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A Narrative review

The interplay of essential and toxic trace elements in prostate cancer: a comprehensive review of risk factors, prevention, and clinical implications

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ABSTRACT

Background: Prostate cancer (PCa) is the second most frequently diagnosed cancer and one of the leading causes of cancer-related mortality among men worldwide. Its development is influenced by a complex interplay of genetic, hormonal, environmental, lifestyle, and metabolic factors. Increasing evidence suggests that trace elements play a critical role in prostate carcinogenesis, tumor progression, and clinical outcomes.

Objective: To comprehensively review the role of essential and toxic trace elements in prostate cancer, their association with disease risk and progression, and their potential implications in diagnosis, prevention, and treatment.

Methodology: A narrative review of the published literature was conducted using peer-reviewed articles, systematic reviews, meta-analyses, and clinical studies addressing prostate cancer epidemiology, risk factors, trace element biology, diagnostic biomarkers, prevention strategies, and therapeutic implications. Relevant evidence regarding zinc, selenium, copper, cadmium, arsenic, lead, and iron was critically evaluated.

Results: Essential trace elements, particularly zinc and selenium, demonstrate protective effects through antioxidant activity, regulation of cellular proliferation, apoptosis, immune function, and maintenance of genomic stability. Conversely, toxic elements such as cadmium, arsenic, and lead have been associated with increased prostate cancer risk through oxidative stress, DNA damage, inflammation, and disruption of androgen receptor signaling pathways. Elevated copper and iron levels may contribute to tumor growth, angiogenesis, and disease progression. Several sociodemographic, environmental, occupational, and lifestyle factors further influence prostate cancer susceptibility and outcomes. Although trace elements show promise as diagnostic and prognostic biomarkers, current evidence remains inconsistent and requires further validation.

Conclusion: Trace elements play an important role in the pathogenesis and progression of prostate cancer. Maintaining adequate levels of essential trace elements while minimizing exposure to toxic metals may contribute to prostate cancer prevention and improved clinical outcomes. Further prospective studies and mechanistic investigations are required to establish the clinical utility of trace element assessment in prostate cancer diagnosis, risk stratification, and targeted therapy.

INTRODUCTION

Prostate cancer (PCa) is the second most frequently diagnosed malignancy and one of the leading causes of cancer-related mortality among men worldwide [1]. The global burden of PCa continues to increase because of population aging, improved diagnostic practices, and greater life expectancy. Despite significant advances in screening, diagnosis, and treatment, prostate cancer remains a major public health challenge because of its complex pathogenesis and heterogeneous clinical behavior [2]. The disease ranges from indolent tumors with minimal clinical significance to highly aggressive cancers associated with substantial morbidity and mortality.The etiology of prostate cancer is multifactorial and involves a complex interaction of genetic, hormonal, environmental, and lifestyle-related factors. Established risk factors include advancing age, family history, ethnicity, obesity, chronic inflammation, dietary habits, and environmental exposures [3,4]. Genetic alterations involving tumor suppressor genes and DNA repair pathways, including PTEN, TP53, and BRCA mutations, have been implicated in prostate carcinogenesis and disease progression. In addition, androgen receptor signaling remains a central driver of prostate cancer development and progression, providing the biological basis for androgen deprivation therapy in advanced disease.Increasing evidence suggests that nutritional and environmental factors may significantly influence prostate cancer risk. Among these, trace elements have attracted considerable attention because of their essential roles in cellular metabolism, immune regulation, antioxidant defense, and maintenance of genomic stability [5]. Trace elements are required in small quantities for normal physiological function; however, both deficiency and excess may contribute to pathological processes, including carcinogenesis. Alterations in trace element homeostasis have been linked to oxidative stress, DNA damage, chronic inflammation, impaired apoptosis, and dysregulated cellular proliferation, all of which are recognized hallmarks of cancer development [6].Among essential trace elements, zinc is particularly important because the prostate gland normally contains one of the highest concentrations of zinc in the human body. Reduced intraprostatic zinc levels have consistently been reported in malignant prostate tissue and may contribute to metabolic alterations that favor tumor growth [7]. Selenium has also been extensively investigated because of its antioxidant and anti-inflammatory properties, which may protect against oxidative DNA damage and cancer progression. Conversely, elevated concentrations of copper and iron have been associated with increased oxidative stress, angiogenesis, and tumor proliferation, suggesting a potential role in disease progression and adverse clinical outcomes [8].In contrast to essential trace elements, toxic metals such as cadmium, arsenic, and lead have been implicated in the initiation and progression of several malignancies, including prostate cancer. These toxic elements may induce carcinogenesis through multiple mechanisms, including generation of reactive oxygen species, DNA damage, epigenetic modifications, endocrine disruption, and chronic inflammation. Occupational exposure, environmental pollution, smoking, industrial activities, and contaminated food or water sources represent important pathways through which individuals may be exposed to these carcinogenic agents [9].Recent advances in molecular oncology have expanded our understanding of the relationship between trace element metabolism and cancer biology. Emerging evidence highlights the involvement of metal-dependent cellular processes, including ferroptosis and cuproptosis, in tumor development and progression. Furthermore, several trace elements are being investigated as potential diagnostic, prognostic, and therapeutic biomarkers in prostate cancer, offering new opportunities for precision medicine and individualized treatment strategies [10].In addition to their biological significance, trace elements may have important implications for prevention and public health. Lifestyle interventions, dietary modification, and reduction of environmental exposure to toxic metals may contribute to lowering prostate cancer risk. Understanding the interplay between essential and toxic trace elements may therefore provide valuable insights into disease prevention, early detection, and therapeutic innovation [11,12]. This review aims to comprehensively examine the role of essential and toxic trace elements in prostate cancer, with particular emphasis on their biological functions, mechanisms of carcinogenesis, clinical significance, diagnostic utility, and potential therapeutic applications. By synthesizing current evidence, this review seeks to provide a comprehensive overview of how trace element homeostasis influences prostate cancer risk, progression, and clinical outcomes.

MATERIALS AND METHODS

Study Design

This study was conducted as a narrative review of the published literature examining the role of essential and toxic trace elements in prostate cancer. The review aimed to synthesize current evidence regarding the association of trace element homeostasis with prostate cancer risk, pathogenesis, progression, diagnosis, prevention, and therapeutic implications.

Literature Search Strategy

A comprehensive literature search was performed using electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. Relevant articles published in English between January 2000 and March 2025 were considered for inclusion. The search strategy incorporated combinations of Medical Subject Headings (MeSH) terms and keywords, including “prostate cancer,” “prostatic neoplasms,” “trace elements,” “zinc,” “selenium,” “copper,” “iron,” “cadmium,” “arsenic,” “lead,” “heavy metals,” “oxidative stress,” “biomarkers,” “carcinogenesis,” and “prostate cancer prevention.” Reference lists of eligible studies and review articles were manually screened to identify additional relevant publications.

Inclusion Criteria

1. Investigated the relationship between trace elements and prostate cancer.

2. Evaluated the biological mechanisms linking trace elements to carcinogenesis or tumor progression.

3. Assessed the diagnostic, prognostic, preventive, or therapeutic significance of trace elements in prostate cancer.

4. Included original research articles, observational studies, clinical trials, systematic reviews, meta-analyses, and evidence-based guidelines.

5. Were published in peer-reviewed journals and available in English.

Exclusion Criteria

1. Focused on malignancies other than prostate cancer without relevant prostate cancer data.

2. Were conference abstracts, editorials, letters to the editor, expert opinions, or non-peer-reviewed publications.

3. Were duplicate publications or contained insufficient methodological information.

4. Were published in languages other than English.

Data Extraction and Synthesis

Relevant information was extracted from eligible studies, including study characteristics, population demographics, trace elements investigated, biological mechanisms, clinical outcomes, and principal findings. The evidence was narratively synthesized and categorized into major thematic areas, including risk factors for prostate cancer, essential trace elements, toxic trace elements, molecular mechanisms of carcinogenesis, diagnostic and prognostic applications, prevention strategies, and therapeutic implications. Findings were critically evaluated to identify areas of consensus, emerging evidence, and existing knowledge gaps within the current literature.

Ethical Considerations

As this study was based exclusively on previously published literature and publicly available data, ethical approval and informed consent were not required.

RISK FACTORS FOR PROSTATE CANCER

Table 1. Major Risk Factors for Prostate Cancer

Risk Factor	Mechanism	Clinical Impact
Advancing Age	Accumulation of genetic mutations and cellular damage	Strongest established risk factor
Family History	Inherited genetic susceptibility	Increased lifetime risk
BRCA1/BRCA2 Mutations	Impaired DNA repair mechanisms	Aggressive disease phenotype
Obesity	Chronic inflammation and hormonal alterations	Increased progression risk
Metabolic Syndrome	Insulin resistance and oxidative stress	Poor clinical outcomes
Smoking	DNA damage and oxidative stress	Increased mortality
Environmental Exposure	Heavy metals and pollutants	Potential carcinogenic effect

Summary of established genetic, environmental, and lifestyle-related risk factors associated with prostate cancer development and progression.

Genetic Factors

Genetic predisposition plays a critical role in prostate cancer risk. Men with a first-degree relative affected by prostate cancer have a substantially increased likelihood of developing the disease compared with the general population. Inherited mutations in genes involved in DNA repair and tumor suppression, including BRCA1, BRCA2, ATM, and HOXB13, have been associated with increased susceptibility and more aggressive disease phenotypes. Furthermore, genomic alterations involving PTEN, TP53, and MYC contribute to tumor initiation, progression, and resistance to therapy [13,14].

Age and Ethnicity

Advancing age is the most important non-modifiable risk factor for prostate cancer. The incidence of prostate cancer increases dramatically after the age of 50 years, with the majority of cases diagnosed in older men. Ethnic disparities have also been observed, with men of African ancestry demonstrating higher incidence rates, earlier disease onset, and increased mortality compared with other populations. These differences are believed to result from a combination of genetic, socioeconomic, environmental, and healthcare access factors [15,16].

Hormonal Factors

Androgen signaling plays a central role in prostate physiology and carcinogenesis. Testosterone and its more potent metabolite, dihydrotestosterone (DHT), regulate prostate cell growth and differentiation through activation of androgen receptors. Dysregulation of androgen signaling pathways may promote malignant transformation and tumor progression. This biological dependence on androgen signaling forms the basis of androgen deprivation therapy, which remains a cornerstone of treatment for advanced prostate cancer [17].

Obesity and Metabolic Syndrome

Obesity has emerged as an important modifiable risk factor associated with aggressive prostate cancer and adverse clinical outcomes. Excess adipose tissue contributes to chronic inflammation, insulin resistance, altered sex hormone metabolism, and increased production of growth factors that may promote tumor development. Metabolic syndrome, characterized by obesity, hypertension, dyslipidemia, and impaired glucose metabolism, has also been linked to increased prostate cancer progression and mortality [16,18].

Inflammation and Infection

Chronic inflammation is increasingly recognized as a contributor to prostate carcinogenesis. Persistent inflammatory processes may induce oxidative stress, DNA damage, cellular proliferation, and epigenetic alterations that favor malignant transformation. Prostatitis, sexually transmitted infections, and other inflammatory conditions have been investigated as potential contributors to prostate cancer risk, although the exact mechanisms remain incompletely understood [18,19].

Lifestyle and Dietary Factors

Dietary habits and lifestyle behaviors may influence prostate cancer risk. Diets rich in saturated fats, processed foods, and red meat have been associated with increased risk, whereas diets abundant in fruits, vegetables, whole grains, and antioxidant-rich nutrients may provide protective effects. Physical inactivity, smoking, and excessive alcohol consumption have also been linked to adverse prostate cancer outcomes. Lifestyle modification therefore represents an important component of cancer prevention strategies [20].

Environmental and Occupational Exposures

Exposure to environmental pollutants and occupational carcinogens has been implicated in prostate cancer development. Agricultural chemicals, pesticides, industrial pollutants, and heavy metals may contribute to carcinogenesis through oxidative stress, endocrine disruption, and DNA damage. Long-term exposure to toxic metals such as cadmium, arsenic, and lead has received particular attention because of their established carcinogenic potential and their ability to accumulate within biological tissues [21].

Socioeconomic and Healthcare Factors

Socioeconomic status and healthcare accessibility significantly influence prostate cancer diagnosis and outcomes. Individuals with limited access to healthcare services often experience delayed diagnosis, reduced screening participation, and poorer treatment outcomes. Educational status, health literacy, and healthcare infrastructure also contribute to disparities in prostate cancer management and survival rates across different populations [22].Collectively, these factors illustrate the multifactorial nature of prostate cancer and highlight the importance of both inherited susceptibility and modifiable risk factors in disease development. Understanding these determinants is essential for designing effective prevention strategies and identifying high-risk populations that may benefit from targeted screening and early intervention [23-24].

ESSENTIAL TRACE ELEMENTS AND PROSTATE CANCER

Trace elements are micronutrients required in small quantities for normal cellular function, metabolism, immune regulation, antioxidant defense, and maintenance of genomic stability. The prostate gland contains relatively high concentrations of several trace elements, particularly zinc, which play important roles in cellular differentiation, apoptosis, and metabolic regulation. Increasing evidence suggests that disturbances in trace element homeostasis contribute to prostate carcinogenesis, tumor progression, and clinical outcomes. Among the essential trace elements, zinc, selenium, copper, and iron have been extensively investigated because of their biological relevance and potential clinical implications in prostate cancer [25-26].

Table 2. Essential Trace Elements and Their Role in Prostate Cancer

Trace Element	Biological Function	Potential Role in Prostate Cancer
Zinc	DNA synthesis, antioxidant defense, apoptosis	Protective; reduced levels observed in PCa
Selenium	Antioxidant activity, immune regulation	May reduce oxidative DNA damage
Copper	Angiogenesis, cellular signaling	Elevated levels linked to tumor progression
Iron	Oxygen transport, cellular metabolism	Excess may promote oxidative stress

Biological functions and potential implications of essential trace elements in prostate carcinogenesis and tumor progression.

Zinc

Zinc is the most extensively studied trace element in relation to prostate cancer. The normal prostate gland accumulates substantially higher concentrations of zinc than most other human tissues. Zinc is involved in numerous physiological processes, including DNA synthesis, gene expression, antioxidant defense, immune function, and cellular apoptosis. One of the unique metabolic characteristics of normal prostate epithelial cells is their ability to accumulate high intracellular zinc concentrations, which inhibit mitochondrial aconitase activity and regulate citrate metabolism [27,28].A consistent finding across multiple studies is the marked reduction of zinc levels in malignant prostate tissue compared with normal prostate tissue. Decreased zinc accumulation may facilitate metabolic reprogramming, increased energy production, and enhanced tumor growth. Experimental studies have demonstrated that zinc deficiency promotes oxidative stress, DNA damage, and dysregulated cell proliferation, thereby contributing to carcinogenesis. Conversely, adequate zinc levels may exert protective effects by promoting apoptosis and suppressing malignant transformation [29,30].Despite these observations, the relationship between dietary zinc intake and prostate cancer risk remains controversial. While some studies suggest a protective role, others report no significant association or even potential adverse effects with excessive supplementation. Consequently, further prospective studies are required to clarify the optimal role of zinc in prostate cancer prevention and management [31].

Selenium

Selenium is an essential micronutrient that plays a critical role in antioxidant defense through its incorporation into selenoproteins, including glutathione peroxidases and thioredoxin reductases. These enzymes protect cells from oxidative stress and DNA damage, both of which are important mechanisms in carcinogenesis. Selenium also influences immune function, inflammation, apoptosis, and cellular proliferation [32,33].Several epidemiological studies have suggested an inverse relationship between selenium status and prostate cancer risk. Adequate selenium levels may reduce oxidative injury to prostate tissue and inhibit tumor development through modulation of inflammatory pathways and enhancement of cellular antioxidant capacity. Experimental studies have further demonstrated that selenium compounds can induce apoptosis and inhibit angiogenesis in prostate cancer cells [34,35].However, findings from large clinical trials have produced conflicting results. While some studies reported potential protective effects of selenium supplementation, others failed to demonstrate significant reductions in prostate cancer incidence. These discrepancies may reflect differences in baseline selenium status, genetic factors, supplementation dosage, and study design. Therefore, although selenium remains biologically promising, its clinical role in prostate cancer prevention remains uncertain [36,37].

Copper

Copper is an essential trace element involved in numerous enzymatic reactions related to energy metabolism, angiogenesis, antioxidant defense, and cellular signaling. Unlike zinc and selenium, elevated copper concentrations have frequently been associated with cancer progression. Increased serum and tissue copper levels have been reported in patients with various malignancies, including prostate cancer [38].Copper contributes to tumor growth through several mechanisms. It serves as a cofactor for enzymes involved in angiogenesis, facilitating the formation of new blood vessels required for tumor expansion and metastasis. Elevated copper levels may also promote oxidative stress and enhance the activity of signaling pathways associated with cell proliferation and survival. Recent studies have highlighted the role of copper-dependent cell death pathways, known as cuproptosis, in cancer biology, suggesting potential therapeutic opportunities through modulation of copper metabolism [39,40.The growing interest in cuproptosis has stimulated research into copper-targeted therapies. Copper chelators and agents that alter copper homeostasis are currently being investigated as potential therapeutic strategies in prostate cancer and other malignancies. Nevertheless, additional clinical studies are required before such approaches can be incorporated into routine clinical practice [41].

Iron

Iron is another essential trace element with important physiological functions, including oxygen transport, DNA synthesis, cellular respiration, and energy production. However, excessive iron accumulation may contribute to carcinogenesis through the generation of reactive oxygen species (ROS) and oxidative DNA damage. Iron-induced oxidative stress can promote genomic instability, inflammation, and tumor progression [42].Recent evidence suggests that dysregulated iron metabolism may play an important role in prostate cancer biology. Cancer cells often exhibit increased iron requirements to support rapid proliferation and metabolic activity. Alterations in iron transport proteins, storage molecules, and regulatory pathways have been reported in prostate tumors. Furthermore, iron-dependent programmed cell death, known as ferroptosis, has emerged as an important mechanism influencing cancer development and treatment response [43,44].The therapeutic implications of ferroptosis have attracted considerable attention in oncology research. Induction of ferroptosis may represent a novel strategy for targeting treatment-resistant prostate cancer cells. Consequently, understanding the relationship between iron metabolism and prostate cancer may facilitate the development of innovative therapeutic approaches and improve patient outcomes [45].

Summary of Essential Trace Elements

Collectively, zinc, selenium, copper, and iron play critical roles in prostate physiology and carcinogenesis. Zinc and selenium generally demonstrate protective biological effects through antioxidant activity, genomic stability, and regulation of cellular proliferation. In contrast, excessive copper and iron levels may contribute to tumor progression through oxidative stress, angiogenesis, metabolic reprogramming, and dysregulation of cell death pathways. Continued investigation of trace element biology may provide valuable insights into prostate cancer prevention, biomarker development, and targeted therapeutic interventions.

Toxic Trace Elements and Prostate Cancer

Toxic trace elements have attracted significant attention because of their potential role in carcinogenesis and tumor progression. Unlike essential trace elements, toxic metals provide no physiological benefit and may contribute to cancer development through oxidative stress, DNA damage, chronic inflammation, and disruption of normal cellular signaling pathways [46,47].

Table 3. Toxic Trace Elements Associated with Prostate Cancer

Toxic Element	Major Sources	Proposed Carcinogenic Mechanisms
Cadmium	Smoking, industrial exposure, contaminated food	Oxidative stress, DNA damage
Arsenic	Contaminated water, industrial pollutants	Epigenetic changes, inflammation
Lead	Occupational exposure, environmental contamination	DNA damage and oxidative stress
Mercury	Industrial waste, seafood contamination	Cellular toxicity and oxidative injury

Chromium (VI)	Industrial exposure	Genetic instability and carcinogenesis

Toxic trace elements implicated in prostate cancer development and their proposed biological mechanisms.

Cadmium

Cadmium is one of the most extensively studied environmental carcinogens associated with prostate cancer. Exposure occurs through cigarette smoking, industrial pollution, contaminated food, and occupational hazards. Cadmium can accumulate in prostate tissue and promote carcinogenesis through oxidative stress, DNA damage, and endocrine disruption. Several studies have reported a positive association between chronic cadmium exposure and increased prostate cancer risk [48-49].

Arsenic

Arsenic exposure primarily occurs through contaminated drinking water, industrial emissions, and agricultural products. Arsenic induces carcinogenesis through oxidative DNA damage, epigenetic modifications, and chronic inflammation. Long-term exposure has been associated with an increased risk of several malignancies, including prostate cancer [50].

Lead

Lead is a persistent environmental pollutant that may contribute to prostate cancer development through oxidative stress and impaired DNA repair mechanisms. Occupational exposure remains a major concern in industrial settings. Although the evidence is less consistent than for cadmium and arsenic, several studies suggest a potential association between lead exposure and prostate carcinogenesis [51].

Mercury and Chromium

Mercury and hexavalent chromium have also been investigated for their potential carcinogenic effects. These metals may induce oxidative stress, cellular toxicity, and genetic instability. However, their specific role in prostate cancer remains less clearly established and requires further investigation [52].

Summary

Current evidence suggests that chronic exposure to toxic trace elements, particularly cadmium, arsenic, and lead, may increase prostate cancer risk through multiple biological mechanisms. Reducing environmental and occupational exposure to these metals may represent an important strategy for cancer prevention and public health protection [53].

DIAGNOSTIC AND PROGNOSTIC APPLICATIONS OF TRACE ELEMENTS

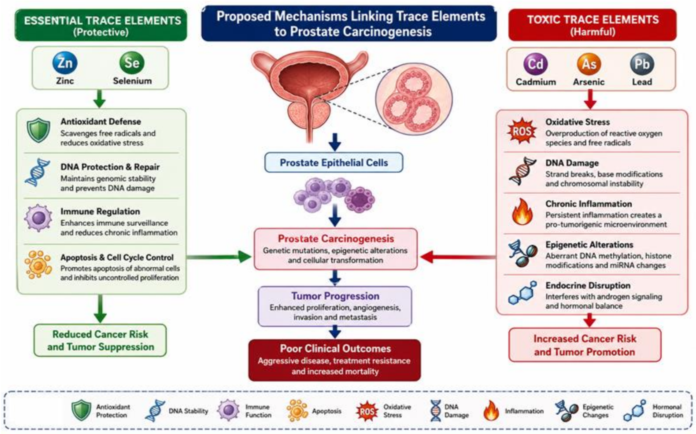
Trace elements have emerged as promising biomarkers for the diagnosis, prognosis, and monitoring of prostate cancer. Alterations in serum, urine, hair, nail, and tissue concentrations of specific trace elements have been associated with prostate cancer development and progression. Several studies have demonstrated significantly reduced zinc concentrations and elevated copper levels in patients with prostate cancer compared with healthy controls, suggesting their potential utility as diagnostic indicators [54].The zinc-to-copper ratio has received particular attention as a potential biomarker because it may better reflect underlying metabolic alterations than individual element measurements alone. Similarly, abnormal selenium levels have been associated with disease risk and clinical outcomes, although findings remain inconsistent across different populations [55].Recent advances in molecular oncology have further highlighted the importance of metal-dependent cellular pathways, including ferroptosis and cuproptosis, as potential therapeutic and prognostic targets. Dysregulation of iron and copper metabolism may influence tumor aggressiveness, treatment response, and disease progression. Consequently, trace element profiling may contribute to personalized risk assessment and treatment planning in the future [56].Despite encouraging findings, the clinical application of trace element biomarkers remains limited because of variability in measurement techniques, population differences, and inconsistent study results. Large prospective studies are required to validate their diagnostic accuracy and prognostic value before routine clinical implementation can be recommended [57].

Table 4. Diagnostic and Therapeutic Applications of Trace Elements in Prostate Cancer

Application	Trace Element	Potential Clinical Utility
Diagnostic Biomarker	Zinc	Early disease detection
Prognostic Biomarker	Copper	Assessment of disease progression
Risk Stratification	Selenium	Evaluation of cancer susceptibility
Therapeutic Target	Iron	Ferroptosis-based therapy
Therapeutic Target	Copper	Cuproptosis-based therapy

Emerging diagnostic, prognostic, and therapeutic applications of trace element research in prostate cancer.

Figure 1. Proposed Mechanisms Linking Trace Elements to Prostate Carcinogenesis



Schematic illustration demonstrating the protective effects of essential trace elements (zinc and selenium) through antioxidant defense, immune regulation, and apoptosis, as well as the carcinogenic effects of toxic trace elements (cadmium, arsenic, and lead) through oxidative stress, DNA damage, chronic inflammation, and epigenetic alterations leading to prostate cancer development and progression[58].Understanding the relationship between trace elements and prostate cancer may provide valuable opportunities for disease prevention and improved clinical outcomes. Maintaining adequate levels of essential trace elements through a balanced diet and healthy lifestyle may help support antioxidant defense mechanisms, immune function, and genomic stability. Foods rich in zinc and selenium, including seafood, nuts, whole grains, legumes, and lean meats, may contribute to maintaining optimal trace element status and reducing oxidative stress [59].Lifestyle modification remains a cornerstone of prostate cancer prevention. Regular physical activity, weight management, smoking cessation, moderation of alcohol consumption, and adherence to a diet rich in fruits and vegetables have been associated with a reduced risk of several malignancies, including prostate cancer. These interventions may also help minimize chronic inflammation and metabolic abnormalities that contribute to carcinogenesis [60].Equally important is the reduction of exposure to toxic trace elements. Occupational safety measures, environmental monitoring, improved industrial regulations, and access to clean water supplies are essential strategies for minimizing exposure to carcinogenic metals such as cadmium, arsenic, and lead. Public health initiatives aimed at reducing environmental contamination may have long-term benefits for cancer prevention at the population level From a clinical perspective, trace element assessment may complement existing diagnostic and prognostic approaches. Although prostate-specific antigen (PSA) testing remains the primary biomarker for prostate cancer detection, future integration of trace element profiling may improve risk stratification and facilitate more personalized treatment strategies. Emerging therapeutic approaches targeting metal-dependent pathways, including ferroptosis and cuproptosis, may also provide novel opportunities for managing advanced or treatment-resistant prostate cancer [61]. Overall, maintaining trace element homeostasis while minimizing exposure to toxic metals represents a promising approach for prostate cancer prevention and management. Continued research is required to establish evidence-based recommendations and clarify the clinical utility of trace element assessment in routine oncological practice.

CONCLUSION

Prostate cancer is a complex and multifactorial malignancy influenced by genetic, hormonal, environmental, metabolic, and lifestyle-related factors. Emerging evidence indicates that trace elements play a significant role in prostate carcinogenesis, tumor progression, and clinical outcomes. Essential trace elements, particularly zinc and selenium, contribute to antioxidant defense, immune regulation, apoptosis, and maintenance of genomic stability, potentially exerting protective effects against prostate cancer development. In contrast, toxic trace elements such as cadmium, arsenic, and lead may promote carcinogenesis through oxidative stress, DNA damage, chronic inflammation, and epigenetic alterations. Additionally, dysregulation of copper and iron metabolism has been associated with tumor progression and may represent novel therapeutic targets through mechanisms such as cuproptosis and ferroptosis. Although trace element profiling shows promise as a diagnostic and prognostic tool, further high-quality prospective studies are required to validate its clinical utility. Maintaining trace element homeostasis and minimizing exposure to toxic metals may contribute to effective prostate cancer prevention and improved patient outcomes.

FUTURE DIRECTIONS

Future research should focus on large-scale prospective studies to better define the relationship between trace element status and prostate cancer risk, progression, and treatment outcomes. Standardized methods for measuring trace element concentrations in biological samples are needed to improve comparability across studies and facilitate clinical application. Further investigation of the molecular mechanisms underlying trace element-mediated carcinogenesis, including oxidative stress, epigenetic modifications, ferroptosis, and cuproptosis, may provide valuable insights into novel therapeutic targets.The development of trace element-based biomarkers for early detection, risk stratification, and prognostic assessment represents another promising area of research. Advances in precision medicine may enable the integration of trace element profiling with genetic, molecular, and clinical parameters to improve individualized patient management. Additionally, public health initiatives aimed at reducing environmental exposure to toxic metals and promoting adequate nutritional intake of essential trace elements may contribute to prostate cancer prevention. Continued multidisciplinary collaboration between oncologists, urologists, toxicologists, nutritionists, and public health researchers will be essential for translating emerging evidence into clinical practice.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

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Author Contributions

Kamran Zaidi: Conceptualization, supervision, manuscript review.

Muhammad Rashid Jamal: Literature search, drafting.

Qamar Zaman: Data synthesis and editing.

Sabahat Javaid: Pathology review and validation.

Muhammad Bakir Hussain: Literature analysis and manuscript revision

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