistical methods and machine learning algorithms were used for various purposes in the context of LDM in Bangladesh but most significantly to create landslide susceptibility maps or identify high-risk areas based on various triggering factors. Notably, Random Forest and Support Vector Machine models are widely embraced machine learning algorithms for mapping vulnerable areas. On the other hand, knowledge-driven techniques (32%) included multi-criteria evaluation methods, such as Analytic Hierarchy Process (AHP; 30.8%), Weighted Linear Combination (WLC; 7.7%), Ordered Weighted Average (OWA;3.8%), fuzzy membership (7.7%), and questionnaire surveys (42.3%). Multi-criteria evaluation methods are predominantly used in susceptibility mapping while questionnaire surveys are effective in investigating landslide incidents with various aspects such as evaluating risk perception and adaptation strategies, historical event documentation and identifying social and community vulnerability associated with landslides and their causes.

3.5. Disaster Phase Focus in Landslide Research

3.5.1. Pre-Disaster Phase

The pre-disaster phase, occurring before a landslide event, involves mitigation and preparedness efforts to reduce potential impacts. A total of 39 papers closely aligned to this phase were selected, encompassing landslide susceptibility mapping, slope stability analysis, developing early warning systems, public health crises related to landslides, preparing landslide inventories, understanding driving forces of landslides, preventing landslides by vegetation, and different mitigation measures. A significant proportion of the articles in this phase are related to creating maps using different data-driven and knowledge-driven techniques crucial in identifying vulnerable areas and applying land use planning to reduce their impact [41]. The analysis shows a significant reliance on data-driven techniques (64%) over the last 16 years (2008–2023), with knowledge-driven and combined approaches (18%) contributing more modestly (Table 1).

Table 1. Statistical summary of pre-disaster landslide studies on various metrics: methods, data sources and type, scale, inventory method, and validation.

Category	No of Papers	Percentage of Papers (%)
Type of method		
1. Data-Driven	25	64
2. Knowledge-Driven	7	18
3. Both	7	18
Type of data source		
1. Primary	11	28
2. Secondary	17	44
3. Both	11	28
Type of data		
1. Spatial	19	48
2. Non-spatial	10	26
3. Both	10	26
Scale of study		
1. Very Large	4	10
2. Large	7	18
3. Medium	22	57
4. Small	6	15

Table 1. *Cont.*

Category	No of Papers	Percentage of Papers (%)
Inventory source		
1. Fieldwork	10	26
2. Earth Observation	8	20
3. Fieldwork and Earth Observation	4	10
4. Previous Inventory-Based	1	3
5. Inventory N/A	16	41
Validation		
1. Yes	29	74
2. No	10	26
Validation process		
1. Statistical Technique	16	55
2. Field	6	21
3. Equation	2	7
4. Previous Research Results	4	14
5. Image Overlay on Google Earth	1	3

Before 2019, researchers in Bangladesh relied predominantly on traditional methods for susceptibility mapping in the Chittagong Hill Districts. However, a notable shift occurred after 2019 (Figure 11), with the adoption of machine learning techniques, particularly Random Forest, and Support Vector Machine. The shift towards data-driven methods, especially post-2019, is attributed to advances in technology and computational power.

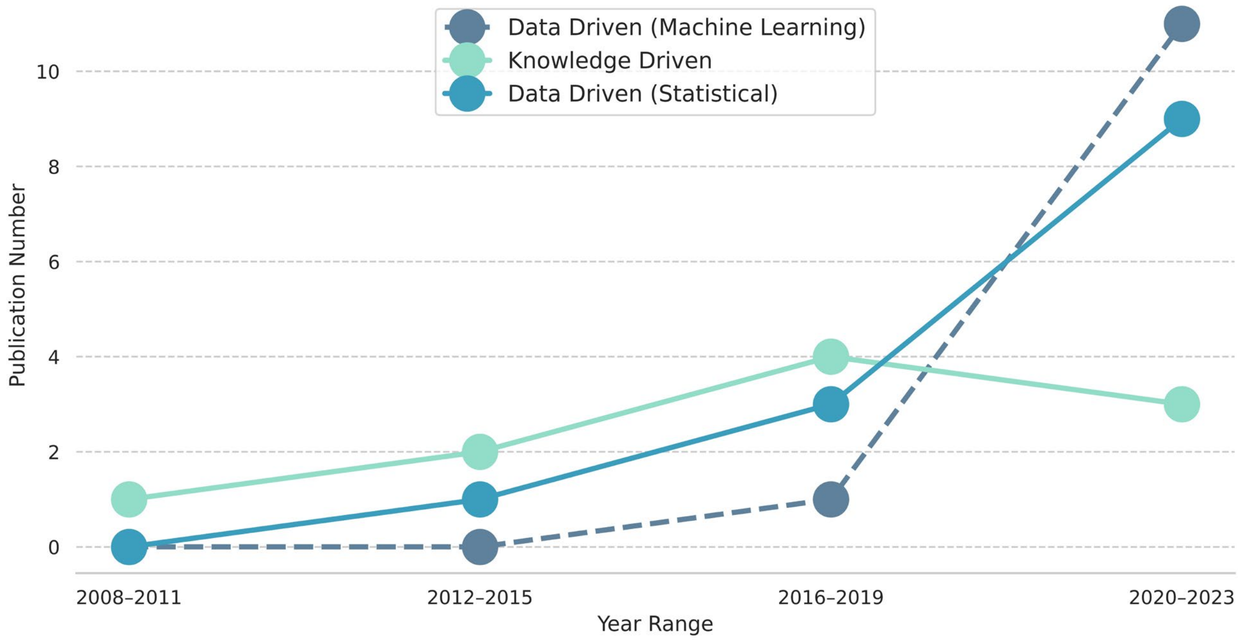

Figure 11. Trend of articles used machine learning, statistical and knowledge driven techniques in LSM.

Due to the availability of geospatial software and technology, GIS and Remote Sensing have played a crucial role in landslide susceptibility mapping and risk assessment in Bangladesh. The prevalence of these methodologies highlights a multidisciplinary approach and underscores the importance of technological advancements in understanding and predicting future landslide occurrences.

The selected articles used either primary or secondary data, with some combining both types. Primary data were collected through empirical methods. including questionnaire surveys and sample collections from the site [42–44]. Secondary data were sourced from open access and government portals such as recent publications, newspapers, landslide inventories, earth observation data, and government and non-government reports. Our review showed that approximately 44% of the research articles focused on the pre-disaster phase used secondary data, and 28% used primary and combined data, indicating the preponderance of secondary data in pre-disaster studies despite its potential for errors. Spatial data were utilized prominently as secondary source data, comprising 48.72%, while non-spatial and combined data accounted for 25.64% of the studies, showing their significant contribution to the research (Table 1).

The analysis categorized the scale of research into four scales: very large, large, medium, and small scale. Medium-scale studies, which focus on district-level or multiple upazila levels, are the most common in the pre-disaster phase, comprising 57% of the studies (Table 1). Very large-scale studies were rare [37,41,45,46], but they offered a better understanding of local features in landslide-susceptible areas and facilitated the implementation of effective measures to mitigate landslide impacts.

Many pre-disaster phase articles utilized landslide inventories, which are crucial for creating hazard and risk maps or validating existing maps. Inventories can be compiled through direct field surveys or high-resolution earth observation data (<5 m spatial resolution) and Google Earth [9].

In the reviewed articles, 41% did not rely on landslide inventories, focusing instead on susceptibility mapping. For those that used inventories, 26% were based on field work, 20% on earth observation, 10% combined both methods, and 3% relied on previously published inventories. However, these studies often lacked detailed information on landslide incidents and did not include official inventory data for landslide locations in the CHA from 2018 to 2023.

The validation process for pre-disaster phase articles focused primarily on confirming the accuracy of susceptibility/hazard maps. Validating prediction models is crucial for assessing their effectiveness in forecasting landslides, identifying effective models, and improving prediction map performance [46]. Most papers (74%) in this phase validated their results using statistical techniques, field methods, equations (RUSLE, R-index), previous research results, and image overlay on Google Earth. A total of 55% used statistical methods, such as the receiver operating characteristic curve (ROC) and the area under curve (AUC), achieving a high validation score of more than 80%. However, these validations are quantitative and lack qualitative checks considering local landslide mechanisms and geomorphological characteristics [47]. Other studies focusing on landslide investigation, landslide inventory, and a slope stability analysis used other validation techniques including fieldwork, equations, previous research results and image overlay on Google Earth.

The factors used in prediction models for landslide susceptibility can be grouped into four categories: geological and geomorphological, topographical, hydrological, and environmental and anthropogenic. Commonly used variables included the slope angle, the aspect, surface geology, the NDVI, rainfall pattern/precipitation, the distance from the road, the distance to drainage/stream, elevation, faults–lineaments, and land use and land cover (LULC), indicating that these are influential factors in triggering landslides (Table 2).

Table 2. Key contributing factors examined in landslide studies during the pre-disaster phase.

Category	Factor/Variable
Geological and Geomorphological	Surface Geology, Surface, Geomorphology, Faults–Lineaments, Lithology, Soil Type Soil Moisture, Soil Texture, Soil Roughness, Soil Permeability, Soil Thickness, Soil Consistency, Soil Brightness Index, Clay Mineral Structure.

Table 2. *Cont.*

Category	Factor/Variable
Topographical	Elevation/Altitude, Topography, Slope Angle, Slope Aspect, Slope Cover, Slope Height, Profile Curvature, Plan Curvature, Relative Relief.
Hydrological	Rainfall Pattern/Precipitation, Stream/Drainage Network, Stream, Drainage Density, Distance to Drainage/Stream, Distance to Water Body, Flow Direction, Flow Accumulation, Stream Order, Watershed, Stream Link, Inundated Type, Stream Power Index (SPI), Topographic Wetness Index (TWI).
Environmental and Anthropogenic	NDVI, Land Cover, Land Use/ Land Cover, Land Use/ Land Cover Change, Forest Loss, Hill Cutting, Distance To Hill-Cut, Distance From Road, Distance From Existing Buildings

However, some other factors are yet to be utilized, such as the Topographic Position Index (TPI), the Terrain Ruggedness Index (TRI), slope standard deviation [48], the depth to groundwater [49], the distance from railroads [50], mean temperature [51], mean wind etc. [51]. Moreover, climate change scenarios and how they might impact landslide characteristics and prevalence are rarely considered. Research on non-structural assessments in this phase was more prevalent likely due to its cost effectiveness compared to structural measures [9]. Non-structural assessments typically involve interdisciplinary approaches, drawing on fields such as geography, geology, hydrology, and social sciences, which attract a broader range of researchers from various backgrounds, leading to a higher volume of publications. Despite susceptibility maps being a non-structural assessment, with numerous publications indicating probable locations vulnerable to landslides, they cannot yet predict which specific areas will fail, a potential advancement for pre-disaster management (Figure 12).

3.5.2. Syn-Disaster Phase

The syn-disaster phase involves taking immediate actions to aid communities affected by a landslide. This phase includes rescuing victims and addressing survivors' urgent needs to preserve and protect lives.

This review identified six articles focused on the syn-disaster phase of landslides, covering landslide impact assessments, assessing health effects, medical response, and social and community vulnerability assessments [7,20,52–55]. These studies collected data via surveys and electronic literature searches. The data were predominantly non-spatial, except for one study [52], which combined spatial and non-spatial data to develop a landslide early warning system for vulnerable Rohingya refugees. Although early warning systems (EWSs) are primarily pre-disaster tools for predicting and preventing landslides, they also play a crucial role in guiding immediate response actions when a landslide is imminent or has occurred. By delivering timely alerts, EWSs help the Rohingya community take protective measures, thereby reducing casualties and damage. Additionally, the data and experiences gathered through these systems enhance future preparedness and risk management strategies [45].

When categorized similarly to pre-disaster phase papers, the analysis showed that 50% used statistical analysis, 33% were knowledge-driven, and 17% combined both approaches (Table 3). These studies primarily used secondary (33%) and combined data (50%), with a major focus on non-spatial data, unlike the pre-disaster phase. Study scales were 33% small and medium, and 17% were large and very large. Only one of the six studies validated its analysis results using F-test and T-test methods [52].

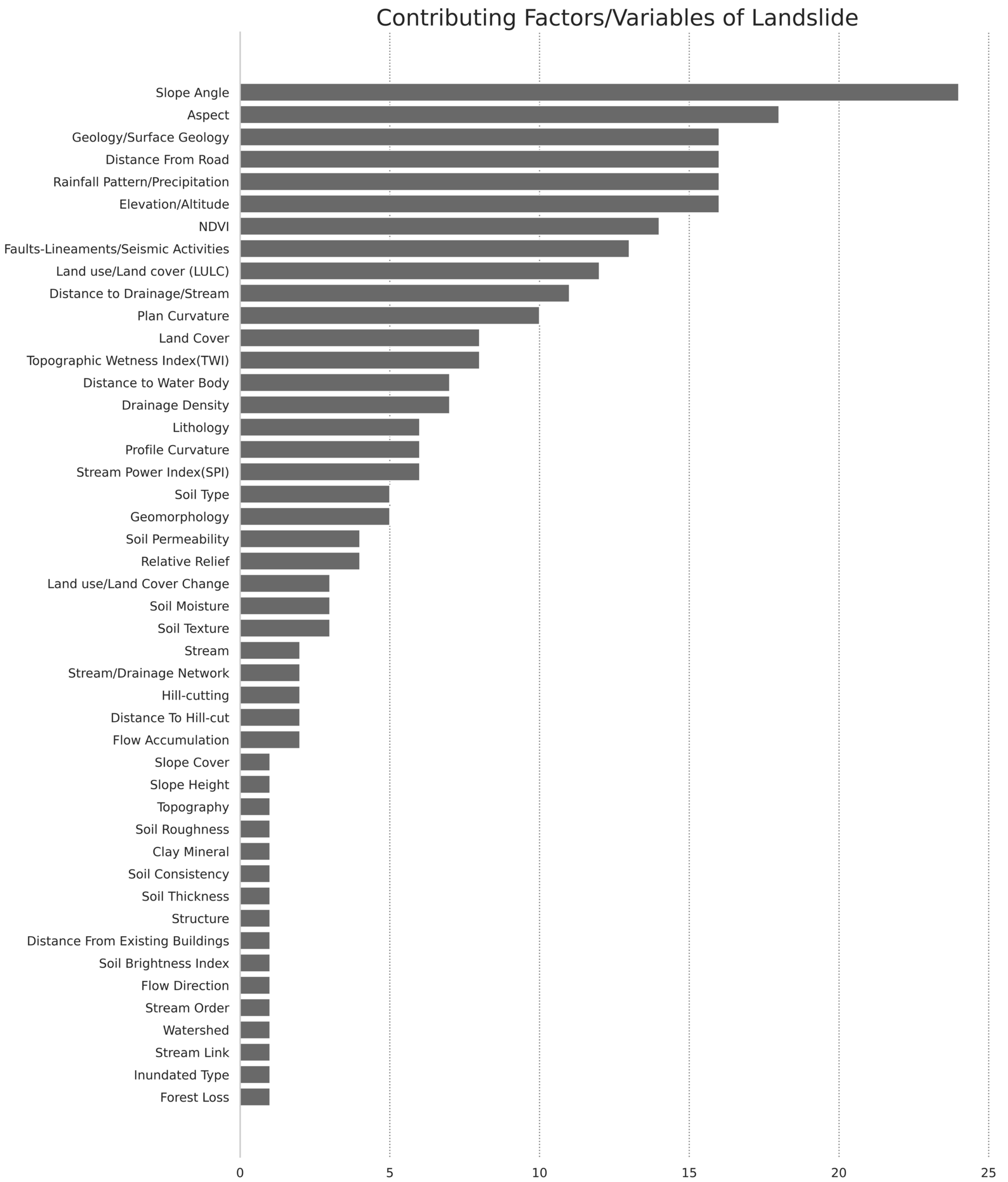

Figure 12. Causative factors of landslides identified in the reviewed articles to delineate landslide-prone areas during the pre-disaster phase.

Table 3. Statistical summary of syn-disaster landslide studies on various metrics: methods, data sources and type, scale, inventory method, and validation.

Category	No of Papers	Percentage of Papers (%)
Method		
1. Data-Driven	3	50
2. Knowledge-Driven	2	33
3. Both	1	17
Data Source		
1. Primary	1	17
2. Secondary	2	33
3. Both	3	50
Data Type		
1. Spatial	0	0
2. Non-spatial	5	83
3. Both	1	17
Scale of Study		
1. Very Large	1	17
2. Large	1	17
3. Medium	2	33
4. Small	2	33
Validated		
1. Yes	1	17
2. No	5	83
Validation Process		
1. Statistical Technique	1	100
2. Field	0	0
3. Equation	0	0
4. Previous Research	0	0

There is a lack of research targeting the syn-disaster phase of landslides in Bangladesh. Evaluating the response to landslide disasters highlights several critical points. While emergency medical care and rehabilitation are essential, studies related to providing adequate care, especially in remote areas, remain unexplored. Early warning systems are important but need to be scalable and integrated within the existing systems. Additionally, studies with comprehensive evaluations of landslide impacts on communities and environments are lacking, both of which are crucial for effective response and recovery.

Community-based approaches are invaluable but require inclusive participation and ongoing assessments of their long-term effectiveness. Studies underscore the importance of involving local communities and harnessing their knowledge to understand the factors that contribute to vulnerabilities and enhance resilience. However, significant challenges such as financial constraints, inadequate infrastructure, and limited skills among government and aid agencies hinder effective landslide disaster management. Overcoming these obstacles necessitates collaboration among governments, NGOs, local communities, and experts to conduct research and develop comprehensive plans that mitigate landslide risks and improve community preparedness and response [7,20,52–55].

3.5.3. Post-Disaster Phase

Recovery, a key post-disaster phase in the LDMC, involves restoration and reconstruction and long-term spatial planning. However, it remains underexplored in research. While response and recovery are vital, their effectiveness is enhanced by integrating them with comprehensive preparedness and mitigation efforts [56].

Only six peer-reviewed papers were identified in this phase examining landslide causes, the relation between precipitation and landslide, suggesting remedies and developing an AI-based insights [11] for town planners. These studies employed both data-driven and knowledge-driven methodologies, with a predominance of primary and non-spatial data. The research included large-scale (50%), medium-scale (33%), and small-scale (17%) studies (Table 4). Validation is often deemed unnecessary for this phase, typically more relevant for prediction models and extensive data analysis.

Table 4. Statistical summary of post-disaster landslide studies on various metrics: methods, da-ta sources and type, scale, inventory method, and validation.

Category	No of Papers	Percentage of Papers (%)
Type of method		
1. Data-Driven	3	50
2. Knowledge-Driven	3	50
Type of Data		
1. Primary	2	33
2. Secondary	1	17
3. Both	3	50
Type of Data		
1. Spatial	1	17
2. Non-spatial	2	33
3. Both	3	50
Scale of Study		
1. Very large	0	0
2. Large	3	50
3. Medium	2	3317
4. Small	1	
Validation		
1. Yes	2	33
2. No	4	67
Validation Process		
1. Field Validation	2	100
2. Others	0	0

Studies on landslide recovery show several issues. Most of them are geographically limited to the Chittagong district, restricting their broader applicability. They often lack comprehensive geophysical analyses, use small datasets, and miss long-term trends. Issues include minimal community involvement, poor organizational coordination, and a scarcity of actionable plans. There are calls for better data collection, advanced technology, community engagement, law enforcement, and thorough planning to improve recovery efforts [6,11,57–60].

3.6. Challenges Faced in Landslide Research

Researchers across all fields encounter general challenges including data limitations and logistical constraints [61–66]. LDM research is no exception, with distinct challenges emerging in each phase. The following table (Table 5) highlights these specific challenges, such as community participation issues, data inadequacies, and the absence of a comprehensive casualty database, which impede effective planning, response, and recovery efforts throughout the LDMC.

Table 5. Specific challenges faced in different disaster phases of landslides in Bangladesh.

Disaster Phase	Challenges Faced	No of Paper	Percentage (%)
Pre-disaster	1.Lack of community participation [5,22,61]	3	17
	2. Challenges with using open-source data [14]	1	6
	3. Inadequate historical landslide datasets [38,67,68]	3	18
	4. Absence of latest remote sensing techniques [69]	1	6
	5. Reliance on key informants and community judgment [56]	1	6
	6. Limited accessibility to landslide locations [70–72]	3	18
	7. Overlooked soil-related factors due to data unavailability [48,72,73]	4	23
	8. Online interviews due to the COVID-19 pandemic [60]	1	6
Syn-disaster	1. Lack of detailed landslide and rainfall data [55,74]	2	50
	2. Absence of official landslide database in Bangladesh [7]	1	25
	3. Insufficient databases on landslide casualties [20]	1	25
Post-disaster	1. Few respondents [63]	1	50
	2. Absence of official databases for landslide casualties [20]	1	50

3.7. Future Directions for Landslide Research

Despite landslides having garnered significant attention from Bangladeshi disaster scientists as a frequently occurring catastrophe, the articles reviewed illuminate significant gaps in existing landslide studies, suggesting directions for future research. These gaps can be categorized across different disaster phases.

Pre-disaster phase

In the context of the landslide disaster management cycle, the pre-disaster phase refers to the period before a landslide occurs, during which activities are focused on prevention, preparedness, and risk reduction measures. Detailed landslide susceptibility assessments, exploring advanced technologies like deep learning and the inclusion of social vulnerability, climate change impacts, and some crucial factors such as soil characteristics, the geology and geochemistry of slope materials into landslide susceptibility mapping, the comparison among various susceptibility models to justify their significance, the validation of the susceptibility maps through detailed field-based study, and developing effective landslide early warning systems can be future areas of investigation for studies focusing on landslide pre-disaster phase.

Most susceptibility models in current research employed regional (division or district) scale data [66–70]. This approach can lead to oversimplification, highlighting the need for studies at local scales (upazila or union level). Additionally, many studies focus only on areas with human settlements and easy access. Addressing inaccessible areas is crucial for filling knowledge gaps and advancing the understanding of landslides. Monsoon rainfall, a significant cause of landslides in Bangladesh [45,71], necessitates incorporating climate change-induced rainfall behavior changes into models. Time series analyses of landslide frequency, extent, and intensity will be crucial.

Most susceptibility maps have been validated statistically rather than through detailed field observations. Regular field investigations in landslide-prone areas before and after the monsoon season are essential for validating and updating existing models. Comparing hazard maps generated through computer assistance, community input, and expert opinions can offer valuable insights into their differences and synergies [72,73].

Future research should prioritize the Rangamati region, integrating deep learning techniques with detailed, fine-scale investigations of geology, geochemistry, and soil studies to enhance their predictive capabilities. Including community vulnerability assessments in landslide susceptibility modeling, particularly in the densely populated Chittagong District, could provide a more comprehensive understanding of the region's risks.

Few studies focus on developing and implementing landslide early warning systems in Bangladesh [52,53]. Future research must develop cost-effective, user-friendly early warning systems and assess public knowledge and attitudes towards these systems to reduce lives lost and property damage effectively.

Syn-disaster phase

In the context of the landslide disaster management cycle, the syn-disaster phase refers to the period during a landslide event, where the focus is on immediate response and emergency actions. Future research on syn-disaster phase should prioritize a detailed characterization of landslide incidents, health impact assessments, community vulnerability assessments, and uncovering the interplay between anthropogenic activities and environmental factors.

A thorough understanding of landslide events is crucial for developing effective risk mitigation and response mechanisms [74,75]. Currently, most research focuses on landslide mapping over broad regions using open-source databases rather than conducting individual, case-based investigations [52,53,66,67,70,76]. Hence, future landslide studies should prioritize the detailed characterization of landslide events immediately after they occur, considering factors such as soil characteristics, geology, geochemistry, and the petrography of slope materials to understand patterns of the damage and triggers of the movement.

Like any other disaster, landslides disrupt people's normal living conditions and impact their lives and properties negatively. However, there is a lack of studies focusing on the impacts of landslide disasters on human health. Investigating the immediate, short-term, and long-term health impacts of landslide disasters is therefore another important area for future research.

Additionally, only a few studies have examined the impact of human modifications of the landscape in triggering landslides in the hilly regions of Bangladesh. Given the complexity and spatial variability of these interactions, a significant number of scientific studies must be conducted in the future. These studies should divide the hilly regions into smaller grids to ensure effective mitigation measures and a comprehensive understanding of the factors involved. One of the important initiatives after a disaster event is relief distribution in the affected community. A computer-based system can significantly enhance relief operations following a landslide disaster. It facilitates data collection and analysis, enables real-time communication, creates detailed maps, assesses population needs, promotes coordination, and monitors response efforts. These functionalities improve the efficiency and effectiveness of disaster relief operations. However, it is important to note that many actions, except the after-disaster relief and recovery, cannot be directly implemented during a disaster; rather, a few pre-disaster measures can significantly reduce casualties and losses when a disaster occurs.

Future research in the Syn-disaster phase should focus on strategies to minimize the impact of disasters on people's lives. Key approaches include developing real-time monitoring and early warning systems utilizing sensors and AI analytics for timely evacuations, as well as community-based preparedness programs that equip residents with essential skills. Additionally, research should emphasize resilient infrastructure and shelter design using innovative materials, along with integrated emergency response frameworks for efficient resource allocation among government agencies and NGOs. Addressing mental health needs through psychosocial support systems, implementing ecosystem-based approaches for natural disaster mitigation, enhancing data collection and sharing mechanisms, and strengthening legal and policy frameworks to enforce disaster risk reduction measures are also critical. By exploring these avenues, future studies can provide comprehensive strategies to build a more resilient society and effectively reduce the impact of disasters.

Post-disaster phase

The post-disaster phase generally represents the timeframe where recovery efforts and activities are primarily concentrated following a landslide disaster. However, it is important to note that recovery operations can sometimes overlap or intersect with the pre-disaster and syn-disaster phases as well. This phenomenon highlights the interconnected and dynamic nature of different stages within the overall landslide disaster management cycle. Recovery efforts may need to be initiated or coordinated concurrently with ongoing preparedness, mitigation, and response measures rather than being confined to a distinct post-disaster period. In the post-disaster phase, several key areas require thorough research to enhance LDM in Bangladesh. These key areas include planned urbanization, restrictive zoning, suitable site selection for resettling at-risk communities, long-term sustainable recovery planning based on multi-criteria evaluation, and the assessment of physical rehabilitation challenges.

The hilly regions of Bangladesh suffer from unplanned urbanization, a major cause of landslide-related fatalities as identified in several studies [76,77]. However, there is a significant gap in scientific research investigating the primary causes of unplanned urbanization in these regions and exploring suitable remedies. Future studies should aim to understand the socio-economic, political, and environmental factors driving unplanned urbanization and develop strategies to promote planned urban growth. This goal includes creating urban plans that integrate disaster risk-reduction measures, improving land use policies, and ensuring the proper implementation of urban planning regulations.

To mitigate landslide risks, it is crucial to divide the hilly regions into several landslide zones, assigning a hazard score to each. This approach identifies high-risk areas, allowing for the restriction or control of development activities within these zones. By preventing inappropriate land uses, this strategy helps minimize landslide risks and ensures that vulnerable areas are preserved or used in ways that reduce risk.

A significant portion of Bangladesh, particularly the eastern and south-eastern hilly region, is highly susceptible to landslide disasters, which challenges the current governmental capabilities for effective mitigation. Relocating vulnerable communities to safer sites is one viable solution. Scientific studies should therefore identify suitable resettlement sites using multi-criteria evaluation techniques, considering factors such as land stability, accessibility, resource availability, and community socio-economic needs. This comprehensive evaluation will ensure safe and sustainable long-term habitation.

Studies are needed to develop long-term, sustainable recovery plans for future landslide resilience. These plans should use multi-criteria evaluations and assess physical rehabilitation challenges, including infrastructure repair, service restoration, and environmental rehabilitation. Research should focus on understanding challenges, developing strategies, evaluating techniques, identifying best practices, and ensuring efforts are environmentally sustainable and socially inclusive.

Addressing these key areas will significantly enhance landslide disaster preparedness, mitigation, and response and recovery strategies in Bangladesh, ultimately contributing to more effective disaster management and risk reduction. To propose a coherent and systematic framework for LDM, these research gaps can be differentiated across different disaster phases, as illustrated in the Figure 13.

In addition to the phase-specific interventions, we propose several future scopes that could be applicable across all phases of the landslide disaster management cycle. These overarching areas for improvement and innovation may include the development of integrated early warning systems given the country's increasing vulnerability due to climate change impact due to deforestation, and human activities in hilly regions. Technologies like Real-Time Kinematic-based landslide monitoring systems [78], AI-driven early warning systems [79], and drone-based remote sensing are essential for improving prediction accuracy, reducing casualties, and ensuring timely evacuation in high-risk areas [80]. The implementation of comprehensive vulnerability assessments through detailed hazard atlases across various administrative boundaries (union, upazila, and district) could be implemented as an integral part of landslide disaster risk reduction. A geoportal with a dynamic interface of hazard-prone areas and vulnerable elements could also assist decision makers in managing future disaster risks [81]. The establishment of robust training and capacity-building programs for local communities and stakeholders. By addressing these broader, cross-cutting aspects, the overall resilience and preparedness of the affected regions can be significantly enhanced, ultimately leading to more effective and coordinated disaster risk reduction efforts.

Figure 13. Future research directions in the context of LDM in Bangladesh.

4. Conclusions

The increasing frequency and severity of landslides, worsened by climate change and human activities, highlight the urgent need for more effective LDM strategies in Bangladesh. This systematic literature review uncovered crucial insights pertaining to LDM in the hilly regions of Bangladesh, highlighting advancements, challenges, and future research directions. Although recent research has demonstrated significant progress in using GIS, remote sensing, and sophisticated data-driven modeling techniques such as Logistic Regression and Support Vector Machines, there are still critical gaps in validating these findings through field studies and integrating socio-economic factors, which are crucial for comprehensive disaster preparedness.

A noticeable increase in research publications has been observed since 2016, which suggests a growing awareness and investment in LDM, but significant challenges persist. These challenges include inadequate landslide inventories, limited access to data, and insufficient geophysical analyses. To reduce these gaps, expanding research efforts to encompass less-studied regions is necessary, as are improving data accessibility and fostering greater community engagement both in research and decision making. Most of the studies were primarily concerned with pre-disaster stages such as mitigation and preparation. It is important for future researchers to put a greater emphasis on the syn-(response) and post-disaster (recovery) stages. Future research should prioritize the integration of deep learning techniques to enhance predictive capabilities, given their strengths in managing complex nonlinear relationships, processing high-dimensional data, and providing real-time predictions. These techniques offer significant improvements in accuracy, generalization, and adaptability [48] (Bui et al., 2020). Additionally, future studies should focus on detailed investigations into geological and soil characteristics and take proactive measures to incorporate the impacts of climate change into LDM frameworks. Furthermore, enhancing public awareness is essential to help communities become more resilient to landslides. This action can make communities capable of effectively mitigating the impacts of landslide disasters in Bangladesh and ensure a safer and more secure future for all inhabitants of the vulnerable regions. All the concluding remarks can be easily visualized with the Figure 14.

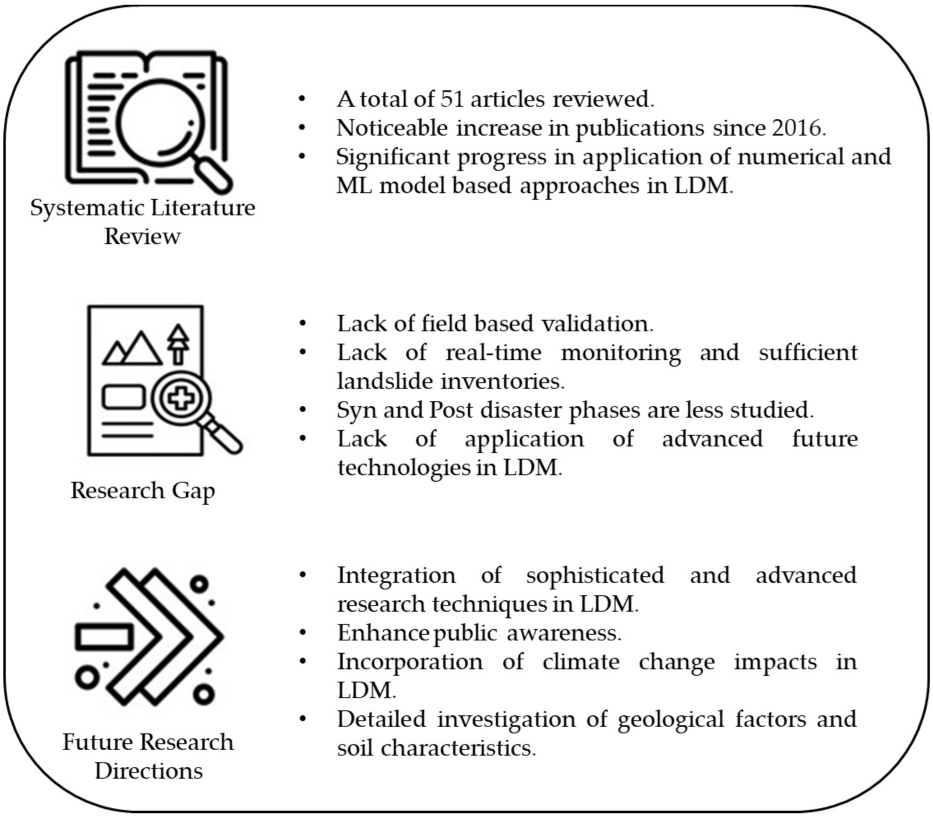

Figure 14. Illustration of concluding remarks of the systematic literature review (SLR).

Finally, the organization of studies into pre-, during, and post-disaster phases is primarily influenced by the practices of various organizations and authors. Our research indicates that studies focused on the post-disaster phase are less common. While pre-disaster studies, such as susceptibility maps, are frequently conducted, the other phases—particularly post-disaster—pose challenges for research. In this phase, it is crucial that policymakers, with input from the scientific community, assess the disaster's impacts, understand the reasons behind its severity, and determine measures to prevent future occurrences. Consequently, works developed during this stage may be better suited for conferences and technical reports rather than peer-reviewed journals, which could explain the imbalance in the number of publications across these temporal stages.

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