International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

2734 17 Avenue SW,
Calgary, Alberta, T3E0A7,
Canada
+15878858911
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ARTICLE TITLE	DIGITAL HEAT-HEALTH EARLY WARNING SYSTEMS FOR OLDER ADULTS: CLINICAL EVIDENCE, HEALTH EQUITY, AND PUBLIC POLICY IMPLICATIONS OF PERSONALIZED CLIMATE-HEALTH TECHNOLOGIES
DOI	https://doi.org/10.31435/ijitss.3(51).2026.5828
RECEIVED	14 May 2026
ACCEPTED	15 August 2026
PUBLISHED	28 August 2026
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DIGITAL HEAT-HEALTH EARLY WARNING SYSTEMS FOR OLDER ADULTS: CLINICAL EVIDENCE, HEALTH EQUITY, AND PUBLIC POLICY IMPLICATIONS OF PERSONALIZED CLIMATE-HEALTH TECHNOLOGIES

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ABSTRACT

Extreme heat poses an increasingly serious threat to public health, particularly among older adults, for whom age-related impairment of thermoregulation, chronic diseases, polypharmacy, social isolation, energy poverty, and poor housing conditions increase the risk of heat-related morbidity and mortality. The aim of this review article is to provide a comprehensive overview of the evidence regarding digital early warning systems for heat-related effects in older adults, with particular emphasis on their clinical basis, potential for personalization, implementation limitations, the significance of health inequities, and implications for public health policy. The review indicates that traditional warning systems, based primarily on meteorological thresholds and population-wide alerts, can reduce mortality and morbidity but often fail to account for individual vulnerability, indoor temperatures, nighttime heat stress, risk perception, or the actual availability of protective measures. Digital solutions, such as home sensors, wearable technologies, predictive models, telephone systems, vulnerability maps, smart cities, and digital twins, can increase the precision of warnings and support protective behaviors. At the same time, their effectiveness depends on acceptability, ease of use, costs, data protection, internet access, and integration with health and social care services. Therefore, hybrid, equitable, and locally adapted systems that combine environmental, clinical, social, and behavioral data with clear response procedures hold the greatest potential.

KEYWORDS

Digital Heat-Health Early Warning Systems, Older Adults, Personalized Climate-Health Technologies, Heat-Related Morbidity and Mortality, Health Equity

CITATION

Maria Woźniak, Zuzanna Zalewska, Julia Szymkowiak, Karolina Reczka. (2026). Digital Heat-Health Early Warning Systems for Older Adults: Clinical Evidence, Health Equity, and Public Policy Implications of Personalized Climate-Health Technologies. *International Journal of Innovative Technologies in Social Science*. 3(51). doi: 10.31435/ijitss.3(51).2026.5828

1. Introduction

Climate change is transforming extreme heat from a periodic environmental threat into a persistent public health problem, requiring not only meteorological but also clinical, social, and technological responses. The literature on heat-health warning systems emphasizes that high temperatures and heat waves increase the risk of deaths, hospitalizations, emergency medical interventions, and exacerbations of chronic diseases. The health effects of heat include both classic heat-related illnesses, such as dehydration, heat exhaustion, and heat stroke, as well as the exacerbation of cardiovascular, respiratory, renal, metabolic, and mental health conditions. Consequently, heat is now analyzed not only as a weather factor but as a complex systemic stressor affecting individuals, households, the healthcare system, and public policy. [2, 7, 11, 12, 13, 14, 15, 20, 23]

Older adults are one of the most important at-risk groups in the context of extreme heat. This is due to physiological deterioration in thermoregulation, reduced sweating capacity and skin blood flow, a higher prevalence of chronic diseases, limited cardiovascular and renal reserve, and the use of medications that may impair heat loss or water-electrolyte balance. However, this risk is not solely biological in nature. The vulnerability of older adults is exacerbated by social and environmental factors, such as living alone, social isolation, low income, energy poverty, poor building insulation, lack of access to air conditioning, limited mobility, and difficulties in accessing health services. For this reason, heat-related risk assessment should combine clinical, environmental, and social data, rather than relying solely on chronological age or outdoor temperature thresholds. [1, 4, 5, 6, 12, 17, 19, 21, 24]

Of particular importance is the fact that a significant portion of older adults' heat exposure occurs indoors. Traditional warning systems typically use meteorological data on outdoor temperature, whereas the actual physiological stress on the body may depend on bedroom temperature, ventilation, building materials, the home's sun exposure, cooling capabilities, and the behaviors of household members. Studies conducted in home settings indicate that elevated nighttime temperatures can disrupt the body's autonomic recovery, increase heart rate, and reduce heart rate variability in older adults. This means that the risk is not limited to the hottest hours of the day; hot nights can prevent physiological recovery and accumulate heat stress, particularly in people with cardiovascular diseases. [1, 5, 6, 20, 21]

Existing heat-health warning systems and heat-health action plans are a key component of public health adaptation to climate change. Available reviews indicate that such systems can reduce mortality, alleviate the burden on emergency medical services, and support protective measures among the population. Examples from various countries also show that warning systems can yield significant economic benefits, especially when the costs of operating the system are compared to the value of avoided deaths, hospitalizations, and medical interventions. At the same time, the effectiveness of these systems varies, as it depends on local climate, demographic structure, the quality of epidemiological data, the alert threshold, communication channels, public trust, and the ability of institutions to respond quickly. [7, 8, 10, 11, 14, 18, 20]

However, classic warning systems have significant limitations. Many of them rely on fixed meteorological thresholds that do not account for local health vulnerability, indoor conditions, the degree of acclimatization, early and late heat waves, or differences among social groups. Research on the seasonality of warning thresholds shows that health risks may be particularly significant outside the traditionally defined midsummer period, when the body and social systems may be less prepared for high temperatures. In turn, analyses of national systems indicate that warnings focused exclusively on meteorological parameters may be poorly correlated with actual health risks. Therefore, there is a growing proposal to transition from general weather alerts to health-risk-based systems covering the entire warm season, with graduated warning levels and epidemiological data. [2, 7, 15, 16, 20, 23]

A second limitation of traditional systems is the insufficient reach of alerts to those most at risk. A study among older residents of Queensland found that less than half of respondents had heard a heat-wave warning, and only a portion of them changed their behavior after receiving such a message. Other qualitative studies show that vulnerable individuals often recognize heat as a potential threat, but at the same time do not relate this risk to themselves, relying on past experiences, or view adaptive measures as ordinary daily activities rather than deliberate health protection. Low risk perception is particularly problematic among older adults, who, despite objectively high vulnerability, may not consider themselves "old," "sick," or in need of protection. [1, 8, 9, 17, 19, 21]

In this context, digital and personalized climate-health technologies are becoming increasingly important. Home temperature sensor systems, wearable devices, machine learning models, automated phone calls, mobile apps, vulnerability maps, smart home systems, urban digital twins, and integrated data platforms can increase the precision of warnings and tailor them to an older adult's actual risk. An example of this approach is an individual digital early warning system tested in the homes of older adults, which demonstrated good usability and improved heat preparedness, although its impact on risk perception and actual protective behaviors requires further evaluation in more robust research projects. In parallel, predictive models of body temperature are being developed, which may in the future support a more dynamic assessment of heat risk at the individual level. [1, 4, 5, 10, 22, 24]

However, the personalization of warnings should not be understood solely as a technical adaptation of the message to temperature or clinical profile. For older adults, it is equally important whether the proposed actions are feasible, affordable, culturally acceptable, and compatible with their daily lifestyle. A recommendation to use air conditioning may be ineffective if the person is concerned about energy costs; a recommendation to go to a cool public place may be unrealistic for someone with limited mobility; and a message in a mobile app may not reach a digitally excluded person. Therefore, digital heat-health early warning systems should be designed as decision-support technologies, not as standalone solutions that replace social services, neighborhood support, primary health care, and local community actions. [3, 4, 8, 17, 19, 21, 24]

The health equity perspective is crucial, as heat exacerbates existing inequalities. Low-income older adults, residents of rural and regional areas, people living alone, people with disabilities, cultural minorities, Indigenous communities, and residents of poorly designed neighborhoods may be both more vulnerable to heat and less able to access protective measures. Research on heat vulnerability indicates that vulnerability maps and indices can support urban planning, resource allocation, and the identification of areas requiring intervention. However, their use requires trust from decision-makers, a consistent methodology, adequate funding, and collaboration among the health, meteorology, urban planning, social services, and emergency management sectors. [3, 8, 13, 17, 19, 21, 23]

Digital heat-wave warning systems are also part of a broader transformation of public health toward systems based on data, prediction, and cross-sectoral collaboration. In the smart city model, data from environmental sensors, 3D maps, geographic information systems, and digital twins can be used to identify micro-risk areas, simulate the effects of urban interventions, and support rapid response. In turn, assistive technologies for older adults, such as smart homes, health monitoring, and alarm systems, can support aging in place, provided they are designed in accordance with user needs, privacy principles, affordability, and ease of use. The combination of these two trends—urban climate resilience and gerontechnology—creates a promising field for innovative yet socially responsible interventions. [5, 6, 22, 24]

The aim of this review article is to provide a synthetic overview of the current evidence regarding digital early warning systems for heat-related effects in older adults, with a particular focus on three interrelated dimensions: clinical, technological, and socio-political. The clinical dimension covers the impact of heat on morbidity, mortality, and physiological indicators of heat stress in older adults. The technological dimension concerns the personalization of alerts, sensors, predictive models, automated notifications, vulnerability maps, and smart city infrastructure. The socio-political dimension encompasses health inequalities, risk perception, barriers to adaptation, costs, acceptability, data protection, and the accountability of public institutions. This approach allows digital heat-health early warning systems to be treated not as a standalone IT tool, but as an element of an integrated public health policy addressing population aging and growing climate risks. [1, 2, 3, 4, 5, 6, 7, 8, 22, 24]

2. Methodology

This article is a focused narrative review with elements of thematic synthesis. This approach was chosen due to the interdisciplinary nature of the topic, which encompasses medicine, public health, digital technologies, gerontology, risk communication, adaptation to climate change, and social policy. Due to the wide variation in the analyzed publications in terms of methods, populations, health indicators, and types of interventions, no meta-analysis was conducted.

The source material included 24 publications on the health effects of heat, heat-health warning systems, personalized warning technologies, the vulnerability of older adults, adaptive behaviors, health inequalities, and implications for public policy. The review included studies that addressed at least one of the following areas: the health effects of high temperatures, warning systems and heat action plans, older adults or other vulnerable groups, digital technologies and sensors, vulnerability maps, predictive models, the economics of warning systems, or public health policy.

The analyzed publications covered various types of studies: observational studies, qualitative studies, randomized controlled trials, systematic and scoping reviews, economic analyses, modeling studies, and articles on public policy. Older publications were used primarily to establish the effectiveness of traditional warning systems and behavioral barriers, while more recent studies were used to discuss personalization, digital technologies, household data, machine learning models, and the integration of warning systems with health policy.

The analysis proceeded in three stages. First, the publications were grouped thematically by major areas: heat-related clinical burden, effectiveness of warning systems, digital technologies and personalization, risk perception and protective behaviors, health inequities, costs and benefits, and public policy. Next, key information was extracted from each study regarding the population, type of intervention or system, data sources, heat exposure indicators, health outcomes, main conclusions, and limitations.

In the final stage, a narrative synthesis of the results was conducted around the three main dimensions of the article: clinical evidence, health equity, and implications for public policy. The clinical dimension included mortality, morbidity, hospitalizations, emergency interventions, indoor temperatures, nighttime heat stress, and physiological indicators. The health equity dimension included energy poverty, social isolation, low risk perception, limited access to cooling, and digital exclusion. The policy dimension addressed warning thresholds, system seasonality, funding, institutional accountability, and intersectoral collaboration.

Due to the diversity of sources, the evidence assessment was descriptive in nature. Particular attention was paid to whether a given publication clearly defined the target population, heat exposure, health outcomes, type of technology or intervention, and implementation context. In the synthesis, greater weight was given to findings that recurred across different types of studies, particularly regarding the importance of individual susceptibility, indoor temperatures, risk perception, cooling costs, technology availability, and the need to integrate meteorological systems with health care and social services.

The main limitation of the adopted methodology is the lack of quantitative aggregation of results and the reliance on available publications, a significant portion of which originate from high-income countries. This limits the ability to directly transfer the findings to all public health systems. Nevertheless, the selected sources allow us to identify the most important trends in the development of digital heat-health early warning systems and to outline the conditions under which they can effectively and equitably protect older adults from the effects of extreme heat.

3. Results

A review of the analyzed publications indicates that digital early warning systems for heat-related health risks in older adults are developing at the intersection of three main areas: traditional heat-health warning systems, individual risk monitoring technologies, and public health policies targeting vulnerable groups. The evidence gathered shows that issuing a weather warning alone is insufficient unless it is linked to actual health risks, local environmental conditions, recipient behaviors, the availability of protective measures, and the structure of social support. The most important finding of this synthesis is therefore the need to transition from "population-based" warning systems to "risk-specific" warning systems that incorporate clinical, environmental, behavioral, and social data. [1, 2, 3, 4, 7, 8, 16, 20]

3.1. Clinical vulnerability of older adults to extreme heat

The analyzed studies unequivocally confirm that older adults are a group particularly vulnerable to the effects of high temperatures. Research and reviews consistently portray aging as a process that reduces thermoregulatory and cardiovascular reserves while simultaneously increasing the prevalence of chronic diseases and the use of medications that may hinder adaptation to heat. Exposure to heat results not only in classic heat-related illnesses but also in increased mortality, hospitalizations, emergency department visits, ambulance calls, and exacerbations of heart, kidney, and respiratory diseases, diabetes, and mental health disorders. Among older adults, this risk is further exacerbated by living alone, low income, limited mobility, poorer housing quality, and difficulties in accessing cooling. [1, 5, 6, 12, 13, 17, 21]

A particularly important finding is that the health risk is not limited to extreme heat waves that meet formal meteorological definitions. Studies on warning systems in China and Canada indicate that hot days with low or moderate risk levels can generate a significant health burden if the system covers the entire warm season and is based on actual epidemiological data. The HHSEW model developed in China demonstrated that an approach based on the full season and graded risk levels identifies a significantly higher number of heat-related deaths than a traditional meteorological system. Similarly, a Canadian model with monthly thresholds shows that systems with a single fixed summer threshold may overlook risks occurring in early spring or fall, when the population is less acclimated. [2, 16, 20]

3.2. Effectiveness and limitations of traditional heat-health warning systems

Traditional heat-health warning systems have demonstrated effectiveness, but their efficacy depends on how they are designed and implemented. Reviews and historical analyses indicate that warning systems can reduce mortality, alleviate the burden on emergency services, and yield significant economic benefits. Examples from France, the United States, Hong Kong, and South Korea suggest that well-organized warnings combined with institutional measures can save lives, especially among older adults and socially vulnerable populations. At the same time, the evidence is less consistent regarding the impact on morbidity, and some studies highlight the difficulty of separating the effect of the warning itself from broader action plans, social changes, infrastructure improvements, and population adaptation. [7, 8, 11, 14, 18]

Findings on costs and benefits indicate that warning systems may be one of the most cost-effective forms of public health adaptation to climate change, although the methodology for valuing health effects remains controversial. Economic analyses show a very wide range of possible benefit-to-cost ratios, depending on whether deaths are counted as the value of a statistical life or as years of life lost. This means that financial decisions regarding heat-health warning systems should be based not only on the simple cost of technical system maintenance, but also on a transparent assessment of avoided mortality, hospitalizations, emergency interventions, and social losses. In practice, the economic argument reinforces the need to fund warning systems, but does not solve the problem of equitable access and effectiveness among the most vulnerable populations. [8, 11, 18]

The greatest limitation of traditional systems is their population-based nature. Many warning systems rely on outdoor temperature, maximum or minimum thresholds, and messages directed at the general public. Such a model may be useful at the administrative level, but it poorly reflects the individual risk of an older adult living in an overheated apartment, taking diuretics, suffering from heart failure, living alone, and avoiding air conditioning due to costs. For this reason, the publications analyzed increasingly call for “smart HHWS” systems that combine meteorological data with health, local, environmental, and social data, and also take into account different target groups. [1, 4, 7, 15, 16, 20]

3.3. Indoor exposure, nighttime heat, and individualized monitoring

An important finding of the synthesis is the growing importance of indoor temperature as a direct risk indicator for older adults. Research on the individual Ethos system and nighttime bedroom temperature shows that home conditions may be more relevant to an older adult’s health than a general message about outdoor temperature. The Ethos system, tested in the homes of people aged 65 and older, demonstrated good usability and improved heat preparedness after the summer season, though it did not result in a significant improvement in risk perception or a marked increase in the use of low-cost cooling methods. However, a study of nighttime temperatures indicated that even higher bedroom temperatures were associated with a greater likelihood of adverse autonomic changes, such as reduced heart rate variability and increased heart rate. [1, 6]

Digital technologies offer the potential for more precise monitoring of heat-related risks, but their effectiveness is not guaranteed. Home sensors, wearable technologies, and smart home systems can provide data on temperature, humidity, activity, sleep, heart rate, and other physiological indicators. Machine learning models can predict skin temperature and core body temperature more accurately than classical biophysical models, suggesting potential for future use in personalized alerts. At the same time, studies emphasize that such models require further validation in real-world settings, across larger and more diverse populations of older adults, and in dynamic home environments, rather than solely in controlled laboratory settings. [5, 24]

3.4. Risk communication and behavioral response among older adults

Evidence on risk communication shows that simply providing information about heat does not guarantee a change in behavior. In a study in Queensland, only a portion of older respondents heard heat wave warnings, and among those who did, not all took protective measures. Individuals who perceived themselves as at risk of heat-related health hazards were more likely to pay attention to warnings and adapt their behavior. This finding is consistent with previous studies and reviews in which perceived risk was one of the key factors determining the response to warning messages. [8, 9, 11, 19]

Automated and targeted communication systems can improve the effectiveness of warnings, particularly when directed at identified at-risk groups. A randomized trial of an automated telephone alert and health advice system found that recipients of the messages were more aware of ways to protect themselves from the heat and were more likely to follow recommended behaviors. Lower use of health services was also observed in some groups. This finding suggests that simple technology, such as a telephone alert system, can be an important complement to more advanced digital solutions, especially for older adults who do not regularly use smartphones or mobile apps. [10, 19, 21]

Older adults' adaptive behaviors are diverse and strongly dependent on available resources. Qualitative studies and reviews indicate that older adults often employ simple protective measures, such as drinking fluids, limiting activity, using fans, covering windows, wearing lighter clothing, changing their daily routine, or staying in cooler parts of the home. However, access to more effective methods, such as air conditioning, is often limited by energy costs, the condition of the home, fear of bills, and a lack of support. For many older adults, adapting to heat is therefore not a matter of knowledge, but of economic, housing, and social opportunities. [17, 19, 21]

3.5. Health equity, vulnerability mapping, and social determinants of heat risk

Health inequities are one of the most important findings of the review. Heat acts as an amplifier of existing inequities, as those most at risk are people who are simultaneously more exposed and less able to respond. This applies to low-income individuals, residents of urban areas with a heat island effect, residents of rural and regional areas, people living alone, people with disabilities, cultural minorities, indigenous communities, and people with limited access to healthcare. In digital systems, this is compounded by the risk of technological exclusion: lack of internet access, lack of digital skills, distrust of technology, sensory and cognitive difficulties, and privacy concerns. [3, 17, 19, 21, 24]

Vulnerability maps and heatwave-health vulnerability indices can support more equitable planning, but their use requires trust and consistent methodology. A qualitative study among professionals involved in heat risk management in Australia found that the HVI is perceived as a useful tool for planning, public information, and designing resilient communities. At the same time, barriers were identified, such as limited resources, low awareness, methodological inconsistencies, and limited trust among decision-makers. This means that vulnerability mapping tools should not be treated solely as technical products, but as part of a political and institutional process requiring interpretation, updating, and cross-sectoral collaboration. [3, 7, 13, 23]

Regional disparities are particularly evident among older adults living outside major cities. A review of older residents in regional and rural Australia found that extreme heat increases mortality and the number of emergency medical interventions, and also impacts social life through event cancellations and people staying home. At the same time, older adults in rural areas often possess practical knowledge about coping with heat, though they do not always perceive it as a health threat. This suggests that warning messages should be designed differently for urban and rural communities, taking into account local culture, service availability, transportation, housing conditions, and social support networks. [21]

3.6. Public policy, intersectoral coordination, and future digital infrastructure

The analyzed publications also indicate that warning systems should be part of broader heat-health action plans, rather than an isolated message. Effective interventions include monitoring weather and health conditions, public education, mobilizing health and social care, support for caregivers, identifying vulnerable individuals, providing cooling centers, home visits, telephone outreach, urban planning measures, and long-term improvements to housing quality. Reviews of community interventions indicate that multi-component action plans are more promising than single information campaigns, as they address both the need for warning and the need for practical assistance in following recommendations. [11, 13, 14, 15]

Findings regarding public policy show that many countries are in the process of transitioning from meteorological temperature alerts to health-based risk assessment systems. Studies on China, Colombia, Canada, France, and Germany highlight the need to integrate meteorological systems with the health sector, establish thresholds based on health data, extend the surveillance season, account for vulnerable groups, and link warnings to response procedures. Institutional accountability is particularly important: the warning system must clearly define who generates the alert, who interprets it, who contacts those at risk, what actions are triggered, and how their effectiveness is assessed after the season. [2, 13, 15, 16, 20, 23]

Smart city technologies and digital twins open up the possibility of further integrating heat-health early warning systems with urban planning. A review of digital twins, 3D modeling, and early warning systems indicates that combining real-time sensor data with city models can support the prediction of the effects of extreme climate events, the identification of risk areas, and communication among stakeholders. In the context of heat, this means the ability to combine information on temperature, building density, green spaces, population density, and the locations of vulnerable individuals. However, this remains an area that is more promising than routinely implemented, requiring further research on practicality, costs, interoperability, and data protection. [22]

From a gerontechnology perspective, the most important condition for success is designing systems with the participation of older adults. A review of technologies supporting the safety and well-being of older adults shows that smart homes, wearable technologies, telecare, and monitoring systems can improve safety, autonomy, and response to threats. At the same time, certain barriers recur: difficulty of use, costs, mismatch with user needs, fear of technology, lack of technical support, and privacy concerns. In the context of digital heat warnings, this means that even the best predictive model will be of little use if the system is difficult to use, too expensive, inaccessible to people with sensory impairments, or lacks caregiver support. [1, 5, 6, 24]

3.7. Integrated model of hybrid, equitable, and personalized warning systems

Ultimately, the findings indicate that the most promising model for protecting older adults from heat is a hybrid system. It should combine population-based weather warnings, local health thresholds, monitoring of indoor conditions, simple communication channels, data on social vulnerability, support from caregivers and institutions, and the ability to personalize recommendations. Such a system should not replace traditional heat-health action plans, but rather enhance their precision and equity. The greatest value of digital technologies should therefore be seen not in the automation of the alert itself, but in better tailoring the warning to the individual, location, time, and realistic capacity for action. [1, 2, 4, 7, 8, 10, 20, 22, 24]

4. Discussion

The results of this review indicate that digital early warning systems for heat-related effects in older adults should be understood not as a simple extension of weather forecasts, but as complex public health interventions based on the integration of meteorological, clinical, household, social, and behavioral data. Traditional heat-health warning systems remain an important foundation for climate change adaptation, as available evidence points to their potential to reduce mortality and, to some extent, morbidity. However, in aging societies, their effectiveness will increasingly depend on the ability to identify the most vulnerable individuals, communicate warnings that are understandable and actionable, and mobilize tangible support, rather than merely issuing high-temperature alerts. [7, 8, 11, 14, 18]

4.1. From meteorological alerts to individualized health-risk assessment

The most important clinical conclusion is the need to shift the focus from the heat wave itself as a meteorological event to the individual heat stress experienced by older adults. In older adults, even a moderately elevated temperature can have serious consequences, particularly when accompanied by cardiovascular, renal, or respiratory diseases, diabetes, polypharmacy, limited mobility, or living alone. Heat thus acts as a decompensating factor that can exacerbate pre-existing health problems before the classic symptoms of heat stroke manifest. This justifies designing warning systems not only around extreme temperature values but also around clinical and functional vulnerability. [1, 5, 6, 12, 21]

Exposure inside the home is of particular importance. For many older adults, the home is the primary place of residence during heat waves, yet it can become an environment where risks accumulate if the building heats up during the day and does not cool down at night. Data on nighttime bedroom temperature and heart rate variability indicate that hot nights can disrupt autonomic recovery and increase the cardiovascular burden. In practice, this means that systems based solely on outdoor temperature may misestimate the risk for a person living in a poorly insulated, overheating home. The integration of home sensors with health alerts is therefore one of the most logical directions for the development of personalized systems. [1, 6, 20]

4.2. Personalization beyond technology: Usability, actionability, and behavioral change

Personalizing warning systems only makes sense if it is linked to action. A study of the Ethos system shows that an individual, home-based warning system can be well-rated in terms of usability and can increase older adults' preparedness for heat. At the same time, the lack of significant improvement in risk perception and limited changes in cooling behaviors indicate that technology alone is not enough. An alert must not only be accurate but also persuasive, understandable, repeatable, and linked to recommendations that are feasible in the user's specific living conditions. [1, 4, 8, 9]

This leads to one of the key tensions in digital heat-health early warning systems: the more technologically advanced the system is, the greater the risk that it will become inaccessible to some of those most in need of protection. Older adults with low incomes, limited digital literacy, sensory disabilities, cognitive impairments, lack of internet access, or low trust in technology may not be able to use mobile apps, wearable devices, or smart home systems. Therefore, digital personalization cannot be equated solely with an app or an algorithm. In many cases, a more equitable solution may be a combination of sensors, automated phone calls, caregiver contact, local social services, and simple text messages. [10, 17, 19, 21, 24]

4.3. Risk perception and communication as determinants of system effectiveness

A key issue is the gap between objective risk and subjective perception of danger. Older adults often do not view themselves as vulnerable to the effects of heat, even when they are medically classified as high-risk. In studies on heat warnings in Queensland, individuals who reported feeling at risk were more likely to notice the warnings and more likely to change their behavior. Similar conclusions emerge from qualitative studies, in which vulnerable individuals were aware of the general risks associated with heat but did not always relate them to their own situation. Effective systems must therefore not only inform people that "it will be hot," but also explain why a particular person or household may be especially at risk. [8, 9, 11, 19, 21]

Risk communication should be more specific and less abstract. General recommendations such as "drink water," "avoid exertion," or "stay in a cool place" are necessary but may be insufficient for people with financial, housing, and social constraints. For an older adult living alone, the message should specify when to call a loved one, when to move to a cooler room, when to contact a doctor, how to safely use a fan, when air conditioning is particularly warranted, and what symptoms should prompt a call for help. Personalization should therefore address both the level of risk and the language of the recommendations, as well as the available courses of action. [10, 14, 17, 19]

4.4. Seasonal thresholds and health-oriented warning models

The review's findings also highlight the need to move away from rigid seasons and fixed warning thresholds. Models featuring a full season of monitoring, graduated risk levels, and monthly variable thresholds better reflect the biological and social dynamics of heat adaptation. Early heat waves can be particularly dangerous because the body and institutions are not yet prepared, while late episodes may occur outside the period of intense administrative vigilance. A fixed summer threshold is therefore a simplification that may not correspond to future climatic conditions. Health-oriented warning systems should take into account the local relationship between temperature and morbidity and mortality, rather than just historical meteorological norms. [2, 15, 16, 20, 23]

At the same time, the development of thresholds based on health data requires better epidemiological surveillance systems. Many existing systems have focused on mortality because it is an indicator that is easier to capture in long time series, but for clinical practice, hospitalizations, emergency department visits, ambulance calls, exacerbations of chronic diseases, sleep disturbances, and indicators of physiological stress. Morbidity indicators can provide earlier warnings than deaths and better reflect the burden on the healthcare system. Incorporating such indicators into digital systems could improve their sensitivity and enable faster preventive action. [6, 7, 12, 14]

4.5. Predictive technologies, machine learning, and smart-city integration

Predictive technologies, including machine learning, may in the future increase the accuracy of individual heat risk assessment. Models predicting the core body temperature and skin temperature of older adults suggest that physiological and environmental data can be used for earlier recognition of increasing heat stress. This potential is particularly important because older adults may not feel the need to take action until their body's stress level is already high. However, the practical application of such models requires caution: demographically diverse data, validation outside the laboratory, clear action thresholds, minimization of false alarms, and transparent rules regarding responsibility for recommendations generated by the system are needed. [4, 5, 24]

Smart city solutions and digital twins can expand the scale of personalization from the individual level to the building, neighborhood, and city levels. Combining data from environmental sensors, 3D models, information on green spaces, building structure, population density, and the location of health services could help identify micro-areas of particular risk. In the context of older adults, such systems could support route planning to cool public spaces, the location of assistance points, the prioritization of phone check-ins, and the assessment of the impact of urban planning interventions. Currently, however, digital twins remain a more promising area of development than a widely implemented public health tool. [3, 13, 22]

4.6. Health equity and the risk of widening digital divides

Health equity should be a design principle, not an afterthought to the system. The greatest benefit from digital alerts will be achieved when systems are deliberately targeted at people who have high exposure, high vulnerability, and low adaptive capacity. Vulnerability indices and maps can help with this, but their effectiveness depends on data quality, decision-makers' trust, and the ability to translate the map into concrete actions. Simply identifying "hot" or "vulnerable" areas will not reduce risk unless it is linked to funding, housing interventions, social services, transportation, home care, and local communication. [3, 8, 17, 19, 21]

The problem of energy poverty highlights the limitations of recommendations based solely on individual responsibility. Air conditioning is an effective way to reduce exposure, but for many older adults, its use involves energy costs, fear of bills, or a lack of the device. Under such conditions, a message recommending cooling may be perceived as unrealistic or even psychologically burdensome. Public health policy should therefore combine warnings with energy subsidy programs, improvements in residential energy efficiency, the creation of accessible cooling spaces, transportation support, and welfare checks for people living alone. [17, 19, 21]

It is worth emphasizing that older adults should not be portrayed solely as passive recipients of protection. Research on adaptation shows that many older adults possess practical knowledge, coping strategies, and local experience that can enrich the design of systems. Especially in rural communities, older residents often employ simple, cost-effective adaptive behaviors, though they do not always interpret them in terms of health risks. Involving older adults, caregivers, local organizations, and indigenous communities in system design can improve the acceptability, language of messages, and feasibility of recommendations. [17, 19, 21, 24]

4.7. Public health governance and intersectoral implementation

From a public policy perspective, the most promising model is a hybrid system in which population-based weather warnings are integrated with health, social, and individual components. Such a system could operate at multiple levels: at the national level by setting standards and thresholds, at the regional level by adapting them to local epidemiology, at the city level by identifying risk areas, and at the household level by providing personalized recommendations. It is crucial that each level of the system has defined procedures: who issues the alert, who contacts older adults, who monitors the effects, who funds the actions, and who is responsible for post-season evaluation. [2, 7, 13, 15, 16, 20, 23]

Implementing such systems requires collaboration among sectors that often operate separately: meteorology, public health, primary health care, emergency medical services, social services, urban planning, housing, energy, and digital technologies. A lack of coordination can lead to a situation where an alert is issued but does not trigger any effective response pathway. The role of primary care and community care is particularly important, as these services can identify older adults with chronic conditions, those who are living alone, have limited mobility, or face difficult housing conditions. A digital alert system should therefore strengthen existing care relationships rather than operate outside of them. [3, 10, 13, 14, 21]

4.8. Ethical, legal, and data-protection challenges

Ethical and legal issues will become increasingly important. A personalized system can process data on health status, home temperature, behavior, location, sleep, and activity. Such data can improve safety, but at the same time poses risks of privacy violations, stigmatization, surveillance, or unequal treatment. Older adults must be clearly informed about what data is collected, who has access to it, how long it is stored, and whether they can opt out without losing support. The principle of data minimization, algorithm transparency, and the possibility of human intervention should form the basis for implementing such solutions. [22, 24]

Assessing effectiveness is also a significant challenge. Many alert systems are evaluated indirectly, by comparing mortality rates before and after implementation or by analyzing self-reported behaviors. In the case of personalized digital systems, more precise indicators will be needed: the number of people effectively reached by the alert, the time from warning to action, changes in indoor temperature, behavioral changes, the number of caregiver interventions, reduction in hospitalizations, impact on loneliness, acceptability, and costs to the user and the system. Without such an evaluation, there is a risk of investing in technologies that are innovative but poorly documented in terms of health benefits. [1, 7, 8, 10, 18, 24]

4.9. Alert fatigue and implementation in a warming climate

The discussion on warning systems should also consider the risk of alert fatigue. As the climate warms, warnings will be issued more frequently, for longer periods, and likely outside the traditional summer season. If messages are too frequent, lack variety, or are unrelated to practical assistance, recipients may stop responding to them. Grading risk levels, personalizing content, and locally adjusting thresholds can mitigate this problem, but require careful design. The goal is not the maximum number of alerts, but the right alert at the right time, for the right person, and with the right course of action. [2, 8, 15, 20]

A limitation of the current evidence base is the predominance of studies from high-income countries and selected geographic regions. Systems developed in Australia, Canada, Europe, China, or the United States cannot be automatically transferred to countries with different infrastructure, different living patterns, limited access to healthcare, or limited digital resources. The example of Colombia shows that in many countries, the key step is still the creation of public policy and a cross-sectoral framework for action. Global implementation of digital heat-health early warning systems therefore requires flexible models that can be adapted to local capabilities, rather than a single universal technological solution. [7, 13, 20, 22, 23]

In summary, digital early warning systems for heat-related effects can significantly improve the protection of older adults, but only if they are designed as clinically sound, socially accessible, and institutionally embedded systems. The greatest weakness of traditional systems is their generality, while the greatest risk of digital systems is unequal access. Future development should therefore combine the advantages of both approaches: the scale of population-wide alerts, the precision of household and physiological data, the simplicity of communication, support for caregivers, and public policies targeted at the most vulnerable individuals. [1, 2, 4, 7, 10, 17, 20, 21, 24]

5. Conclusion

5.1. Synthesis of key findings

Extreme heat is a growing health threat to aging populations, and older adults require special protection due to the coexistence of physiological vulnerability, chronic diseases, polypharmacy, functional limitations, and social factors such as loneliness, low income, energy poverty, and poor housing conditions. The available evidence indicates that the effects of heat are not limited to classic heatstroke but encompass a wide spectrum of consequences: increased mortality, hospitalizations, emergency calls, exacerbations of cardiovascular, renal, respiratory, metabolic, and mental illnesses, as well as disturbances in sleep and the body’s autonomic recovery. Therefore, protecting older adults from heat should be treated as a priority in environmental medicine, geriatrics, and public health. [1, 5, 6, 12, 13, 21]

5.2. Need for health-oriented warning systems

Traditional heat-health warning systems are a necessary and proven tool for adapting to climate change; however, their population-based nature limits their ability to protect the most vulnerable individuals. Systems based solely on outdoor temperature, fixed thresholds, and general messages may overlook the actual risks faced by older adults living in overheated homes, experiencing hot nights, suffering from chronic illnesses, or unable to follow recommendations due to financial and social constraints. Therefore, future warning systems should transition from simple weather alerts to tiered, season-wide, and health-oriented risk assessment models. [2, 7, 15, 16, 20, 23]

5.3. Role of digital and personalized technologies

Digital and personalized climate-health technologies can significantly enhance the effectiveness of warnings by integrating data on weather, indoor conditions, the local environment, physiological status, social vulnerability, and user behavior. Home sensors, wearable technologies, predictive models, automated phone calls, vulnerability maps, smart home systems, and digital twins of cities create the possibility of more precise risk identification and faster activation of protective measures. However, their greatest value lies not in individual devices, but as part of an integrated public health system that translates data into clear, actionable, and locally tailored recommendations. [1, 4, 5, 10, 22, 24]

5.4. Health equity as a condition of effectiveness

The success of such systems depends on their equitable design. Digital technologies can reduce health inequities, but they can also exacerbate them if they are primarily accessible to people with higher incomes, better housing, internet access, digital literacy, and family support. Therefore, alert systems for older adults must take into account energy costs, access to air conditioning, housing quality, social isolation, disability, limited mobility, differences between urban and rural areas, and the need for simple communication channels. Personalization should encompass not only the risk assessment algorithm but also the method of communication, available forms of assistance, and the user's actual capacity to act. [3, 8, 17, 19, 21, 24]

5.5. Public health and policy recommendations

The most promising approach is a hybrid model, combining population-based weather warnings with individual and local health and social support. Such a system should include health-based warning thresholds, monitoring of indoor temperatures, identification of high-risk individuals, simple and multi-channel messages, and the involvement of primary care, caregivers, social services, local governments, and emergency services. It should also clearly define institutional responsibilities: who issues the alert, who contacts older adults, what actions are initiated, how interventions are funded, and how the system's effectiveness is evaluated after the heat wave season. [7, 10, 13, 14, 18, 20]

5.6. Future research directions

Further research should focus on assessing the actual effectiveness of digital heat-health early warning systems in home and community settings, rather than solely on their technical feasibility. Research is needed that includes diverse populations of older adults, longer observation periods, clinical and behavioral indicators, indoor temperature data, user costs, and the impact on health inequalities. It is particularly important to determine whether these systems actually reduce hospitalizations, emergency calls, cardiovascular burden, loneliness, and mortality, as well as whether they are accepted by older adults, caregivers, and healthcare professionals. [1, 5, 6, 8, 10, 24]

5.7. Final summary

In summary, digital early warning systems for heat-related effects in older adults have significant clinical, technological, and social potential, but their effectiveness depends on integration with public health policy. The best chance for protecting health lies in an approach that combines data precision, simple communication, local action, funding for home adaptations, social support, and ethical data management. In the face of an aging population and intensifying heat waves, such systems should become not merely an add-on to weather forecasts, but an integral part of the basic infrastructure for health protection and societal resilience to climate change. [1, 2, 3, 4, 7, 17, 20, 22, 24]

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All authors have read and agreed to the published version of the manuscript.
No conflicts of interest to declare.
Statement on the Use of AI-Assisted Technologies: The authors employed ChatGPT during the drafting of this work solely to refine linguistic expression and improve clarity. All AI-generated suggestions were carefully reviewed and edited by the authors, who take complete accountability for the final content and scientific integrity of the article.

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