

Research Article

The Role of Antioxidants in Inflammatory Immune Response: Evaluating Fruit and Vegetable Consumption for NCD Prevention in Nabire, 2025

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Abstract: Non-communicable diseases (NCDs) remain a leading cause of global morbidity and mortality, with chronic inflammation as a key pathophysiological mechanism. Antioxidants from fruits and vegetables have demonstrated potential to modulate inflammatory immune responses, thus contributing to NCD prevention. This study aimed to evaluate the effectiveness of fruit and vegetable consumption promotion policies in preventing NCDs by modulating inflammatory immune responses in Nabire District in 2025. The research employed a mixed-methods design, incorporating both quantitative and qualitative data from 384 adult respondents. Data were gathered through food consumption surveys, inflammatory biomarker analysis (CRP, IL-6, TNF- α), and an evaluation of policy implementation. Descriptive and inferential analyses were conducted using SPSS 28.0 and R version 4.3.0. Results revealed that average fruit and vegetable consumption in Nabire residents remained below the WHO recommended intake (289g/day vs. 400g/day), although there was a noticeable improvement compared to previous years. A significant negative correlation was found between antioxidant intake and inflammatory biomarkers ($r=-0.478$, $p<0.001$). Policy implementation reached 74% coverage with a 62% compliance rate, indicating significant improvements in reach compared to prior assessments. The study concludes that fruit and vegetable consumption promotion policies show enhanced potential in modulating inflammatory immune responses for NCD prevention. However, continued efforts in strengthening policy implementation and adopting innovative monitoring strategies, particularly through digital health technologies, are essential for achieving sustained impact.

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1. Introduction

Non-communicable diseases (NCDs) remain a significant global health challenge, contributing to 74% of all global deaths by 2023 (World Health Organization, 2024). In Indonesia, the prevalence of NCDs continues to increase alarmingly, with diabetes mellitus reaching 10.2%, hypertension 36.8%, and coronary heart disease 2.1% in 2023 (Ministry of Health of the Republic of Indonesia, 2024). Papua, particularly Nabire District, shows a significant upward trend in NCDs, with the prevalence of diabetes mellitus reaching 3.1% and hypertension 28.4% in 2024 (Papua Health Office, 2024).

The pathophysiology of NCDs is closely linked to chronic low-grade inflammation mediated by pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF- α), interleukin-6 (IL-6), and C-reactive protein (CRP) (Chen et al., 2024). Oxidative stress acts as a major trigger in the activation of this inflammatory pathway, creating a vicious cycle that accelerates the progression of NCDs (Kumar & Singh, 2024).



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Endogenous and exogenous antioxidants play a crucial role in neutralizing reactive oxygen species (ROS) and modulating inflammatory immune responses (Martinez-Gonzalez et al., 2024). Consumption of fruits and vegetables rich in antioxidants such as vitamin C, vitamin E, beta-carotene, flavonoids, and polyphenols has been epidemiologically proven to correlate with a reduced risk of NCDs (Thompson et al., 2024).

The Indonesian government, through the Ministry of Health, has updated Ministerial Regulation No. 15 of 2024 concerning the Latest Balanced Nutrition Guidelines, emphasizing the importance of consuming at least 400 grams of fruit and vegetables per day, with an emphasis on diversity of colors and types. However, data from the 2023 Indonesian Nutrition Status Survey (SSGI) shows that 92.8% of the Indonesian population still consumes fruit and vegetables below the WHO recommendations (Ministry of Health, 2024).

Evaluation of the implementation of fruit and vegetable consumption promotion policies, particularly in the context of modulating the inflammatory immune response for NCD prevention, still requires a more comprehensive approach, integrating digital technology and artificial intelligence for monitoring and evaluation. Nabire District, as one of the regions with unique geographic and sociodemographic characteristics in Papua, requires an innovative evaluation approach to optimize the effectiveness of health policies in the digital era.

This study aims to evaluate the role of antioxidants in modulating the inflammatory immune response and the effectiveness of fruit and vegetable consumption promotion policies for NCD prevention in Nabire District in 2025, incorporating digital health technology as an evaluation and monitoring tool.

2. Preliminaries or Related Work or Literature Review

2.1 Pathophysiology of Non-Communicable and Inflammatory Diseases

Non-communicable diseases (NCDs) are a group of chronic diseases not transmitted through direct contact, with four main groups: cardiovascular disease, diabetes mellitus, cancer, and chronic lung disease (Benziger et al., 2016). The pathogenesis of NCDs involves a complex interaction between genetic, environmental, and lifestyle factors that converge on chronic inflammatory pathways.

Low-grade chronic inflammation is a common characteristic of NCDs, characterized by persistent increases in inflammatory mediators in the systemic circulation (Pahwa et al., 2016). This process is mediated by the activation of nuclear factor-kappa B (NF- κ B), which induces the expression of pro-inflammatory genes, producing cytokines such as TNF- α , IL-1 β , IL-6, and acute-phase proteins such as CRP (Liu et al., 2017).

2.2 Oxidative Stress and Reactive Oxygen Species

Oxidative stress is defined as an imbalance between ROS production and cellular antioxidant capacity, with recent understanding of the role of ferroptosis and mitochondrial dysfunction in the pathogenesis of NCDs (Chen & Wang, 2024). The main ROS involved in NCD pathogenesis include superoxide anion (O $_2^{\bullet-}$), hydrogen peroxide (H $_2$ O $_2$), and hydroxyl radical (\bullet OH), with increasing understanding of the role of lipid peroxidation products and advanced glycation end products (AGEs).

Recent research has shown that excessive ROS production not only activates redox-sensitive transcription factor pathways such as NF- κ B and activator protein-1 (AP-1) but also triggers epigenetic modifications through DNA methylation and histone modifications, contributing to chronic disease progression (Nakamura et al., 2024).

2.3 Antioxidant Systems and Immune Response Modulation

The antioxidant defense system consists of enzymatic and non-enzymatic components that work synergistically to neutralize ROS, with recent understanding of the role of the Nrf2 pathway and antioxidant response elements (ARE) in cellular defense (Zhang et al., 2024). Key enzymatic antioxidants include superoxide dismutase (SOD), catalase, glutathione peroxidase, and newly discovered enzymes such as peroxiredoxins and thioredoxins.

Modulation of the immune response by antioxidants occurs through more complex mechanisms than previously understood: (1) direct scavenging of ROS, (2) inhibition of NF- κ B and NLRP3 inflammasome activation, (3) modulation of anti-inflammatory gene expression through epigenetic mechanisms, (4) stabilization of immune cell membranes, and (5) regulation of autophagy and mitophagy processes (Calder et al., 2024).

2.4 Fruit and Vegetable Phytochemicals as Antioxidants

Recent research has identified novel bioactive compounds in fruits and vegetables, including rare flavonoids, unique polyphenolic structures, and previously unknown

antioxidant peptides (Kumar & Goel, 2024). In addition to classic flavonoids, research from 2024-2025 revealed the potential of stilbenes, lignans, and alkaloids as potent anti-inflammatory agents.

The bioavailability of phytochemicals is now more comprehensively understood, with the role of the gut microbiome in polyphenol metabolism and the production of bioactive metabolites with systemic activity (Panche et al., 2024). Personalized nutrition approaches based on individual genetic polymorphisms in antioxidant enzymes are beginning to be applied to optimize dietary intake recommendations.

2.5 Epidemiological Evidence of Fruit and Vegetable Consumption and NCD Prevention: A Recent Meta-analysis

A comprehensive 2024 meta-analysis of 148 cohort studies demonstrated a stronger dose-response relationship than previously established between fruit and vegetable consumption and a reduced risk of NCDs. Every 200g increase in daily fruit and vegetable consumption was associated with a 12% reduction in the risk of coronary heart disease, 18% in stroke, 15% in type 2 diabetes, and 5% in cancer (Aune et al., 2024).

Intervention studies using wearable devices and continuous biomarker monitoring demonstrated that personalized fruit and vegetable interventions can reduce inflammatory markers with greater efficacy than standard population-based approaches (Hermsdorff et al., 2024).

2.6 Fruit and Vegetable Consumption Promotion Policy and Strategy

The WHO has updated its recommendation to a minimum of 500g of fruits and vegetables per day, emphasizing color diversity and phytochemical variety for optimal NCD prevention (World Health Organization, 2024). Current promotion strategies integrate digital health technologies, artificial intelligence for personalized recommendations, and community-based participatory approaches with cultural adaptation.

The latest model combines Digital Health Behavior Change Theory with the Traditional Health Belief Model, incorporating mobile health applications, social media interventions, and gamification strategies for sustained behavior change (Shaikh et al., 2024).

3. Proposed Method

This study used a mixed-methods design with an integrated digital health evaluative approach to assess the implementation and impact of fruit and vegetable consumption promotion policies in Nabire District. The quantitative component employed a cross-sectional design with longitudinal follow-up to analyze the relationship between antioxidant intake and inflammatory biomarkers, while the qualitative component employed a phenomenological approach with digital ethnography methods.

The study was conducted in Nabire District, Papua Province. The location was selected based on regional characteristics with a high prevalence of non-communicable diseases (NCDs), the implementation of existing fruit and vegetable consumption promotion policies, and the availability of adequate digital health infrastructure.

The study population was adults aged 18-65 years who resided in Nabire District and had smartphone access for digital health monitoring. Inclusion criteria included: (1) being 18-65 years old, (2) having resided in Nabire for at least one year, (3) not currently taking high-dose antioxidant supplements, (4) having a smartphone with the research application, and (5) being willing to participate in digital monitoring for six months.

Exclusion criteria: (1) suffering from acute infectious or chronic inflammatory diseases, (2) being pregnant or breastfeeding, (3) having a history of active autoimmune disease, (4) regularly taking anti-inflammatory medication, and (5) not being able to use digital technology.

The sample size was calculated using a proportion estimation formula with a precision of 4%, a confidence level of 95%, an expected proportion of 60% (based on a pilot study), and a design effect of 1.2 for clustered sampling, resulting in a minimum of 384 respondents. The sampling technique used stratified random sampling based on administrative areas (urban, peri-urban, and rural) with proportional allocation and oversampling to compensate for potential dropouts in digital monitoring.

Data was collected through an integrated digital platform that included: (1) a mobile food diary application with AI-powered food recognition, (2) wearable devices for continuous physiological monitoring, (3) point-of-care inflammatory biomarker testing using portable devices, and (4) digital surveys with adaptive questioning algorithms.

Data analysis was conducted using advanced statistical methods, including machine learning algorithms for pattern recognition, mixed-effects models for longitudinal analysis,

and network analysis for policy implementation pathways. The software used included SPSS 28.0, R version 4.3.0, Python 3.9 for machine learning, and specialized digital health analytics platforms.

4. Results and Discussion

4.1 Respondent Characteristics

The study involved 384 respondents, with a response rate of 94.7% and a digital engagement rate of 87.3% during the follow-up period. Respondent characteristics showed a mean age distribution of 41.8 ± 13.2 years, with a female predominance (60.4%). Seventy-two percent of respondents had a high school education or higher, and 52.3% worked in the formal sector, with increased adoption of remote work post-pandemic.

The upper-middle economic status increased to 31.7% compared to previous estimates, with an average family income of IDR 3,200,000 per month. The average digital literacy score was 7.2/10, with 89.3% of respondents comfortable using smartphone applications for health monitoring.

The prevalence of overweight and obesity reached 38.4% and 21.7%, respectively, indicating an increasing trend. 19.2% of respondents had a history of active smoking (a decrease from the previous period), and 8.7% consumed alcohol regularly. Moderate to vigorous physical activity was performed by 61.8% of respondents for at least 150 minutes per week, with a significant increase in home-based and technology-assisted exercise.

4.2 Fruit and Vegetable Consumption with Digital Monitoring

The average fruit and vegetable consumption of respondents was 289.7 ± 102.4 grams per day, representing an 8.3% increase compared to the 2020 estimate but still below the latest WHO recommendation of 500 grams per day. Fruit consumption (138.2 ± 61.7 g/day) showed a more significant increase compared to vegetable consumption (151.5 ± 72.3 g/day).

Digital food recognition identified a higher consumption diversity, with 23 types of fruit and 31 types of vegetables regularly consumed. The most popular fruits were bananas (81.2%), papaya (69.7%), oranges (48.4%), and apples (34.6% - increased availability). For vegetables, kale (85.4%), spinach (71.2%), tomatoes (58.7%), and broccoli (23.1% - new entry) were the most popular.

Machine learning analysis identified consumption patterns with 3 distinct clusters: Traditional Consumers (42.3%), Transitional Consumers (38.9%), and Progressive Consumers (18.8%) with significant differences in antioxidant intake profiles.

4.3 Antioxidant Intake with Enhanced Measurement

Respondents' average antioxidant intake showed improvement, with vitamin C reaching 89.7 ± 38.4 mg/day (closer to the RDA), vitamin E reaching 10.8 ± 5.2 mg/day (improved but still suboptimal), and beta-carotene reaching $3,240 \pm 1,410$ μ g/day (significant increase). Total flavonoid intake reached 287.3 ± 148.6 mg/day, indicating substantial improvement.

Advanced phytochemical analysis identified intakes of novel antioxidants, including anthocyanins (45.2 ± 23.7 mg/day), proanthocyanidins (78.4 ± 41.2 mg/day), and stilbenes (12.6 ± 8.9 mg/day). Machine learning models identified optimal antioxidant combination patterns that correlated with the lowest inflammatory profiles.

Personalized nutrition algorithms based on genetic polymorphisms (available to 67% of respondents) showed significant inter-individual variations in antioxidant needs and utilization efficiency.

4.4 Inflammatory Biomarkers with Continuous Monitoring

Continuous and point-of-care biomarker monitoring showed mean CRP concentrations of 2.41 ± 1.67 mg/L (an improvement from previous estimates), IL-6 2.89 ± 1.94 pg/mL, and TNF- α 7.83 ± 3.92 pg/mL. A total of 28.1% of respondents had CRP levels >3 mg/L (reduced cardiovascular risk prevalence).

Advanced inflammatory profiling included additional markers: IL-10 (anti-inflammatory) 8.24 ± 4.16 pg/mL, adiponectin 12.4 ± 6.8 μ g/mL, and high-sensitivity troponin 2.1 ± 1.4 ng/L. Composite inflammatory index scores indicated that 34.7% of respondents were in the low-risk category, 47.2% were in the moderate-risk category, and 18.1% were in the high-risk category.

Wearable devices capturing continuous physiological parameters (heart rate variability, skin conductance, sleep quality) showed strong correlations with traditional inflammatory biomarkers ($r=0.623-0.741$, $p<0.001$).

4.5 Relationship of Antioxidant Intake with Inflammatory Biomarkers: AI-Enhanced Analysis

Machine learning analysis confirmed a significant negative association between antioxidant intake and inflammatory biomarkers with improved precision. Random Forest models showed vitamin C as the strongest predictor of CRP reduction (feature importance 0.287), followed by total flavonoids (0.243) and anthocyanins (0.189).

Deep learning neural networks identified complex non-linear relationships and interaction effects between different antioxidants. Optimal antioxidant combinations for inflammatory modulation differed significantly across individual genetic profiles and baseline inflammatory status.

Network analysis revealed antioxidant-inflammatory pathways, with centrality measures indicating quercetin and vitamin E as key nodes in anti-inflammatory networks. Personalized intervention algorithms based on individual profiles demonstrated a 23-35% increased efficacy compared to population-based approaches.

4.6 Policy Implementation Evaluation with Digital Analytics

Digital policy implementation tracking showed improved coverage, reaching 74.2% of the target population, with real-time monitoring capabilities. Digital awareness campaigns through social media and mobile applications achieved a reach rate of 68.4% with an engagement rate of 34.7%.

An AI-powered chatbot for nutrition education demonstrated 78.3% user satisfaction with an average interaction time of 8.4 minutes per session. Gamification elements in mobile applications generated 67.9% sustained engagement over a six-month period.

Digital distribution tracking for community garden programs demonstrated 52.3% household participation, with yield optimization algorithms increasing productivity by 34%. Blockchain-based supply chain tracking for local fruits and vegetables demonstrated 89.2% traceability coverage.

Real-time sentiment analysis of social media mentions showed 72.4% positive sentiment regarding fruit and vegetable promotion programs, with improved public perception trends.

4.7 Program Effectiveness Analysis with AI-Driven Insights

An AI-driven comparative analysis between high-intensity digital intervention areas and standard implementation areas showed significant differences in outcomes. Digital-enhanced areas showed a 27.3% increase in fruit and vegetable consumption compared to baseline, versus 14.8% in standard areas ($p < 0.001$).

Automated biomarker trend analysis showed a 43% faster improvement in inflammatory profiles in the digital intervention groups. Predictive models identified optimal intervention timing and personalization strategies with 78% accuracy in outcome prediction.

Cost-effectiveness analysis using AI-optimized resource allocation showed a cost per unit of CRP improvement of IDR 1,840,000 per mg/L (a 21% improvement in cost-efficiency). Machine learning-driven program optimization demonstrated the potential for an additional 30% cost reduction with maintained efficacy.

5. Discussion

5.1 The Evolution of Fruit and Vegetable Consumption Patterns in the Digital Era

The increase in fruit and vegetable consumption among Nabire District residents to 289.7 g/day represents a positive trend, but still requires acceleration to reach the 2024 WHO target of 500 g/day. Digital monitoring capabilities provide more accurate insights than traditional dietary recall methods, with an error reduction of up to 34% (Zhang et al., 2024).

The emergence of the Progressive Consumers cluster (18.8%) indicates the adoption of modern dietary patterns with increased consumption of previously uncommon fruits and vegetables such as broccoli and apples. This indicates successful market penetration and improved supply chain accessibility, likely related to post-pandemic supply chain innovations and digital marketplace adoption.

Machine learning pattern recognition reveals distinct behavioral triggers for each consumer cluster, enabling targeted intervention strategies. Traditional Consumers demonstrated the strongest response to culturally adapted messaging, while Progressive Consumers were more responsive to scientific evidence and personalized recommendations (Sobal & Bisogni, 2024).

5.2 Personalized Antioxidant Requirements and Precision Nutrition

Advanced phytochemical profiling confirms heterogeneity in antioxidant intake patterns, with significant implications for precision nutrition approaches. Identification of novel

antioxidant intakes, such as proanthocyanidins and stilbenes, suggests dietary diversification that can optimize anti-inflammatory potential (Kumar & Pandey, 2024).

Genetic polymorphism-based personalized recommendations for 67% of respondents provide proof-of-concept for precision public health applications. Variations in antioxidant metabolism genes such as GSTM1, GSTT1, and SOD2 polymorphisms show up to three-fold differences in optimal intake requirements (Jiang, 2024).

Integration of continuous biomarker feedback with personalized recommendations demonstrates superior outcomes compared to standard population-based approaches, supporting a paradigm shift toward individualized nutrition interventions in population health programs.

5.3 Advanced Inflammatory Profiling and Multi-Biomarker Approaches

Expanding beyond traditional inflammatory markers (CRP, IL-6, TNF- α) to include anti-inflammatory markers (IL-10, adiponectin) and tissue-specific markers (high-sensitivity troponin) provides comprehensive inflammatory phenotyping. The composite inflammatory index approach demonstrated improved discriminatory power for identifying high-risk individuals (C-statistic 0.847 vs. 0.723 for single-marker approaches).

Integration of continuous physiological monitoring from wearable devices with biochemical markers revealed real-time inflammatory dynamics undetectable by traditional point-in-time sampling. Heart rate variability emerged as a strong surrogate marker for systemic inflammation, with practical implications for low-cost monitoring strategies.

Identification of optimal antioxidant combinations through network analysis provides actionable insights for food-based interventions. Synergistic effects between quercetin and vitamin E demonstrate the potential for targeted functional food development with enhanced anti-inflammatory properties.

5.4 Digital Health Technologies in Policy Implementation

Digital transformation in policy implementation shows significant improvements in reach, engagement, and monitoring capabilities. AI-powered chatbots with 78.3% user satisfaction demonstrate scalability for population-level nutrition education with maintained quality and personalization (Bandura, 2024).

Gamification strategies with 67.9% sustained engagement over six months demonstrate potential for addressing traditional challenges in behavioral maintenance. Integration of social features and competitive elements can optimize peer support mechanisms crucial for long-term behavior change (Rogers, 2024).

Blockchain-based supply chain tracking with 89.2% traceability coverage addresses food safety and quality concerns, which are crucial for consumer confidence. Transparency in the supply chain can increase willingness to pay for local produce and support sustainable local food systems.

5.5 AI-Driven Program Optimization and Predictive Analytics

Machine learning applications in program optimization show transformative potential for public health policy implementation. Predictive models with 78% accuracy in outcome prediction can enable proactive interventions and resource allocation optimization (Dehghan et al., 2024).

Real-time optimization algorithms can identify optimal intervention timings based on individual behavioral patterns and contextual factors. Personalized nudging systems can leverage behavioral economics principles to maximize intervention effectiveness with minimal resource requirements.

Cost-effectiveness improvements through AI-driven resource allocation show the potential for scaling effective interventions in resource-constrained settings. 21% cost reduction with maintained efficacy demonstrates clear value proposition for technology adoption in public health programs.

6. Conclusions

This study provides empirical evidence, supported by digital technology, that antioxidant intake from fruits and vegetables plays a significant role in modulating the inflammatory immune response in Nabire District. Enhanced precision through AI-driven analysis confirmed a stronger negative correlation between antioxidant intake and inflammatory biomarkers, supporting the scientific rationale for personalized nutrition approaches in NCD prevention. The implementation of a fruit and vegetable consumption promotion policy demonstrated marked improvement with 74% coverage and enhanced effectiveness through digital health integration. Gamification and AI-powered personalization strategies

demonstrated scalable solutions for sustainable behavior change with improved cost-effectiveness ratios. Integration of genetic profiling, continuous monitoring, and machine learning analytics demonstrates the feasibility and superiority of precision public health approaches. Personalized interventions based on individual profiles show 23-35% increased efficacy, supporting paradigm shift toward individualized population health strategies. Evidence of digital health technology effectiveness in remote and resource-limited settings like Papua shows significant potential for scaling innovations across similar contexts. Sustainability requires continued investment in digital infrastructure, capacity building, and ethical framework development for responsible AI applications in public health.

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