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REVIEW

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Identifying influential climatic factors for urban risk studies in rapidly urbanizing Region

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Abstract

Severe weather events, such as heat waves, floods, pollution, and health threats, are becoming more common in metropolitan places across the world. Overcrowding, poor infrastructure, and fast, unsustainable urbanization are some of the problems that India faces, and the country is also susceptible to natural disasters. This research analyzes climatic variables affecting urban hazards in Bangalore (also known as Bengaluru) via a thorough review. Heat waves, urban floods, heat islands, and drought were identified in 156 qualifying publications using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method. Contributing variables were also considered. City development and urbanization were key to changing climate and increasing urban dangers. While long-term climatic variable distribution is uneven, warming is evident. The report promotes strong urban planning techniques, comprehensive policies, more green areas, and sustainable development beyond short-term heat response programs to boost urban climate resilience. This study shows how climate, land use, and urban dangers are interconnected. Future studies may benefit by categorizing urban risk studies and identifying climatic factors.

Keywords Climatic variables, Risk assessment, Sustainable urban development, Urbanization, Climate-resilient cities

1 Introduction

The accelerated urbanization in various regions worldwide has accentuated the complexities and vulnerabilities of urban environments, manifesting in heightened risks (Hossain, S., Spurway, K., Zwi, A. B., Huq, N. L., Mamun, R., Islam, R., … & Adams, A. M., 2017). In the context of rapid urbanization, the identification and analysis of influential climatic factors on urban risks are critical for effective risk management and sustainable urban development (Kotharkar & Ghosh, 2021). Research activities focused on identifying influential climatic factors for urban risk studies in rapidly urbanizing regions aim to explore the multifaceted relationship between climatic variables and emerging urban risks (Jabareen, Y. 2013). These studies adopt a systematic approach, often leveraging advanced methodologies such as statistical analyses, GIS-based assessments, and climatic modelling to dissect the intricate interplay between urbanization dynamics and climatic influences.

Urban areas suffer severely due to a consistent rise in urban risks like heat waves, urban heat islands, urban floods, pollution, various diseases etc. Urban areas are becoming prone to frequent exogenous and endogenous

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risks like disaster risks, health hazards, pandemics, epidemics, unhealthy pollution episodes and other unexpected risks (Monstadt & Schmidt, 2019). Experts from around the world recently found that India is the largest exposed country to disasters like floods, heat waves, and drought (Brahmananda Rao 2021). As there is the unsustainable rate of urbanization with a substantial population highly dependent on human resources and poor-quality infrastructure with overcrowded housing, leads to severe implications for urban risks (Dhorde et al., 2022). Hence urban areas face various extremities like increased greenhouse gases, climate change, temperature rise, and air pollution due to urbanization as it alters the air movement, decreases evapotranspiration, and increases the heat storage (Srikanth & Swain, 2022). Air pollution due to industrialization leads to more heat and triggers more respiratory problems as modernization consumes lots of energy (Chen et al., 2021). Moreover, various human activities are damaging ecosystems, polluting habitats, congesting and inefficient planning and consuming in a disorderly way which negatively and indirectly impacts climate and thereby the climatic factors. As there is also a surge in the average temperature, hence along with other natural and anthropogenic reasons, climate change also plays an important reason in various urban risks and casualties (Hu et al., 2019; Pattnayak et al., 2019). There are various critical factors which control Urban Microclimate (UMC, which includes all climatic factors like temperature, relative humidity, wind direction and speed etc.) such as built-up, vegetation, and urban parks both at the mesoscale and macroscale (Makropoulou, 2017). Therefore, in this article, we identified and discussed the climatic factors which led to the emergence of and re-emerging of urban risks. There is a rallying call for civil society to make cities resilient against the risks to prevent disastrous outcomes (Cutter, 2021). This study will provide the necessary and relevant information which can become the foundation for increasing resilience. Specifically, this literature review will categorise the urban risk studies and their associated climate variables which will help in future research opportunities in detecting research trends and current topics of interest.

Many studies are being done on urban risks like Surface Urban Heat Islands (SUHI), urban flooding, and urban heat in various regions of the world (Wu et al., 2019; Zhao et al., 2020). Urban heat and heat-related risks due to heat waves and UHI have been studied and reviewed by many researchers urging policymakers to formulate heat mitigation strategies (He et al., 2022). The future scenario for New Jersey as studied by (Rosenzweig et al., 2005) depicted a decline in wind speed an increase in cloud cover and an increase in the frequency and duration of heat waves which will create heat-related morbidity and mortality. There have been massive health consequences due to heatwaves in Russia with a death toll of 56,000 and in California and China with 5758 heatwave-related cases (Kotharkar & Ghosh, 2021). Urban flood risk due to extreme precipitation further increases atmospheric moisture and thereby delays the convection process as studied by Doan et al., 2022 in Singapore. Orimoloye et al., 2019 studied the impacts of climate variability in South Africa and found increased climatic extremes and threats to human health and the environment.

This work focuses: (1) on identifying the climatic factors associated with these urban risks (2), on the effect of these factors on urban risks in general, and (3) on tracing the major urban risks in India and risks which are particular to the Urban Bangalore (i.e. also Bengaluru) region in India.

The investigation predominantly revolves around discerning key climatic factors contributing to urban risks prevalent in rapidly urbanizing regions. Heatwaves, floods, urban heat islands, and droughts represent focal points within this exploration, as they are recurrent and significantly impacted by climatic shifts aggravated by urban development.

Through meticulous analysis and data synthesis, these studies seek to unearth patterns, correlations, and trends in climatic variables influencing urban risks. Such actions often span interdisciplinary collaboration involving climatologists, urban planners, geographers, and environmental scientists to provide comprehensive insights.

The outcomes of these studies serve as pivotal guidance for policymakers, urban planners, and disaster management authorities. They inform strategies for resilient urban planning, infrastructure development, and policy formulation aimed at mitigating the adverse effects of urban risks. Additionally, these investigations aid in bolstering community resilience by advocating for measures like green infrastructure, sustainable development, and adaptive strategies to counter the escalating challenges posed by rapid urbanization and climatic variations in urban settings.

2 Study area

This review is carried out for Urban Bangalore (where Bengaluru and Bangalore are alternative names for the same city) district in Karnataka state of India. As it is a highly populated city in India with a tremendous increase in infrastructure as per the 2011 census, therefore is more prone to urban risks and hence studying the climatic factors is essential to better understand the risks. Bangalore is situated at 900 m above sea level having geographical coordinates as 12.9700° N, 77.6536° E and is a metropolitan city in the southern part of India. The city enjoys a tropical savannah climate having moderate temperatures

(35 °C to 38 °C) in April/May with maximum temperature ranges of 33 °C and moderate temperatures (10 ^{0}C) in winter with maximum temperatures as low as 14 °C. The monsoon season lasts up to September starting from June (Kanga S 2022).

Most of the area of Bangalore is prone to overland flow as 30% of central Bangalore is impervious during an intense rainfall event. Annual average rainfall in Bangalore is 850 nm with 80% contribution from northeast and southwest monsoon thereby giving an average of 60 rainy days per year (Mujumdar et al., 2021). There has been tremendous growth in population (4.1 million in 1991 to 12 million in 2017) in urban Bangalore in the last two decades as per the 2011 census which necessitates the study of urban thermal behaviour (Siddiqui, Kushwaha, Raoof, et al., 2021). Land growth of the city has been at the expense of lakes and urban green surfaces which was 69 km^2 in 1949 to more than 700 km^2 in 2017 and caused temperature rise (Shah et al., 2021). Figure 1 shows the study area: (a) location in India (b) location in Karnataka state (c) Bangalore Urban.

However, it is now severely affected by the effects of climate change giving rise to urban floods, urban heat islands, increased temperatures etc. Bangalore's floodways' are becoming blocked, and its natural flood storage is disappearing due to the encroachment of wetlands, floodplains, etc. (Mujumdar et al., 2021). UHI is also being triggered by the effect of climate change posed due

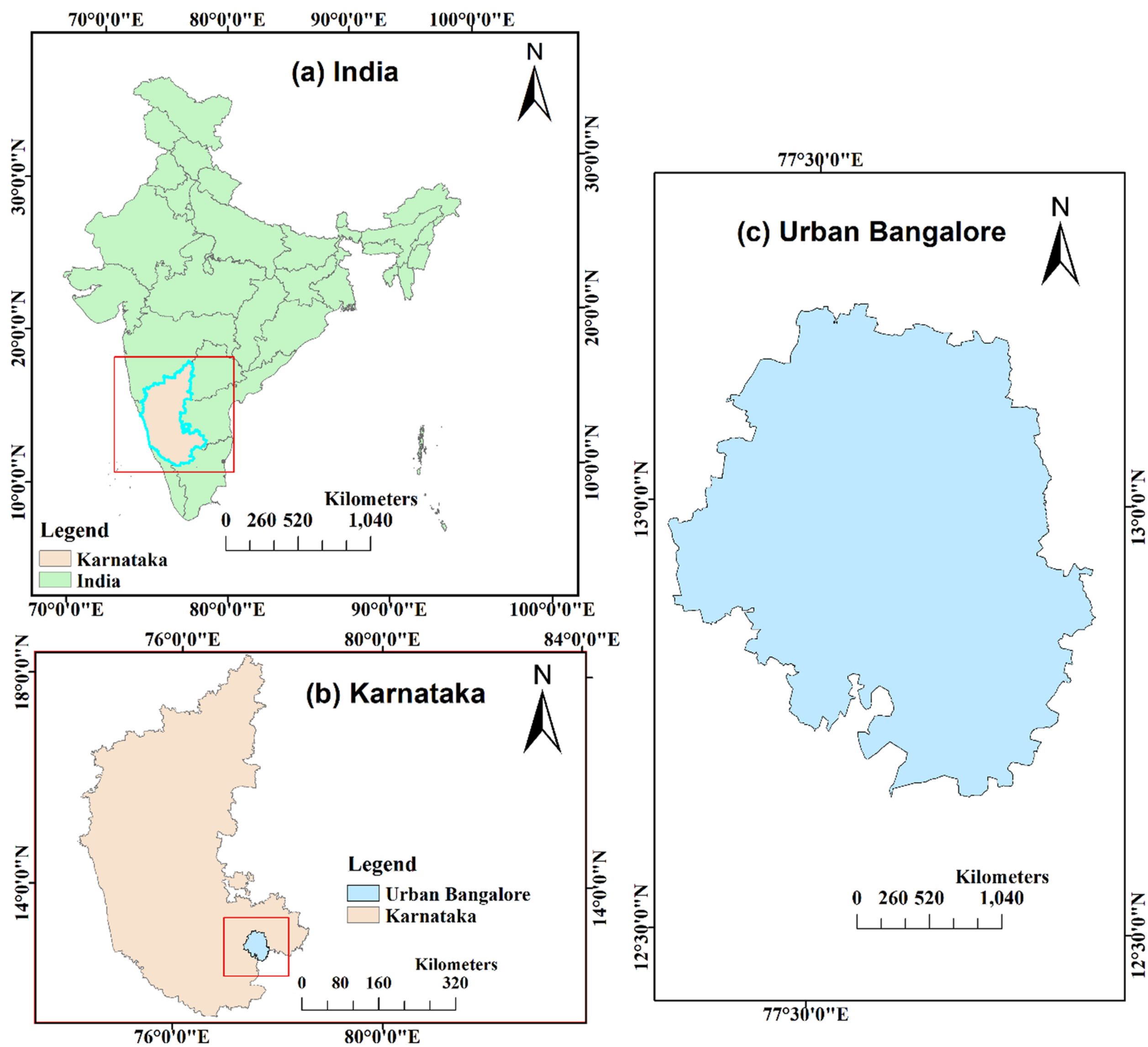

Fig. 1 Study area: (**a**) Its location in India (**b**) Its location in Karnataka state (**c**) Bangalore Urban district

to unscientific and unplanned urbanization in the district which creates discomfort among the residents (Sussman et al., 2019). Therefore, studying urban risks and their associated climate factors will provide useful insights for researchers and policymakers.

3 Methodology

The review conducted for this study involves four principles according to (Williams et al., 2021): (Ahmed et al. 2018)identify (Ardoin and Bowers 2020), plan (Arunab and Mathew 2023), assessment & evaluation (Arunab and Mathew 2023), synthesis. The methodology adopted for systematic literature review (SLR) to screen out the relevant studies is PRISMA stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses and it is the preferred reporting item for systematic review and meta-analysis protocols (Liberati et al., 2009). PRISMA-P is meant to be used primarily by authors preparing systematic review protocols for publication, public consumption, or otherwise. This technique ensures strong and reproducible results (Debray 2017). PRISMA has been used to improve quality of systemic review protocols and has been applied in significant number of studies related to health (Gundogan et al., 2020), disaster (Nandgude et al., 2023), education (Ardoin & Bowers, 2020), climate change (Bherwani et al., 2020a), risk management (N. Kumar et al., 2021), and engineering (Gharbia et al., 2020) among others. This SLR involves research question identification as its first step. Secondly, it involves an extensive literature survey using relevant keywords and Boolean operators using the sole database Scopus. The purpose was to achieve results in the form of articles, reviews, conference papers, and book chapters within the scope of this study related directly to urban risks. The operators used to perform searches for this review are "AND", "OR" and " ". AND with OR operators are used to connect different search queries. AND operator used to have all search terms in the results thereby ensuring precise results whereas OR operator is used to have at least one term out of all search terms in the results thereby allowing access to a large number of documents in results. The symbol " " is used to give documents having loose phrases which is to combine multiple search terms under quotation marks, and they appear together in abstract, title, or keywords. Various search strings using Boolean operators were developed to obtain the desired results as mentioned in Table 1. Keywords used during the research were climatic factors, drought, urban flood, heat waves, urban heat island, diseases, disaster, urban risk, and a combination of these as a condition to get the screened results. The condition was to keep the results within the scope of the study, which is studying various urban risks in India, various urban risks in Bangalore city, and their associated climatic factors. After that third step includes screening relevant publications using different criteria. Search results were limited

Table 1 Details of keywords and Boolean operators used

Logic	Search string	No. of results	No. of chosen results
Urban risks	"Urban risks"	25	12
	"Urban risk" AND "disaster" OR "hazards"	16	10
	"risk" AND "climate variables" OR "climate factors" OR "meteorological parameters"	115	30
	"urban" AND "risks" AND "hazard"	638	50
	"urban" AND "risk" AND "climate change"	235	48
Individual Studies on Risk	"Heat waves" AND "risk"	97	20
	"Urban heat Island" + AND "risk"	39	14
	"Urban flood" AND "risk"	70	20
	"drought" AND "risk"	646	20
	"diseases" AND "risk"	611	8
Specific to the Bangalore region	"Heat waves" + "Bangalore"	1	1
	"Urban heat Island" + "Bangalore"	16	8
	"Urban flood" + "Bangalore"	10	5
	"drought" + "Bangalore"	24	5
	"diseases" + "Bangalore"	768	3
	"climate" AND "Bangalore"	1	1
Total		**3312**	**255**

to the last 30 years of publication to ensure comprehensive research. The search was refined by giving the time frame for the study as from 1990 to 2022 and opting for article and review papers only.

By adopting this methodology 3312 papers were obtained and further they were manually screened using inclusion and exclusion criteria. Publications were screened based on their title and abstract and those papers were included which gave information about various risks in urban regions and factors affecting them and led them to trigger. Papers giving information about factors used in various models and risk indices for identifying the vulnerable regions to that risk were also included. Further, studies giving information on climatic variables or climate change studies and their negative impacts related to urban risks were also included.

Publications which are not related to the above-mentioned condition were excluded from screening. Studies about microbial infections, toxic metals or elements, management studies, genetic abnormalities in plants, water supply and sanitation, milk contamination with heavy metals, internet usage risks and other non-relevant studies were excluded. Papers talking about slums, river basins, Himalayan cities, and rural areas were also excluded and gave the required results of 255 papers. The papers published for peri-urban, coastal, Himalayan, plateau, river basins and slum areas were excluded from our study. Figure 2 reports the PRISMA Methodology for SLR using (Haddaway et al., 2022).

Further, research papers of journals having an impact factor of more than two and only peer-reviewed journal articles were included, and it was further screened by removing duplicates. Now after a full-text reading of 255 papers, we filtered and excluded 11 papers and left with 244 papers relevant to our study. This is called the manual screening of publications which were selected for full manuscript reading. Further, a search was done particularly for the study area of Bangalore giving information on above mentioned criteria which provided 28 articles relevant to our study.

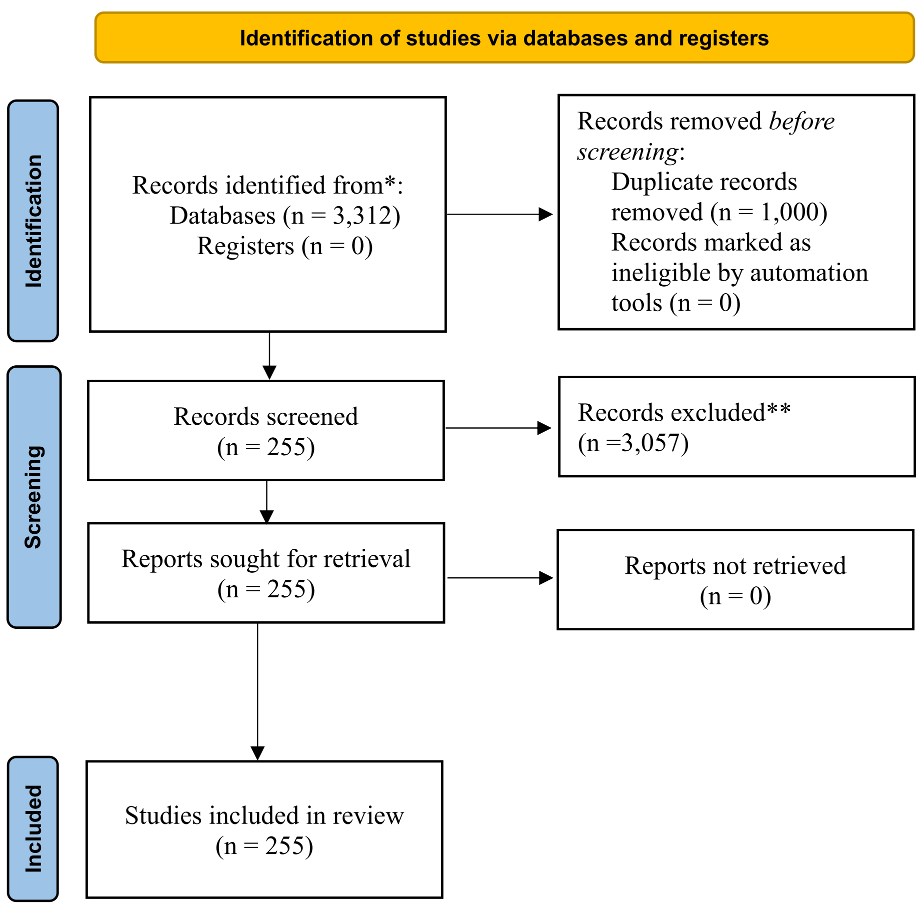

Fig. 2 PRISMA methodology

4 Result & discussion

4.1 Glimpse and Assessment of various urban risks and their associated climatic factors

Recently IPCC 2021 research predicted global temperatures to increase due to climate change which will further increase the frequency of meteorological extremities (IPCC 2023). There are various urban risks identified in the Indian region. There are so many other risks associated with one risk there are habitat destruction, drought, biodiversity loss, and wildfires which intensify with the heat waves. Another, there are many health-related risks and fatalities which are associated with extreme heat and hence economy suffers from productivity loss (Sutanto et al., 2020). When plains and hilly region stations hit a peak temperature of 30^0 or 40^0 C, it is deemed a heat wave by The Indian Meteorological Department (IMD) (Suthar et al., 2023). Heat waves are responsible for mortalities and have become the second most disastrous event. They further cause heat stress and are termed a silent killer (Srivastava et al., 2022). Urban heat island (UHI) is associated with the warming of an urban area about its surrounding rural area which tends to heat-related diseases and mortality as it amplifies heat waves and unhealthy heat stress further (Chandra et al., 2022). UHI is the result of unplanned and uncontrollable urbanization which alters the earth's surface and puts it under different ecological and environmental threats (Raj et al., 2020). Many studies are being done on UHI (Srikanth & Swain, 2022; Raj et al., 2020; Shastri et al., 2017; Sharma et al., 2023; all of which show urbanization impact on Land Surface Temperature (LST) which leads to the formation of SUHI particularly more at nighttime than in daytime in many cities.

Urban areas in India face significant risk from seismic activity due to their location in seismically active zones and high population density. Major cities like Delhi, Mumbai, and Kolkata are vulnerable to earthquakes, with many buildings constructed without adherence to seismic standards. Poor infrastructure and informal settlements further exacerbate the risk, amplifying the potential for loss of life and property damage. Despite historical precedents like the 2001 Gujarat earthquake, awareness and preparedness remain insufficient. Addressing urban seismic risk necessitates stringent building codes, infrastructure improvements, community engagement, and effective disaster management strategies to enhance resilience and reduce vulnerability. But there is no risk in Bangalore.

The dynamics of heatwaves are very important to understand as it has become a great concern with temperature extremes having disastrous impacts on human health and agriculture (Rohini & Rajeevan, 2023). Rohini 2016 reported a rise in the frequency and length of heatwaves over India that is statistically significant and discussed the increasing frequency of heatwaves may be due to the increasing phenomenon of El Nino. Perkins 2012 and Kotharkar & Ghosh, 2021 showed heatwave frequency, duration, and intensity to be increasing in recent decades as projected by the Intergovernmental Panel on Climate Change (IPCC). Neetu 2022 discussed 11% mortality due to increasing heatwaves as the temperature reaches above 40^0C. Heatwaves will lead to severe intense hazards over the Ganges and Indus River agricultural basins and a reduction in labour capacity to 90% and further to 40% in upcoming years (by 2200) as shown by Dunne 2013. This urban heating has also led to the deterioration of waterbodies as studied in Ahmedabad and Bangalore (Siddiqui, Kushwaha, Nikam, et al., 2021). There is an increased number of heat-related mortality cases caused by the impact of extremely high temperatures in urban areas (Rathi et al., 2023). Another study conducted in Pune also associated mortality with ambient temperature and concluded men were at higher risk for both heat and cold temperatures (Ingole et al., 2022). Rajasthan, Ahmedabad experienced high mortality due to extreme ambient temperatures documented by (Murari et al., 2015). Fire risks due to rising temperatures remain largely invisible but affect nearly 11 million people as observed in Delhi with a strong relationship between a warming city and an increasing number of fires in urban areas (Bankoff et al., 2023).

Severe and frequent flooding due to drastic population growth leads to the loss of human and animal lives and their assets. This happens due to an increase in flood peak and runoff as rainwater infiltration started to decrease due to unplanned urbanization and another reason is climatic variability which also aggravated the risk of urban flood. Urban flooding hinders basic urban functions and results in an outbreak of many epidemics and loss of life and property (Gupta, 2007). After the fatal Mumbai floods in 2005, the National Disaster Management Authority (NDMA) of India started paying attention to urban floods and addressing them as a separate disaster having its guidelines released in 2008 (N. Sharma, 2016). Flood modelling and flood inundation maps are prepared on a regional scale to combat such events by delineating regions more vulnerable to risk (Rangari et al., 2019). The special report by the Intergovernmental Panel on Climate Change (IPCC) predominantly indicates the vulnerability of South Asian countries towards multiple hazards and the linkage of climate change to this event in cities (Avashia & Garg, 2020). Therefore, understanding the climatic factors is of utmost importance for its linkage towards urban risks. A report by Ali 2019 showed an increase in multiday events of extreme rainfall and flood rather than single-day events across the Indian subcontinent soon. Roxy 2017 observed a threefold increase in extreme precipitation throughout Central India between 1950 and 2012. Another study by Machado et al., 2019 investigated and observed forested and tree-covered regions are comparatively less vulnerable to flooding as studied by land use patterns in Salvador city of Brazil. An assessment of Dhaka city was done by Ahmed et al., 2018 to explore the effect of urban growth and climate change on the city. A study by Reddy & Bhavani (2023) analysed the effect of land use changes on flood inundation using a hydrological model. Many studies conducted flood vulnerability analyses at the local level to identify the vulnerable zones in the city either using flood vulnerability index or by using machine learning methods (Parvin et al., 2022, Bansal et al., 2022, Kadaverugu et al., 2022, Vaddiraju & Talari, 2022, Tomar et al., 2021). Urban flooding further leads to malnutrition and health risks in humans by crop destruction and thereby shortage of food. 47% of children in India suffer from malnutrition as reported in the World Bank Report of Malnutrition in India (2009) (Majra & Gur, 2009). Many other risks come up with floods like diarrhoea, water-borne infections, and rodent-borne diseases (Kovats & Akhtar, 2008; (Orimoloye et al., 2019).

Drought is another recurring urban risk that causes huge loss to the economy and life and it's a very complex phenomenon marking the condition of water shortage. Rapid modernization and climate change lead to this deadliest natural phenomenon therefore studying and identifying the major climatic-driven factors affecting its occurrence is important (Wilhite et al., 2007). There are many kinds of drought as meteorological drought, agricultural drought, hydrological drought, and socio-economic drought as classified by Wilhite and Glantz (Wilhite and Glantz (1985) which are due to less precipitation, reduced soil moisture, reduction in water in water bodies and socioeconomic impact respectively. Drought early prediction for planning and mitigation is also a key challenge in front of the researcher (Mathbout et al., 2018). There are a variety of drought prediction models based on stochastic, physical and machine-learning methods. Researchers must appropriately choose the model according to the data series, regional characteristics and concept of the model algorithm used (Tian et al., 2016). Drought forecasting accuracy can be achieved by incorporating multiple drought indicators such as The Temperature State Index (TCI), Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), The Crop Moisture Index (CMI) and others (Nandgude et al., 2023). Rural population is heavily dependent on agriculture for survival in India which in turn depends on monsoon rainfall, therefore drought studies are of great concern (Pei et al., 2018). Much research has been done for drought vulnerability assessment either using machine learning models or by construction of a Standardized precipitation index (SPI). Prajapati et al., 2021 concluded the importance of multiple indicators like the Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI) and Vegetation Condition Index (VCI) for realistic drought monitoring and characterization. (Kokilavani et al., 2021) used SPI to assess spatial and temporal variation in drought and its strong potential in the identification of drought. Das et al., 2021 studied the future drought conditions like its frequency, duration, severity, and peak using SPI and SPEI with the help of GCMs of the novel NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). Long-term drought trends and variations in drought parameters (duration, frequency, intensity) were identified by using Climate Research Unit (CRU) based SPEI (Choudhury et al., 2021).

Another deadly disaster risk in urban areas is earthquakes resulting in enormous devastation and paralyzing the community causing mortality and morbidity (Lawrence et al., 2020). The largest death toll is brought by earthquakes due to no seismic protection in highly populated and economically important locations. Resilience maps and knowing the vulnerability of the cities can assist in the city's risk management effectively (Tasmen et al., 2023). Metropolitan cities like Delhi NCR are more vulnerable to earthquakes falling under seismic Zone IV and are more aggravated due to the exponential growth of the infrastructure (Sandhu et al., 2020).

Another crucial risk in urban areas is pollution which creates a toll on human health and puts constraints on economic growth and productivity. Air pollution is caused by to slow degradation of harmful substances or pollutants which alters air's physio-chemical and biological properties. These pollutants are in turn affected due to various climatic factors and anthropogenic factors (B. Ghosh et al., 2023). In urban areas, meteorological parameters have an important influence on pollutant variations (Sanda et al., 2023). Particulate matter (PM10 & PM2.5) pollution in the air can cause premature deaths and is very toxic for humans. A study conducted in urban areas of Northeast Delhi observed a high carcinogenic effect of PM on the population (Islam & Saikia, 2020). Air quality in Agra exceeded far the acceptable levels of hazard quotient (HQ) for PM2.5-1.0 (3.80) and PM1.0-0.5(4.26) and was found to have a high carcinogenic risk for an adult and child.

There are many other risks associated with urban areas which are not directly linked to climate change or climatic factors but are affected due to unplanned urbanization as discussed. Groundwater pollution also represents a high risk for non-carcinogenic risks in the human population in urban areas. A study in Bhubaneswar by Nayak et al., 2023 found out the acidic pH of the groundwater creates serious health risks in children and adults. Severe fluoride and nitrate contamination were found in the groundwater of North-West Delhi creating high public health risk with high hazard risk for children (Sarma & Singh, 2023). Similar research was done in smart cities of Telangana and in the Sonipat district of Haryana to check the toxicity of groundwater and observed cumulative hazard quotient to be more than one for both children and infants (Guddeti & Kurakalva, 2023; S. Shukla et al., 2023). Freshwater pollution due to high concentrations of metals and metalloids poses severe health risks to the human population as studied by Kumari & Hansdah, 2023 in the Ranchi district of Jharkhand. Soil pollution caused due to polycyclic aromatic hydrocarbons (PAHs) is studied by Sankar et al., 2023 in industrial cities of India, Jamshedpur and Amravati for human health risk assessment and contamination evaluation. It emphasises anthropogenic factors to be the significant sources of contamination. Another study in Varanasi city by (Mishra et al., 2023) detected metal pollution load at industrial sites of the area in soil environment and observed its potential to pose chronic health risks. This study indicates changes in land use to be the major factor causing an imbalance in the soil environment. The soil in the Gurugram district of Haryana was found to be less contaminated with trace metals and have low health risks (Dixit et al., 2020). Tsunamis and cyclones are more prevalent climatic extremes in coastal megacities.

Due to its geographic and demographic diversity, India faces a variety of urban hazards influenced by climate. India experiences severe heatwaves, exacerbated by Urban Heat Islands (UHI) caused by increased impervious surfaces, reduced green cover, and anthropogenic heat. Urban flooding due to heavy precipitation events, inadequate drainage systems, rapid urban expansion, changes in natural water channels are caused by erratic rainfall patterns, declining groundwater levels, overexploitation of water resources, and inadequate water management systems.

Climate factors including lesser precipitation, higher evaporation, and prolonged dry spells worsen these problems, including air pollution and health hazards from extreme air pollution. Temperature inversions, sluggish weather, and particle matter accumulation worsen air quality, causing respiratory disorders and health risks. Multidimensional solutions like green infrastructure development, sustainable urban design, efficient drainage systems, and catastrophe readiness are required for urban risk mitigation methods. A holistic understanding of the climatic factors contributing to these risks is essential for effective risk assessment, adaptation, and the formulation of robust urban resilience strategies in India. Table 2 presents the summary of urban risks and their affecting variables.

There are several dangers that are intertwined with certain climatic elements in the urban environment of Bangalore. These risks shape the urban landscape and influence vulnerabilities.

4.2 Urban risk identification and their associated climatic factors for Urban Bangalore

Climate change due to urbanization proved to be a potent global concern due to its ability to increase the frequency of urban extremities in the twenty-first century. Therefore, this urge for further study for robust preparedness and policy framing, whose first step is to identify climatic factors affecting urban risk (Nandi & Swain, 2022). Bangalore, one of the Indian megacities, has experienced several urban extremities which creates several challenges in sustaining resilience in the urban ecosystem. Climate change and urban development together produce a cascading effect and intensify the urban risks and urban people's vulnerability. Bangalore was one of the 100 smart cities chosen for the Indian Smart Cities mission, in 2015 for making a resilient environment to urban extremities (Das et al., 2022). Bangalore is facing challenges of thermal discomfort and Urban Microclimate (UMC) changes due to large-scale regional ecological challenges and, conversion of green areas to concrete coupled with climatic variability. This has led the city to an increased probability of increased extremities like heat strokes, health disorders, urban heat islands, drought, and urban flood (Vailshery et al., 2013)). Prolonged Heavy rainfall is one of the leading factors causing urban floods in Bangalore which has shown an increasing and significant monthly trend in the city (SINGH et al., 2015). Another study observed an increasing warming trend in Bangalore at a local level called the heat island effect with LULC changes and increasing LST in paved surfaces. One article found out air quality index of Bangalore to be very high, indicating high pollution levels during pre-COVID years (Suresh et al., 2022). Bangalore comes under the category of high pollution potential according to the ventilation coefficient (VC) and air pollution potential index (APPI) given by Kannemadugu et al., 2021 which will harm human health. A study conducted to find urban eco-environmental quality (UEQ) in three megacities Ahmedabad, Hyderabad, and Bangalore observed Bangalore to have the most degraded UEQ (1.08 to 0.80) and have a higher rate of degradation than other cities (Pramanik et al., 2022). Groundwater depletion has been observed in metro cities like Bangalore which is a demandable resource for agriculture and drinking

Table 2 Summary of urban risks and their affecting variables

Research paper	Place	Other factors	Climatic factors	Urban risk	Main findings
(Chanda et al., 2023)	Gujarat	Land use land change, climatic factors	Change in maximum temperature, daytime minimum land surface temperature	Crimean Congo Hemorrhagic Fever (CCHF),	A combination of factors contributes to the occurrence of CCHF in Gujarat. These are daytime LST, maximum temperature, land use pattern, elevation, buffalo density
(Mathew et al., 2022)	Ahmedabad	Land surface temperature	Land Surface Temperature	SUHI	LST affecting SUHI is strongly linked to land surface variables such as vegetation, soil, water, and builtup.
(D. S. Kumar et al., 2014)	Chennai	Environmental and socioeconomic conditions	Rainfall Temperature	Malaria	There is a strong prevalence of malaria in Chennai due to its high association with rainfall and temperature and is likely to aggravate with unhygienic living conditions
(A. Sharma & Kale, 2022)	Surat	LULC	Land Surface Temperature, Rainfall	Urban Heat Island	The trend of rainfall gives increasing results with the UHI effect.
(Biswas & Ghosh, 2022)	Kolkata	LULC	Land Surface Temperature	Urban Heat Island	LST was found to be increasing with urbanization as have maximum value over built-up and barren land.
(Dasgupta et al., 2013)	Kolkata	Sea level rise, storm surges, intense rainfall	Rainfall	Urban flood	Kolkata is highly prone to flood hazard
(Kesavan et al., 2021)	Chennai	LULC	Land Surface Temperature	Urban Heat Island	More built-up leads to growing UHI hotspots in urban areas as they increase LST values.
(Mohammad & Goswami, 2023)	Bhopal and Guwahati	enhanced vegetation index (ΔEVI), evapotranspiration (ΔET), and white sky albedo (ΔWSA)	Land Surface Temperature,	Surface urban heat island	Evapotranspiration was found to be a major control for daytime SUHI. During daytime Bhopal shows urban cool island whereas Guwahati shows SUHI. But daytime SUHI in comparison to nighttime SUHI is usually found to be negative in cities.
(Siddiqui, Kushwaha, Nikam, et al., 2021)	Lucknow, Kolkata, and Pune	aerosol optical depth (AOD) and normalised difference vegetation index (NDVI)	LST	Surface urban heat island	To study urban heating or UHI the nighttime LST is a better indicator because nighttime LST shows positive UHI than daytime.

Table 2 (continued)

Research paper	Place	Other factors	Climatic factors	Urban risk	Main findings
(Heaviside et al., 2017)	Review	Urbanization	High Air Temperature	Heat Stress	UHI further aggravates heat risk due to heat waves and impacts human health.
(P. Kumar & Sharma, 2022)	Sonipat municipality	Urbanization	Air temperature	Heat Stress	Heat stress gets aggravated during pre-monsoon and during summer monsoon.
(Avashia et al., 2021)	Ahmedabad	Global Warming, built up	LST, Air Temperature	Heat-related Mortality	Using LST as a microclimate representation gives better results for heat-related mortality than air temperature.
(N. Singh et al., 2019)	Varanasi	Air quality, climatic variables	Daily mean temperature, Diurnal temperature variation (DTV)	Heat-related Mortality	The major impact of climate change on human health was observed with a significant association between daily mean temp. and human mortality.
(Pandey et al., 2012)	Delhi	Urbanization	High temperature and low wind speed	With more pollutant concentration, Urban Heat Island	Low wind speed favours cool island formation due to less removal of pollutants from the atmosphere
(Suthar et al., 2023)	Rajasthan and Karnataka	Temperature	Maximum Air Temperature	Heat waves	Air temp. is well correlated with LST and Black carbon and the Machine learning model can accurately predict air temp. for defining heatwave conditions.
(Shahfahad et al., 2023)	Delhi and Mumbai	Impervious surfaces	DTR and extreme temperature	Heat waves	Cities become more vulnerable to heat waves with increasing extreme temperatures and decreasing DTR.
(Srivastava et al., 2022)	Indian region	Meteorological parameters	Maximum temperatures, minimum temperatures, relative humidity, wind speed	Heat Waves	Heatwave hazard impact was found more in northeast India.
(P. Kumar et al., 2022)	Kolkata, Chennai, Delhi, and Mumbai,	Urbanization, concrete structure	maximum temperature, relative humidity, wind speed and solar radiation	Heat Waves	More relative humidity and high temperature favor dangerous-heat stroke events.
(K. K. Shukla et al., 2022)	Northwest India	Anthropogenic activities	Temperature, Relative humidity	Heat stress	Rising temperature and relative humidity make northwest India vulnerable to heat stress.
(Dhorde et al., 2022)	41 urban regions of southern India	Impervious surfaces	Climate extremes such as high moisture and high temperature during southwest monsoon	Heat Stress and health risks	Heat stress found more at north-east parts due to high summer temp. and high humidity during monsoon.

Table 2 (continued)

Research paper	Place	Other factors	Climatic factors	Urban risk	Main findings
(DESAI et al., 2021)	Mumbai and Pune	Temperature, Relative humidity	Temperature, Relative humidity	Heat Stress	In Pune heat stress remain consistent during summer whereas in Mumbai it has increased according to heat index.
(Neethu & Ramesh, 2022)	India	Urbanization	Max temperature, mean surface temperature, Wind speed	Heat waves	There is increasing trend of thermal discomfort in northwest India.
(P. Singh et al., 2022)	Delhi	LULC	LST	Urban Heat Island	Maximum temp. shows increasing trend in the city which along with land use is main driving force for urban heat island.
(Awasthi et al., 2022)	World	LULC	Surface air Temperature, Relative humidity	Heat wave	There is increasing trend in temperature and number of heatwaves days around the world
(S. Kumar et al., 2022)	Delhi urban watershed (The Qudesia Nallah catchment and the Jahangirpuri drain catchment)	Urbanization, Climate change	Rainfall	Urban flood	Future rainfall damage predicted to be very high due to greater likelihood of rainfall extremes
(Mukherjee & Bardhan, 2021)	Kolkata	Unregulated urbanization	Rainfall, air temperature	Urban Flood	Urbanization and poor drainage along with increased precipitation make city vulnerable to flood risk.
(Bagyaraj et al., 2023)	Chennai	Distance to river,, land use/land cover, elevation, slope, drainage density, soil type,	Rainfall	Urban flood	Low elevation and regions having high runoff densities found to be more vulnerable to flood risk.
(Vemula et al., 2019)	Hyderabad	Extreme rainfall	Extreme rainfall	Urban flood	Future rainfall projected through Storm Water Management Model (SWMM) is extreme and will lead to urban flooding by increased runoff
(Bansal et al., 2022)	Dehradun		Rainfall	Urban flood	
(Nandgude et al., 2023)	Review	Evapotranspiration Soil moisture, Elnino, grounwaterlevel	Precipitation, Temperature, humidity, wind speed,	Drought	Machine learning models prove to effectively forecast drought conditions.
(Danodia et al., 2021)	Bundelkhand	Soil moisture	Rainfall	Drought	Drought conditions appear to be effective more in northern regions of the study area.

Table 2 (continued)

Research paper	Place	Other factors	Climatic factors	Urban risk	Main findings
(Das et al., 2021)	India	Evapotranspiration,	Rainfall, Temperature	Drought	Region is more vulnerable to short-term drought conditions than long-term and temperature plays vital role in drought monitoring.
(Neeti et al., 2021)	Central India	Evapotranspiration	Rainfall,	Drought	One region shows severe short-term drought and other region shows less severe long term drought.
(O. Singh et al., 2021)	NCT Delhi	Evaporation	Maximum temperature, minimum temperature and mean temperature, relative humidity, and wind speed	COVID-19 pandemic	Except rainfall COVID-19 has been found to be positively related to other climatic factors.
(B. Ghosh et al., 2023)	Kolkata, Howrah	Anthropogenic activities	Climatic factors	Volatile organic compounds which are air pollution causing pollutants leading to Leukaemia, cancer risks in human	Winters favours the increase in pollutants concentration than in summers.
(Nayak et al., 2023)	Bhubneswar	Anthropogenic activities	Climatic factors	Groundwater pollution causes non-carcinogenic risks.	There is high risk for noncarcinogenic risk to develop in humans.
(Mahata & Shekhar, 2023)	Kolkata Metropolitan City	Urbanization, climate change, extreme heat	Temperature	Heat stroke & other health problems	Older adults and weaker communities face more health risks due to extreme heat.
(Kayastha et al., 2022)	Review	Climate change, anthropogenic sources	Reduced rainfall	Groundwater pollution	Insufficient rainfall and its altered hydrological pattern due to climate change have increased electrical conductivity and salinity of groundwater.
(Mohanavelu et al., 2020)	7 Indian cities	Climate variability, excessive pumping, Drought	Reduced rainfall	Groundwater depletion	Major relationship found between rainfall and groundwater level change dynamics.

Table 3 Summary of urban risks and their affecting variables

Paper	Urban risk	Causal factors	Climatic factors	Key findings
(Kanga et al., 2022)	Urban Heat Island	Urbanization	LST	Urbanization has caused a rise in temperature and led to UHI
(Shah et al., 2021)	LULC	Air Temperature, Land Surface Temperature	Canopy Urban Heat Island Surface Urban Heat Island	Urban Green Spaces can mitigate UHI.
(Kumar Goyal et al., 2023)	Drought	Soil Moisture, Runoff, Normalised Difference Vegetation Index (NDVI), and Precipitation	Precipitation	Urban drought risk was found to be the maximum in smart cities based on the variability of these parameters and index calculation.
(Singh et al., 2015)	Urban flood	Extreme rainfall, proximity of urban area to flood plains of rivers	Extreme rainfall	No significant trend in heavy rainfall but at the local level it is a matter of concern.
(Arunab & Mathew, 2023)	Urban heat island	LULC, Air temperature, LST	Air, temperature, LST	Bangalore is found to have increasing UHI intensity
(Jain, 2023)	SUHI, Heat stress, Heat mortality	Urbanization, LST, 2 m Air temperature	Air, temperature, LST	High SUHI Maxima values particularly during nighttime ad pre-monsoon time.
(S. Ghosh et al., 2022)	UHI	LST, NDVI, NDBI, NDWI	LST	Involves studying spatiotemporal dynamics of LST and Indices important for development decisions of a new town for UHI.
(Siddiqui, Kushwaha, Nikam, et al., 2021)	UHI	LST, NDVI, NDBI, ISA (impervious surface area)	LST	Results show Bangalore city experiences the urban cool island effect and ISA proved to be a better metric.
(Neog, 2021)	Heat stress	Daily air temperature and Relative Humidity	Daily air temperature and Relative Humidity	Heat stress during the COVID period has declined in cities
(Gouda et al., 2021)	Air pollution Risk	Vehicular, industrial emissions	Rainfall, windspeed, temperature	Rainfall and wind speed have a significant correlation with pollutants than temperature.
(Saha et al., 2021)	Potential evapotranspiration. Crop water demand, population density,	Annual rainfall, average temperature,	Drought	Central and east part of the state shows high vulnerability to drought.
(Mujumdar et al., 2021)	Urbanization	rainfall	Urban Flood	Near-real time flood forecast model has been prepared.
(Shah et al., 2021)	LULC	Air Temperature, Land Surface Temperature	Canopy Urban Heat Island Surface Urban Heat Island	Urban Green Spaces can mitigate UHI.
(Siddiqui, Kushwaha, Raoof, et al., 2021)	Built-up, vegetation	Land Surface Temperature	Surface Urban Heat Island	It was found that impervious surface area is the main factor affecting LST.
(Davis et al., 2022)	LULC	Extreme rainfall	Urban flood	The Personal Computer Storm Water Management Model (PCSWMM) is applied for flood forecasts.

purposes and is a major risk (Sarkar et al., 2020).P. Kumar et al., 2016 studied the climate change vulnerability of Bangalore city Spatial Multi-Criteria Evaluation (SMCE) and found 91% of Bangalore metropolitan area under a high degree of climate vulnerability. A study by Vailshery et al., 2013 emphasises street trees to curb air pollution and microclimatic alterations brought by urbanization and climate change in Bangalore. There is also a high risk of premature mortality in Bangalore along with Delhi, Hyderabad, Mumbai, and Chennai, due to ischemic heart disease, IHD, chronic obstructive pulmonary disease, COPD, stroke and lung cancer diseases which are caused by $PM_{2.5}$ exposure (Shende & Qureshi, 2021). Dengue haemorrhagic fever (DHF) has become epidemic with India soon becoming the major niche for dengue infection. The mortality rate from dengue fever is found to be 8.6% in patients admitted to KIMS Hospital & Research Centre, Bangalore. There is also a high risk of developing low-birthweight (LBW) babies with Non-Communicable Diseases (NCDs) during adulthood which are strongly correlated with ambient and indoor air pollution.

4.3 Climatic factors responsible for Urban Bangalore

Climatic factors were listed among all factors aggravating or affecting various urban risks with the help of a thorough literature review and are mentioned in Table 3 above. We found out set of climatic parameters such as air temperature, LST, rainfall, relative humidity, wind speed, and DTR affecting these risks in urban areas. In Bangalore, the major climatic variables observed were LST and rainfall.

Temperature which aggravates heat stress impact, urban heat island formation gets unbalanced due to urban disturbances, broken wind patterns and heat generation from anthropogenic activities within the city. Major factors affecting heat waves are surface air temperature heat accumulation and reduced heat transfer which gets more intensified with low soil moisture and simultaneously reduced evaporative cooling (Neethu et al., 2020).

Precipitation is another critical climatic parameter which is getting enhanced and affected due to due to aerosols and particulates of air pollution, increase in surface roughness, and intense urbanization.

Humidity is important to maintain urban dryness as with increasing temperatures or with the formation of UHI relative humidity is decreased causing urban dry island (UDI). But during winters it is increased, and air becomes moister than its surroundings (Choi et al., 2018). During the rainy season, 58–96% relative humidity is considered comfortable with local rainfall occurring due to the convergence of water vapour (Bherwani et al., 2020b). Windspeed is affected due to weather conditions and hindrances brought by the higher roughness of buildings which creates the difference between urban and countryside temperatures (Bherwani et al., 2020c).

5 Conclusion

Identifying influential climatic factors in rapidly urbanizing regions such as Bangalore is pivotal for crafting effective risk mitigation strategies. This study highlights the intricate interplay of various climatic variables with urban dynamics, amplifying a spectrum of risks. The assessment pinpoints heatwaves and the Urban Heat Island effect, worsened by diminished green spaces and escalating urbanization, as major contributors to heightened temperatures. The inadequate stormwater drainage and shifting precipitation patterns exacerbate urban flooding risks. Irregular rainfall and depleting groundwater drive water scarcity and drought conditions. Air pollution, soil erosion, and sporadic landslides further compound urban risks, influenced by diverse climatic conditions. This comprehensive analysis underscores the urgency for holistic urban planning and climate-resilient policies. Critical strategies involving green infrastructure, efficient drainage, water conservation, and pollution abatement are imperative. Emphasizing adaptive measures and sustainable development, fused with climate considerations, becomes pivotal to fortifying urban resilience in swiftly urbanizing regions like Bangalore. This understanding of influential climatic factors lays the foundation for crafting robust urban landscapes capable of tackling and mitigating multifaceted urban risks amid ongoing urbanization and climate shifts.

Authors' contributions

Ms Saloni Mangal (SM), Dr. Deepak Kumar (DK), and Dr Anil Kumar Gupta (AG) conceived and designed the framework of the research, and Ms Saloni Mangal (SM), performed the research, Dr Maya Kumari, Dr. Renu Dhupper (RD) along with Dr Deepak Kumar (DK) analyzed the data with contributions to the editorial input. Conceptualization, methodology and formal analysis: SM, DK, MK, AG; investigation: DK, AG, MK, RD; visualization: SH, MK, DK; writing—original draft: SM, MK, DK; writing—review and editing: SM, MK, DK; All authors read and approved the final manuscript.

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Not applicable.

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