ENVIRONMENTALISM IN HEALTHCARE

Caring for Tomorrow Ecologically

edited by **Jacqueline A. Stagner | David S.-K. Ting**

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Dedication

To everyone who cares for other souls.

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Preface

Environmentalism in Healthcare: Caring for Tomorrow Ecologically draws together international experts from the fields of healthcare, engineering, architecture, sociology, policy, and others to disclose the latest insights into forging viable means to care for an aging society ecologically. It focuses on the challenges and areas where remedies can be most feasibly implemented to mitigate the current shortfalls. Some adjustments in the way we currently operate can substantially furnish a healthier tomorrow.

Ayoub, **Ceesay**, **Daglilar,** and **Tahan** confront the challenges of an aging society and sustainable healthcare head-on in the opening chapter, "Sustainability in Healthcare and Its Future Impact on the Aging Generation." Their comprehensive chapter addresses an aging population and within this backdrop, the coupled human–environment interactions. Green initiatives mean well, but they must also be cost- and implementation-effective. For example, to fully realize the potential of green chemistry, environmentally friendly materials must also be easily recyclable for reuse. Circular systems that extend from cradle to grave to cradle to cradle pave the path forward.

Beauty is much more than skin deep. In Chapter 2, "Environment- and Microbiome-Friendly Skincare Products," **Kaur**, **Noorbakhsh**, **Arzani Birgani**, and **Sidhu** enlighten us with the dynamic ecosystem of microorganisms of the skin microbiome. With increasing environmental stressors, healthy skin is an indispensable shield that also safeguards a viable immune system. They propose bettering tomorrow's health via a holistic approach of integrating cutting-edge science with environmental consciousness. Shifting towards eco-friendly natural alternatives can further skin and related health while simultaneously lowering environmental damage.

Our tendency to fall and injure ourselves tends to increase as we age. It follows that fall-related health is a growing issue with an aging population. **Ebrahimi**, **Ting**, and **Carriveau** propose

strategies to mitigate this in Chapter 3, "Mitigating Falls among the Aging Population." Our healthcare system is confronted with one in three adults over 65 years old falling at least once a year. Studies have shown that this can be drastically reduced with the help of technologies such as wearable sensors, real-time monitoring, and artificial intelligence. To further the multi-pronged remedy, the built environment also needs to be revamped into an age-friendly one. Above all, exercise programs and community involvement are essential. It is thus clear that collaborative efforts between healthcare providers, policymakers, and technology developers are pivotal for healthier aging.

On the topic of digital healthcare, Chapter 4 is "Healthcare Digital Twin: Transformative Perspectives in Socio-Technical Systems." **Mohanty**, **Vaishali**, and **Alla** delve into the transformative potential of digital twin (DT) technology in healthcare. DT aims at bridging physical systems and virtual models to enable real-time monitoring, simulation, and predictive analytics. Fragmented health records, dynamic governance structures, cultural and linguistic diversity, and the emotional sensitivity inherent to medical data are added challenges in the successful application of DT as compared to its application in an industrial setting. Interdisciplinary collaboration that is built on an inclusive, adaptive, and ethically sound platform is the healthy way forward.

At the intersection of healthcare, environmental sustainability, and non-communicable diseases, an appropriate balance is sought. **Aylı** presents "Towards Sustainable Care: Green Solutions for Managing Chronic Conditions" as Chapter 5. Details, including how healthcare practices affect the environment and how pollution and climate change contribute to the increase in non-communicable diseases, are elucidated. The trajectory is characterized by high resource consumption and serious waste production, which fuel the very diseases we aim to treat. The author calls for a paradigm shift toward a multi-disciplinary remedy that invokes green hospital programs, sustainable pharmaceutical solutions, and ecologically friendly therapeutic approaches.

In terms of its carbon footprint, healthcare is a serious culprit, and hence, "Eco-friendly Practices: Reducing Healthcare's Carbon Footprint" is the topic of Chapter 6. In this chapter, **Qadrie**,

Ashraf, **Maqbool**, and **Dar** advocate the integration of renewable energy sources such as solar and wind within healthcare facilities. They further recommend replacing conventional systems such as lighting and heating, ventilation and air conditioning (HVAC) with the latest green options such as LED and smart HVAC systems. It would be remiss not to attend to healthcare waste. It's time to practice "do no harm."

With HVAC consuming a substantial portion of the total energy usage, Chapter 7 is devoted to hospital HVAC, "Recent Advances in Energy-Saving Technologies for Hospital Heating, Ventilation, and Air Conditioning Systems." **Wang**, **Carriveau**, and **Ting** remind us that ensuring optimal indoor air quality, temperature, and humidity is essential for patient comfort, health, and safety; it is worth pointing out that Florence Nightingale was the statistician, nurse, and pioneer on this front. Integrating renewable energy sources such as solar power, geothermal energy, wind, and biomass into HVAC systems is a given. To fully capitalize on efficiency, minimize waste, and improve system adaptability to meet varying operational demands, advanced energy management strategies involving machine learning and artificial intelligence are necessary.

Human behavior plays a critical role in the implementation and operation of promising solutions. In Chapter 8, "The Effect of Social Capital on Eco-Friendly Behavior," **Abbasi**, **Sheykhi**, **Shokati Amghani**, and **Savari** make known social capital as a valuable resource to mitigate environmentally harmful actions. Social capital accounts for the role of social factors in environmental psychology. The benign idea is to enhance residents' sense of belonging and trust within their communities so that good stewardship comes naturally. They expound on the key dimensions of social capital that affect pro-environmental behaviors. Imagine widespread embracement of social capital, healthier psychology, healthier environments, and healthier health, drastically reducing the tax on the healthcare system.

This volume ends with a chapter on urban water quality by **Sharma**, **Dehalwar**, and **Pandey**, "Measures to Manage the Urban Water Quality for Public Health." The recent surge in urbanization stresses the importance of life-sustaining potable water. To protect public health, measures must be taken to ensure a safe and high-

quality water supply, including that for healthcare facilities. Community engagement and public awareness campaigns are needed to foster responsible water use, pollution prevention, and adoption of sustainable practices. Much can be learned from the presented case studies from urban areas in Delhi.

This volume reveals our healthcare status. There are as many promising solutions as the number of challenges. Together, we can realize Caring for Tomorrow Ecologically. Environmentalism in Healthcare is the very essence of a healthy tomorrow.

David S.-K. Ting and Jacqueline A. Stagner
Turbulence & Energy Laboratory
University of Windsor

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This book would not have been realized without the assiduous experts who compiled the chapters and the anonymous reviewers who uplifted the quality. The editors truly enjoy working with the amazing publishing team, who invoke simplicity to ease our striving and boost our efficiency. Providence alone transformed this dream into a reality.

Chapter 1

Sustainability in Healthcare and Its Future Impact on the Aging Generation

Mark E. Ayoub, Muhammed Murtada Ceesay, Ebubekir S. Daglilar, and Veysel Tahan

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1.1 Introduction

Healthcare is a vital part of our society. As we continue to confront the challenges of an aging society, sustainable healthcare will be key to maintaining a high standard of care for older generations without compromising the ability of future generations to thrive. Green chemistry has proven to be an essential framework for achieving sustainability in the chemical industry and beyond. In this chapter, we review the process of aging and its implications, the deep and profound interaction between humans and environment and the direct effect on the aging population, the costs of healthcare administration and the impact of their consequent pollution on the environment, the importance of green initiatives

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and available options, and avenues for future initiatives with their modes of application and cost.

1.1.1 Sustainability in Healthcare and Its Future Impact on the Aging Generation

This chapter explores the relationship between aging, environmental factors, and healthcare sustainability (Fig. 1.1). It highlights the complexities of aging, distinguishing between normal aging and changes driven by disease. Research from the Baltimore Longitudinal Study of Aging (BLSA) reveals common age-related changes, stressing that aging is influenced by both programmed genetic alterations and random cellular damage. These processes affect different age groups in varying ways, with older populations being particularly vulnerable to environmental toxins and stressors. The challenges of separating the effects of aging from environmental influences complicate efforts to understand how these factors impact life expectancy and disease.

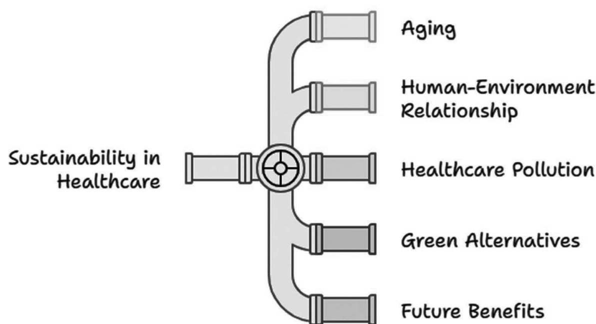

Figure 1.1 Chapter outline. ⏎

The chapter also addresses the environmental burden of healthcare, especially highlighted during the COVID-19 pandemic, due to the surge in single-use medical supplies such as personal protective equipment (PPE). As the healthcare sector contributes significantly to global pollution, the text advocates for adopting sustainable alternatives, such as biodegradable materials and

energy-efficient processes. By moving toward greener practices, healthcare institutions can reduce their environmental impact while maintaining high standards of patient care, ultimately contributing to a more sustainable future.

1.2 Aging

What is aging? The BLSA aims to understand "normal aging" by separating age-related changes from those caused by disease or other factors. This research has revealed common changes that nearly everyone experiences as they age. By studying aging and disease together, scientists have identified links between various health conditions and the aging process. Overall, discoveries from the BLSA have reshaped our understanding of aging and laid the groundwork for future research on disease prevention and healthy aging. With continued participation from study participants, the BLSA aims to address questions about disease resistance and healthy aging, potentially leading to innovative approaches for extending health span and lifespan [1].

Within the older population, heterogeneity is notable, with characteristics varying notably across different age groups. Thus, analyses often segment the older population into specific age brackets, such as 55–64 years, 65–74 years, 75–84 years, and 85 years and older. The effects of aging on health, social dynamics, and economic aspects are typically more pronounced in these older age groups, warranting closer scrutiny in demographic studies. Moreover, shifts in life expectancy, reductions in mortality rates, and changes in the proportion surviving to various ages provide tangible indicators of the evolving demographic landscape, reflecting advancements in public health and healthcare interventions [2].

Theories of aging can be broadly categorized into deterministic and stochastic mechanisms. Deterministic theories propose programmed alterations in gene expression or structure, while stochastic theories suggest random alterations in macromolecules, cells, and organ systems [3]. However, the line between these categories can blur, as stochastic alterations in individual cells

may lead to predictable outcomes in larger cell populations. For instance, terminal differentiation, where populations of cells cease dividing after differentiation, can be seen as both stochastic and deterministic [3].

Programmed aging is observed in species with single massive episodes of reproduction, while placental mammals experience various stochastic processes due to their extended reproductive phases. The relative contributions of these mechanisms may vary based on the organism's reproductive strategy. Several theories of aging have been proposed, including deterministic theories such as developmental switches in gene expression and neuroendocrine-cascade theories, and stochastic theories like intrinsic mutagenesis and protein-synthesis error catastrophe. These theories have implications for understanding the impact of environmental agents on aging processes [4].

Deterministic theories like the neuroendocrine-cascade hypothesis of aging suggest that age-related changes in hormone regulation may contribute to various age-associated problems. Stochastic theories propose mechanisms such as intrinsic mutagenesis, protein-synthesis error catastrophe, and free radical damage, which can lead to the accumulation of cellular damage over time. Thymic involution, a hallmark of immunosenescence, is an early and significant precursor of aging in humans and other mammals, suggesting potential targets for environmental modulation. Understanding these theories provides insights into how environmental agents may influence aging processes and age-related diseases (Fig. 1.2) [5].

1. **Deterministic:** Developmental Switches in Gene Expression, Neuroendocrine-Cascade Theories.
2. **Stochastic:** Intrinsic Mutagenesis Theory, Protein-Synthesis Error Catastrophe, Free Radicals, Posttranslational Glycation of Proteins and DNA, Thymic Involution as a Pacemaker of Immunosenescence.

Being one of the most populous countries in the world, with approximately 320 million inhabitants, the United States of America has experienced steady population growth over the past decade, indicating improvements in living conditions and

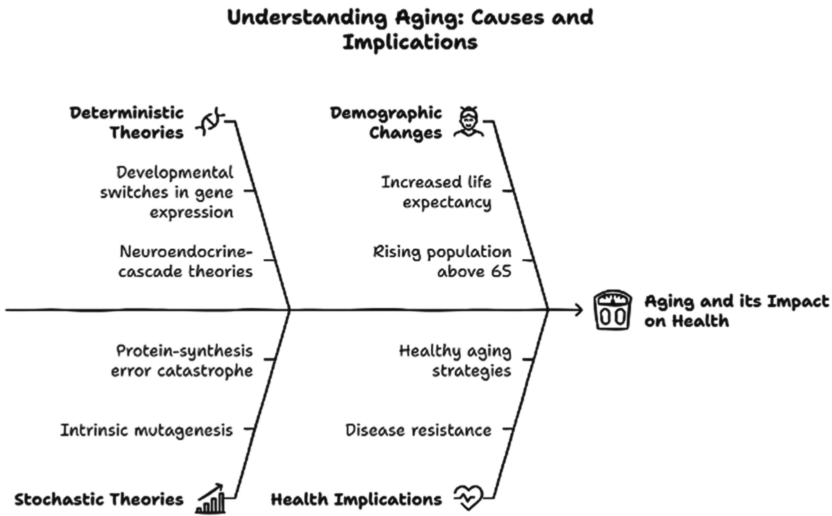

Figure 1.2 Schematic review of the aging process using the Deterministic and Stochastic theories with consideration of population demographic changes and the overall health implications. ⏎

healthcare. Such advancement has led to a steady increase in life expectancy at birth in the United States. This is evident in the age distribution of the United States. In 2012, 13.58% of the population was above 65 years of age, and in 2022, 17.13% of the population was above 65 years of age [6]. Figure 1.3 shows a comparison between the population of the U.S. in the years 2000, 2010, and 2020, and the increase in the number of people above 65 years of age over time using the U.S. Census Bureau [7].

The inquiry into whether environmental factors are shortening both lifespan and life expectancy, or if we are nearing natural limits in both realms, precipitates a profound exploration of aging processes and environmental influences. A discourse ensues, contemplating the potential redirection of research away from the intricate mechanisms of aging towards attenuating the impact of environmental toxins on longevity. The argument is that by targeting age-associated diseases caused by environmental factors not inherently linked to aging, we could potentially improve the quality of life in old age.

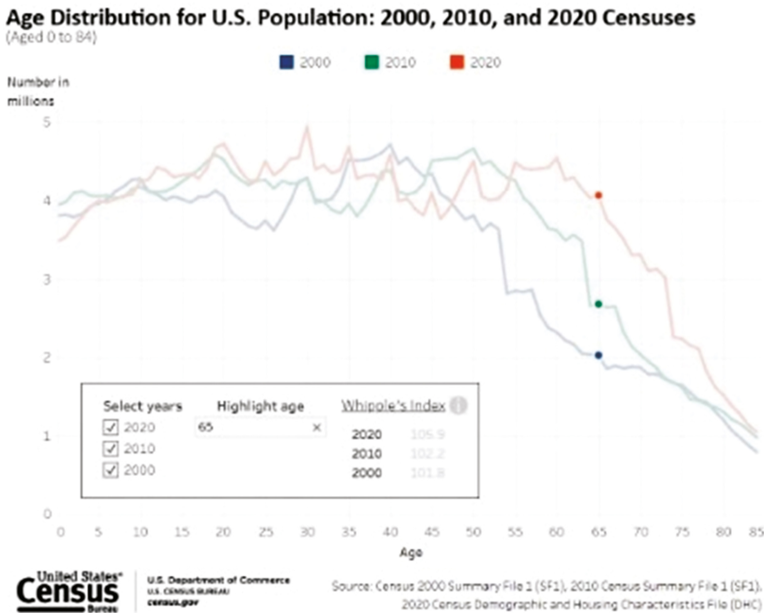

Figure 1.3 Graph comparing trend of U.S. population with age 65+ in years 2000, 2010, and 2020. ⏎

Yet, the understanding of precisely how environmental agents modulate aging processes remains enigmatic, primarily due to the scarcity of comprehensive research in this domain. It is conjectured that exposures to environmental factors during pivotal developmental stages could imprint upon age-related phenomena later in life. For instance, the exposure to certain agents during fetal development or early childhood may predispose individuals to age-related neurodegenerative conditions, such as Parkinson's disease. Moreover, elderly individuals may exhibit heightened susceptibility to environmental toxins owing to age-related alterations in cellular function and diminished physiological resilience [8].

Classic studies indicate a gradual decline in the functional capacity of physiological systems with age, affecting responses to environmental stresses. Whereas young adults are shielded by their homeostatic reserves, older individuals may exhibit attenuated adaptive responses, rendering them more vulnerable

to environmental challenges. This heightened vulnerability is reflected in elevated mortality rates among the elderly in response to environmental stressors that may not prove fatal in younger cohorts [9].

Distinguishing between age-related changes and those induced by environmental exposures presents a scientific challenge, exacerbated by the intertwining of aging and chronic environmental exposure. Laboratory inquiries into aging within controlled settings possess limited generalizability to real-world contexts, where aging unfolds amidst multifaceted environmental dynamics. Moreover, the pursuit of biomarkers that are exclusively indicative of aging or toxicity has yielded only partial success, reflecting the incomplete understanding of the underlying mechanisms [10].

These challenges extend to epidemiological and demographic studies of human aging, where disentangling the contributions of intrinsic aging and environmental factors remains a difficult task. Consequently, it is challenging to predict the impact of environmental exposures on life expectancy and disease prevalence in old age. Addressing these complexities requires interdisciplinary collaboration and a comprehensive approach to studying aging and environmental influences [11].

As individuals age, they exhibit greater variation in biological responses compared to younger individuals. This variation can impact their vulnerability to the effects of toxic substances, with physiological aging playing a role but not fully explaining the susceptibility. Elderly populations are more vulnerable to environmental insults due to increased incidence of disease and age-related changes in physiological functions. Figure 1.4 illustrates how changes in skin anatomy, immune function, and drug metabolism affect the elderly negatively.

Studies have shown that older individuals respond differently to drugs and environmental agents compared to younger individuals, often experiencing more adverse reactions. Diseases and chronic conditions are common among the elderly, further complicating their susceptibility to environmental factors. Physiological changes associated with aging, such as alterations in drug metabolism and immune function, can influence their response to toxic agents [12].

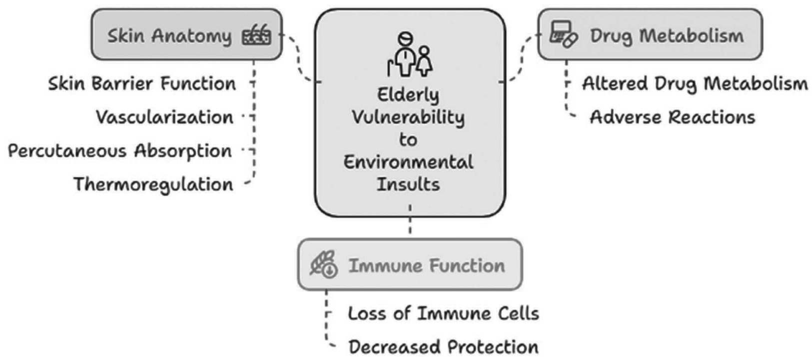

Figure 1.4 Physiological changes associated with negative outcomes in the elderly.

Changes in the immune system, nervous system, and skin anatomy and function occur with age, affecting susceptibility to environmental insults. For example, age-related changes in skin barrier function and vascularization can increase percutaneous absorption of chemicals and impair thermoregulation. Loss of immune cells and melanocytes in the skin may decrease protection against radiation and foreign antigens. Additionally, age-related decreases in sensory perception, including pain perception, make the elderly more vulnerable to environmental injuries [5].

1.3 Human-Environment Relationship

Toxicology involves the examination of how harmful effects are exerted by environmental agents, along with empirically determining their toxicity and risk to human populations. This field heavily depends on comparing experimental findings with extensive databases gathered from standardized testing protocols applied to various chemicals and types of radiation [13].

To comprehend how environmental agents might worsen aging processes, it is necessary to consider the mechanisms of aging in relation to known toxic substances. Identifying screening tests that assess interactions between environmental agents and aging processes or increased risks to elderly individuals is crucial. Additionally, assessing these agents in whole-animal systems

that reflect human responses and utilizing existing databases are essential steps [14].

Aging exhibits similarities to toxic processes, as age-related changes often resemble those induced by toxic substances. Studying aging as a toxic process is justified by its link to age-related diseases and its consistent presence during experiments. Although many environmental agents can induce aging-like changes at high doses, such mimicry tends to be partial and specific to certain tissues [14].

The significance of neurotoxicology and immunotoxicology cannot be overstated, as many environmental agents have yet to be tested for their effects on the nervous and immune systems, which are particularly vulnerable in the elderly. Challenges in understanding the relationship between the environment and aging include the unknown mechanisms of aging and the absence of comparative data for validating tests [14]. To understand the roots of the challenges of studying toxicology in the aging population, we depicted the following graph (Fig. 1.5).

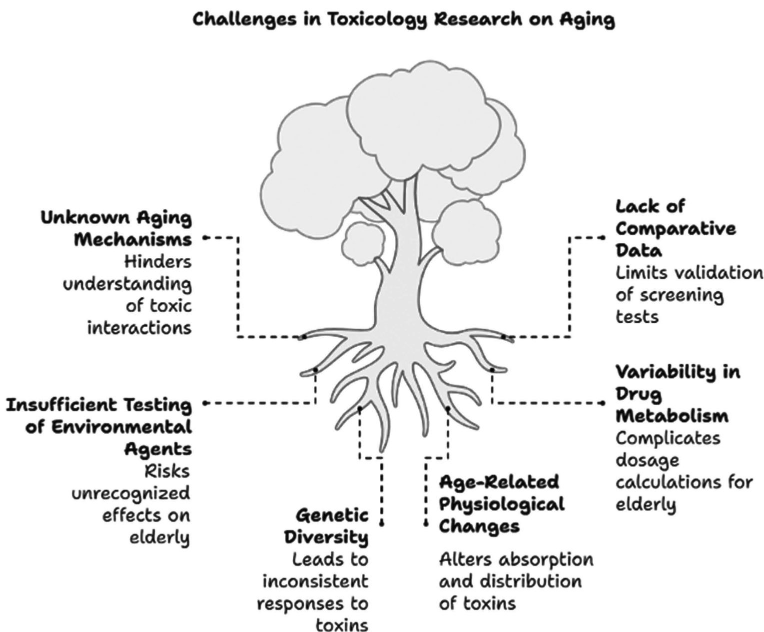

Figure 1.5 An overview of the major challenges facing toxicology research in the aging population. ⏎

To overcome these challenges, it is crucial to identify agents that interact with aging processes, sensitize individuals to other agents, or pose increased risks to the elderly. Furthermore, assessing the effects of acute or subacute exposures at various life stages and predicting how old animals respond to environmental agents are important considerations in toxicological research related to aging [15].

Chemicals can enter the body via inhalation, ingestion, or skin contact, potentially exerting local or systemic effects. While the liver primarily metabolizes toxic substances, other organs like the kidneys, lungs, and gastrointestinal tract also contribute. Most toxicants are eliminated through urine or bile, with some volatile ones expelled through exhaled air [16].

Research on how aging affects the body's handling of chemicals has mainly focused on drugs rather than environmental toxins. However, insights from drug studies are relevant to toxicology, as many toxic substances undergo similar metabolic pathways. Age-related changes in carcinogen metabolism are complex and not fully understood, with limited and conflicting data available [17].

Alterations in pharmacokinetics, such as absorption, distribution, metabolism, and elimination, can influence drug responses, particularly in the elderly, who often exhibit increased sensitivity to certain medications due to changes in these processes. Absorption mainly occurs through the skin, lungs, and gastrointestinal tract, with age-related changes like reduced gastrointestinal motility potentially affecting absorption rates [15, 18, 19].

The distribution of toxicants throughout the body depends on factors like body composition and binding to plasma proteins. Age-related changes, such as decreased lean body mass and alterations in protein binding, can affect the volume of distribution. Metabolism and elimination processes can also be impacted by age, with some evidence indicating reduced hepatic enzyme activity in older individuals [20].

Renal function commonly declines with age, affecting the elimination of drugs excreted through the kidneys. While there is variability in the extent of renal decline among individuals, adjustments in drug doses are often necessary in elderly patients to prevent toxicity [20].

Variations in drug elimination rates are also observed among fetuses, neonates, children, and adults, underscoring the importance of considering age-related pharmacokinetic differences in drug dosage calculations and treatment strategies. Additionally, the genetic diversity within the human population leads to varying responses to environmental chemicals, even among individuals with similar exposures [21–25].

The process of absorption plays a crucial role in transporting toxic substances across body membranes, primarily occurring through the skin, lungs, and gastrointestinal tract. Skin, being a significant absorption site, can be affected by injuries or other factors, altering its permeability. Similarly, toxicants can enter the bloodstream through the lungs, especially when inhaled as gases or aerosols. The gastrointestinal tract also serves as a route for absorption, influenced by factors like gastrointestinal motility and the properties of the toxicant [26–30].

Physiological changes associated with aging, such as increased gastric pH and reduced gastrointestinal motility, can affect absorption from the gastrointestinal tract in older individuals. However, while some studies suggest a delay in the time to peak plasma concentration after oral drug administration in the elderly, the extent of absorption generally remains unchanged compared to younger subjects [31, 32].

Once absorbed into the bloodstream, toxicants are distributed throughout the body. The distribution depends on factors like cell membrane permeability and affinity for body components. Age-related changes, such as alterations in body composition and plasma protein binding, can affect the volume of distribution and thus the concentration of toxicants in the blood [20].

Metabolism and elimination processes transform and remove toxicants from the body. Metabolism can alter the chemical nature of toxicants, facilitating their elimination. Aging can affect hepatic drug metabolism, but the evidence is indirect and varies depending on the drug and individual factors. Renal function declines with age, impacting the elimination of drugs excreted by the kidneys [28, 33, 34]. Differences in drug metabolism and elimination exist across various age groups, emphasizing the need for tailored dosages and further research into pharmacokinetic processes in

different populations [35–37]. The interplay of environmental chemicals and aging underscores the complexity of human responses to toxic exposures, which are influenced by genetic variability and individual characteristics (Fig. 1.6) [20].

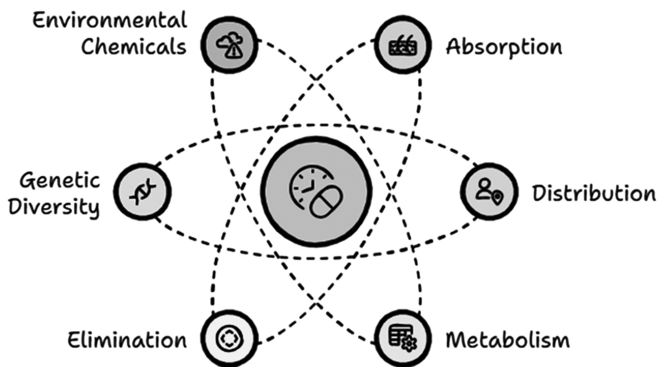

Figure 1.6 Interplay of different factors influencing pharmacokinetics in the aging population. ⏎

The mechanisms through which toxic substances exert their effects are highly varied and can differ between specific agents and even at different doses of the same agent. These mechanisms are often characterized by the dose required to induce the toxic effect and the specificity of that effect. This characterization is particularly relevant when considering aging, as the decline in physiological functions associated with age affects various tissues without specificity to particular cells or tissues, although the precise mechanism of aging remains unknown [38].

At the molecular level, toxic agents can cause damage by creating harmful chemical species that target specific components of biological molecules. The search for toxic mechanisms common to both aging and specific agents should include those with broad actions, given that aging affects all tissues broadly. Additionally, identifying agents that affect specific aspects of the aging phenotype would allow for a more detailed understanding of the underlying mechanisms.

Damage can occur in specific molecules, leading to a wide range of toxic effects. For instance, damage to DNA can have pleiotropic effects (Fig. 1.7). Some agents induce general toxic effects by producing damaging species, such as free radicals, which can interact with various biomolecules. Different tissues can be susceptible to toxicity at different exposure levels. For example, ionizing radiation can induce different toxic effects at varying doses, illustrating the importance of dose-dependent responses [39].

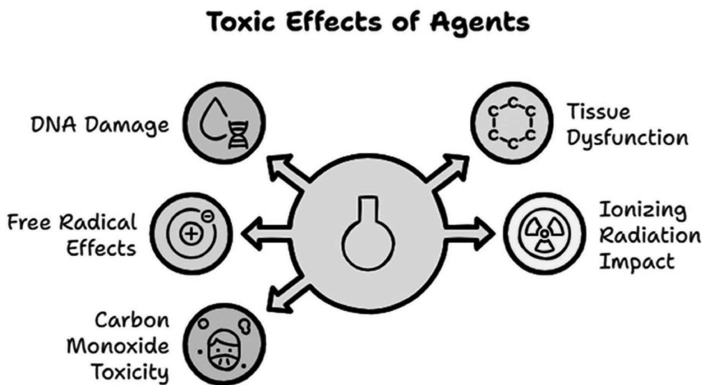

Figure 1.7 Overview of how various agents exert their toxic effects. ⏎

Toxic agents may exhibit both specific and nonspecific actions. For instance, carbon monoxide binds to hemoglobin, reducing its oxygen-carrying capacity and causing toxicity. Some agents produce nonspecific toxic effects that can affect multiple tissues, although the specific response may vary depending on exposure dose [40].

Cellular mechanisms of toxicity can lead to tissue-level effects. Toxic agents may cause tissue dysfunction by altering the function of enough cells in a specific tissue. Alternatively, toxic stress on individual cells can result in various toxic effects, including cancer, heritable mutation, and teratogenesis. Aging is characterized by alterations in most cells across various tissues, suggesting a similarity to the cellular effects of toxic agents [41].

While aging research has aimed to identify the molecular changes underlying cellular aging, establishing a definitive molecular etiology has proven challenging. Therefore, comparisons at the

cellular and tissue levels between toxic agents and aging may provide valuable insights [42].

Toxic effects at the tissue level are commonly observed in intact animals, often due to toxic stress at the site of exposure or metabolic action, or in susceptible target cells. Understanding the toxic mechanisms at the tissue level requires consideration of their cellular and molecular etiology [42].

The study of individual differences in response to drugs, influenced by environmental, age-related, and genetic factors, is termed pharmacogenetics [43]. This field is particularly significant in toxicology as it elucidates how genetic variations can predispose individuals to toxic effects from xenobiotics [30]. Genetic differences in drug metabolism pathways and enzyme activities can affect susceptibility to tissue damage caused by reactive metabolites [44].

The expression of genetic factors and their impact on drug toxicity may manifest differently depending on age, with certain conditions being expressed only later in life [24]. With drugs being more commonly prescribed to older individuals, the incidence of pharmacogenetically related toxicity may increase with age [45]. Age-related effects on gene frequencies in pharmacogenetic conditions have been observed, such as with the acetylation polymorphism [46].

Pharmacogenetic conditions, characterized by aberrant enzymatic conversion of drugs, often result in toxic responses due to drug accumulation [43]. For example, slow acetylators, resulting from gene mutations, may exhibit increased susceptibility to adverse drug reactions [47]. Geographic variations in gene frequencies of pharmacogenetic conditions further complicate the understanding of their effects [48].

Environmental factors, such as smoking and diet, can interact with genetic factors to influence drug disposition [49]. The total interindividual variation in drug elimination among heterogeneous populations is attributed to both genetic and environmental factors [50]. This complexity underscores the challenge of identifying specific factors contributing to variations in drug response [45].

Understanding the dynamic interactions between genetic, environmental, and developmental factors is crucial for comprehensively studying drug response [45]. This interdisciplinary

approach helps elucidate the mechanisms underlying inter-individual variations in drug metabolism and toxicity, ultimately informing personalized medicine strategies.

1.4 Healthcare Pollution

It is well established in our scientific community that global warming is an imminent threat to our society. The United Nations recently surveyed 50 Nobel laureates, and more than one-third cited "population rise/environmental degradation" as the biggest threat to mankind, followed by nuclear war [51]. Climate-related hazards include extreme weather events, sea level rise, an increase in air pollution, an increase in water- and vector-borne illnesses, just to name a few. According to World Health Organization (WHO) research, 37% of heat-related deaths are attributed to human-induced climate change, and heat-related deaths in those over 65 years of age have risen by 70% in the last two decades. Additionally, WHO projects an increase in yearly deaths due to climate change impacts on diseases like malaria and coastal flooding by 250,000 [51]. Climate change has a direct implication for our healthcare system.

The COVID-19 pandemic has shed light on many aspects of our healthcare system, specifically, it has brought attention to the healthcare waste sector. The increased use of PPE (i.e., gloves, masks, surgical gowns, face shields) during the pandemic was astronomical. During the early stages of the COVID-19 pandemic, the WHO estimated a global demand of 89 million medical masks, 76 million examination gloves, and 1.6 million goggles per month, which were used by healthcare professionals [52]. This raises a question: How is medical waste disposed of and managed?

Healthcare waste is generated by hospitals, laboratories, nursing homes, and research centers and can be broken down into non-hazardous (80–85%) and hazardous waste (15–20%) [53]. Hazardous materials include needles and syringes, body parts, blood, soiled dressings, pharmaceuticals, toxic chemicals, and PPE. Infectious waste must be disposed of and managed carefully to prevent harm and further spread of disease. The concern

about how healthcare waste is managed arose in the 1980s after medical waste was found washing up on coastal beaches. This prompted Congress to enact the Medical Waste Tracking Act (MWTA) of 1988. The regulations of this short two-year program expired after the EPA concluded that the disease-causing potential of medical waste is the greatest at the point of generation and naturally tapers off after that point [54]. After the MWTA expired in 1991, states took on the role of regulating medical waste based on the data collected during that program. Many states have since further developed their programs regulating waste disposal [54].

Healthcare waste contains highly toxic metals, chemicals, pathogenic viruses, and bacteria that have the potential to cause disease and contaminate the environment (Fig. 1.8). Therefore, healthcare waste must be treated before disposal to ensure public safety. Current treatment methods of healthcare waste treatment and disposal include thermal processes (i.e., incineration, autoclaving), chemical processes, irradiation processes, and others, which include recycling, reusing, and sanitary landfilling [55]. The incineration process appears to be the most preferred method of treating waste, given its success in reducing waste quantities and in eliminating microorganisms [56, 57]. Incinerators have been shown to create organic pollutants such as dioxins [58]. Dioxins are also called persistent organic pollutants because they take a very long time to break down once they are in the environment. These are highly toxic and carcinogenic pollutants, and the EPA estimates 90% of human exposure comes from animal fats [59]. One study showed that cows grazing near incinerators had a higher concentration of dioxins than those grazing further away from incinerators [60]. This supports the idea that incinerators can lead to bioaccumulation from the pollutants they produce.

In the U.S., the annual growth in health services spending is now higher than before the COVID-19 pandemic, as shown in Fig. 1.9 [61].

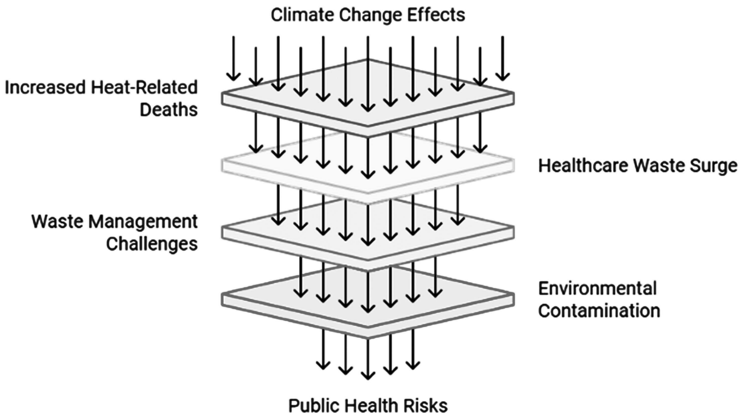

Figure 1.8 Cumulative impact of modern healthcare waste and climate change on public health.

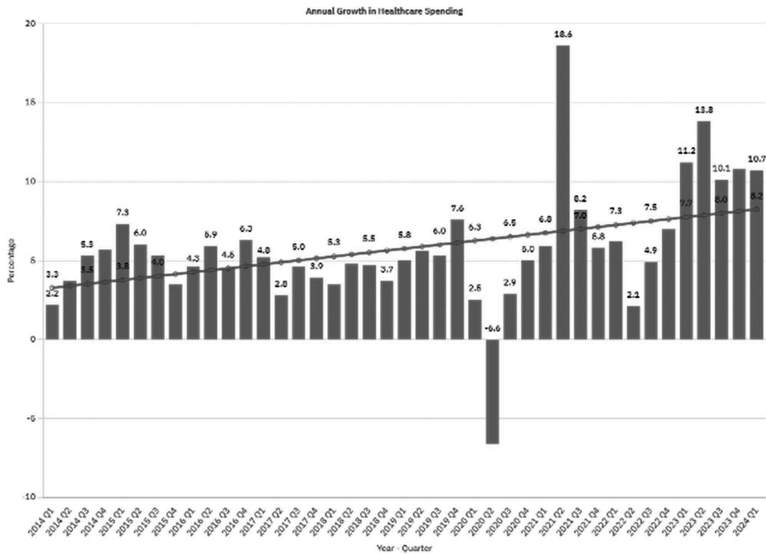

Figure 1.9 Trend of annual spending in healthcare services from 2014 to 2024 using data from the U.S. Census Bureau. ⏎

The economic impact of healthcare delivery extends far beyond medical expenses, touching every aspect of patients' and caregivers' lives. Understanding this economic burden is essential to raising awareness of the public health crisis posed by expenditure, informing policy proposals, and ultimately improving the lives of affected individuals and their families. This knowledge encompasses not only out-of-pocket costs but also the ripple effects on labor market participation and productivity, which influence how policymakers and the public allocate resources. It also equips healthcare providers to uncover and address hidden costs and barriers to care [62].

Medical waste encompasses any waste generated through healthcare activities, such as treatment, diagnosis, immunization, and research. If not handled and disposed of properly, it can pose significant risks to public health and the environment. Proper management of medical waste ensures the safety of patients, healthcare workers, and the surrounding community, maintaining hygienic conditions within healthcare facilities. The disposal of medical waste is not merely about adhering to regulatory requirements—it carries substantial financial implications. Inefficient or improper waste management can result in increased operational costs, legal penalties, and reputational damage. By gaining insights into the costs associated with medical waste disposal, healthcare facilities can implement cost-effective and compliant strategies to manage this crucial aspect of their operations.

Medical waste is classified into several categories based on its characteristics and risks (Fig. 1.10):

1. **Infectious Waste:** It includes materials that can transmit infectious diseases, such as contaminated blood or laboratory cultures.
2. **Sharps Waste:** This includes items like needles, syringes, and scalpels that can cause injuries and spread infections.
3. **Hazardous Waste:** It covers materials with toxic properties, including certain chemicals, pharmaceuticals, and devices.

4. **Pharmaceutical Waste:** This includes expired or unused medications that require careful disposal to prevent misuse or environmental harm.

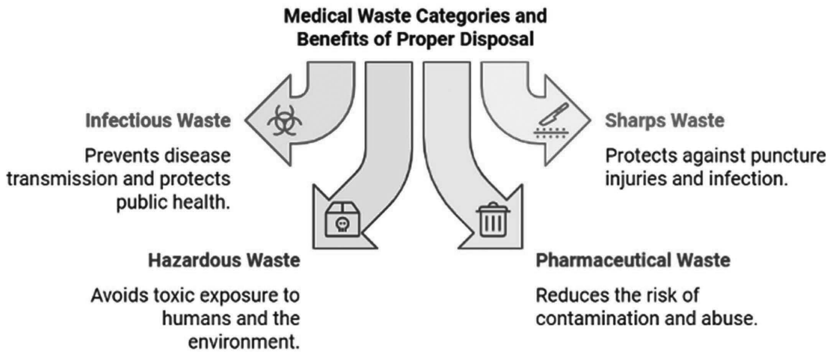

Figure 1.10 Different categories of medical waste as described by the WHO and the outcomes of their proper disposal. ⏎

Each category of medical waste demands compliance with specific regulatory requirements to minimize risks:

1. **Infectious Waste:** Prevents disease transmission.
2. **Sharps Waste:** Protects against puncture injuries and infection.
3. **Hazardous Waste:** Avoids toxic exposure to humans and the environment.
4. **Pharmaceutical Waste:** Reduces the risk of contamination and abuse.

According to the WHO, about 85% of waste generated by healthcare activities is general, non-hazardous waste comparable to domestic waste [63]. The remaining 15% is considered hazardous material that may be infectious, chemical, or radioactive [63]. In contrast, in 2023, only 25% of health facilities had basic healthcare waste management services [64]. Such contrast between production and proper disposal underscores the importance of adhering to the previously mentioned guidelines, which ensure safe disposal practices while preventing financial repercussions to ensure a greener environment.

1.5 Green Alternatives

As environmental degradation intensifies, the healthcare sector is increasingly recognized for its significant role in contributing to global pollution. Human health is intricately connected to the health of our planet, and it is becoming clearer that our efforts to improve health can inadvertently exacerbate environmental issues. The healthcare sector, which includes hospitals, public health systems, and pharmaceutical companies, is responsible for approximately 4.4% of global greenhouse gas (GHG) emissions, with hospitals alone being among the most energy-intensive facilities [65, 66]. In countries like the U.S., healthcare contributes up to 8.5% of total emissions, highlighting the urgent need for a shift toward greener practices [67].

The production and disposal of single-use medical equipment, coupled with energy consumption in healthcare facilities, significantly impact the environment. The COVID-19 pandemic further underscored this issue, generating vast quantities of waste from PPE and other disposable medical supplies. The disposal of these items, often through incineration, adds to the pollution burden, releasing harmful chemicals into the atmosphere if not managed properly [68, 69].

Moreover, the healthcare sector's reliance on fossil fuels for energy use in cooling, heating, and powering facilities compounds its contribution to environmental degradation (Fig. 1.11) [70]. Given the healthcare industry's mission to improve and safeguard human health, it must take a more active role in addressing climate change. From reducing emissions through energy-efficient systems to adopting biodegradable materials and promoting sustainable practices across supply chains, the sector has a unique opportunity—and responsibility—to lead in the fight against climate change. Embracing these green alternatives is not only essential for the environment but also vital for ensuring long-term health and well-being [71, 72]. According to the U.S. Energy Information Administration (EIA), the Commercial Buildings Energy Consumption Survey (CBECS) revealed that inpatient healthcare buildings were the third most energy-intensive buildings in 2018, despite a downward trend from 2012 (Fig. 1.12) [73].

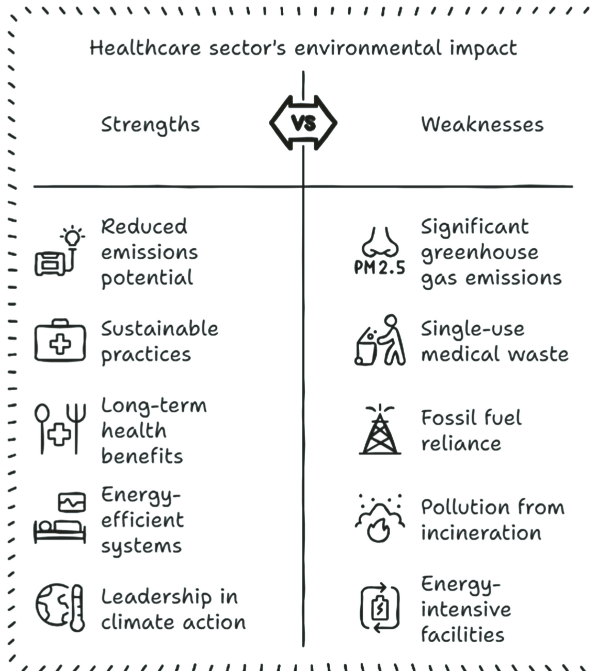

Figure 1.11 Strengths and weakness of modern healthcare impact on the environment. ⏎

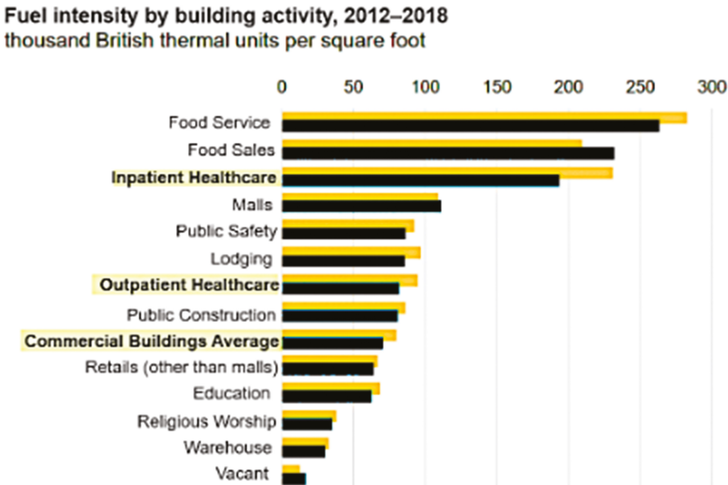

Figure 1.12 Fuel intensity level by building activity showing the consumption of healthcare in comparison to average buildings in 2012 (Yellow) and 2018 (Black) using data from the CBECS by the U.S. EIA. ⏎

1.5.1 Importance of Green Alternatives in Healthcare

Pollution is a major contributor to morbidity and mortality, accounting for an estimated 9 million premature deaths globally in 2015, or 16% of all deaths. Most of these environmentally mediated deaths are linked to air pollution, with many experts identifying climate change as the most pressing public health issue of the 21st century [74]. Disruptions in food production, water supplies, and coastal areas are expected unless substantial action is taken to reduce GHG emissions [75]. Ironically, healthcare systems significantly contribute to pollution that negatively impacts human health. In fact, healthcare in the U.S. [76], Australia [77], England [78, 79], and Canada [80] emits around 748 million metric tons of carbon dioxide equivalents annually. If these healthcare systems were considered a nation, they would rank seventh globally in terms of GHG emissions [81].

Ensuring quality in healthcare includes preventing harm to patients, improving efficiency, and eliminating unnecessary care. To reduce healthcare-related pollution, addressing overuse of resources and optimizing the sector's environmental footprint could lead to better population health. Environmental sustainability, although often overlooked, is an essential component of healthcare quality.

The healthcare industry's reliance on traditional instruments, particularly disposable plastics and energy-intensive devices, has a significant environmental footprint. The use of single-use items like syringes, gloves, and PPE, especially during the COVID-19 pandemic, contributed to massive amounts of waste, including an estimated 87,000 tons of PPE waste in 20 months [69, 76]. Additionally, the sector's energy use for sterilization, heating, cooling, and equipment operation further exacerbates GHG emissions. For example, hospitals account for around 60% of the healthcare sector's total energy consumption [67]. These practices increase emissions and contribute to resource depletion, ultimately harming public health.

The shift toward green alternatives in healthcare is crucial to reduce the sector's environmental damage. By adopting biodegradable medical tools, energy-efficient sterilization methods,