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REVIEW

Redox Imbalance in Breast Cancer: From Mechanisms to Targeted Therapeutic Strategies

Rusul Saad[1], Ons Hussain Sahib[2], Yasser Jassim Dawood[3], Montadher Ali Mahdi[3], Kareem Salim Abod[4]

[1]Department of Science, College of Basic Education, Mustansiriyah University, Baghdad, Iraq. [2]College of Science, Mustansiriyah University, Baghdad, Iraq. [3]National Center for Cancer Research, University of Baghdad, Baghdad, Iraq. [4]Al-Nukhba University College, Baghdad, Iraq, for Academic Evaluation, Iraq.

Abstract

Breast cancer continues to be a predominant source of morbidity and mortality globally, with oxidative stress identified as a key factor in its onset, advancement, and resistance to treatment. Reactive oxygen species (ROS) drive genomic instability, induce DNA damage, and activate oncogenic signaling pathways that promote malignant transformation and tumor progression. At the same time, problems with both enzymatic and non-enzymatic antioxidant defenses speed up the disease and make treatment less effective. This review elucidates the dual role of oxidative stress in breast cancer, focusing on its influence on tumor biology and therapeutic response by analyzing key antioxidant systems-including superoxide dismutases, catalase, and glutathione peroxidases and emphasizing their adaptive upregulation during early carcinogenesis and subsequent decline as the disease progresses. Nanotechnology-based delivery systems are discussed for their ability to enhance tumor selectivity, overcome drug resistance, and minimize systemic toxicity while restoring redox balance. However, finding the best way to use these methods to get the most therapeutic benefit while causing the least amount of systemic toxicity is still a big problem. Future perspectives emphasize the necessity of identifying and clinically validating oxidative stress biomarkers to facilitate early detection, prognostication, and personalized therapeutic strategies. Additionally, a more profound comprehension of redox biology and its interaction with immune modulation is essential for the advancement of innovative and effective redox-based interventions in breast cancer management.

Keywords: Breast cancer- Oxidative stress- Reactive oxygen species (ROS)- Tumor progression- Immune modulation

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1. Introduction

Breast cancer, marked by significant genetic heterogeneity and complex etiology, remains a considerable global health challenge despite significant progress in early diagnosis and treatment strategies. An increasing body of evidence underscores oxidative stress and dysregulated redox signaling as pivotal factors in essential oncogenic processes, such as tumor initiation, clonal development, metastasis, and therapeutic resistance [1, 2]. The introduction of hormone treatments, HER2-targeted medicines, and immunotherapy has markedly enhanced clinical outcomes; yet, treatment failure and disease recurrence continue to be predominantly influenced by enduring redox imbalances within the tumor micro environment [3, 4].

The dynamic interplay between reactive oxygen species (ROS) production and antioxidant defense mechanisms drives breast cancer progression by inducing genomic instability, perpetuating chronic inflammation, promoting angiogenesis, facilitating immune evasion, and triggering epithelial–mesenchymal transition (EMT) [5, 6]. Oxidative stress significantly influences the tumor microenvironment by altering stromal and immune cell activities, collectively promoting a more aggressive and treatment-resistant phenotype. Notably, current treatment paradigms aim to exploit this redox vulnerability, either by reinstating natural antioxidant capacity or by enhancing

Corresponding Author:
Dr. Montadher Ali Mahdi
National Center for Cancer Research, University of Baghdad, Baghdad, Iraq.
Emails: montadhermalky@yahoo.com; Montadher.a@bccru.uobaghdad.edu.iq

oxidative stress to selectively induce cancer cell death [7, 8].

In this review, we present a thorough synthesis of molecular and clinical perspectives regarding the involvement of oxidative stress in breast cancer development. We also talk about the possible uses of redox-based biomarkers for predicting disease and treating it, as well as new ways to change redox levels. A more thorough understanding of the oxidative environment in breast cancer could lead to more targeted treatments, which would be a new source of hope for better patient outcomes.

1.1 Oxidative Stress and Reactive Oxygen Species (ROS): General Concepts

Reactive oxygen species (ROS) are very reactive molecules that come from oxygen. They include free radicals like superoxide anion ($O_2^{\bullet -}$) and hydroxyl radical (•OH), in addition to non-radical species like hydrogen peroxide (H_2O_2) and singlet oxygen ($^1O_2$) [9]. Primarily produced as by-products of mitochondrial oxidative phosphorylation, reactive oxygen species (ROS) play crucial roles in regulating several cellular processes, which include proliferation, differentiation, and immunological responses under physiological settings [10].

An intricate antioxidant defense system strictly controls ROS levels to keep cellular redox equilibrium. This system includes both enzymatic antioxidants, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), and non-enzymatic antioxidants, like glutathione (GSH), vitamins C and E, and thioredoxin [11]. Maintaining proper cellular function and preventing oxidative damage depends on the right balance between the production of ROS and the activity of antioxidants.

Oxidative stress occurs when this redox balance is upset, causing too much ROS to build up and overwhelm the body's own antioxidant defenses [12]. The oxidative damage that follows to DNA, lipids, and proteins harms the integrity of the genome, messes with cellular signaling networks, and starts pro-inflammatory cascades, all of which are important for oncogenic transformation and tumor growth [13, 14].

Historically, reactive oxygen species (ROS) were perceived merely as harmful metabolic by-products; however, recent research reveals a more complex perspective, acknowledging their dual function as essential signaling mediators and pathogenic instigators. At regulated levels, reactive oxygen species (ROS) function as secondary messengers in vital signaling pathways needed for cellular adaptability and survival; nonetheless, prolonged or excessive ROS exposure can trigger cellular senescence, apoptosis, or malignant transformation, contingent upon the cellular environment [15, 16]. In breast cancer, chronic oxidative stress not only induces mutagenesis and genomic instability but also facilitates tumor cell proliferation, apoptotic resistance, angiogenesis, immunological evasion, and metastatic spread [17, 18].

Consequently, a detailed understanding of ROS biogenesis and redox regulatory networks is critical to elucidate their contribution to breast carcinogenesis [19]. These processes do not occur in isolation; they are influenced by intrinsic factors such as chronic inflammation, hormonal dysregulation, and metabolic disturbances. Together, these elements create a tumor-promoting redox environment that highlights the urgent need for innovative redox-targeted therapeutic strategies [20].

2. ROS in Breast Carcinogenesis

2.1 Initiation Stage: Oxidative Stress, DNA Damage, and Genomic Instability

Breast carcinogenesis commences with the gradual accumulation of genetic and epigenetic modifications, wherein oxidative stress acts as a primary catalyst. Several risk factors including chronic inflammation, hormonal imbalances, environmental exposures, and metabolic dysregulation converge on mitochondrial dysfunction and aberrant activation of NADPH oxidases, thereby driving excessive ROS production in mammary epithelial cells [21, 22]. Mitochondrial dysfunction, coupled with the aberrant activation of ROS-producing enzymes such as NADPH oxidases, exacerbates intracellular oxidative stress, leading to a range of DNA lesions, including 8-oxo-2'-deoxyguanosine (8-oxo-dG) adducts, single- and double-strand breaks, and chromosomal instability [23, 24].

Importantly, oxidative DNA damage leads to the build-up of mutations in important oncogenes and tumor suppressor genes, such as TP53 and BRCA1/2, which are often changed in breast cancer [25]. Moreover, ROS-induced telomere attrition and malfunction promote replicative senescence evasion and cellular immortalization, creating conditions conducive to premature malignant transformation [26]. In summary, long-term oxidative stress creates a base of genetic instability that leads to the start of breast cancer.

2.2 Promotion Stage: Chronic Inflammation, Redox Imbalance, and Neoplastic Progression

During the promotion phase, chronic oxidative stress and persistent inflammation work together to make preneoplastic cells grow in number. Pro-inflammatory cytokines, including TNF-α, IL-1β, and IL-6, primarily released by invading immune cells such as macrophages and neutrophils, further enhance ROS generation inside the tumor microenvironment [27]. Increased ROS levels not only cause more damage to DNA, but they also make important cancer-causing signaling pathways stronger[28]:

The activation of NF-κB encourages the transcription of genes linked to proliferation, angiogenesis, and immune evasion [29].

The activation of STAT3, which is commonly done through IL-6 signaling, increases inflammation, growth, and survival that help tumors grow [30].

The inactivation of PTEN by ROS-mediated oxidation leads to the hyperactivation of the PI3K/Akt/mTOR pathway, which causes metabolic reprogramming and

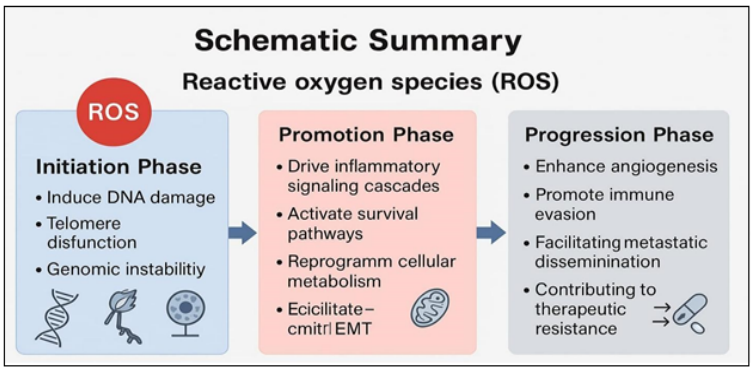

Figure 1. Schematic Overview of ROS Involvement in Cancer Development and Progression.

resistance to apoptosis [31].

Oxidative stress also causes epigenetic reprogramming by changing how DNA methyltransferases (DNMTs) and histone-modifying enzymes work. This turns off tumor suppressor genes and turns on oncogenic circuits [32]. ROS-induced epithelial–mesenchymal transition (EMT), marked by the upregulation of transcription factors including Snail, Slug, and Twist, confers increased motility, invasiveness, and stem cell-like characteristics to cells, thereby contributing to breast cancer heterogeneity and therapeutic resistance [33, 34].

2.3 Progression Stage: Malignant Transformation, Angiogenesis, and Metastasis

During the progression phase, oxidative stress regulates critical molecular processes that enhance tumor aggressiveness and facilitate systemic dispersion. Increased levels of reactive oxygen species (ROS) stabilize hypoxia-inducible factor-1 alpha (HIF-1α) in normal oxygen conditions, a process known as "pseudohypoxia." This leads to the upregulation of angiogenic mediators such vascular endothelial growth factor (VEGF) and encourages the formation of new blood vessels [35].

At the same time, ROS-mediated activation of matrix metalloproteinases (MMP-2, MMP-9) breaks down the extracellular matrix (ECM), which makes it easier for tumor cells to invade and spread [36, 37]. Oxidative stress that lasts a long time also weakens the cytotoxic capabilities of tumor-infiltrating lymphocytes (TILs) and natural killer (NK) cells, which helps the tumor escape the immune system and proliferate [38].

Importantly, long-term exposure to ROS makes tumor cells better at repairing DNA and turns on mechanisms that stop cells from dying, such as increasing the levels of Bcl-2 family proteins and keeping NF-κB signaling going. This makes tumor cells more resistant to chemotherapy and radiotherapy. So, oxidative stress not only speeds up the growth of breast cancer, but it also makes it very hard to treat effectively [39, 40].

Schematic Summary

Reactive oxygen species (ROS) are essential at all phases of breast carcinogenesis:

1-Initiation Phase: ROS cause DNA damage, telomere malfunction, and genomic instability, which are all things that can lead to cancer [41].

2-Promotion Phase: ROS start inflammatory signaling cascades, turn on survival pathways, change how cells use energy, and make it easier for epithelial–mesenchymal transition (EMT) to happen. All of these things help tumors grow and adapt [42].

3-Progression Phase: ROS boost angiogenesis, promote immune evasion, facilitate metastatic dispersion, and contribute to treatment resistance, promoting tumor aggressiveness and poor prognosis [43].

A comprehensive understanding of ROS-mediated mechanisms presents intriguing pathways for the identification of novel biomarkers and therapeutic targets, ultimately aimed at enhancing tailored tactics and improving clinical outcomes for breast cancer patients (Figure 1).

3. Antioxidant Systems in Breast Tissue

3.1 Overview of Cellular Antioxidant Defense Mechanisms

Like other tissues that grow quickly, breast tissue is always subjected to a lot of oxidative stress from both inside and outside the body. To mitigate the harmful effects of reactive oxygen species (ROS), a complex and meticulously regulated antioxidant defense network has developed, consisting of both enzymatic and non-enzymatic elements [44].

Superoxide dismutases (SODs), catalase (CAT), and glutathione peroxidases (GPx) are the main enzymatic antioxidants that protect cells. SODs turn superoxide anions ($O_2^{\bullet -}$) into hydrogen peroxide (H_2O_2), which is then broken down into water and molecular oxygen by catalase. This stops the formation of highly reactive hydroxyl radicals (•OH). GPx enzymes also use glutathione (GSH) as an electron donor to break down hydrogen peroxide and lipid hydroperoxides, which helps minimize oxidative damage even more [45].

Simultaneously, non-enzymatic antioxidants such as glutathione, vitamins C and E, thioredoxin, and peroxiredoxins function as vital free radical scavengers, neutralizing reactive oxygen species (ROS) prior to their potential damage to crucial cellular components, including DNA, lipids, and proteins. These tiny molecules serve as an important extra layer of defense that works with enzymatic systems to keep cells stable [46].

The dynamic interaction between antioxidant enzymes

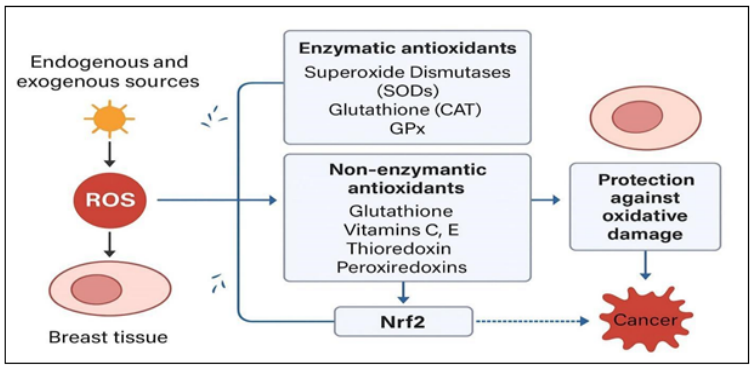

Figure 2. Overview of Cellular and Antioxidant Defense Mechanisms.

and redox-sensitive transcription factors, particularly Nuclear Factor Erythroid 2-Related Factor 2 (Nrf2), guarantees a rapid and flexible cellular response to oxidative disturbances. The activation of the Nrf2 pathway results in the transcriptional upregulation of numerous cytoprotective genes that play roles in redox control, detoxification, and cellular repair mechanisms. Consequently, preserving the fragile equilibrium between reactive oxygen species (ROS) production and antioxidant defenses is crucial for protecting breast tissue integrity and averting the emergence of oxidative stress-related diseases, including malignant transformation (Figure 2) [47, 48].

3.2 Antioxidant Responses in Early-Stage Breast Lesions

During the initial stages of breast carcinogenesis, especially in precursor lesions like ductal carcinoma in situ (DCIS), there is often an increase in antioxidant defense systems. Continuous exposure to oxidative stress, influenced by hormonal variations, chronic inflammation, and environmental carcinogens, triggers an adaptive antioxidant response to reduce ROS-induced cellular damage [1, 49].

The Nuclear Factor Erythroid 2-Related Factor 2 (Nrf2) signaling pathway is a key part of this reaction. In oxidative stress, Nrf2 breaks away from its cytoplasmic inhibitor, Keap1, and moves to the nucleus, where it binds to antioxidant response elements (ARE) in the promoter regions of target genes [50]. This transcriptional activation causes a lot of cytoprotective genes to be turned on, such as heme oxygenase-1 (HO-1), NAD (P) H quinone dehydrogenase 1 (NQO1), and glutamate-cysteine ligase catalytic subunit (GCLC). It also strengthens classical antioxidant enzymes like SOD, catalase, and GPx [47].

This increased ability to fight oxidative damage helps protect cells and keep them in balance, but it could also help tumors grow by helping cells with cancer-causing mutations survive and multiply. In early breast tumors, this redox adaption creates an environment that supports the clonal growth of genetically abnormal cells, which helps the transition from pre-invasive to invasive cancer [51].

3.3 Collapse of Antioxidant Defenses During Cancer Progression

As breast lesions proceed from ductal carcinoma in situ (DCIS) to invasive breast carcinoma, natural antioxidant defenses are increasingly undermined. Oxidative stress that doesn't go away, caused by changes in the tumor microenvironment and changes in metabolism, causes important enzymatic antioxidant systems to stop working. A significant decrease in the activity of essential enzymes, such as superoxide dismutase (SOD), catalase, and glutathione peroxidase (GPx), hinders the cell's capacity to neutralize excessive reactive oxygen species (ROS), hence aggravating genomic instability and promoting tumor progression [1, 52].

Epigenetic dysregulation exacerbates this decline; promoter hypermethylation of antioxidant genes including SOD2 and GPX3 has been observed in breast cancer tissues, leading to transcriptional suppression and a subsequent reduction in antioxidant capacity. The downregulation of these protective genes allows oxidative damages to build up, which leads to mutagenesis and the clonal spread of aggressive tumor phenotypes [53, 54].

Nuclear Factor Erythroid 2-Related Factor 2 (Nrf2) has a more complicated role as the disease gets worse. While temporary activation of Nrf2 acts as a defense against oxidative damage, long-term and persistent activation may unintentionally increase the survival of tumor cells by upregulating gene networks that protect cells and promote survival, which can lead to resistance to treatment [48, 55].

Mitochondrial dysfunction, marked by the depletion of manganese-dependent superoxide dismutase (Mn-SOD) and diminished glutathione (GSH) levels, exacerbates oxidative stress in tumor cells. As redox homeostasis declines, breast cancers become increasingly aggressive, have enhanced metastatic potential, and develop resistance to standard medicines, presenting significant obstacles for effective therapeutic management (Figure 3) [56, 57].

4. Therapeutic Implications: Targeting Oxidative Stress

4.1 Antioxidants as Preventive and Therapeutic Agents

Since oxidative stress is a key factor in the development of breast cancer, a lot of research has focused on using antioxidants as both preventive and therapeutic treatments. Antioxidants are thought to restore redox balance, reduce DNA damage caused by ROS, and stop chronic inflammation. This could slow the growth of premalignant lesions and make traditional treatments work better [58, 59].

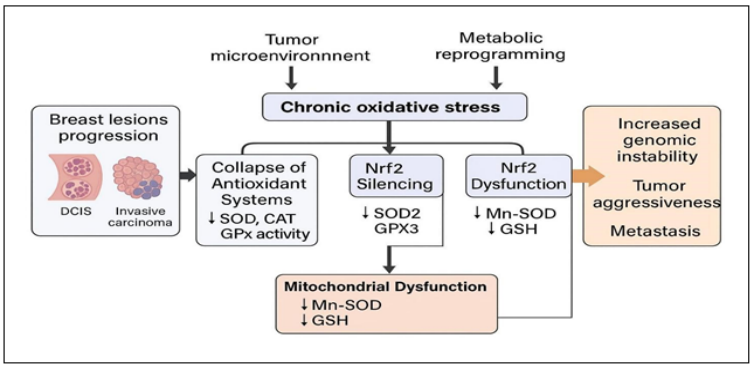

Figure 3. Role of Chronic Oxidative Stress and Nrf2 Dysregulation in Breast Cancer Progression

Epidemiological data indicate that diets abundant in natural antioxidants such as vitamins C and E, β-carotene, and polyphenolic compounds may correlate with a reduced risk of breast cancer development. Vitamin C is a powerful water-soluble antioxidant that removes a wide range of ROS, restores damaged vitamin E, and strengthens the body's immunological surveillance systems. On the other hand, vitamin E is an important lipid-soluble antioxidant that protects cell membranes from lipid peroxidation and keeps them strong while they are under oxidative stress [60-62].

Natural polyphenols, such as curcumin, resveratrol, and epigallocatechin gallate (EGCG), have attracted significant attention due to their multifaceted anti-cancer activities. These substances not only show strong antioxidant and anti-inflammatory properties, but they have also been shown to stop breast cancer cells from growing, moving, and spreading in preclinical models [63, 64].

In addition to dietary modifications, pharmacological supplementation with antioxidant chemicals has been explored as a chemopreventive approach, especially among groups with a heightened risk of breast cancer. Nevertheless, randomized clinical trials have produced inconsistent results, with variations arising from differences in study designs, antioxidant formulations, dose regimes, and patient characteristics. Even with these inconsistencies, antioxidant-based therapies still show promise, especially for people who have a family history of breast cancer or molecular markers that show they are still under oxidative stress [65, 66].

4.2 Pro-oxidant Therapies: Inducing ROS Overload in Cancer Cells

Unlike antioxidant treatments that aim to neutralize reactive oxygen species (ROS), a new therapeutic approach seeks to exploit the inherent susceptibility of cancer cells to oxidative stress by intentionally creating ROS overload. Breast cancer cells, akin to other malignancies, frequently function near a critical threshold of oxidative stress, attributable to heightened metabolic activity, mitochondrial malfunction, and oncogene-induced ROS generation. Therapeutic elevation of ROS levels over this threshold can specifically induce death in cancer cells while preserving normal cells that possess more resilient antioxidant mechanisms [39, 51].

Numerous standard chemotherapeutic drugs, including as cisplatin and paclitaxel, partially exert their cytotoxic effects by inducing the production of excessive reactive oxygen species (ROS), resulting in oxidative damage and the activation of intrinsic apoptotic pathways [67]. Based on this idea, new drugs that target redox homeostasis are being actively researched. These encompass inhibitors of thioredoxin reductase and glutathione synthase, both of which impair the antioxidant buffering ability of cancer cells and enhance ROS-induced cytotoxicity [68].

Photodynamic therapy (PDT) has also become a viable pro-oxidant treatment for breast cancer. PDT entails the application of a photosensitizing chemical succeeded by localized light activation, leading to site-specific reactive oxygen species (ROS) production and targeted tumor cell destruction [69]. PDT has a big advantage over traditional methods like surgery or radiation therapy since it causes less damage to nearby healthy tissues, which lowers systemic toxicity. Early-phase clinical trials have yielded promising outcomes, highlighting the potential of PDT and other pro-oxidant strategies as supplementary or alternative therapies to standard breast cancer treatments [70].

4.3 Challenges and Controversies in Redox-Targeted Therapies

Even though changing oxidative stress in breast cancer could lead to new treatments, there are still many problems and disagreements that make it hard to put redox-targeted therapies into practice. A fundamental challenge is in the dualistic characteristics of reactive oxygen species (ROS) and antioxidants in cancer biology [71]. Antioxidants can protect normal cells and possibly stop them from becoming cancerous, but taking too many or the wrong kind of antioxidants can actually protect breast cancer cells from the oxidative damage that chemotherapy or radiotherapy can cause, which can make the treatment less effective [72].

The timing, dosage, and molecular context of antioxidant intervention are crucial factors influencing therapeutic outcomes. Antioxidant therapy during the initial phases of carcinogenesis may provide chemopreventive advantages; conversely, in existing tumors, improper application could unintentionally enhance tumor cell survival and resistance [73]. Moreover, the inherent variability of redox homeostasis among

Table 1. Summary of Selected Redox-Targeting Agents and Their Therapeutic Characteristics in Breast Cancer

Therapy/Agent	Mechanism of Action	Stage Targeted	Benefits	Limitations
N-Acetylcysteine (NAC)	Replenishes glutathione, scavenges ROS	Early stages, chemoprevention	Reduces oxidative DNA damage; enhances antioxidant defenses	Poor tumor penetration; requires sustained delivery
Vitamin E	Lipid-soluble antioxidant; inhibits lipid peroxidation	Early-stage breast lesions	Protects cell membranes; synergizes with chemotherapy	Risk of highdose toxicity
Curcumin	Antioxidant, antiinflammatory, modulates NFκB and ROS levels	Early to intermediate stages	Multifunctional; low systemic toxicity	Poor bioavailability; rapid metabolism
Resveratrol	Scavenges ROS, activates antioxidant pathways (Nrf2)	Early invasive stages	Inhibits proliferation; induces apoptosis	Low bioavailability; high metabolic clearance
Doxorubicin (at low doses)	Induces ROSmediated apoptosis selectively in tumor cells	Advanced breast cancer	Effective cytotoxic agent	Cardiotoxicity; therapy resistance
Photodynamic Therapy (PDT)	Generates local ROS bursts upon activation	Early and localized tumors	Tumor-selective cytotoxicity; minimal systemic side effects	Requires precise light delivery; limited penetration depth
Redox-sensitive Nanoparticles	Deliver antioxidants or pro-oxidants selectively to tumor sites	Experimental/preclinical stages	High selectivity; reduced offtarget toxicity	Need for clinical validation; potential toxicity concerns

various breast cancer subtypes and individual patients poses considerable challenges to the formulation of universally effective antioxidant-based treatments [48].

Pro-oxidant methodologies encounter significant constraints. While raising ROS levels above a lethal threshold is an effective way to kill cancer cells, uncontrolled oxidative damage can harm nearby normal tissues, making inflammation worse, hurting organ function, and raising the risk of secondary cancers. Consequently, meticulous regulation of oxidative stress levels is crucial to optimize treatment efficacy while reducing unintended toxicities [49, 74].

It is imperative to identify and validate robust biomarkers that indicate oxidative stress levels, antioxidant capacity, and redox vulnerabilities to facilitate patient stratification, enhance therapeutic strategies, and promote the customization of redox-targeted therapies in breast cancer treatment [75].

4.4 Future Perspectives: Redox Modulation as a Therapeutic Strategy

Future treatment improvements in breast cancer should focus on enhancing the comprehension of the molecular regulators that control redox homeostasis in tumor cells. Understanding these regulatory networks will be very important for creating targeted therapies that change oxidative stress pathways in a specific way [76, 77].The combination of redox-targeting drugs with recognized therapeutic modalities, such as chemotherapy, radiation, and immunotherapy, constitutes a promising approach to overcome therapeutic resistance and improve clinical efficacy.

New technologies, especially in nanomedicine, provide new ways to precisely control redox. Nanoparticle-based delivery methods that may selectively transport antioxidants or pro-oxidant chemicals to tumor tissues have a lot of potential to make treatments more effective while reducing side effects [69]. Furthermore, the clinical incorporation of redox biomarkers may facilitate the dynamic monitoring of oxidative stress levels, hence enabling the early identification of treatment resistance and permitting individualized therapy modifications [78].

In conclusion, while addressing oxidative stress holds significant potential for enhancing breast cancer outcomes, its clinical efficacy necessitates a sophisticated and context-sensitive strategy. A thorough comprehension of the interactions among oxidative stress, antioxidant responses, and tumor biology will be essential for the successful translation of redox-targeted therapeutics into clinical practice [79] (Table 1).

5. Future Directions

The expanding recognition of oxidative stress as a central driver of breast carcinogenesis has opened promising avenues for translational research and therapeutic innovation. A comprehensive understanding of the intricate interplay between reactive oxygen species (ROS), antioxidant defense systems, oncogenic signaling pathways, and immune modulation is essential for the development of next-generation redox-based interventions [80].

A critical priority for future research is the identification and rigorous clinical validation of oxidative stress–related biomarkers. Quantitative assessment of oxidative DNA damage products (such as 8-oxo-dG), lipid peroxidation markers, and antioxidant enzyme activity profiles may provide valuable prognostic and predictive information. Beyond their diagnostic utility, these biomarkers could serve as dynamic indicators of tumor redox status, enabling real-time monitoring of treatment response and early detection of therapeutic resistance. Integrating redox biomarkers into clinical workflows may therefore facilitate risk stratification, personalized treatment selection, and adaptive therapeutic decision-making [81, 82].

Importantly, emerging evidence highlights a profound connection between oxidative stress and immune

regulation within the tumor microenvironment. Persistent ROS elevation can impair the cytotoxic activity of tumor-infiltrating lymphocytes (TILs) and natural killer (NK) cells, promote immune evasion [83], and modulate cytokine signaling networks that shape antitumor immunity. Future investigations should aim to clarify how redox imbalances influence immune checkpoint pathways and the responsiveness to immunotherapeutic strategies. The incorporation of redox biomarkers to predict immunotherapy outcomes represents a particularly compelling direction, as oxidative stress signatures may help identify patients most likely to benefit from immune checkpoint inhibitors or combination regimens [17].

Therapeutically, the rational integration of redox-modulating agents with chemotherapy, radiotherapy, and immunotherapy offers significant potential to overcome resistance mechanisms. Tailored modulation of oxidative stress either by restoring antioxidant capacity in normal tissues or selectively inducing ROS overload in malignant cells-must be guided by precise molecular profiling. Advances in nanotechnology-based delivery systems further support this precision approach by enhancing tumor selectivity, improving drug bioavailability, and minimizing systemic toxicity, thereby optimizing the therapeutic index of redox-active compounds [84].

Ultimately, progress in this field will require interdisciplinary collaboration bridging molecular oncology, immunology, redox biology, and bioengineering [85]. By coupling mechanistic insight with biomarker-driven patient stratification, redox modulation may evolve from a theoretical concept into a clinically actionable strategy, contributing to more precise, immune-informed, and personalized management of breast cancer [86, 87].

In conclusion, oxidative stress is a key factor in the genesis and progression of breast cancer because it causes genomic instability and weakens antioxidant defenses. Redox-targeted therapy, encompassing both antioxidant and pro-oxidant approaches, present significant opportunities but necessitate meticulous, context-dependent implementation to prevent inadvertent tumor protection or damage. Future endeavors should concentrate on the incorporation of oxidative stress biomarkers into clinical practice to facilitate tailored therapy, alongside the integration of redox modulation with conventional treatments to augment efficacy and surmount resistance. To make breast cancer care better, more accurate, and more focused on the needs of the patient, we need to learn more about redox dynamics.

Clinical trial

Not applicable.

Clinical trial number

Not applicable.

References

1. Dong R, Wang J, Guan R, Sun J, Jin P, Shen J. Role of Oxidative Stress in the Occurrence, Development, and Treatment of Breast Cancer. Antioxidants. 2025 01 17;14(1):104. https://doi.org/10.3390/antiox14010104
2. Bel'skaya LV, Dyachenko EI. Oxidative Stress in Breast Cancer: A Biochemical Map of Reactive Oxygen Species Production. Current Issues in Molecular Biology. 2024 05 13;46(5):4646-4687. https://doi.org/10.3390/cimb46050282
3. Dawood Y, Mahdi M, Jumaa A, Saad R, Khadim R. Evaluation of LH, FSH, oestradiol, prolactin and tumour markers CEA and CA-125 in sera of Iraqi patients with endometrial cancer. Scripta Medica. 2024;55(4):419-426. https://doi.org/10.5937/scriptamed55-49925
4. Palma M. Advancing Breast Cancer Treatment: The Role of Immunotherapy and Cancer Vaccines in Overcoming Therapeutic Challenges. Vaccines. 2025 03 24;13(4):344. https://doi.org/10.3390/vaccines13040344
5. Moloney JN, Cotter TG. ROS signalling in the biology of cancer. Seminars in Cell & Developmental Biology. 2018 08;80:50-64. https://doi.org/10.1016/j.semcdb.2017.05.023
6. Zhang J, Wang X, Vikash V, Ye Q, Wu D, Liu Y, Dong W. ROS and ROS-Mediated Cellular Signaling. Oxidative Medicine and Cellular Longevity. 2016 01;2016(1):4350965. https://doi.org/10.1155/2016/4350965
7. Harris IS, DeNicola GM. The Complex Interplay between Antioxidants and ROS in Cancer. Trends in Cell Biology. 2020 06;30(6):440-451. https://doi.org/10.1016/j.tcb.2020.03.002
8. Dodson M, Castro-Portuguez R, Zhang DD. NRF2 plays a critical role in mitigating lipid peroxidation and ferroptosis. Redox Biology. 2019 05;23:101107. https://doi.org/10.1016/j.redox.2019.101107
9. Mahdi M, Dawood Y, Sabah R, Abd Al-Rahman S. Evaluation of Oxidative Stress, Anti-Oxidant, Vitamins and Co-Factor Elements in The Sera of Gastric Cancer in Iraqi Patients. Asian Pacific Journal of Cancer Prevention. 2024 Oct 01;25(10):3651-3660. https://doi.org/10.31557/APJCP.2024.25.10.3651
10. Sena L, Chandel N. Physiological Roles of Mitochondrial Reactive Oxygen Species. Molecular Cell. 2012 Oct;48(2):158-167. https://doi.org/10.1016/j.molcel.2012.09.025
11. Ighodaro O, Akinloye O. First line defence antioxidants—Superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx): Their fundamental role in the entire antioxidant defence grid. Alexandria Journal of Medicine. 2018;54(4):287–293. https://doi.org/10.1016/j.ajme.2017.09.001
12. Liguori I, Russo G, Curcio F, Bulli G, Aran L, Della-Morte D, Abete P. Oxidative stress, aging, and diseases. Clinical Interventions in Aging. 2018;13:757–772. https://doi.org/10.2147/CIA.S158513
13. Klaunig J, Kamendulis L. The role of oxidative stress in carcinogenesis. 2004;44:239-67. https://doi.org/10.1146/annurev.pharmtox.44.101802.121851
14. Khalifa M, Ghadhban A, Hade I, Ali M. Evaluation of quality of life for women with breast cancer. Scripta Medica. 2024;55(1):115-118. https://doi.org/10.5937/scriptamed55-47068
15. Schieber M, Chandel N. ROS function in redox signaling and oxidative stress. Current Biology. 2014;24(10):453– 462. https://doi.org/10.1016/j.cub.2014.03.034
16. Sies H, Jones D. Reactive oxygen species (ROS) as pleiotropic physiological signalling agents. Nature Reviews Molecular Cell Biology. 2020;21(7):363–383. https://doi.org/10.1038/s41580-020-0230-3

17. Nogueira V, Hay N. Molecular pathways: Reactive oxygen species homeostasis in cancer cells and implications for cancer therapy. Clinical Cancer Research. 2013;19(16):4309–4314. https://doi.org/10.1158/1078-0432.CCR-12-1424
18. Panis C, Herrera A, Victorino V, Campos F, Freitas L, Rossi T, Cecchini R. Oxidative stress and hematological profiles of advanced breast cancer patients subjected to paclitaxel or doxorubicin chemotherapy. Breast cancer research and treatment. 2012;133(1). https://doi.org/10.1007/s10549-011-1693-x
19. Abdulla K, Aljebori S, Dh H, Mohson K, Sabah Rasoul N, Mahdi M. Risk factors for cervical cancer in Iraqi women. Libri Oncologici: Croatian Journal of Oncology. 2023;51(2-3):59–64. https://doi.org/ 10.20471/LO.2023.51.02-03.09
20. Kattan Z, Minig V, Leroy P, Dauça M, Becuwe P. Role of manganese superoxide dismutase on growth and invasive properties of human estrogen-independent breast cancer cells. Breast cancer research and treatment. 2008;108(2):203-15. https://doi.org/10.1007/s10549-007-9597-5
21. Hecht F, Pessoa CF, Gentile LB, Rosenthal D, Carvalho DP, Fortunato RS. The role of oxidative stress on breast cancer development and therapy. Tumor Biology. 2016 04;37(4):4281-4291. https://doi.org/10.1007/s13277-016-4873-9
22. Klaunig, J. E., & Wang, Z. (2010). Oxidative stress in female cancers. Current Pharmaceutical Design, 16(3), 255–269. https://doi.org/10.2174/138161210790883615..
23. Cerutti P, Amstad P. Inflammation and Oxidative Stress in Carcinogenesis. Nigam S, Honn KV, Marnett LJ, Walden TL. Eicosanoids and Other Bioactive Lipids in Cancer, Inflammation and Radiation Injury. 1993;:387-390. https://doi.org/10.1007/978-1-4615-3520-1_75
24. Poetsch AR. The genomics of oxidative DNA damage, repair, and resulting mutagenesis. Computational and Structural Biotechnology Journal. 2020 01;18:207-219. https://doi.org/10.1016/j.csbj.2019.12.013
25. Fridlich R, Annamalai D, Roy R, Bernheim G, Powell SN. BRCA1 and BRCA2 protect against oxidative DNA damage converted into double-strand breaks during DNA replication. DNA Repair. 2015 06;30:11-20. https://doi.org/10.1016/j.dnarep.2015.03.002
26. Sahin E, DePinho RA. Linking functional decline of telomeres, mitochondria and stem cells during ageing. Nature. 2010 03;464(7288):520-528. https://doi.org/10.1038/nature08982
27. Habanjar O, Bingula R, Decombat C, Diab-Assaf M, Caldefie-Chezet F, Delort L. Crosstalk of Inflammatory Cytokines within the Breast Tumor Microenvironment. International Journal of Molecular Sciences. 2023 02 16;24(4):4002. https://doi.org/10.3390/ijms24044002
28. Reczek CR, Chandel NS. ROS-dependent signal transduction. Current Opinion in Cell Biology. 2015 04;33:8-13. https://doi.org/10.1016/j.ceb.2014.09.010
29. Zhou Y, Li T, Jia M, Dai R, Wang R. The Molecular Biology of Prostate Cancer Stem Cells: From the Past to the Future. International Journal of Molecular Sciences. 2023 04 19;24(8):7482. https://doi.org/10.3390/ijms24087482
30. Johnson DE, O'Keefe RA, Grandis JR. Targeting the IL-6/JAK/STAT3 signalling axis in cancer. Nature Reviews Clinical Oncology. 2018 04;15(4):234-248. https://doi.org/10.1038/nrclinonc.2018.8
31. Trinh V, Nguyen Huu T, Sah D, Choi J, Yoon H, Park S, Lee S. Redox regulation of PTEN by reactive oxygen species: its role in physiological processes. Antioxidants. 2024;13(2):199. https://doi.org/10.3390/antiox13020199
32. García-Guede Á, Vera O, Ibáñez-de-Caceres I. When oxidative stress meets epigenetics: implications in cancer development. Antioxidants. 2020;9(6):468. https://doi.org/10.3390/antiox9060468
33. Lee S, Jeong E, Ju M, Jeon H, Kim M, Kim C, Park H, Han S, Kang H. Reactive oxygen species induce epithelial-mesenchymal transition, glycolytic switch, and mitochondrial repression through the Dlx-2/Snail axis in MCF-7 breast cancer cells. Molecular Medicine Reports. 2019;19(2):983–991. https://doi.org/10.3892/mmr.2019.10466
34. Nes J, Kruijf E, Putter H. Co-expression of SNAIL and TWIST determines prognosis in estrogen receptor-positive early breast cancer patients. Breast Cancer Research and Treatment. 2012;133(1):49–59. https://doi.org/10.1007/s10549-011-1684-y
35. Basheeruddin M, Qausain S. Hypoxia-inducible factor 1-alpha (HIF-1α) and cancer: mechanisms of tumor hypoxia and therapeutic targeting. Cureus. 2024;16(10). https://doi.org/10.7759/cureus.70700
36. Niland S, Riscanevo A, Eble J. Matrix metalloproteinases shape the tumor microenvironment in cancer progression. International journal of molecular sciences. 2021;23(1):146. https://doi.org/10.3390/ijms23010146
37. Kessenbrock K, Plaks V, Werb Z. Matrix metalloproteinases: Regulators of the tumor microenvironment. Cell. 2010;141(1):52–67. https://doi.org/10.1016/j.cell.2010.03.015
38. Wong J, Dolcetti R, Rhee H, Simpson F, Souza-Fonseca-Guimaraes F. Weaponizing natural killer cells for solid cancer immunotherapy. Trends in Cancer. 2023;9(2):111–121. https://doi.org/10.1016/j.trecan.2022.10.009
39. Trachootham D, Alexandre J, Huang P. Targeting cancer cells by ROSmediated mechanisms: A radical therapeutic approach?. Nature Reviews Drug Discovery. 2009;8(7):579–591. https://doi.org/10.1038/nrd2803
40. Reczek C, Chandel N. The two faces of reactive oxygen species in cancer. Annual review of cancer biology. 2017;1:79–98. https://doi.org/10.1146/annurev-cancerbio-041916-065808
41. Klaunig J, Wang Z. Oxidative stress in carcinogenesis. Current Opinion in Toxicology. 2018;7:116–121. https://doi.org/10.1016/j.cotox.2017.11.014
42. Ju S, Singh M, Han S, Ranbhise J, Ha J, Choe W, Kang I. Oxidative stress and cancer therapy: controlling cancer cells using reactive oxygen species. International journal of molecular sciences. 2024;25(22):12387. https://doi.org/10.3390/ijms252212387
43. Chatterjee R, Chatterjee J. ROS and oncogenesis with special reference to EMT and stemness. European Journal of Cell Biology. 2020;99(2–3):151073. https://doi.org/10.1016/j.ejcb.2020.151073
44. Sies H, Berndt C, Jones D. Oxidative stress. Annual Review of Biochemistry. 2017;:715-748. https://doi.org/10.1146/annurev-biochem-061516-045037
45. Ighodaro O, Akinloye O. First line defence antioxidants—superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPX): Their fundamental role in the entire antioxidant defence grid. Alexandria Journal of Medicine. 2018;54(4):287–293. https://doi.org/10.1016/j.ajme.2017.09.001
46. Forman H, Zhang H, Rinna A. Glutathione: Overview of its protective roles, measurement, and biosynthesis. Molecular Aspects of Medicine. 2009;30(1–2):1–12. https://doi.org/10.1016/j.mam.2008.08.006
47. Kensler T, Wakabayashi N, Biswal S. Cell survival responses to environmental stresses via the Keap1–Nrf2–ARE pathway. Annual Review of Pharmacology and

Toxicology. 2007;47:89–116. https://doi.org/10.1146/annurev.pharmtox.46.120604.141046
48. Hayes J, Dinkova-Kostova A. The Nrf2 regulatory network provides an interface between redox and intermediary metabolism. Trends in Biochemical Sciences. 2014;39(4):199–218. https://doi.org/10.1016/j.tibs.2014.02.002
49. Liou G, Storz P. Reactive oxygen species in cancer. Free Radical Research. 2010;44(5):479–496. https://doi.org/10.3109/10715761003667554
50. Dawood YJ, Saad R, Mahdi MA, Hamoody JA. Evaluation of LDH, AFP, b-hCG and tumour markers CEA and CA-125 in sera of Iraqi patients with ovarian cancer. Scripta Medica. 2025;56(2):275-282. https://doi.org/10.5937/scriptamed56-56933
51. Gorrini C, Harris IS, Mak TW. Modulation of oxidative stress as an anticancer strategy. Nature Reviews. Drug Discovery. 2013 Dec;12(12):931-947. https://doi.org/10.1038/nrd4002
52. Gurer-Orhan H, Ince E, Konyar D, Saso L, Suzen S. The Role of Oxidative Stress Modulators in Breast Cancer. Current Medicinal Chemistry. 2018 Oct 24;25(33):4084-4101. https://doi.org/10.2174/0929867324666170711114336
53. Sundar IK, Yao H, Rahman I. Oxidative Stress and Chromatin Remodeling in Chronic Obstructive Pulmonary Disease and Smoking-Related Diseases. Antioxidants & Redox Signaling. 2013 05 20;18(15):1956-1971. https://doi.org/10.1089/ars.2012.4863
54. Cao S, Yan B, Lu Y, Zhang G, Li J, Zhai W, Guo W, Zhang S. Methylation of promoter and expression silencing of GPX3 gene in hepatocellular carcinoma tissue. Clinics and Research in Hepatology and Gastroenterology. 2015 04;39(2):198-204. https://doi.org/10.1016/j.clinre.2014.09.003
55. Rojo De La Vega M, Chapman E, Zhang DD. NRF2 and the Hallmarks of Cancer. Cancer Cell. 2018 07;34(1):21-43. https://doi.org/10.1016/j.ccell.2018.03.022
56. Hosseinzadeh A, Seirafianpour F, Sheibani M, Taheri M, Naeini AJ, Reiter RJ, Mehrzadi S. Therapeutic Aspects of Melatonin-sirtuin Crosstalk: An Updated Review of Current Data Based on Cellular Mechanisms. Current Drug Targets. 2025 08;26(10):683-708. https://doi.org/10.2174/0113894501360934250512052503
57. Devi GR, Allensworth JL, Evans MK, Sauer SJ. The Role of Oxidative Stress in Breast Cancer. Cancer. 2014;:3-14. https://doi.org/10.1016/B978-0-12-405205-5.00001-5
58. Azrad M, Turgeon C, Demark-Wahnefried W. Current Evidence Linking Polyunsaturated Fatty Acids with Cancer Risk and Progression. Frontiers in Oncology. 2013;3. https://doi.org/10.3389/fonc.2013.00224
59. Wang Y, Qi H, Liu Y, Duan C, Liu X, Xia T, Chen D, Piao H, Liu H. The double-edged roles of ROS in cancer prevention and therapy. Theranostics. 2021;11(10):4839-4857. https://doi.org/10.7150/thno.56747
60. Harris HR, Bergkvist L, Wolk A. Vitamin C intake and breast cancer mortality in a cohort of Swedish women. British Journal of Cancer. 2013 07;109(1):257-264. https://doi.org/10.1038/bjc.2013.269
61. Mocanu M, Nagy P, Szöllősi J. Chemoprevention of Breast Cancer by Dietary Polyphenols. Molecules. 2015 Dec 17;20(12):22578-22620. https://doi.org/10.3390/molecules201219864PMID 26694341
62. Mahdi MA, Dawood YJ, Jumaa AH, Abod KS, Manssor KJ. From ROS to Tumorigenesis: Understanding the Oxidative Pathways in Cervical Cancer Progression. Asian Pacific Journal of Cancer Biology. 2026 01 07;11(1):259-266. https://doi.org/10.31557/apjcb.2026.11.1.259-266
63. Shanmugam M, Rane G, Kanchi M, Arfuso F, Chinnathambi A, Zayed M, Alharbi S, Tan B, Kumar A, Sethi G. The Multifaceted Role of Curcumin in Cancer Prevention and Treatment. Molecules. 2015 02 05;20(2):2728-2769. https://doi.org/10.3390/molecules20022728
64. Bishayee A, Sethi G. Bioactive natural products in cancer prevention and therapy: Progress and promise. Seminars in Cancer Biology. 2016 Oct;40-41:1-3. https://doi.org/10.1016/j.semcancer.2016.08.006
65. Jung AY, Cai X, Thoene K, Obi N, Jaskulski S, Behrens S, Flesch-Janys D, Chang-Claude J. Antioxidant supplementation and breast cancer prognosis in postmenopausal women undergoing chemotherapy and radiation therapy. The American Journal of Clinical Nutrition. 2019 01;109(1):69-78. https://doi.org/10.1093/ajcn/nqy223
66. Abod K, Mahdi M, Al-Massoodi A, Mansoor K, Jaafar J. Impact of oxidative stress on patients before and after exposure to sevoflurane and desflurane inhalational anaesthesia. Scripta Medica. 2025;56(6):1151-1159. https://doi.org/10.5937/scriptamed56-60087
67. Wang H, Gao Z, Liu X, Agarwal P, Zhao S, Conroy D, He X. Targeted production of reactive oxygen species in mitochondria to overcome cancer drug resistance. Nature Communications. 2018;9(1):562. https://doi.org/10.1038/s41467-018-02915-8
68. Bekhet O, Eid M. The interplay between reactive oxygen species and antioxidants in cancer progression and therapy: a narrative review. Translational cancer research. 2021;10(9):4196. https://doi.org/10.21037/tcr-21-629
69. Wang X, Hu J, Wang P, Zou J. Recent advances of photodynamic therapy for breast cancer: The role of nanotechnology, photosensitizers and light sources. Frontiers in Oncology. 2021;11:723426. https://doi.org/10.3389/fonc.2021.723426
70. Gunaydin G, Gedik M, Ayan S. Photodynamic therapy for the treatment and diagnosis of cancer–a review of the current clinical status. Frontiers in Chemistry. 2021;9:686303. https://doi.org/10.3389/fchem.2021.686303
71. Panieri E, Santoro M. ROS signaling and redox biology in endothelial cells. Cellular and molecular life sciences. 2015;72(17):3281–3303. https://doi.org/10.1007/s00018-015-1928-9
72. Ambrosone C, Zirpoli G, Hutson A, McCann W, McCann S, Barlow W, Albain K. Dietary supplement use during chemotherapy and survival outcomes of patients with breast cancer enrolled in a cooperative group clinical trial (SWOG S0221. Journal of Clinical Oncology. 2020;38(8):804–814. https://doi.org/10.1200/JCO.19.01203
73. Abdulla K, Findakly S, Majeed A, Mahdi M, Biden B. Comparison of Ovarian and Cervical Cancer Prevalence in Iraqi Women with Lowered Serum Antioxidant Levels. Journal of Contemporary Medical Sciences. 2025;11(1). https://doi.org/10.22317/jcms.v11i1.1709
74. Taay YM, Mohammed MT, Abbas R, Ayad A, Mahdi MA. Determination of some biochemical parameters in sera of normotensive and hypertensive obese female in Baghdad. Journal of Physics: Conference Series. 2021 03 01;1853(1):012037. https://doi.org/10.1088/1742-6596/1853/1/012037
75. Kumari S, Badana AK, G MM, G S, Malla R. Reactive Oxygen Species: A Key Constituent in Cancer Survival. Biomarker Insights. 2018 01 01;13:1177271918755391. https://doi.org/10.1177/1177271918755391
76. Kong Q, Lillehei K. Antioxidant inhibitors for cancer therapy. Medical Hypotheses. 1998 Nov;51(5):405-409. https://doi.org/10.1016/S0306-9877(98)90036-6

77. Adler V, Yin Z, Tew KD, Ronai Z. Role of redox potential and reactive oxygen species in stress signaling. Oncogene. 1999 Nov 01;18(45):6104-6111. https://doi.org/10.1038/sj.onc.1203128
78. Nelson WG, De Marzo AM, DeWEESE TL, Isaacs WB. The Role Of Inflammation In The Pathogenesis Of Prostate Cancer. Journal of Urology. 2004 Nov;172(5S). https://doi.org/10.1097/01.ju.0000142058.99614.ff
79. Stich HF, Anders F. The involvement of reactive oxygen species in oral cancers of betel quid/tobacco chewers. Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis. 1989 09;214(1):47-61. https://doi.org/10.1016/0027-5107(89)90197-8
80. Sinha BK, Mimnaugh EG. Free radicals and anticancer drug resistance: Oxygen free radicals in the mechanisms of drug cytotoxicity and resistance by certain tumors. Free Radical Biology and Medicine. 1990;8(6):567-581. https://doi.org/10.1016/0891-5849(90)90155-C
81. Loft S, Møller P. Oxidative DNA Damage and Human Cancer: Need for Cohort Studies. Antioxidants & Redox Signaling. 2006 05;8(5-6):1021-1031. https://doi.org/10.1089/ars.2006.8.1021
82. Pompella A, Visvikis A, Paolicchi A, Tata VD, Casini AF. The changing faces of glutathione, a cellular protagonist. Biochemical Pharmacology. 2003 Oct;66(8):1499-1503. https://doi.org/10.1016/S0006-2952(03)00504-5
83. Sies H. What is Oxidative Stress?. Keaney JF. Oxidative Stress and Vascular Disease. 2000;224:1-8. https://doi.org/10.1007/978-1-4615-4649-8_1
84. Lucky SS, Soo KC, Zhang Y. Nanoparticles in Photodynamic Therapy. Chemical Reviews. 2015 02 25;115(4):1990-2042. https://doi.org/10.1021/cr5004198
85. Cantin AM, North SL, Hubbard RC, Crystal RG. Normal alveolar epithelial lining fluid contains high levels of glutathione. Journal of Applied Physiology. 1987 07 01;63(1):152-157. https://doi.org/10.1152/jappl.1987.63.1.152
86. Muenst S, Läubli H, Soysal SD, Zippelius A, Tzankov A, Hoeller S. The immune system and cancer evasion strategies: therapeutic concepts. Journal of Internal Medicine. 2016 06;279(6):541-562. https://doi.org/10.1111/joim.12470
87. Aboelella NS, Brandle C, Kim T, Ding Z, Zhou G. Oxidative Stress in the Tumor Microenvironment and Its Relevance to Cancer Immunotherapy. Cancers. 2021 01;13(5):986. https://doi.org/10.3390/cancers13050986

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