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Towards Integrated Air Pollution Policies: Addressing the Health and Environmental Impacts of Artisanal Crude Oil Refining

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ABSTRACT

This study examines the environmental and public health crises associated with artisanal crude oil refining in developing regions, emphasizing its role in exacerbating air pollution and exposure to carcinogenic pollutants. Through an analysis of air quality data, health impact assessments, and policy reviews, the study identifies significant gaps in regulatory enforcement and community protection. Findings reveal high concentrations of hazardous air pollutants linked to respiratory diseases, cardiovascular conditions, and increased cancer risks, particularly among children, pregnant women, and individuals with preexisting health conditions. The absence of stringent policies leaves affected communities vulnerable to long-term health and ecological consequences. The study underscores the urgent need for an integrated policy framework that enforces stricter environmental regulations, promotes sustainable refining alternatives, and strengthens community resilience through targeted interventions. By bridging the gap between environmental science and policy, this research provides a foundation for actionable strategies to mitigate the immediate and long-term impacts of artisanal refining.

Keywords: Artisanal crude oil refining; Air pollution; Health impacts; Environmental degradation; Sustainable development; Public health; Pollution control technologies; Regulatory frameworks

INTRODUCTION

Crude oil refining is a cornerstone of the global energy sector, providing essential petroleum products for industrial and domestic use. However, an illegal and informal alternative, the artisanal crude oil refining has emerged. This practice is widespread in Africa and Latin America, where economic hardship, weak regulatory enforcement, and inadequate formal refining infrastructure drive local communities toward unauthorized refining activities. Although artisanal refining provides a source of livelihood for some, it is associated with severe environmental degradation and public health risks.

In Latin America, artisanal refining has been documented in countries such as Mexico and Colombia, where illegal oil extraction and refining contribute to widespread pollution and security concerns. In Mexico, crude oil theft known locally as *huachicol*, involves siphoning crude oil from pipelines for processing in makeshift refineries. This activity has led to devastating explosions, soil contamination, and air pollution (Berbotto and Chaimey, 2021). Similarly, in Colombia, illegal refining is often linked to armed groups that operate clandestine refineries in remote forested areas, leading to deforestation and the contamination of water bodies. Despite government crackdowns, these activities persist due to high fuel demand and the economic desperation of local populations (Bargent, 2021). In Nigeria, artisanal refining is particularly entrenched in the Niger Delta region, where it is driven by poverty, unemployment, and limited access to legally refined petroleum products. The Petroleum Industry Act (PIA) of 2021, the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act, and the Harmful Waste (Special Criminal Provisions) Act explicitly prohibit unauthorized crude oil refining. However, weak enforcement and systemic corruption have allowed the practice to thrive. Artisanal refining in Nigeria typically involves crude techniques, where unprocessed oil is heated in makeshift furnaces, producing low-quality petroleum products while releasing toxic emissions into the air. Studies indicate that up to 80% of heavy crude remains unrefined, leading to extensive waste and pollution (Ephraim-Emmanuel *et al*., 2022; Udo *et al*., 2020).

The environmental consequences of illegal refining are far-reaching. This process releases harmful substances, including volatile organic compounds (VOCs), particulate matter, and polycyclic aromatic hydrocarbons (PAHs), which have been linked to respiratory diseases, cardiovascular conditions, and cancer (Onakpohor *et al*., 2020; Echendu *et al*., 2022). In heavily affected communities, residents suffer from chronic lung infections, reduced lung function, and increased cases of asthma (Meo *et al*., 2009). Additionally, the widespread contamination of soil and water sources due to crude oil spills has dire implications for food security and access to clean drinking water (Ikezam *et al*., 2021; Luke, 2023).

Despite policies such as the Petroleum Industry Act (PIA) of 2021 and the NESREA Act, significant gaps remain in addressing the artisanal refining crisis. A major challenge is weak enforcement, as corruption, inadequate funding, and lack of coordination among regulatory bodies hinder the effective implementation of environmental and energy policies (Odubo & Odubo, 2022). Additionally, while current laws criminalize artisanal refining, they fail to provide alternative livelihood opportunities for those engaged in the practice. Without viable economic alternatives, many individuals will continue to refine crude oil for survival. Another critical shortcoming is the lack of environmental monitoring and remediation programs, for long-term ecological and health hazards (Echendu *et al*., 2022). Furthermore, public health policies do not adequately integrate long-term health assessments for residents of polluted areas, placing vulnerable populations such as children, pregnant women, and individuals with preexisting conditions at heightened risk.

While previous research has highlighted the environmental and health risks of artisanal refining, many studies rely on small-scale or qualitative assessments, with limited data on air pollution levels and long-term health outcomes (Ephraim-Emmanuel, 2023; Richard, 2023). This study seeks to bridge that gap by integrating air quality data, health risk assessments, and policy analysis, offering a more comprehensive understanding of the crisis. Tackling the challenges of artisanal crude oil refining require a comprehensive strategy integrating strict regulatory enforcement, community engagement, and sustainable economic alternatives. Reducing reliance on illegal refining activities requires strategic investment in cleaner energy alternatives and community-based economic opportunities, while enhanced environmental monitoring and health surveillance

can support more targeted and informed policy responses. This study highlights the urgency of a holistic approach that integrates regulation, economic resilience, and proactive environmental and health safeguards to mitigate adverse impacts on public health, ecosystems, and long-term sustainability.

Health Impacts of Air Pollution from Artisanal Crude Oil Refining

The health impacts of air pollution resulting from artisanal crude oil refining are significant and wide-ranging, affecting respiratory and cardiovascular systems, increasing cancer risks, and disproportionately impacting vulnerable populations (Table 1). Common in regions like the Niger Delta, artisanal refining releases harmful pollutants, including particulate matter (PM), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) into the atmosphere (Nriagu *et al*., 2016; Ephraim-Emmanuel, 2023). These pollutants are major contributors to chronic respiratory diseases such as chronic obstructive pulmonary disease (COPD), emphysema, and chronic bronchitis. Particulate matter, particularly $PM_{2.5}$, can penetrate the lungs, and enter the bloodstream, exacerbating existing health conditions and contributing to new respiratory illnesses.

Table 1: Health impacts of air pollution from artisanal crude oil refining and public health implications

Health Impact	Affected Populations	Key Health Effects	Public Health Implications
Respiratory effects	Workers, children, elderly	Chronic respiratory diseases (e.g., COPD, asthma), impaired lung function, infections	Increased healthcare burden from chronic diseases, hospitalizations, and treatment
Cardiovascular effects	Adults, elderly, people with heart disease	Increased risk of heart disease, hypertension, stroke, and heart attacks	Higher mortality rates, long-term care needs, and economic strain on healthcare
Cancer risks	Workers, surrounding communities	Lung cancer and other cancers (skin, bladder) linked to toxic pollutants (e.g., benzene)	Increased incidence of cancer, long-term healthcare costs, and reduced life expectancy
Vulnerable populations	Children, pregnant women, elderly	Increased risk of asthma, preterm birth, low birth weight, developmental delays	Disproportionate health impacts, long-term developmental and maternal health issues
Long-term health consequences	The general population, especially the elderly	Chronic diseases, premature mortality, reduced life quality	Increased chronic disease burden, healthcare costs, and reduced productivity
Economic and social impacts	Low-income communities, workers	Loss of productivity, premature death, high healthcare costs	Economic strain, perpetuation of poverty, and health disparities

Ephraim-Emmanuel, 2023; Richard, 2023; Echendu *et al*., 2022; Onakpohor *et al*., 2020

Air pollution from artisanal crude oil refining poses serious health risks, particularly for vulnerable populations. Fine particulate matter and pollutants like benzene and formaldehyde exacerbate respiratory conditions, leading to increased incidences of asthma and allergies, especially in children and the elderly. Chronic exposure to these pollutants not only triggers immediate respiratory distress but also causes long-term complications, including impaired lung function. Studies show that children exposed to high pollution levels may experience stunted lung growth, while adults may suffer progressive respiratory decline, often resulting in irreversible damage.

Beyond respiratory illnesses, air pollution from crude oil refining heightens the risk of acute respiratory infections. It weakens the immune system, leading to higher hospitalization rates, particularly among children and individuals with preexisting conditions. The situation is worsened by inadequate healthcare infrastructure in these regions, further complicating treatment and recovery.

Cardiovascular complications are another major concern. Exposure to pollutants such as carbon monoxide, sulfur dioxide, and nitrogen oxides triggers systemic inflammation, raising blood pressure and increasing the risk of heart disease. Fine particulate matter, particularly $PM_{2.5}$, has been directly linked to strokes and heart attacks, as it promotes blood clot formation and arterial plaque buildup. Long-term exposure has also been associated with hypertension, further elevating cardiovascular risks for those living near refining sites.

Equally alarming is the elevated cancer risk linked to artisanal refining. The combustion of crude oil releases carcinogenic substances such as polycyclic aromatic hydrocarbons (PAHs), benzene, and formaldehyde, significantly increasing the likelihood of lung, skin, and bladder cancers. Workers in artisanal refining operations exposed to these hazardous pollutants face the highest risks. However, the effects extend beyond refining sites as obtained with pollution.

Certain groups, including children, pregnant women, the elderly, and individuals with chronic illnesses, are disproportionately affected by pollution. Children's developing lungs and higher respiratory rates make them more susceptible to long-term conditions like asthma and reduced lung function. Pregnant women exposed to high pollution levels face increased risks of preterm birth, low birth weight, and pregnancy complications such as preeclampsia. The elderly, particularly those with existing health conditions, experience worsened symptoms, leading to higher hospitalization and mortality rates.

Low-income and marginalized communities, often dependent on artisanal refining for survival, bear the brunt of pollution-related health issues. These communities are frequently located in pollution hotspots where harmful emissions are concentrated, worsening health disparities and socioeconomic challenges. The interplay between environmental degradation and economic instability creates a cycle of poor health and poverty, making it difficult for affected populations to advocate for cleaner air and better healthcare resources.

The long-term health consequences of exposure to pollutants include chronic diseases such as chronic obstructive pulmonary disease (COPD), heart disease, and various cancers. The increased demand for medical care due to pollution-related illnesses often overwhelms local healthcare facilities, leading to inadequate treatment and worsening health outcomes.

The economic and social ramifications of pollution are profound. Illness and premature mortality reduce workforce productivity, leading to decreased economic output in affected regions. High rates of absenteeism, declining productivity, and rising healthcare costs perpetuate cycles of poverty and limited social mobility. The financial burden of treating pollution-related diseases strains national and local healthcare budgets, particularly in resource-limited areas, further exacerbating economic disparities.

Tackling these challenges demands a comprehensive approach that centers on environmental justice and public health. Many affected communities struggle with limited access to clean air, adequate healthcare, and essential social resources to counteract pollution's effects. Strengthening regulatory policies, adopting cleaner technologies, and expanding healthcare services are vital steps in addressing the health inequalities worsened by pollution. Equally important is the participation of low-income and marginalized populations in policy decisions, ensuring their voices shape sustainable solutions for pollution control and public health.

Environmental Impacts of Artisanal Crude Oil Refining

The environmental impacts of artisanal crude oil refining are significant and multifaceted, affecting air quality, water resources, soil health, and biodiversity; and contributing to climate change (Table 2). Characterized by unregulated and inefficient practices, artisanal refining poses substantial risks to local ecosystems and human health. One of the most immediate consequences is the degradation of air quality. The refining process releases a variety of toxic pollutants, including particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), and polycyclic aromatic hydrocarbons (PAHs) into the atmosphere. These emissions contribute to the formation of ground-level ozone, a key component of smog that leads to serious health issues (Ikezam *et al*., 2021; Ephraim-Emmanuel *et al*., 2022).

In addition to human health impacts, poor air quality harms local ecosystems, as many plant and animal species are sensitive to pollution, resulting in diminished biodiversity and disrupted habitats (Ikezam *et al*., 2021; Ephraim-Emmanuel *et al*., 2022).

Table 2: Environmental Impacts of Artisanal Crude Oil Refining

Impact Category	Key Issues	Consequences
Air quality degradation	Emission of toxic pollutants ($PM_{2.5}$, VOCs, CO, SO_2, PAHs)	Smog formation, respiratory and cardiovascular diseases, ecosystem damage
Water pollution	Oil spills, contaminated runoff, hazardous substances in water	Fish kills, reduced biodiversity, unsafe drinking water
Soil contamination	Oil residue, heavy metal contamination	Loss of fertility, bioaccumulation of toxins, agricultural disruption
Deforestation and habitat loss	Land clearing for refining, destruction of natural habitats	Loss of biodiversity, soil erosion, habitat destruction
Climate change contributions	Greenhouse gas emissions (CO_2, CH_4), land use change	Accelerated global warming, reduced carbon sequestration, land degradation
Waste generation	Solid waste (charcoal, spent catalysts), hazardous byproducts	Soil and water contamination, persistent environmental pollution
Cumulative environmental stress	Combined effects of refining and other activities like deforestation	Regional environmental crises, unsustainable land use practices

Luke, 2023, Ephraim-Emmanuel *et al*., 2022; Ikezam *et al*., 2021; Nwozor *et al*., 2020

Water pollution is another critical consequence of artisanal crude oil refining. Uncontained oil spills and runoff from refining sites often contaminate nearby water bodies, including rivers, lakes, and groundwater. These pollutants introduce hydrocarbons, heavy metals, and other toxic substances into aquatic ecosystems, severely impacting marine life (Amangabara, 2012). Research has documented fish kills and a decline in biodiversity in waters contaminated with pollutants like benzene, which cause reproductive failures and organ damage in aquatic organisms (Amangabara, 2012). This deterioration in water quality also poses significant health risks to humans, making the water unsafe for drinking, irrigation, or recreational use (Amangabara, 2012). The effects of artisanal refining on soil health are similarly concerning. Spilled crude oil and waste byproducts from refining processes seep into the soil, introducing harmful substances such as heavy metals and organic compounds that persist for long periods (Amangabara, 2012). This contamination disrupts soil ecosystems, leading to a loss of fertility and rendering the land unsuitable for agriculture or grazing (Ikezam *et al*., 2021; Amangabara, 2012). The bioaccumulation of these toxins in plants and animals further exacerbates the issue, as these substances are transferred to the food chain, posing long-term health risks to both human and local wildlife (Amangabara, 2012).

Deforestation and habitat loss directly result from the expansion of artisanal refining operations. As demand for crude oil increases, more land is cleared for refining activities, leading to widespread habitat destruction, especially in tropical regions (Ikezam *et al*., 2021; Nwozor *et al*., 2020). This poses a significant threat to biodiversity, as many species rely on these ecosystems for survival. Beyond driving species decline, the destruction of forests and natural habitats also accelerates erosion and sedimentation in nearby water bodies, further degrading water quality and disrupting aquatic ecosystems (Ikezam *et al*., 2021; Nwozor *et al*., 2020).

The contribution of artisanal refining to climate change cannot be overlooked. The inefficient, highly polluting nature of these activities results in significant greenhouse gas emissions, including carbon dioxide (CO_2) and methane (CH_4) (Ikezam *et al*., 2021; Nwozor *et al*., 2020). The carbon footprint of unregulated artisanal refining is substantially higher than that of more regulated industrial refining, exacerbating the global climate crisis (Ikezam *et al*., 2021; Nwozor *et al*., 2020). Moreover, land use changes linked to the expansion of artisanal refining reduce the natural carbon sequestration capacity of forests and wetlands, further intensifying global warming impacts (Ikezam *et al*., 2021; Nwozor *et al*., 2020).

Although artisanal refining operations face significant waste generation and management

challenges; yet many regions lack the infrastructure to manage this waste effectively (Ikezam *et al.*, 2021; Nwozor *et al.*, 2020). As a result, toxic byproducts are often disposed of improperly, contaminating nearby water bodies and landfills, and creating long-term environmental risks (Ikezam *et al.*, 2021; Nwozor *et al.*, 2020). The prolonged presence of heavy metals and other persistent organic pollutants (POPs) in the environment can have enduring effects on local ecosystems and future generations (Ikezam *et al.*, 2021; Nwozor *et al.*, 2020). Existing environmental challenges, such as deforestation and resource overexploitation, further compound the stress caused by artisanal refining. The demand for land to support this illegal form of refining often leads to conflicting land uses, placing additional pressure on fragile ecosystems (Ikezam *et al.*, 2021; Nwozor *et al.*, 2020). In some regions, the combination of artisanal refining and other forms of environmental degradation has led to regional environmental crises that not only affect local populations but also have cross-border repercussions, such as pollution and ecosystem disruption (Ikezam *et al.*, 2021; Nwozor *et al.*, 2020).

Current Policies and Regulatory Gaps towards Artisanal Crude Oil Refining mitigation

Artisanal crude oil refining presents a multifaceted challenge that spans environmental, health, and socioeconomic issues. A major barrier to effective governance and mitigation efforts is the absence of specific regulations for this informal sector. In many oil-rich countries, laws tailored to the unique nature of artisanal refining are often lacking, as these operations typically exist outside formal regulatory frameworks. Existing environmental regulations are primarily geared toward large-scale industrial operations and fail to account for the small-scale, informal nature of artisanal refining, which can result in severe environmental degradation and health risks (Ikezam *et al.*, 2021; Odubo & Odubo, 2022). The issue is exacerbated by inadequate enforcement mechanisms, as local authorities frequently struggle with limited resources and a lack of political will to regulate these activities effectively (Nriagu *et al.*, 2016; Ephraim-Emmanuel *et al.*, 2022). Figure 1 presents a conceptual framework developed in this study, outlining potential strategies for addressing the regulatory gaps in artisanal crude oil refining.

Figure 1: Conceptual framework outlining potential strategies for addressing the regulatory gaps in artisanal crude oil refining

The lack of coordination between national and regional policies further complicates the regulation of artisanal crude oil refining. National efforts to curb air pollution and safeguard environmental health often conflict with local ones, leading to inconsistencies that undermine mitigation strategies (Odubo & Odubo, 2022; Echendu *et al*., 2022). This disjointed approach is particularly evident in the health, environmental, and labor sectors, where fragmented policies fail to provide a comprehensive response to the public health and ecological risks posed by artisanal refining (Ikezam *et al*., 2021; Odubo & Odubo, 2022). Furthermore, existing policies do not account for the informal nature of these operations, leaving them largely unregulated and beyond the reach of government oversight (Onwuna *et al*., 2022).

Air pollution control measures are particularly limited in the context of artisanal refining. Many countries lack air quality standards tailored to the emissions from artisanal refining, which include harmful pollutants like sulfur oxides, volatile organic compounds (VOCs), and particulate matter (Echendu *et al*., 2022; Onakpohor *et al*., 2020). The absence of adequate pollution monitoring infrastructure further exacerbates this issue, as few countries can monitor pollution levels around artisanal refining sites (Ephraim-Emmanuel *et al*., 2022; Onwuna *et al*., 2022). As a result, the failure to regulate hazardous emissions from these operations poses significant risks to both environmental and public health (Ikezam *et al*., 2021; Ephraim-Emmanuel, 2023).

The lack of accurate report on pollution levels and health impacts from artisanal refining poses a significant challenge to effective policy development. Due to the informal nature of these operations, research on the specific health effects of air pollution from artisanal refining remains limited, making it difficult to formulate evidence-based policies (Ephraim-Emmanuel *et al*., 2022; Ephraim-Emmanuel, 2023). The absence of reliable baseline data on pollution levels, health outcomes, and socioeconomic effects further hampers policymakers' ability to grasp the full extent of the issue and implement targeted interventions (Nriagu *et al*., 2016; Ephraim-Emmanuel *et al*., 2022). Without comprehensive data, awareness remains low, and the urgency needed to address the problem is diminished (Onwuna et al., 2022).Community engagement and awareness are crucial for effective policy implementation, yet these are often lacking in the context of artisanal refining. Public awareness campaigns on the dangers of air pollution from artisanal refining are limited, resulting in inadequate pressure on authorities to take action (Odubo & Odubo, 2022; Echendu *et al*., 2022). Moreover, communities directly impacted by artisanal refining are often excluded from policy development processes, reducing the relevance and effectiveness of regulatory measures (Ikezam *et al*., 2021; Odubo & Odubo, 2022). Local governments and communities may also lack the capacity to implement and enforce regulations, particularly in remote or impoverished areas where artisanal refining is prevalent (Onwuna *et al*., 2022; Echendu *et al*., 2022).

Occupational health and safety standards for workers in artisanal refining are alarmingly weak. Workers often lack access to protective equipment, safe working conditions, and training on handling hazardous substances; exposing them to chemicals such as benzene, hydrogen sulfide, and sulfur dioxide (Ephraim-Emmanuel, 2023). Without structured health monitoring programs workers face long-term health risks (Ephraim-Emmanuel *et al*., 2022; Ephraim-Emmanuel, 2023). This lack of oversight also impacts surrounding communities, as emissions from these operations have far-reaching public health consequences (Ikezam *et al*., 2021; Ephraim-Emmanuel *et al*., 2022).

At the international level, significant policy gaps and weak enforcement mechanisms persist regarding artisanal crude oil refining. Although global agreements like the Paris Agreement and the Stockholm Convention exist, they are not specifically tailored to address the unregulated, informal activities of artisanal refining (Odubo & Odubo, 2022; Echendu *et al*., 2022). The weak enforcement of these international frameworks complicates the situation, as many countries fail to prioritize or implement regulations to govern artisanal refining (Onwuna *et al*., 2022; Echendu *et al*., 2022). Moreover, the absence of established global standards or best practices limits the potential for coordinated international efforts to address the impacts of this sector (Odubo & Odubo, 2022; Echendu *et al*., 2022).

Policy shortcomings are also evident in promoting cleaner alternatives to artisanal refining. There is a lack of incentives for adopting cleaner technologies and sustainable refining practices that could reduce air pollution and environmental damage (Odubo &

Odubo, 2022; Echendu *et al.*, 2022). Furthermore, governments often fail to create pathways or provide incentives for transitioning artisanal refiners to formal, regulated operations with access to cleaner technologies and better working conditions (Onwuna *et al.*, 2022; Echendu *et al.*, 2022). The lack of sustainable livelihood alternatives for communities engaged in artisanal refining exacerbates the issue, as many people enter this sector due to economic necessity (Ikezam *et al.*, 2021; Odubo & Odubo, 2022).

The socioeconomic factors driving artisanal refining must also be addressed. In many oil-rich regions, such as Nigeria's Niger Delta, poverty and the lack of alternative livelihood opportunities force communities to turn to artisanal refining as a means of survival (Odubo & Odubo, 2022; Richard *et al.*, 2022). This context underscores the need for comprehensive policies that tackle both the environmental impacts of artisanal refining and the underlying economic drivers sustaining the sector (Odubo & Odubo, 2022; Echendu *et al.*, 2022). Without addressing these root causes, efforts to regulate and mitigate the impacts of artisanal refining are unlikely to succeed.

Sustainability and Sustainable Development: Toward Integrated Air Pollution Policies for Artisanal Crude Oil Refining Mitigation

The issue of air pollution from artisanal crude oil refining is a critical concern that requires an integrated approach to policy formulation (Table 3). The artisanal refining sector, is common in many developing regions, often operates with insufficient environmental safeguards, leading to significant air quality deterioration and adverse health effects. This highlights the need for comprehensive policy frameworks that combine air pollution control with public health initiatives. Such integration is vital to tackle both the environmental degradation and the health risks associated with artisanal refining practices. Studies have demonstrated that air pollution from these activities contributes to increased respiratory diseases and other health complications, emphasizing the need for a coordinated response from both the health and environmental sectors (West *et al.*, 2013; Kelly & Fussell, 2011).

Collaboration across multiple sectors is crucial for developing effective policies that address the root causes of pollution while promoting sustainable development. Environmental agencies, health departments, and energy sectors must work together to create comprehensive strategies that tackle pollution and improve public health outcomes. The synergy between improving air quality and public health can result in policies that prioritize both environmental sustainability and health benefits. For example, initiatives aimed at reducing emissions from artisanal refining could simultaneously reduce the incidence of pollution-related diseases, thus enhancing community health and productivity (Zeng *et al.*, 2019; McCollum *et al.*, 2013).

Utilizing policy tools such as environmental regulations, health assessments, and economic incentives is essential for encouraging cleaner technologies in artisanal refining. Strong regulations can establish emission standards for artisanal refineries, while health assessments provide valuable data on the impacts of pollution on local populations. Economic incentives, such as subsidies for cleaner technologies, can motivate refiners to adopt more environmentally friendly practices. Research suggests that implementing strict air quality regulations can significantly reduce harmful emissions, leading to improved public health outcomes (Jin *et al.*, 2016; Shu *et al.*, 2022).

Transitioning to sustainable alternatives in artisanal refining is a key strategy for reducing air pollution. Adopting cleaner technologies, such as low-emission refining methods, can significantly curb the release of harmful pollutants into the atmosphere. For instance, small-scale, low-emission technologies have effectively reduced emissions while maintaining the economic viability of local refiners (Calel & Dechezleprêtre, 2016; Vuuren *et al.*, 2006). Additionally, promoting energy transitions and reducing dependence on crude oil can lessen air pollution. Encouraging the use of renewable energy sources like solar or biogas can offer cleaner alternatives, reducing reliance on traditional, polluting refining methods (Yang, 2023; McCollum *et al.*, 2013).

Technological innovation plays a crucial role in transitioning to cleaner refining practices. Investments in research and development of cost-effective pollution control technologies, such as smokeless refining stoves and air filtration systems, can greatly reduce emissions from artisanal refineries.

Table 3: Integrated Strategies for Mitigating Health and Environmental Impacts of Artisanal Crude Oil Refining

Policy focus	Sustainability and development actions	Public health focus
Integrated air pollution and health policies	Integrate air quality and health policies for holistic solutions.	Address dual impacts on air quality and public health.
	Collaborate across sectors to address pollution and health risks.	Minimize exposure to hazardous pollutants.
	Prioritize improving air quality and reducing pollution-related diseases.	Reduce respiratory and cardiovascular diseases.
	Use regulations and incentives to promote cleaner refining practices.	Protect vulnerable populations from health risks.
Sustainable alternatives to artisanal refining	Adopt cleaner refining technologies with lower emissions.	Reduce the health burden from exposure to toxic pollutants.
	Transition to renewable energy sources for cleaner production.	Improve long-term health outcomes through cleaner energy.
	Invest in low-cost pollution control technologies for artisans.	Lower respiratory illnesses and related healthcare costs.
	Promote renewable energy in refining-dependent communities.	Support healthier living environments for local populations.
Community-based solutions and empowerment	Engage communities in designing contextually appropriate solutions.	Empower local populations to adopt healthier practices.
	Raise awareness of health risks and cleaner alternatives.	Educate on the dangers of air pollution and mitigation methods.
	Provide training on sustainable refining practices and technologies.	Increase community capacity to address health risks.
	Offer financial incentives for adopting clean technologies.	Incentivize health-focused, sustainable behaviors.
Strengthening governance and enforcement	Strengthen regulations and enforce air pollution standards.	Ensure public health protection through regulatory enforcement.
	Establish systems for monitoring emissions and compliance.	Monitor air quality and health outcomes regularly.
	Create clear guidelines for sustainable refining practices.	Promote safe working conditions and public health guidelines.
	Empower local authorities to enforce environmental regulations.	Ensure local authorities are focused on public health.
Policy Integration at the local and national levels	Develop context-specific policies considering local conditions.	Tailor health policies to meet local public health needs.
	Foster multi-stakeholder collaboration for effective policy implementation.	Integrate health perspectives into environmental policies.
	Integrate indigenous knowledge into modern environmental policies.	Promote culturally sensitive health interventions.
	Align policies with sustainable development goals (SDGs).	Achieve health-focused SDGs, particularly for vulnerable groups.
Strengthening international cooperation and knowledge sharing	Share best practices and technologies across borders.	Global health cooperation to mitigate refining impacts.
	Coordinate policies regionally for cross-border environmental issues.	Address transnational public health challenges.
	Provide technical support and funding for developing countries.	Support healthcare infrastructure and pollution management.
	Promote global research and data sharing on refining impacts.	Build a global understanding of health impacts from refining.
Long-term vision for sustainable development	Diversify local economies away from artisanal refining.	Support community resilience and improved health outcomes.
	Focus on ecosystem restoration and pollution remediation.	Reduce health risks from environmental degradation.
	Embed sustainability in all pollution mitigation strategies.	Promote long-term public health through environmental sustainability.
	Monitor and adapt policies to ensure sustainable progress.	Track health improvements through policy adjustments.

Studies have shown that introducing such technologies can significantly improve air quality and public health (Guo *et al*., 2016; Shu *et al*., 2022). Supporting green energy initiatives in communities reliant on artisanal refining can also provide economic pathways to move away from traditional practices that contribute to air pollution (Han *et al*., 2023).

Community engagement is a vital aspect of designing and implementing policies to reduce air pollution from artisanal refining. Involving local communities in policy development ensures that solutions are both contextually relevant and culturally appropriate. Public education campaigns about the health risks of artisanal refining and the benefits of cleaner alternatives can foster community-level behavioral changes (Kishimoto *et al*., 2017; Kelly & Fussell, 2011). Capacity-building and training programs can equip local artisans with the skills to implement cleaner refining practices, empowering them to actively mitigate pollution (Li, 2022; Peng *et al*., 2021).

Economic incentives are also key to encouraging sustainable practices among artisanal refiners. Offering financial support or subsidies for those transitioning to cleaner technologies can make it economically viable for local refiners to adopt less-polluting methods. Research indicates that economic incentives can effectively drive the adoption of cleaner practices across sectors, including artisanal refining (Tessum *et al*., 2017; Bollen *et al*., 2009).

Strengthening governance and enforcement mechanisms is crucial to ensuring compliance with air pollution standards. Enhanced regulatory frameworks that enforce stricter emissions standards for artisanal refining can significantly reduce air pollution. Establishing robust monitoring and compliance systems is essential to track emissions and hold refiners accountable for violations (Gao *et al*., 2019; Jiang *et al*., 2015). Clear guidelines for sustainable refining practices should be developed and made accessible to local stakeholders to ensure that everyone involved understand their responsibilities (Modak *et al*., 2015; Fontanella *et al*., 2007).

Policy integration at both local and national levels is necessary to address the diverse impacts of artisanal refining. Developing context-specific policies on local environmental, economic, and social conditions will likely lead to more effective outcomes. Multi-stakeholder collaboration involving national governments, local authorities, NGOs, and international organizations can help implement integrated policies that balance environmental, health, and socioeconomic concerns (Gupta *et al*., 2020; Zeng *et al*., 2019). Including indigenous knowledge and practices in modern policies can promote a more inclusive approach to sustainability by recognizing the value of traditional environmental management techniques (Zong *et al*., 2020).

Strengthening international cooperation and knowledge sharing is essential to address the transboundary nature of air pollution. Global collaboration can facilitate the sharing of best practices, technologies, and expertise to mitigate the environmental impacts of artisanal crude oil refining. Transnational policy coordination is crucial in regions where artisanal refining spans multiple countries, ensuring collective action is taken to address shared environmental challenges (West *et al*., 2013; Han *et al*., 2023). Financial and technical assistance for developing countries can support the implementation of sustainable refining practices, enabling them to transition away from polluting methods (Jin *et al*., 2016; West *et al*., 2013).

A long-term vision for sustainable development must prioritize economic diversification away from artisanal refining. Developing alternative, environmentally sustainable livelihoods that are economically viable can help build resilience in affected communities. Environmental restoration and reclamation efforts should also be prioritized, focusing on soil and water conservation, reforestation, and pollution remediation to create healthier environments for local populations (McCollum *et al*., 2013; Shu *et al*., 2022). Sustainable development should be at the core of air pollution mitigation strategies, ensuring that environmental, economic, and social sustainability are addressed simultaneously for lasting solutions (Zeng *et al*., 2019; Zong *et al*., 2020).

Finally, continuous monitoring of the outcomes of implemented policies is critical to ensuring that air pollution mitigation and sustainable development goals are consistently met. Adaptive management strategies should be used to adjust policies based on monitoring data, ensuring they tackle the evolving challenges of air pollution from artisanal refining (Li, 2022; Peng *et al*., 2021). By fostering a comprehensive approach that integrates air pollution control with public health initiatives,

technological innovation, community engagement, and international cooperation, society can move toward a more sustainable future for communities impacted by artisanal crude oil refining.

CONCLUSION

Artisanal crude oil refining poses significant public health and environmental sustainability challenges, especially in developing regions. The unregulated nature of these practices leads to severe health consequences, including respiratory and cardiovascular diseases, cancer risks, and long-term exposure to hazardous pollutants. Vulnerable populations, such as children, pregnant women, and individuals with pre-existing health conditions are disproportionately affected by these pollutants. Environmentally, artisanal refining contributes to air and soil pollution, water contamination, and overall ecosystem degradation. Addressing these issues requires the urgent implementation of integrated air pollution policies that promote cleaner refining technologies but enforce stricter regulations and support community-based initiatives. Collaboration between policymakers, stakeholders, and local communities is crucial to prioritize sustainable, health-conscious solutions that mitigate the harmful effects of artisanal refining and protect both human and environmental health.

Comprehensive, well-coordinated policies are key to reducing the health and environmental impacts of artisanal crude oil refining. While these small-scale operations may provide short-term economic benefits, their long-term consequences are detrimental to public health and the environment. A multifaceted approach, including the development of cleaner refining technologies, stronger regulatory frameworks, and economic diversification, is essential for transitioning away from harmful practices. Future research should focus on cost-effective pollution control technologies, the long-term health effects of exposure, and scalable, sustainable alternatives. Additionally, effective policy enforcement, community engagement, and international cooperation are necessary to address the complex relationship between air pollution, public health, and sustainable development in regions reliant on artisanal crude oil refining.

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