SUNTEXT REVIEWS

SunText Review of Medical & Clinical Research
ISSN: 2766-4813

Open Access
Research Article
Volume 6:4

Allogeneic Hematopoietic Stem Cell Transplantation in the Era of Climate Change: Risks, Challenges, and Adaptive Strategies

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Received date: 18 November 2025; **Accepted date:** 24 November 2025; **Published date:** 30 November 2025

Citation: Stamati E (2025) Allogeneic Hematopoietic Stem Cell Transplantation in the Era of Climate Change: Risks, Challenges, and Adaptive Strategies. SunText Rev Med Clin Res 6(4): 239.

DOI: https://doi.org/10.51737/2766-4813.2025.139

Abstract

Background: Allogeneic hematopoietic stem cell transplantation (allo-HSCT) is a potentially curative procedure for malignant and non-malignant hematological disorders. Despite advances, allo-HSCT remains associated with high morbidity and mortality due to infections, graft-versus-host disease (GVHD), and organ toxicities. The accelerating climate crisis introduces novel challenges, particularly for immunosuppressed recipients.

Objective: This review examines allo-HSCT in the context of climate change, highlighting risks, outcomes, and adaptation strategies

Methods: Literature from PubMed, Scopus, and Web of Science (1980-2024) was reviewed, integrating data on transplantation, infectious complications, and environmental health.

Results: Climate-related stressors, including heat waves, poor air quality, fungal proliferation, and natural disasters, exacerbate vulnerabilities in HSCT patients. Geographic variation suggests disproportionate risks in warmer, polluted regions. Healthcare disruption during climate events poses further threats to continuity of care.

Conclusion: Integrating climate resilience into transplantation medicine is essential. Mitigation includes improved infection surveillance, resilient infrastructure, and disaster planning.

Keywords: Allogeneic HSCT; Climate change; Immunosuppression; Infections; GVHD; Resilience; Environmental health

Introduction

Allogeneic hematopoietic stem cell transplantation (allo-HSCT) is a cornerstone of hematology and oncology. It is indicated for acute leukemias, chronic myeloid leukemia, lymphomas, myelodysplastic syndromes, aplastic anemia, and congenital immunodeficiencies [1-4]. The first successful human allo-HSCT was reported in 1968 [5], and since then advances in HLA typing, conditioning regimens, and donor availability have improved outcomes [6,7]. Nevertheless, allo-HSCT is associated with major risks: graft-versus-host disease (GVHD), infectious complications, and organ toxicities [8,9]. Long-term survival is further compromised by chronic GVHD and late effects such as secondary malignancies [10]. At the same time, the climate crisis is reshaping global health. Rising temperatures, worsening air quality, shifting infectious disease patterns, and an increased frequency of extreme weather events represent new threats [11,12]. These risks are magnified in immunocompromised populations, including allo-HSCT recipients. Despite these

concerns, the intersection of transplantation and climate change remains underexplored.

Indications of Allo-HSCT

Allo-HSCT is indicated for both malignant and non-malignant hematological disorders. Malignant indications include acute myeloid leukemia, acute lymphoblastic leukemia, chronic myeloid leukemia, lymphomas, and myelodysplastic syndromes [2,3]. Non- malignant indications include severe aplastic anemia, thalassemia, sickle cell disease, and congenital immunodeficiencies [4]. The introduction of high-resolution HLA typing and haploidentical transplantation has expanded donor availability, improving access to allo- HSCT worldwide [6].

Conditioning Regimens and Donor Selection

Conditioning regimens prepare the recipient for donor engraftment. Myeloablative conditioning is associated with higher toxicity but stronger disease eradication. Reduced- intensity conditioning offers lower toxicity and is often used in older or comorbid patients [7]. Donor selection remains a key determinant of outcome. Matched sibling donors are ideal, but unrelated, cord blood, and haploidentical donors are increasingly utilized [6].

Complications

Complications after allo-HSCT are multifactorial:

- Infectious complications: Bacterial sepsis, viral reactivations (CMV, EBV), and invasive
- fungal infections (Aspergillus, Candida) are leading causes of non-relapse mortality [8,9].
- GVHD: Acute GVHD occurs in 30–50% of recipients, while chronic GVHD remains a major determinant of long-term morbidity [12].
- Organ toxicities: Hepatic veno-occlusive disease, pulmonary fibrosis, and cardiotoxicity are frequent [13].
- Late effects: Infertility, secondary cancers, and metabolic syndromes compromise long- term quality of life [14].

Long-Term Outcomes

Outcomes after allo-HSCT depend on disease status at transplant, age, donor compatibility, conditioning regimen, and post-transplant complications. Overall survival rates range from 40–70% depending on indication [6,8]. Non-relapse mortality remains significant due to infections and GVHD. Chronic GVHD contributes to impaired quality of life and long-term disability [10].

Climate Change and HSCT

The climate crisis introduces novel risks for allo-HSCT recipients:

- Heatwaves: Extreme heat exacerbates cardiopulmonary complications, alters drug pharmacokinetics, and increases mortality [15].
- Air Pollution: Exposure to PM2.5, ozone, and wildfire smoke worsens pulmonary complications in immunocompromised hosts [16].
- Fungal Infections: Warm, humid conditions favor proliferation of Aspergillus spores, raising infection risk [17].
- Natural Disasters: Floods, wildfires, and hurricanes disrupt hospital operations, supply chains, and access to care [18,20].
- Psychosocial Stress: Displacement, economic instability, and stress impair adherence to therapy and recovery [19].

Discussion

Allo-HSCT recipients are highly vulnerable to both medical and environmental risks. Climate change exacerbates traditional complications through increased infectious exposure, organ stress from heat, and impaired healthcare access. Mitigation strategies include:

- Enhanced infection surveillance with region-specific prophylaxis.
- Hospital infrastructure resilient to heat and air pollution (filtration, cooling).
- Disaster preparedness planning to secure continuity of care.
- Research integrating environmental data into transplant outcomes [16,17].

International collaboration is essential to establish guidelines and protect transplant populations in the era of climate crisis.

Conclusions

Allo-HSCT is a life-saving intervention, but success is challenged by both medical complications and external environmental pressures. The climate crisis represents an emerging determinant of outcomes in this fragile population. Integrating climate resilience into clinical practice, research, and policy is necessary to safeguard allo-HSCT recipients. Future work should quantify risks and guide adaptation strategies for sustainable transplantation care.

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