

Garlic Peel–Derived Bioactives in Redox Homeostasis: Physiological Mechanisms and Therapeutic Implications

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Abstract

These bioactive compounds, such as phenolic, flavonoids, and organosulfur, present in garlic peels have a joint action in providing support to the immune system, metabolic system, neurological system, and cardiovascular system. Although the data so far presented have just been sourced from experimental studies, the information from the molecules discussed in the current review should prompt more research conducted on and involving only the human species. These bioactive compounds in garlic peels could be effective for balancing the redox homeostasis, hence useful for both treatment and prevention in terms of an applied physiological issue. We discuss how these phytochemicals chemically influence antioxidant defense systems, including their action on redox-sensitive signaling pathways, the activation of intrinsic antioxidant enzymes, and the control of reactive oxygen species. The biological activities of bioactive agents in garlic peel preparations on metabolic disease states, neurological processes, inflammatory disease states, and cardiovascular disease states are currently under investigation. The present review aims to reveal to readers the medicinal potential of garlic peel as a functional physiological resource via experimentally collected data from *in vitro*, *in vivo* research, and expected extrapolative research. A richer awareness of this agent's sites of action may prove useful in designing innovative 'redox-directed' therapies to prevent and promote health states.

Keywords

Garlic peel bioactives; Redox homeostasis; Oxidative stress; Antioxidant signaling pathways; Inflammatory modulation; Applied physiology

1. Introduction

A crucial element of normal cellular and systemic homeostasis is the maintenance of a healthy level of redox balance, which governs energy metabolism,

signal transference, immune response, and tissue pliability. Previously known as the byproducts of metabolism that can cause cellular damage, reactive oxygen species are recognized as critical players in the signal transduction processes. A continuous

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imbalance in the level of reactive oxidative species can lead to oxidative stress, which can result in the onset of many diseases, including metabolic, neurological, cardiovascular, and inflammatory diseases[1].

Therefore, endogenous antioxidant defense systems such as enzymatic activities involving the actions of glutathione peroxidase, catalase, and superoxide dismutase are vital in the regulation of the redox status of the cell. After the exhaustion of the defense mechanisms of the cell, bioactive compounds from the exterior of the cell are of significant importance in the regulation of redox status if they are able to interrupt redox signal pathways. Consequently, the utility of phytochemicals from plants in the regulation of the redox status of the cell as well as the regulation of the functions of ROS in signal pathways has received significant interest[2].

While garlic (*Allium sativum*) has been recognized as a herb with health and medicinal properties for centuries, the possible health benefits of garlic peel have only recently been discovered. Garlic peel is rich in several types of bioactive compounds, such as phenolics, flavonoids, and organosulfur compounds, exhibiting redox-modulating and anti-inflammatory activities. Rather than being mere direct antioxidants, such compounds also modulate redox-sensitive signaling pathways to help preserve both cellular and systemic homeostasis[3].

This assessment attempts to extensively collect the information available on the mechanisms of action of the bioactive compounds found in the extracts from garlic peels in the context of providing a better understanding of the physiology of the human body in the context of the roles played by the most important organ systems in the human body. The goal of this article is to highlight the significance of bioactive compounds found in the peels of the garlic plant in the context of the redox mechanisms in the human body in its varied applications in physiology[4].

2. Redox Homeostasis in Physiological Systems

2.1 Cellular Redox Balance and Reactive Oxygen Species

The balanced equilibrium between the generation of reactive oxygen species and their elimination through antioxidant reactions is termed redox homeostasis. For example, reactive oxygen species, which include superoxide anion, hydrogen peroxide, and hydroxyl radicals, are continually produced as a consequence of enzymatic reactions during the course of physiological

reactions. Low or moderate concentrations of ROS act as a secondary message, impacting immunological reactions, vasodilation, cell growth, as well as differentiation, as opposed to their damaging role[5].

Reactive oxygen species such as ROS have been proposed to affect redox-sensitive proteins, kinases, as well as transcription factors, mediated as physiological redox signaling, which operates in a *in loco et tempore* kind of regulation; thus, when this redox status homeostasis goes out of balance, as a result of increased ROS formation as well as a depletion in antioxidant defenses, oxidative stress occurs, which, in turn, leads to lipid peroxidation, protein oxidation, DNA damage, as well as modifications in cellular signaling[6].

2.2 Endogenous Antioxidant Defense Mechanisms

To avoid peroxidative damage, a cell is provided with a group of antioxidants. Enzymatic antioxidants, for example, superoxide dismutase, catalase, and glutathione peroxidase, appear to play a major role in avoiding oxidative damage through scavenging and dismutation of peroxides and other dangerous free radicals. These enzymes have joined forces to enhance the balance between oxidation reactions in the cell and avoid damage from oxidative responses[7].

Antioxidant systems play a critical role in the regulation of redox signals. These antioxidant systems are important since they regulate redox signals. These antioxidant systems, unlike detoxification agents, play a critical role in the regulation of the amount of reactive oxygen species present. In the human body, antioxidant production is regulated through the regulation of gene expression. This regulation of antioxidants works as a feedback mechanism in the human body. It ensures the right responses from the human body during physical challenges. When the process goes wrong, the strength and balance of the cells, as well as tissues, will be affected[8].

2.3 Redox Regulation at the Tissue and Systemic Level

Adjustment of the homeostasis in the processes of redox can influence tissue functions, hence the physiology of the whole organism. For the cardiovascular system in particular, the functions of the organism that depend on the processes of redox signaling comprise vascular remodeling, the availability of NO, and the functioning of endothelial cells. For the nervous system in particular, excessive effects of reactive oxygen species can cause degeneration if the processes of the homeostasis of the

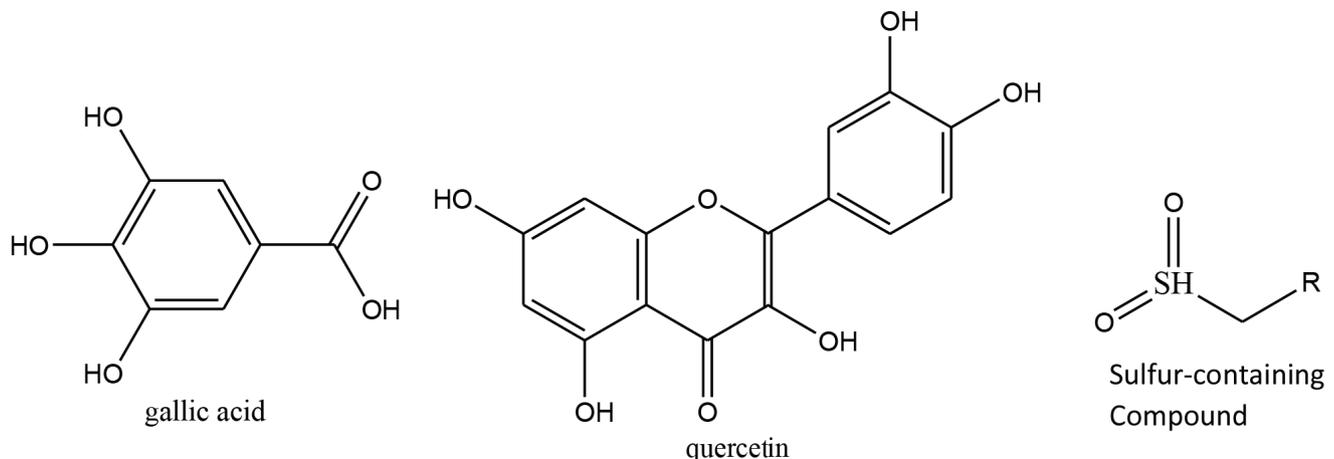


Figure 1: Representative chemical structures of selected garlic peel bioactives.

processes of the redox are not well coordinated in the processes of the signaling pathway[9].

The relationship between oxidative stress and immune system, metabolic, and proinflammatory challenges underscores the importance that these regulators have over managing these events. They have a crucial role to play in balancing these activities referred to as redox activity. This activity can either be controlled and fine-tuned with great precision or adjusted, with some compounds having the aim to eliminate ROS[10].

3. Bioactive Constituents of Garlic Peel

These various bioactive molecules in garlic peel may potentially have a huge impact on oxidative signals and redox balance. Such a characteristic could improve the health benefit of the plant. In fact, garlic peels contain residual organosulfur compounds from garlic, and phenolic and flavonoid compounds at much higher levels than garlic. Their chemical characteristics are significant in their ability to influence redox-sensitive cell signaling and maintain equilibrium[11].

3.1 Phenolic Compounds and Flavonoids

The major bioactive compounds in garlic peel are flavonoids and phenolic acids. Due to their potent redox-modulating properties, these compounds may help lower a reactive oxygen species overload, thus supporting physiological redox signaling. In biological systems, the literature shows that phenolics inhibit the process of lipid peroxidation, safeguard the integrity of cellular membranes, and preserve mitochondrial function under conditions of oxidative stress[12].

Flavonoids influence signaling processes in the course of the cell by influencing kinase and

transcriptional responses related to oxidative pressure. They also possess direct antioxidant activity. Phenolic compounds in garlic peels support all of these functions and assist in enhancing proper cell activity and functionality and resilience to oxidative pressure by boosting desired adaptation rather than random scavenging[13].

3.2 Organosulfur Compounds and Redox-Active Metabolites

The organosulfur compounds present in the garlic peel are significant as they have a potent reaction with the target cells that react sensitively to the reduction-oxidation content, even at lower levels than those found in the garlic cloves. These organosulfur compounds are significant to the intracellular mechanisms of the reduction-oxidation buffering systems that respond to the glutathione and the enzyme activity by interacting with the thiol groups that are present in the protein. Other significant properties are the control of the levels of the nitric oxide and the inflammation[14].

3.3 Bioavailability and Physiological Relevance

Their physiological functionality due to garlic peel bioactives is very much dependent on their absorption, metabolism, and biodistribution. The metabolic processing of phenolic and flavonoid compounds into metabolites occurs in the body after ingestion. These may shield their redox-modulating and signaling functionality. The metabolites produced could serve as interactors with the body's defense systems, which may provide sustained antioxidant responses. Cell and animal studies reveal the potential of garlic peel bioactives to achieve high levels in target tissues, although comprehensive studies have not been many

Table 1: Major garlic peel–derived bioactives and their redox-related physiological relevance

Bioactive class	Representative compounds	Primary redox-related action	Physiological relevance
Phenolic acids	Gallic acid, ferulic acid	ROS neutralization, metal chelation	Protection against lipid peroxidation, cellular redox balance[16]
Flavonoids	Quercetin derivatives	Mitochondrial stabilization, redox signaling modulation	Endothelial protection, metabolic regulation[17]
Organosulfur compounds	Sulfur-containing metabolites	Thiol interaction, glutathione regulation	Vascular tone regulation, immune redox control[18]
Mixed polyphenols	Peel extract fractions	Antioxidant enzyme induction	Systemic oxidative stress reduction[19]

in humans. Their maintenance of redox balance via influence on inflammatory pathways establishes a potential role in the regulation of diseases associated with redox balance[15].

4. Mechanisms of Redox Modulation by Garlic Peel Bioactives

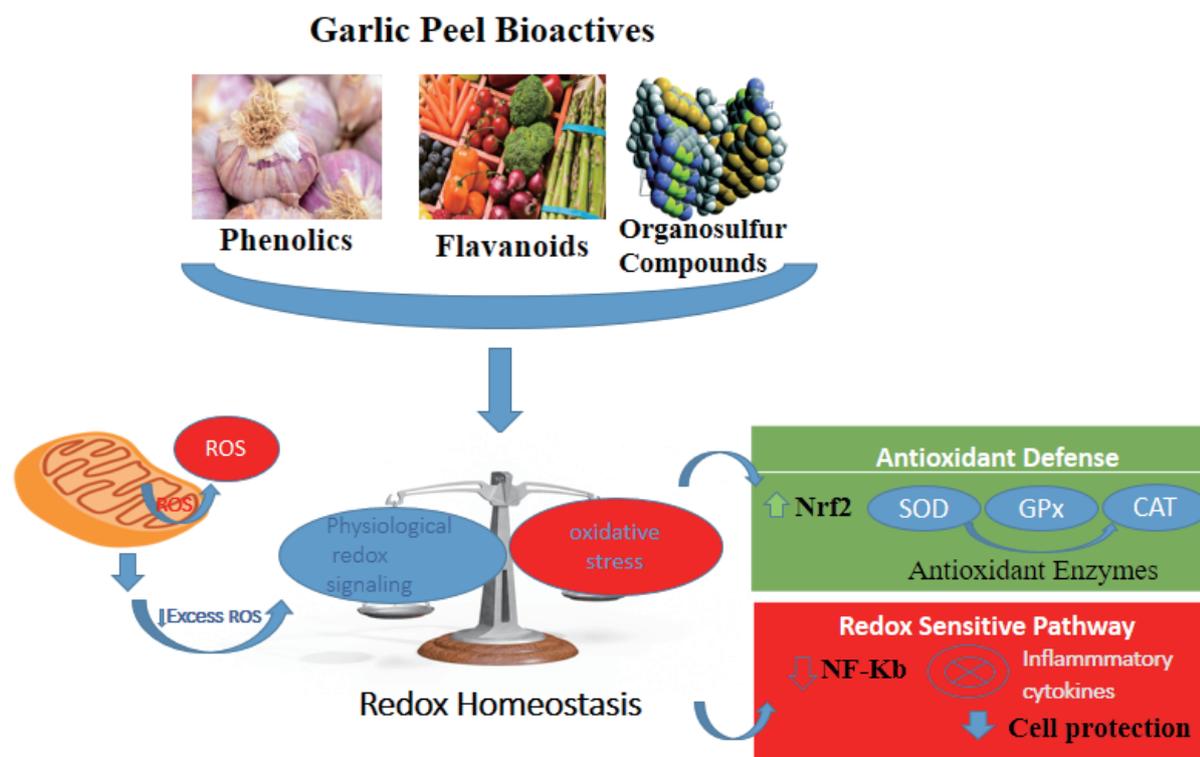
Rather than depending on the scavenging of antioxidants, the mode of action of the bioactive compounds derived from the garlic peels is through their ability to act as redox modulators. By interacting with the redox-modulated targets, the mode of action of the compounds results in the modification of the pathways involved in inflammation, oxidative stress, mitochondrial function, as well as the adaptability

of the cells. This information is essential for the appreciation of the value of the compounds, thus the therapeutic value[17].

By regulating the production of reactive oxygen species (ROS) in the mitochondria, stimulating the natural antioxidant defense system, and modulating the redox signal pathway, the bioactive compounds of garlic peels, including phenolics, flavonoids, and organosulfur compounds, maintain the intracellular redox homeostasis through the suppression of the generation of ROS, which is associated with cellular instability caused by the effects of oxidative stress[20].

4.1 Regulation of Reactive Oxygen Species and Mitochondrial Redox Balance

Through the regulation of the buildup and degradation

**Figure 2:** Redox modulation by garlic peel–derived bioactives at the cellular level.

of reactive oxygen species (ROS), bioactive compounds found in the peel of garlic control redox balance in the body. Through the reduction of the overproduction of ROS species, phenolic and flavonoid bioactive compounds found in the peel of the garlic are effective in the regulation of mitochondrial electron transport. This greatly decreases the level of electrons leaking from the mitochondria, representing another mechanism through which many of the redox imbalances culminating in oxidative stress in the disease state arise. Importantly, the bioactive compounds found in the peel of the garlic are not detrimental in the full cessation of the production of ROS in the body. This is not the case; the compound ensures the production of ROS necessary in various cellular signal pathways in metabolism regulation in the body[21].

4.2 Activation of Antioxidant Signaling Pathways

On another note, the application of bioactive components found in garlic peel extracts will depend greatly on their role in boosting internal antioxidant defense systems. This is because bioactive compounds have an impact on pathways for producing protection proteins and antioxidant enzymes. On the role of bioactive components found in garlic peel extracts as antioxidants: There is an alteration of redox sensors by bioactive components found in extracts of garlic peels that enhances cellular resilience to oxidative stress through the activation of antioxidant-related cellular processes that boost the production of natural defense mechanisms involving antioxidants that play an essential role in detoxification processes[22].

4.3 Modulation of Inflammatory and Redox-Sensitive Signaling

The connection that exists between oxidative stress and inflammation in the body can never be taken lightly. The garlic peel bioactive compounds have the capacity to lower the level of inflammation. There is no doubt about the ability of the bioactive compounds found in the garlic peel to reduce inflammation by adjusting the pathways associated with inflammation. Among the advantages that are attributed to the bioactive components found in the garlic peel is the

reduction of oxidative activation of the inflammatory pathways and cytokines. Such pathways are the major causes of chronic inflammation, which results in significant damage. Issues that are associated with inflammation indicate that the bioactive components found in the garlic peel are crucial in conditions where inflammation results due to oxidative imbalances[23].

4.4 Integration of Redox and Cellular Homeostatic Signaling

Bioactives present in the peels regulate the balance between the cell and the processes involving oxidation through various routes. The overall effects of bioactives involving inflammation, antioxidants, and mitochondrias govern a physiological response that increases the adaptability of the cell. During periods involving metabolic stress, inflammation, and environmental conditions, regulation in the oxidation process helps to avoid problems in the body through critical processes, which is more important in applied physiology to maintain functional balance rather than focusing on single molecules[24].

5. Physiological Implications Across Organ Systems

Bioactives of garlic peels modify redox levels by influencing the functions of tissues, organs, and cells. It assists in the prevention and adaptation of different systems involved in various chronic diseases by restoring the oxidative balance and controlling the redox-sensitive pathways[28].

Through re-establishing homeostasis among various organ systems, garlic peel bioactives exercise various physiological impacts throughout the body. This balance results from the modulation of oxidative signaling. It enhances the functions of endothelium in the cardiovascular system, increases mitochondrial efficiency in metabolic tissues, protects the central nervous system, and modulates inflammatory responses in immune cells[29].

5.1 Cardiovascular Physiology

Maintaining redox balance in the cardiovascular

Table 2: Molecular and cellular mechanisms by which garlic peel bioactives regulate redox homeostasis

Mechanistic level	Target pathway/process	Physiological outcome
Mitochondrial	Reduced electron leakage	Lower ROS overproduction[25]
Antioxidant signaling	Upregulation of endogenous enzymes	Enhanced cellular resilience[26]
Redox-sensitive transcription	Modulation of stress-response genes	Adaptive oxidative defense[23]
Inflammatory signaling	Suppression of redox-driven inflammation	Reduced tissue injury[27]

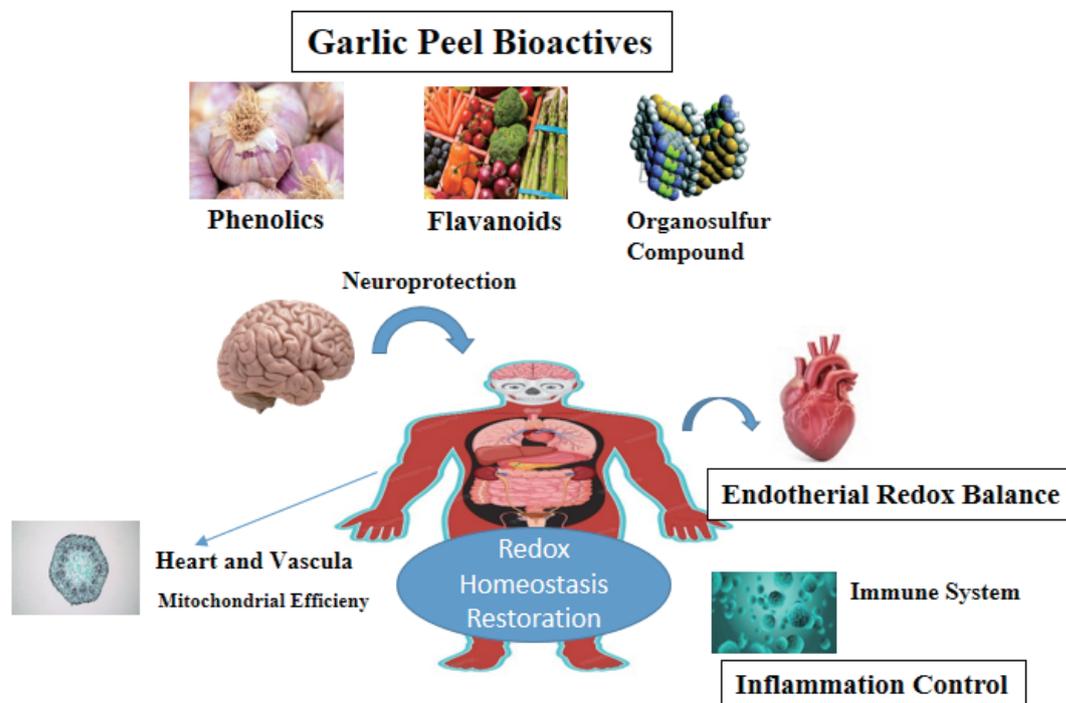


Figure 3: Systemic physiological effects of garlic peel bioactives through redox homeostasis restoration.

system can be considered crucial in order to perform proper functions of the heart as well as regulate vascular tone and endothelial integrity appropriately. Excessive oxidative stress can hasten vascular inflammation as well as endothelial dysfunction and mitigate the availability of nitric oxide. Bioactive compounds present in the peels play a crucial role in enhancing the function of endothelial cells and providing protection from oxidative damage. Garlic peels also function to regulate nitric oxide levels, and this is aligned to the balance between oxidative and reductive reactions in the body. These levels have to be regulated to avoid conditions such as hypertension and atherosclerosis, which occur when there is oxidative stress[30].

5.2 Metabolic and Hepatic Physiology

In this respect, redox control plays a major role in maintaining the balance of lipid metabolism, insulin signaling, and liver function. Chronic oxidative stress causes metabolic inflammation, fat accumulation, and impairment in glucose utilization. Bioactive agents present in garlic skin exert a beneficial influence on metabolic syndrome by modulating antioxidant systems and mitochondrial function in highly metabolic tissues; they promote detoxification through the processes of lipid peroxidation, thus helping to reduce oxidative stress. Based on their effects on metabolic signaling, these compounds may be useful in the treatment of insulin resistance, non-alcoholic fatty

liver disease, and metabolic syndrome[31].

5.3 Neurophysiological Effects

The nervous system is known to require a lot of oxygen, and the amount of antioxidants is very low, thereby increasing its vulnerability to oxidative stress. Increased oxidative stress, however, can cause neuroinflammation, leading to neurodegeneration. The right amount is, however, necessary for synaptic plasticity, neurotransmission, and survival. Garlic peel bioactives are known to have neuroprotective activities through antioxidant activities, improvement of mitochondrial function, as well as modifications to the pathways that are influenced by oxidation, leading to inflammation in the brain[32].

5.4 Immune and Inflammatory Responses

Redox signaling is involved in the generation, activation, and inflammatory responses of immune cells. While ROS is essential for the immune defense of the human body, too much oxidative stress, which causes human cells to age, may impair the immune system, leading to inflammation. It appears the bioactive compounds present in the peels of garlic, which restore the balance of the immune redox, play a critical role in the regulation of the production of ROS, as well as reducing the pro-inflammatory effects of redox. This indicates the value of the compounds in the practical applications of the science of physiology,

Table 3: Organ-specific physiological effects of garlic peel-derived bioactives

Organ system	Redox-related dysfunction	Effect of garlic peel bioactives
Cardiovascular	Endothelial oxidative stress	Improved nitric oxide signaling, vascular protection[34]
Metabolic/Hepatic	Mitochondrial oxidative overload	Improved lipid and glucose metabolism[35]
Nervous system	Neuronal oxidative damage	Neuroprotection, mitochondrial support[36]
Immune system	Chronic inflammatory ROS	Balanced immune redox signaling[7]

Table 4: Translational relevance of garlic peel bioactives in redox-associated disorders

Pathophysiological context	Redox imbalance involved	Potential role of garlic peel bioactives
Cardiometabolic disorders	Chronic oxidative stress	Adjunct redox modulation[41]
Neurodegenerative conditions	Mitochondrial dysfunction	Neuroprotective support[42]
Inflammatory diseases	Redox-driven inflammation	Immune redox regulation[43]
Aging-related decline	Reduced antioxidant capacity	Physiological resilience enhancement[44]

as the compounds participate in the regulation of the immune response. This is particularly the case if the great inflammation results from oxidative stress[33].

6. Therapeutic and Preventive Implications

The bioactive compounds present in garlic peels have immense potential to affect redox balance at the cellular level, tissue level, and systemic level as well. This creates an excellent opportunity for tackling any condition related to chronic inflammation and oxidative stress successfully. Unlike antioxidants that may counteract oxidative stress by directly interacting with reactive oxygen species as such compounds act as physiological modulators by trying to restore redox balance while preserving key signals intact with them[37].

Hence, the maintenance of redox homeostasis is vital, as disturbances in the same have resulted in neurodegenerative diseases, metabolic syndromes, cardiovascular diseases, and the effects of natural aging. If considered from the perspective of prevention, the usefulness of the bioactive compounds found in the peel of the garlic plant can be extended to the enhancement of the body's natural antioxidant reserve mechanism, as well as the maintenance of the function of the mitochondrial reserve mechanism, thus inhibiting the natural inflammation of the body[38].

The bioactive compounds present in the peels have the potential to become effective additions to presently available medications to enhance their efficacy. The compounds can present potential in decreasing oxidative stress and increasing the flexibility of the cells. This could help in ensuring positive reactions to medications for conditions such as inflammatory and cardiovascular diseases. However, the potential

use in clinical therapy is limited at present by the lack of information obtained in adequate clinical trials involving humans. The gap in information makes it harder to provide guidelines for the use and dosages due to the existing lack of information regarding standard dosages. However, instead of perceiving the potential use and application of garlic peels only as a source for general antioxidant intake, the understanding of the mechanisms and pathways for the use and potential application are the foundation for further research into the use and efficacy in the balancing of redox reactions in physiology[39,40].

7. Current Limitations and Research Gaps

Garlic peels bioactives exhibit redox-modulating and physiological effects. However, there are quite a few challenges regarding their application in physiological and therapeutic settings. One major concern is the limited emphasis on *in vitro* and animal studies. Indeed, there are very few investigations that attempt to address their effects on human physiology. This scientific gap obviously limits our ability to transfer mechanistic findings to the clinical or population level[45].

Another major limitation is the diversity of garlic peel preparations used in various studies. Variability in the levels of bioactives, chemical composition, and preparation/extraction methodologies make standardization difficult. This further presents a challenge in the comparisons between these studies. It hinders reproducibility and dose-response relationship understanding crucial in both physiological and translational studies[46].

The bioavailability of bioactives and their metabolites in garlic peels is not known. Although

there is evidence of biological activity of phenolic and organosulfur compounds in laboratory studies, their bioavailability and metabolism in human tissues is not known. It is important that there be a clear scientific basis of the pharmacokinetic characteristics of bioactives in order to set proper levels of exposure and likely treatment times. There is a significant lack of data on safety from long-term use and interactions, especially when used on a chronic basis and with medications. This is concerning since several body functions may be impacted by redox states. Excessive and improper modulation of redox can lead to unforeseen problems. In order to support the practical use of bioactives from garlic peels, the concerns about them need to be dealt with[47].

8. Future Perspectives

So, it is suggested for the further study on the bioactive molecules of garlic peels to follow the physiological way of connecting the effects to their molecular mechanisms. To validate the results of the study and the role of the antioxidant properties of garlic peel bioactive molecules in human body states of sick and sound conditions, it is necessary to perform human investigations well-organized for the processes of inflammation, body organ functions, mitochondrions, and antioxidants[48].

The next area is the standardization of bioactive compounds from garlic peels. This is done by scrutinizing and identifying the content of phenolic compounds, flavonoids, and organosulfur compounds, among other compounds. This is of critical importance in order to convert findings from mechanisms of actions to effective treatments[49].

Such developments within the field of redox biology provide opportunities to identify the connection with the antioxidant mechanisms within the body and the bioactive compounds present within garlic peel. Such research could target the field of identifying the connection of the bioactive compounds with the redox-sensitive mechanisms within the body's attempt to tackle situations such as aging, metabolic diseases, or inflammation. More studies would have to take a detailed approach with regard to the ways in which the bioactive compounds present within garlic peel can take a place within the redox-focused treatments. In conjunction with the therapeutic benefits as well as the mechanisms through which the garlic bioactive compounds can provide balance to the body's redox mechanisms, it would have to take into consideration a combination of approaches that would likely carry a connection with physiology as well as the field of redox

biology[50].

9. Conclusion

Chronic health problems have been shown to stem from imbalances in what is referred to as redox homeostasis, which is pivotal in maintaining health and proper bodily function. Existing literature indicates that physiologic roles in humans are significantly affected by bioactive components of garlic peel via regulation of oxidation signaling pathways to maintain a state of equilibrium in terms of reducing inflammation and regulating levels of redox instead of being general antioxidants.

The phenolics, flavonoids, and organosulfur compounds present in the peels have a synergistic effect on the immune, metabolism, nervous, and cardiovascular components. The existing knowledge on these compounds is based on experimental models. This review appreciates the need to have human-based research on these compounds. The bioactive compounds in the peels have a high prospect to regulate the redox equilibrium, especially if the bioavailability, standardization, and physiological testing are enhanced, leading to a desired effect.

Author Contribution

All authors contributed to the conception, literature review, writing, editing, and final approval of the manuscript.

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Conflict of Interest

The author declare that there is no conflict of interest.

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