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Review

Climate change and community conflicts in Sub-Saharan Africa: A review of the evidence

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This paper delves into the link between climate and conflict in Africa, drawing insights from climate science, political ecology, and peace studies, and it emphasizes the need for integrated climate adaptation and peacebuilding policies, rooted in inclusive governance, social justice, and community-based approaches aligned with the Sustainable Development Goals. Quantitative data analysis supports associations between climate variables and conflict incidence, while case studies in the Sahel, Horn of Africa, and Lake Chad Basin demonstrate climate influences on communal violence. Further research into root causes is needed to inform structural solutions.

Key words: Climate change, conflict, Sub-Saharan Africa, evidence review, climate adaptation, peacebuilding policies.

INTRODUCTION

Climate change is increasingly recognized as exacerbating conflicts in Africa [United Nations Environment Programme (UNEP), 2015]. The Intergovernmental Panel on Climate Change (IPCC) (2023) highlights that shifts in rainfall, rising temperatures, and severe weather events can negatively impact livelihoods (IPCC, 2023), leading to heightened social and political tensions, particularly in humanitarian emergencies such as those observed in the Sahel (Global Risk Insights, 2019). This evidence underscores the first key question of our review: What does empirical evidence indicate about the statistical relationships between climate variables and African conflict incidence? According to the IPCC, climate change affects every region of the world differently, with varying levels of impact (IPCC, 2023). Climate change is now understood to result in negative impacts such as more intense rainfall, potentially leading to flooding, and severe droughts in many regions (Boehm and Schumer, 2023, March 20). These observations highlight the second key question of our review: How does climate change interact with contextual political, economic, and social factors to influence conflict risks? This review synthesizes evidence from multiple academic disciplines regarding climate-conflict linkages in Africa. It unpacks these complex dynamics by applying perspectives from climate science, political ecology, and peace and conflict studies. Case studies of community clashes in the Sahel, Horn of Africa, and Lake Chad Basin are presented to illustrate the third key question of our review: What conflict prevention and peacebuilding strategies are necessary to integrate climate change adaptation?

Evidence gaps, policy implications, and areas for further research are discussed in this review. Each part elaborates on the three key questions, providing a comprehensive

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overview of the current state of knowledge on the climate-conflict nexus in Africa. Climate change's role in exacerbating African conflicts is increasingly recognized (United Nations Environment Programme [UNEP], 2015). The Intergovernmental Panel on Climate Change (IPCC) (2023) highlights that shifts in rainfall, rising temperatures, and severe weather events can adversely affect livelihoods (IPCC, 2023), leading to heightened social and political tensions, often culminating in humanitarian emergencies, as observed in the Sahel (Global Risk Insights, 2019, July). According to the IPCC, climate affects every region of the world differently (IPCC, 2023), with climate change known to cause negative impacts such as more intense rainfall, potentially leading to flooding, and severe droughts in many regions (Boehm and Schumer, 2023, March 20). This review synthesizes evidence from various academic disciplines on climate-conflict linkages in Africa, analyzing the complex dynamics through perspectives from climate science, political ecology, and peace and conflict studies. Case studies of community clashes in the Sahel, Horn of Africa, and Lake Chad Basin are presented to illustrate these dynamics.

The review addresses the following key questions:

1. What does empirical evidence indicate about statistical relationships between climate variables and African conflict incidence?
2. How does climate change interact with contextual political, economic, and social factors to influence conflict risks?
3. What conflict prevention and peacebuilding strategies are needed to integrate climate change adaptation?

CLIMATE CHANGE IMPACTS IN AFRICA

Temperatures in Africa have risen faster than the global average over the past 50 years (Serdeczny et al., 2017). In its 2022 report, the IPCC states that extreme weather events such as droughts, floods, and tropical cyclones have increased in frequency and severity (IPCC, 2022), necessitating greater resources to address them. Specifically focusing on Africa, temperatures are projected to rise between 4–6ºC over subtropical regions and between 3–5ºC over tropical regions by 2100 under the A2 scenario of the Special Report on Emission Scenarios (low mitigation) (Engelbrecht et al., 2015). Furthermore, temperatures in Africa are projected to increase by an average of 2 to 8ºC compared to 1986 to 2005 levels under high emissions scenarios (Engelbrecht et al., 2015). These climatic shifts significantly impact the livelihoods of populations dependent on climate-sensitive sectors such as agriculture, fisheries, and pastoralism (UNEP, 2011). Mbow et al. (2019) emphasize that rising temperatures, altered rainfall patterns, and desertification can lead to decreased crop yields, livestock productivity, and fishery outputs, thereby threatening rural food supply and income. Additionally, sea-level rise and coastal erosion degrade settlements, infrastructure, and ecosystems in coastal regions (IPCC, 2022). Unpredictable rainfall disrupts the hydropower potential and water supplies of many nations (Conway et al., 2017). Climate "hotspots" are expected to result in population displacement to urban areas and across borders, often exacerbating social tensions (Rigaud et al., 2018).

QUANTITATIVE EVIDENCE ON CLIMATE-CONFLICT LINKAGES

The interplay between climate change and conflict unfolds amidst a spectrum of meteorological extremes. According to a study conducted by researchers at the University of California, Berkeley, and Princeton University, even minor changes in normal temperature and precipitation patterns can significantly increase the potential for conflict (University of California, Berkeley, 2013). Furthermore, Burke et al. (2013) analysis of 60 quantitative studies revealed a notable and positive correlation between rising temperatures and conflict. Finally, a 1% temperature increase might escalate civil war risks by 4.5%, potentially leading to a 54% surge in armed clashes by 2030 (Earth.Org, 2020).

Studies indicate that even minor temperature changes can substantially elevate conflict potential, with a 1% temperature increment potentially increasing civil war risks by 4.5%, suggesting a 54% surge in armed clashes by 2030 (Earth.Org, 2020). While socio-political strife often sparks conflict, climate-related challenges, accentuated by the Clausius-Clapeyron equation, exacerbate hydro-meteorological disasters. These climatic fluctuations, whether in the form of prolonged droughts or sudden downpours, can either exacerbate or intensify conflict across various landscapes.

This phenomenon is particularly evident in Africa, where climate change acts as both a precursor to and a consequence of conflict (The Conversation, 2022). These swings in climatic conditions, manifesting as prolonged droughts or sudden downpours, either amplify or escalate conflict across diverse terrains, notably in Africa, where climate change serves as both a signal of and a response to strife (Earth.Org, 2020).

According to those involved in research, implementation, and policy-making, the nexus between climate change and conflict presents a potential risk for climate change to intensify and escalate conflict (Mercy Corps, 2020). This issue is particularly noticeable in fragile situations affected by conflict, placing them in dual jeopardy: they are more vulnerable to the severe ramifications of climate change while simultaneously lacking the ability to accommodate or mitigate these effects. This situation amplifies preexisting factors contributing to instability and violent contention in these susceptible contexts (Mercy Corps, 2020). Moreover, stakeholders recognize that this issue is nuanced and multi-dimensional, with indications pointing to a notable escalation in conflict risk due to climatic fluctuations (Earth.Org, 2020; Mongabay News, 2022). Conflicts can arise from both ends of meteorological extremes, whether excessive rainfall or drought scenarios.

Persistent rainfall shortages tend to indicate instability over a broader geographic expanse, while intense rainfall events appear to increase the likelihood of clashes within more confined spaces over wider spans (Earth.Org, 2020).

The ongoing conflicts across Africa underscore the profound effects of climatic changes on pastoralist rangelands, agroecological zones, and water access points. These environmental pressures intersect with governance challenges and demographic stressors, exemplified by the Darfur conflict, recognized as the first major conflict primarily driven by climate change (Scientific American, 2009). Specifically, droughts and desertification in Darfur have precipitated clashes between pastoralist and farming communities over severe resource shortages (Audubon, 2012).

Similarly, variations in rainfall and recurrent droughts have sparked uncontrolled migration patterns and intense competition over grazing lands and water points across the Horn of Africa's agro-pastoralist systems (McGuirk et al., 2020). Lake Chad serves as another example where climate stresses have significantly diminished vital resources, with the lake losing 90% of its water over recent decades, leading to tensions between fishers, herders, and farmers in the borderlands between Niger, Nigeria, Chad, and Cameroon (AP News, 2023). As the impacts of climate change intensify across Africa's agro-pastoralist systems, the complex secondary effects of environmental degradation and demographic shifts contribute to escalating conflicts (SEI, 2022).

Current conflicts across the African continent reflect the significant impact of climatic changes. A case in point is the Darfur conflict, acknowledged as the first conflict majorly driven by climate change. The region experienced a drastic shortfall in rainfall, marked by 30 to 75% below expected levels, playing a pivotal role in triggering civil unrest (Earth.Org, 2020).

However, it is crucial to clarify that climate change is not the sole instigator but a potent exacerbator of conflicts. The tapestry of socio-political dynamics significantly shapes the conflict landscape (Mongabay News, 2022), necessitating a broader lens to understand and address the confluence of factors intensifying tensions and conflicts.

Several quantitative studies have explored the correlation between climate variables, such as temperature and rainfall, and African conflict risks. For instance, Burke et al. (2009) and Hsiang et al. (2013) outlined how deviations from typical climatic conditions, like mild temperatures and normal precipitation, significantly heightened conflict risks, especially within impoverished populations. Their findings revealed that each standard deviation of higher rainfall or warmer temperatures escalated intergroup conflict by 14% and, in certain regions, by over 50%.

Moreover, rising temperatures strongly correlate with higher risks of conflicts in Sub-Saharan Africa from 1981-2002, as encapsulated in Burke et al. (2015)'s study. Specifically, computing cumulative effects, they found that, on average, a 1 standard deviation shift toward more adverse climatic conditions spurred a 1.2% rise in interpersonal clashes and a 4.5% increase in intergroup contention across the region over this period (Burke et al., 2015).

Other researchers argue that socio-political factors can create an indirect connection through climatic disruptions that significantly mediate the connection between climate variables and conflicts (Buhaug, 2015; Benjaminsen, 2016).

For example, Raleigh and Kniveton (2012) postulate that adverse effects on economic growth and activity in climate-sensitive sectors mediate climate impacts on conflicts. Additionally, political marginalization of certain groups emerges as a crucial determinant in this narrative (Rüttinger et al., 2015).

Under the lens of Political Ecology and Environmental Security, the framework proposed by Peluso and Watts (2001) emphasizes how environmental factors, including climate change, intersect with political, social, and economic contexts to shape conflicts. This perspective challenges the deterministic notion that environmental shifts inevitably lead to conflict, highlighting instead the importance of understanding how such environmental changes are influenced by power dynamics, governance shortcomings, and historical antagonisms among groups (Ide, 2018). For example, changes in rainfall patterns can significantly impact agricultural livelihoods, but these impacts do not inherently provoke violence.

The response to these environmental shifts is often shaped by a complex interplay of factors, including power dynamics, governance structures, and historical tensions among diverse groups (Ide, 2018). Emerging from this perspective, the political ecology framework views environmental factors such as climate change as intertwined with political, social, and economic contexts, creating conditions conducive to violent conflicts (Peluso and Watts, 2001). The challenges faced by agricultural livelihoods due to variations in rainfall do not directly lead to violence; rather, the response is influenced by power relations, governance failures, and historical discord among groups (Ide, 2018).

Concurrently, the environmental security paradigm suggests that climate-related impacts, such as diminishing water availability, act as 'threat multipliers,' exacerbating tensions in populations already vulnerable due to poverty, inequality, and weak state infrastructures (Scheffran et al., 2012).

While climate disturbances rarely directly initiate conflict, they increase risks by compromising human security and livelihoods. This interpretation is supported by Mach et al. (2019), who argue that climate disruptions heighten conflict risk by undermining human security and livelihoods. The environmental security paradigm interprets climate impacts such as reduced water availability as 'threat multipliers,' exacerbating tensions, particularly when populations are already vulnerable due to poverty, inequality, and weak state structures (Scheffran et al., 2012). Direct causation of conflict by climate disruptions is seldom observed. However, they amplify risks by threatening human security and livelihoods (Mach et al., 2019). Both theoretical frameworks underscore the necessity to move beyond mere climatic variables and explore the complex socio-political and economic dynamics that fuel conflicts across the African terrain in conjunction with climate change.

CLIMATE INTERACTIONS WITH COMMUNAL CONFLICTS: SAHEL, LAKE CHAD BASIN, AND THE HORN OF AFRICA

The Sahel has experienced rising temperatures, reduced and erratic rainfall, and desertification (Mbow et al., 2019). Indeed, the Sahel region has been experiencing significant environmental changes, including rising temperatures, reduced and erratic rainfall, and desertification (Mbow et al., 2019). These changes have reduced farmers' arable lands and pastoralists' pastures, intensifying resource competition (Copernicus, 2016).

The Darfur conflict perfectly illustrates how these environmental stresses can contribute to conflict. Indeed, this protracted conflict emerged from a complex interplay of environmental stress, traditional land rights loss, and ethnic tensions (Tufts University, 2019).

Similarly, the Lake Chad region has been significantly impacted by climate change. The lake's surface area has shrunk by 90% since the 1960s due to rising temperatures (AP News, 2021). This dramatic decrease and overexploitation have led to diminishing water resources and collapsing fisheries, disrupting local livelihoods and contributing to social unrest (Cornell University, 2015). Now, the insurgent group Boko Haram has been exploiting these desperate conditions. They have capitalized on the hardships communities face due to climate change, using it as a recruitment tool (Mercy Corps, 2016.). Indeed, increased rainfall variability in the Horn of Africa has been linked to heightened pastoral conflicts (Greiner, 2013). Recurrent droughts have also been identified as triggers for ethnic violence between Kenyan herders and farmers competing for pasture and water resources (Linke et al., 2018). However, the interconnection between climate change and conflict is intricate. While some research underscores a direct tie between droughts and disputes, others suggest it is more about how these environmental challenges amplify existing societal issues. This regionally diverse research affirms that climate disruptions intersect with historical, political, and socioeconomic stressors to amplify insecurity and conflicts. Further case study insights are needed from central, southern, and north African sub-regions.

RESEARCH GAPS AND FUTURE DIRECTIONS

There are still many areas that require further exploration to understand the relationship between climate change and conflict. Firstly, the cultural and gender dimensions of climate fragility risks are poorly understood (UN Women, 2022a).

This includes examining how different cultural identities and gender roles influence communities' responses to the effects of climate change (UN Women, 2020). For example, in many societies, particularly in sub-Saharan Africa, women are often more vulnerable to the impacts of climate change due to their roles in food production and water collection (UNEP, n.d.). Secondly, the precise mechanisms linking climatic variables to conflict remain unclear, indicating a need for further research (Burke et al., 2009). While some studies suggest that climate change can exacerbate existing social and economic inequalities, potentially leading to conflict in Africa (Hsiang and Burke, 2014), others argue that the relationship is not straightforward (NBER, 2014). Thirdly, significant uncertainties exist in the quantitative findings of climate-conflict research (Ide, 2020). These uncertainties arise from various factors, including the complexity of the climate system, the challenge of isolating the effects of climate change from other conflict drivers, and the limitations of current climate models (Burrows and Kinney, 2016).

Lastly, there is often a lack of concrete policy solutions for addressing climate-related conflicts (PreventionWeb, 2022). While some strategies have been proposed, such as improving climate change adaptation and mitigation efforts, more work is needed to develop effective and sustainable solutions (IPCC, 2022). In terms of future research directions, there is a need for more contextual studies focused on Africa. These studies could explore how conflict responses to climate pressures influence cultural identities, perceptions, and power dynamics. Moreover, given the gendered vulnerabilities associated with climate change, it is crucial to pay closer attention to women in these research efforts (CR, 2023).

Finally, using mixed methods and other socio-demographic approaches could provide more insights into the complexities of climate-conflict interactions (NBER, 2013).

CONCLUSION

Climate change is considered a catalyst as it amplifies the risks of conflict in Africa. However, analyzing this relationship through a purely environmental lens should no longer suffice. To devise effective structural solutions, we must deeply understand the intertwining sociopolitical contexts that shape climate fragility risks. We can counteract these amplified risks by combining peacebuilding efforts and climate adaptation strategies, building inclusive institutions, and fortifying community resilience. Ultimately, addressing the nexus between climate change and conflict requires adopting a holistic approach that includes climate adaptation, peacebuilding, inclusive governance, and UN migration policies aligned with UN sustainable development objectives, while also fostering sustainable peace initiatives.

POLICY RECOMMENDATIONS

Integrating climate change adaptation within peacebuilding programs and conflict early warning systems can be a crucial step towards mitigating the impacts of climate change on conflict (UNDP, 2020). Inclusive governance, strengthened land tenure, and access to justice are vital in reducing group marginalization tied to resource losses from climate impacts (UNDP, 2020). Addressing barriers to climate-driven mobility through planned relocation policies and migration pathways is another important strategy (UNFCCC, 2015; UNU, 2017). Aligning interventions with Sustainable Development Goals like Goal 13 (Climate Action) and Goal 16 (Peace) can ensure that efforts to address climate change are integrated with broader development objectives (UN, 2023a, b). Lastly, supporting locally-led, community-based peace initiatives among pastoralist and farmer groups can effectively resolve resource conflicts (FAO, 2016; Peace Insight, 2019).

LIMITATIONS

The limitations of this study on climate change and conflict in Sub-Saharan Africa stem from the dynamic nature of the fields and the availability of regional literature. It primarily relies on existing literature, which might not fully capture the intricate relationship between climate variables and conflict due to socio-political and economic complexities.

Additionally, the specific focus on Sub-Saharan Africa limits access to comprehensive and current studies, thereby affecting the depth of analysis.

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CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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Behavioural communication change for empowering small-scale farmers in addressing climate change: Perceptions, mitigation and adaptation strategies

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Climate change poses a serious threat to Kenya's food security, necessitating immediate and steadfast attention to the development and implementation of comprehensive climate risk management and adaptation strategies at both the national and sub-national levels. This study is a crucial undertaking that utilizes the direct knowledge and experiences of farmers in Kisumu, Kenya, to tackle important problems necessary for the effective implementation of strong climate change frameworks in the country. Its focus is to encourage small-scale farmers to adapt and mitigate and to undertake proactive measures to avoid maladaptation food insecurity scenarios. This study highlights major insights by utilizing a combination of content analysis, focus group discussions, and a thorough comparison of results with vast secondary data covering weather patterns from 1988 to 2017. The findings reveal a clear truth, although farmers are aware of the long-term changes in climatic factors, such as temperature variations and shifts in rainfall patterns, they find it difficult to accurately connect these changes with the broader idea of climate change. Notwithstanding this consciousness, farmers struggle with the hazards presented by climate variability and catastrophic weather occurrences without strong measures in response. While some farmers occasionally modify their farming operations both on and off the pitch, these adjustments are mainly reactive rather than proactive responses to climate change. These measures include adjusted planting and harvesting timetables, the cultivation of resilient crops, the adoption of agroforestry practices, occasional migrations to urban areas, and the dependence on remittances from external sources. These strategies are implemented as temporary alternatives to cope with the negative effects of climate change. This study emphasizes the necessity for proactive policy actions to address climate change, urging strong frameworks to manage and adapt to risks within the African context. Kenya's food security situation underscores the urgent need for practical, proactive initiatives.

Key words: Perception, climate risk management, vulnerability, passive adaptation, small-scale farmers.

INTRODUCTION

In the past few decades, incidences of climate variability and seasonal uncertainty have been on the rise globally

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(Wiebe et al., 2019). According to Muiruri et al. (2022), climate incidents including increased temperature, erratic rainfall, frequent floods, and prolonged droughts have undermined efforts for food production in sub-Saharan countries including Kenya. Projections indicate that approximately 50% of the agricultural production will be lost in developing countries if temperatures rise by 1 to 2°C (Change IPCC, 2014). Kenya has experienced a rise in annual temperature by 1.0°C since 1960, at an average rate of 0.21°C each decade. In Kisumu County, there was a decline in annual precipitation between 1960 and 2009 as well as an average increase in temperature according to meteorological data observations (Gioto et al., 2016). Targeted transformation within the food production value chain is therefore an important requirement for effective management of anticipated climate risks. This therefore calls for a detailed examination of factors that influence how farmers perceive climate change and associated risk management strategies. However, this is a complex task that involves the physiological interpretation of factors such as knowledge, beliefs, attitudes, and practices that are associated with changes in local climate patterns (Whitmarsh and Capstick, 2018). The perception of farmers about climate variability is defined by household characteristics, historical experiences of how seasonal climate patterns have undermined or enhanced productivity, accessibility of climate knowledge, and socio-cultural and geographic contexts of food production practices (Whitmarsh and Capstick, 2018). According to Singh et al. (2017), for effective achievement of long-term adaptation goals, technical knowledge must reside within the communities. It is important to note that since the level of technical knowledge is somehow influenced by the experience and/or educational background of an individual, perception can holistically be viewed as a cognitive process that entails receiving and decoding sensory information (Kabir et al., 2016).

In this study, the seven climatic characteristics and several consequences that farmers have experienced because of climate change were used to describe their perspective on variability in climate patterns. Temperature variations, rainfall levels, beginning and ending dates, farming season duration, frequency of flooding and drought, and other indicators were all considered. Climate variability affected soil fertility and erosion hazards, agricultural production, and natural and managed forest cover, all of which influenced how farmers in Katuk Odeyo experienced it. Temperature increases and rainfall decreases contribute to soil moisture stress and poor crop performance patterns, which affect crop growth, food crop production patterns, and livelihood strategies in sub-Saharan Africa. According to prior research, most smallholder farmers in sub-Saharan African countries see climate change as a key factor that underpins their food security (Tesfahunegn et al., 2016). Farmers in most parts of sub-Saharan Africa have either noticed and/or reported a drop in precipitation and an increase in air temperatures as indicators of climate variability, according to Ochieng et al. (2017). Meteorological observations appear to support farmers' views of climate variability (Mkonda et al., 2018). Climate change has shifted cropping calendars, resulting in shorter cropping seasons as well as changes in rainfall amount, distribution, and timing (e.g., late-onset and early cessation), all of which have a significant impact on agricultural production (Mubiru et al., 2018) and make households more vulnerable to climatic risks. As a result, findings from surveys of farmers' perspectives on climate variability could be useful in identifying possible areas for climate policy, adaptation, and mitigation, and could further guide sustainable agricultural activities that benefit farmers (Masud et al., 2017). Despite the importance of farmers' climate views, Western Kenya, like many other developing country regions, lacks documentation of local indicators and implications of climate change (Recha, 2017). To offset the effects of climate change, Africa's agricultural industry must undergo fundamental transformation through individual farmer initiatives as well as the introduction of new regulations. Kenya's small-scale farming sector can be stabilized and increased productivity in the face of climate unpredictability and uncertain rainfall by implementing climate-smart agriculture practices. Because Kenyan smallholder farmers are less educated, have weaker adaptive capacities, and rely on rain-fed agriculture, reorienting agricultural output for them is a difficult challenge.

Among the coping methods investigated in this study were cropping and soil management practices such as intercropping, terraces, tied-ridging, fertilizer application, planting strips, crop rotation, and contour farming. A study conducted by Kibue et al. (2016), for example, found that knowledge about agriculture has a significant impact on how people perceive and respond to climate change. Mango et al. (2017) discovered that characteristics such as group participation, education level, land ownership, and access to affordable financing were major predictors of the adoption of soil and water conservation strategies in the Katuk Odeyo in the Lake Victoria basin (Kenya) and the Chinyanja Triangle of the Zambezi River basin (Zambia, Malawi, and Mozambique). According to Macharia et al. (2014), livestock manure is used by most smallholder farmers in Kenya's central highlands to boost soil fertility. This strategy boosts agricultural productivity while decreasing greenhouse gas emissions (Macharia et al., 2020; Musafiri et al., 2020a). Few African studies have attempted to link farmers' perceptions of climatic variability and field-based adoption of adaptation and mitigation measures to socioeconomic, institutional, and environmental variables. While much research on the subject has concentrated on institutional and socioeconomic issues, very few have examined how national officials have considered local views and/or perspectives when making choices.

According to Reimer et al. (2012), approaches that adopt regression models are inadequate in elaborating strategies that are directly dependent on farmers' behavior and/or perspectives. Without delving far enough into institutional, regulatory, and environmental aspects, Asare-Nuamah and Botchway (2019) investigated the association between socioeconomic variables and climate perception predictions in northern Ghana. Without investigating environmental and policy factors, Marie et al. (2020) calculated the impacts of socio-economic and institutional variables on farmers' adoption of climate adaptation practices in northwestern Ethiopia. These practices included using improved crop varieties, planting at different times of the year, conserving soil and water, mixed cropping, irrigation, and diversifying income sources. In their study of Kenya, Ethiopia, Uganda, and Tanzania, Shikuku et al. (2017) focused on socio-economic and institutional variables, while Asayehegn et al. (2017) looked at the effects of socio-economic variables in Central Kenya, along with a small set of institutional factors (access to extension services and affordable credit), and environmental factors (agro-ecological zones) that underpin food production. As a result, the study set out to determine how farmers' view climate variability, their tactics for adapting to and mitigating the effects of climate change, policy implications, and the complexities and dynamics surrounding these factors. Three important contributions were made by the study. Given the multi-faceted nature of farmer adoption processes, the study first established a connection between farmers' views on climate variability, indicators, and repercussions and a more comprehensive set of farms' socio-economic, institutional, and policy frameworks (Reimer et al., 2012). Secondly, the research elaborated on the intensity and quantity of the adaptation techniques that were being adopted by the farmers. Thirdly, the study assessed the historical factors that motivate small-scale farmers to employ adaptive measures. This research is significant because it will add to the body of knowledge aimed at enhancing policy frameworks through the incorporation of experiences and perspectives of small-scale farmers in sub-Saharan Africa.

This study investigated the perspectives of smallholder farmers towards climate impacts, using Katuk Odeyo, a hamlet in Kisumu County, Kenya, as a representative sample. The findings are presented in Table 3. The relevant secondary data (Opande et al., 2019b) contained climate data from three weather stations in Kisumu, Ahero, and Katito, along with information on local adaptation drivers and responses. The study area is characterized by a semi-arid climate and experiences food insecurity due to a combination of socio-economic and environmental factors (Raburu et al., 2012). Additionally, the area faces issues related to low productivity in farm work (Recha, 2017). In addition, the process of land degradation and fragmentation has resulted in the loss of land that could have been utilized for agricultural purposes (Opande et al., 2019a). Consequently, the farmers are facing a significant and intimidating gulley that stretches for several kilometers. Efforts to enhance productivity in the current conditions have resulted in excessive cultivation, depletion of soil nutrients, and more erosion (Onyango et al., 2012). Opande et al. (2019a) identified several challenges that hinder effective adaptation and food production. These challenges can be categorized as poverty, weak social networks, insufficient technical capacity, and limited access to essential resources such as land, climate information, innovative solutions, viable and affordable financial instruments, and extension services.

The relationship between climate change and agriculture

The linkage between climate change and agriculture is intertwined. Agricultural discourse has evolved from an earlier thinking of just increasing the production of staple foods to a means of looking at food security in all its facets including availability, nutrition, the health and well-being of producers and consumers, and the sustainability of the production landscape (Sambasivan et al., 2013). This holistic approach has led to an increase in land cover changes and intensive food production systems that are known to emit large volumes of greenhouse gases (GHGs) (Solomon et al., 2007). A deep dive into GHG emissions indicates that collectively agriculture and deforestation contributed an estimated two-thirds of emissions in Kenya (GoK, 2016) and one-fifth (21%) globally between 2000 and 2010 (approximately 44 billion tonnes) according to the Food and Agriculture Organization (FAO, 2020). In 2018, emissions from agriculture and related land use and land use processes accounted for 17% of global GHG from all sectors, down from the 2000s. The reduction was due to increasing emissions from other economic sectors that are equally growing at relatively faster rates. In particular, N^2O emissions from livestock manure left on pastures by grazing animals and the application of manure to cropland contributed an additional 1Gt CO^2 eq in 2018 (Tubiello, 2019). At the global level, N^2O emissions from synthetic fertilizers contributed 13% to the total (0.7GtCO^2eq) while CH^4 emissions from rice cultivation contributed a further 10% (0.5GtCO^2eq) according to FAO (2020). High emissions from the agricultural sector are mainly due to an increased allocation of land space and the use of chemical fertilizers to provide for the high demand for meat and its products.

The link between agriculture and climate change is intricate and has gradually hindered endeavors for food production, especially in intense monoculture systems. Specifically, farm animals, primarily bovines, consume over 95% of the soy produced worldwide. Cederberg et al. (2009) reported that the production processes of one kilogram of bovine meat result in the emission of approximately 200 kg of carbon dioxide. This indicates that in the case of a country such as China, which has approximately 700 million pigs, a total of 80 million tonnes of soy must be either domestically produced or imported only to satisfy the need for pig feed.

The variations in climate can negatively affect agriculture by disrupting temperatures, precipitation, and other weather patterns. These disruptions can lead to reduced water availability, soil fertility, increased pests and weed infestation, and unintended physiological changes in food crops. The severity of climate effects on food production can vary from low to high and can have either positive or negative outcomes depending on various factors such as the specific region or geography (Mendelsohn et al., 2006), socioeconomic status of the community (Tripathi, 2017), access to climate information, early warning systems, and institutional support (Opande et al., 2019b). Tol et al. (2004) discovered that an increase of 1°C in temperature and a rise of 0.2 m in sea level had a beneficial impact on certain countries in the Middle East region. In contrast, similar shifts resulted in adverse effects in certain underdeveloped countries particularly those that are situated in regions with low latitudes and lack sufficient infrastructure for disaster prevention and management (Hertel and Lobell, 2014).

Agriculture can on the other hand offer opportunities for mitigating carbon emissions through sequestration, sustainable soil and land use management, and biomass production (FAO, 2020). For instance, 105 out of the 189 countries that committed in 2016 to limit their national carbon emissions to 2°C - if possible, to 1.5°C - mentioned agriculture as a key mitigation sector. However, to achieve the 2°C target, an estimated 1 $GtCO^2eq$ must be reduced annually from agriculture alone by 2030. This is a significant challenge given the increasing demand for food from an increasing global population.

Key climate change frameworks in Kenya

The Government of Kenya has shown commitment to fighting climate change by ratifying the Kyoto Protocol in 2005 and contributing to various continental, regional, and national frameworks. At the national level, summaries of selected legal frameworks that are relevant to food security and climate change have been highlighted in the following.

Constitution of Kenya (2010)

Some articles in this document provide grounds for the formulation of adaptation and mitigation legislations, policies, and strategies. For instance, in Article 11 under Culture, the roles of science and indigenous technologies in national development are recognized. Further, it emphasizes that legislation will be enacted to recognize and protect ownership of indigenous seeds and plant varieties for community use. It goes further (Chapter 4, Article 42) to guarantee the right to a clean and healthy environment under the Bill of Rights. Article 43 on Economic and Social rights states that "every person has a right to be free from hunger and should have adequate food of acceptable quality". In Chapter 5 on Land and Environment, Article 69 provides for obligations in respect of the environment while Article 72 requires Parliament to pass legislation relating to sustainable management of the environment.

The Kenya Vision 2030 (2008)

This document is the country's development blueprint and aims to transform Kenya into a "newly industrializing, middle-income country by 2030 in a clean and sustainable environment". This document recognizes the role that agriculture should play towards the achievement of a sustained annual GDP growth rate of 10%. This document, which is based on three pillars: economic, social, and political, recognizes climate change as a risk that could slow the country's development.

Kenya Climate Smart Agriculture Strategy (2017-2026)

This strategy aims to promote efforts for climate adaptation and resilience building of agricultural systems while minimizing GHG emissions. It targets three main objectives:

(a) sustainably increase agricultural productivity and incomes,
(b) adapt and build resilience to climate change, and
(c) reduce and/or remove greenhouse gas emissions.

National Climate Change Action Plan (2018-2022)

This plan provides mechanisms for realizing low-carbon climate-resilient development pathways. The plan emphasizes sustainability and in parallel prioritizes adaptation and enhanced climate resilience for vulnerable groups.

The Climate Risk Management Framework (2017)

This framework integrates disaster risk reduction, climate change adaptation, and sustainable development so that they are pursued as mutually supportive rather than stand-alone goals. The framework thus promotes an integrated climate risk management approach as a central link for policy and planning at the national and county levels.

National Climate Change Framework Policy (2018)

This policy aims to integrate climate change considerations into planning, budgeting, implementation, and decision-making. The policy targets key sectors that are relevant for fast-tracking economic development and the social well-being of the citizens. The key sectors targeted include environment, water, and forestry; agriculture, livestock and fisheries, trade, extractive industries, energy, physical infrastructure, tourism; and health. This policy specifically, aims to enhance the adaptive capacities, and resilience of communities as precursors for low-carbon development.

LITERATURE REVIEW

Climate variability and its associated impacts have emerged as significant challenges for agricultural systems worldwide, particularly in sub-Saharan Africa (SSA). In this literature review, we examine the perspectives of smallholder farmers in SSA, focusing on Katuk Odeyo, a representative sample in Kisumu County, Kenya. We draw upon a range of studies to explore farmers' perceptions of climate change, the adaptation strategies they employ, and the socio-economic, institutional, and environmental factors that shape their responses.

Perception of climate variability

Smallholder farmers in SSA, including those in Katuk Odeyo, have experienced firsthand the adverse effects of climate variability on agricultural productivity. Studies by Muiruri et al. (2022) and Gioto et al. (2016) highlight how increased temperatures, erratic rainfall patterns, floods, and droughts have undermined food production efforts in Kenya. IPCC projections (2014) indicate that even a modest temperature rise of 1 to 2°C could lead to significant agricultural losses in developing countries. In Kisumu County, the observed increase in temperature and decline in precipitation further exacerbates soil moisture stress, affecting crop growth and livelihood strategies (Gioto et al., 2016). Farmers perceive climate change through a combination of historical experiences, access to climate knowledge, and socio-cultural contexts (Whitmarsh and Capstick, 2018). Ochieng et al. (2017) found that farmers across SSA have noticed decreases in precipitation and increases in temperatures, aligning with meteorological observations.

Adaptation strategies

To cope with climate variability, smallholder farmers in Katuk Odeyo and similar regions employ a variety of adaptation strategies. Cropping and soil management practices such as intercropping, terracing, and crop rotation are commonly used (Kibue et al., 2016). Mango et al. (2017) identified factors such as education level, group participation, and access to financing as predictors of the adoption of soil and water conservation strategies. Livestock manure application, as observed by Macharia et al. (2014), not only enhances soil fertility but also mitigates greenhouse gas emissions. However, challenges such as poverty, limited access to resources, and weak social networks hinder effective adaptation efforts (Opande et al., 2019a).

Factors influencing adaptation

The adoption of climate adaptation measures among smallholder farmers is influenced by a multitude of socio-economic, institutional, and environmental factors. Knowledge about agriculture plays a crucial role in shaping farmers' perceptions and responses to climate change (Kibue et al., 2016). Access to resources such as land, climate information, and financial instruments also affects farmers' ability to adapt (Opande et al., 2019a). Furthermore, socio-cultural factors, including group participation and land ownership, influence the adoption of adaptation strategies (Mango et al., 2017). Institutional support, including extension services and affordable credit, is vital for facilitating adaptation at the grassroots level (Asayehegn et al., 2017).

Research gaps and policy implications

Despite the growing body of literature on farmers' perceptions and adaptation strategies, several research gaps persist. Reimer et al. (2012) argue that regression models alone may not adequately capture the complexity of farmers' behavior and perspectives. Moreover, studies often overlook environmental and policy factors that influence adaptation decisions (Asare-Nuamah and Botchway, 2019; Marie et al., 2020). There is a need for interdisciplinary research that considers the interplay between socio-economic, institutional, and environmental variables in shaping farmers' adaptation practices.

Summary

Understanding smallholder farmers' perspectives on climate variability and adaptation strategies is crucial for informing policy interventions in SSA. Farmers in Katuk Odeyo and similar regions face numerous challenges due to climate change, including food insecurity and loss of agricultural productivity. Effective adaptation requires addressing socio-economic, institutional, and environmental barriers while leveraging farmers' local knowledge and experiences. Future research should adopt interdisciplinary approaches to capture the multifaceted nature of farmer adaptation and inform evidence-based policy frameworks that promote climate resilience in agricultural systems.

METHODOLOGY

The study area is locally known as Katuk Odeyo and is in the Nyakach area of Kisumu County, Kenya. The area is semi-arid and has long experienced food insecurity, complex socio-economic and environmental challenges (Raburu et al., 2012), low farm labour productivity, and population pressure (Onyango et al., 2012). Further, the subdivision of cultivation land into smaller plots and, land degradation due to gulley formation and deforestation among other factors, has collectively undermined food production systems (Recha, 2017; Opande et al., 2019a).

An in-depth analysis of the region being examined uncovers little economic progress and insufficient catastrophe readiness mechanisms (Recha, 2017). Moreover, the community's vulnerability to climate impacts like as flooding, soil erosion, and land degradation has been exacerbated by insufficient access to climate information (Opande et al., 2019b). Nevertheless, to gain a clearer understanding of how climate impacts have negatively affected the well-being of communities, it is crucial to comprehend how the accessibility and affordability of food, the availability of clean and portable water, and the provision of health and education services have collectively weakened the ability of households to adapt (Opande et al., 2019a). Thousands of marginalised and impoverished families, who are facing difficulties in producing sufficient food for their sustenance, suffer from the consequences of insufficient incorporation of farmer perspectives into climate planning initiatives. While there have been efforts by various players and NGOs to improve the ability of farmers to withstand challenges in the study area (Recha, 2017), there is a lack of research on how shaping farmers' perceptions can increase the adoption of climate-smart innovations to boost food security.

The research methodology used a careful stratified random selection approach to guarantee a well-balanced representation of 315 homes from five different clans within a particular village setting. The initial data-gathering process consisted of transect walks and participatory mapping, guided by the village population register. This register provided a critical model for comprehending the complex socio-economic, environmental, and climate factors present in the research area. The initial preparation was crucial in establishing the foundation for the following stages of data gathering. The main data was collected by intentionally utilizing Focus Group Methods (FGMs), a purposeful decision made to enable a thorough examination of participant viewpoints, interpretations, and community dynamics. Focus Group Meetings, chosen over individual interviews for their capacity to provide inclusive perspectives and accelerate the understanding of community perceptions and lifestyles, facilitated extensive group discussions involving participants from diverse clans, aged between 30 and 60 years, and representing different genders.

In addition, this method allowed for the formation of smaller subcategories within the larger groupings, which made it easier to analyze the different perspectives of farmers with marginal, small, and medium-sized farms, and tenant farmers. The segmentation, which was conducted based on landholding sizes, sought to reveal a wide range of perspectives and experiences within the agricultural community. In addition to community interaction, the study integrated climatic data obtained from three Kenya meteorological stations located near Kisumu. This data served as crucial external references for temperature and rainfall trends. This methodology combines quantitative and qualitative methodologies to analyze the research region. It incorporates population statistics, weather information, and community interaction to gain a thorough picture of the complex dynamics in the area. The analysis involved exploring themes and making comparisons to identify common patterns and connections between the investigated town and its surrounding areas.

FINDINGS AND DISCUSSION

Farmers' perception of how local climate impacts affect food security

Certainly, the initial stage of cultivating a favorable attitude among farmers is imperative for promoting successful adaptation techniques within the agricultural domain. Gaining insight into farmers' perceptions of climate change is a crucial foundation. This entails assessing not only their knowledge of climate change but also exploring the extent of their comprehension of its presence and prospective effects on their farming methods. The perspectives of farmers serve as a guide for directing the theory of change and implementation of solutions that can effectively address the socio-economic challenges associated with managing climate risks and producing food. The strategy suggested by Frank et al. (2011), highlights the importance of integrating feedback spheres and a thorough grasp of farmers' perspectives into adaptation processes. This technique emphasizes two primary goals. Firstly, it aims to determine if farmers recognize the existence of climate change and its expressions within their specific local environment. This acknowledgment acts as a fundamental component for later stages in adaptation planning. Additionally, the objective is to comprehend the farmers' impression of climate change, as this perception greatly impacts their inclination to participate in mitigation and adaptation endeavors and more importantly in identifying and harnessing any opportunities that come along with climate change.

It is thus crucial to prioritize risk management methods by for instance encouraging farmers to adopt investigative approaches and climate-resilient technologies to recognize and manage climate hazards. This however entails increasing efforts to reduce any anthropogenic-induced hazards as well as actively adjusting agricultural methods to manage the evolving climate conditions. By aligning adaptation measures with the perceived risks and requirements of a farming community, the probability of effective adoption of sustainable and beneficial techniques is increased. Essentially, this method highlights the significance of incorporating farmers' perspectives on climate change into the planning and execution of adaptation measures. By doing this, it not only recognizes the influence of perception on behavioral reactions but also establishes a basis for cooperation and enforcement of efficient risk management measures that

Table 1. Basic demographic, socio-economic, and cultural profiles of the study area.

Attribute	Group 1	Group 2	Group 3	Group 4	Group 5
Clan name	Obinju	Kamango	Kamwana	Kobiero	Warieya
Farmer religion	Christians	Christians	Christians	Christians	Christians
Farm size	Small holders	Small holders	Small holders	Small holders	Small holders
Age	40-50	50-60	50-60	40-50	50-60
Farming experience	< 25 years	> 25 years	> 25 years	> 25 years	> 25 years
Level of education	Primary/ Secondary	Primary/ Secondary	Primary/ Secondary	Primary/ secondary	Primary/ Secondary
Primary occupation	Farming	Farming	Farming	Farming	Farming
Secondary occupation	Retired/small scale business	Retired/small scale business	Retired/small scale business	Retired/small scale business	Retired/small scale business

are customized to the requirements and comprehension of local farmers.

During the focus group discussions (FGDs), farmers affirmed facing challenges linked to global warming and/or less frequent and undependable precipitation, escalating soil degradation as well as incidences of flooding and or surface water runoff, delayed onset of rains, and increasing frequencies and intensity of floods over the past two decades. The farmers further elaborated on how a large gulley, several kilometers long, has undermined their livelihoods by eroding several hectares of farmland. The farmers jointly agreed that in the last three decades, precipitation patterns have changed, although differing opinions on increasing temperatures also came up. In-depth discussions indicated that this divergence in opinion was due to differences in the way individuals perceive interlinkages between direct sunshine and reduced tree coverage. Further, farmers who believed that warming is real argued that reducing tree coverage and subdividing land for new homesteads, is the reason behind diminishing precipitation, increasing warmth, and high speeds of surface water runoff. It is important to note that this perception complements scientific evidence (Recha, 2017). It is however important to note that 20 out of the 30 farmers could not directly link the fluctuating weather patterns with the formation and expansion of the large gulley. However, all 30 farmers came to a consensus that the fluctuation in weather patterns is compromising their efforts for food production. The attributes of the participants are presented in Table 1. The table indicates that the community is mainly made up of small-scale farmers between 40 and 60 years old who have generally not gone beyond the secondary level of education and have around 25 years of farming experience. Findings indicate that the community is unable to develop and manage effective food systems without extension services and access to climate resources such as early warning systems (Table 2; the availability of basic resources). Effective extension services and access to climate resources are vital for building positive perceptions towards climate adaptation and/or mitigation (Tripathi and Mishra, 2017). According to Bryan et al. (2013), the inability to access usable and time-bound climate information and targeted technical support can lead to a negative or no perception to climate change.

In-depth discussions revealed that those under 40 years old stood out in the community because they were relatively more educated, exposed and/or had access to newspapers, radio, TV, and smartphones. This observation confirms the relevance of digital media in awareness raising (Sampei and Aoyagi-Usui, 2009) and increasing access to information for influencing perception towards climate-smart food systems (Tripathi and Mishra, 2017). Further probing revealed that the farmers have responded by changing their planting times and/or adopting climate-smart seeds for those who can afford them. Affordability and availability of seeds was thus a key determinant for accelerating the uptake of smart agriculture. It also came out that the farmers preferred adaptation drivers: (a) social networks and collective action mainly through women groups and religious gatherings and (b) peer learning through experiments in peer farms to enable learning by doing.

These findings emphasize three important aspects: (a) encouraging farmers to attend social gatherings is important especially if opinion leaders and influencers will speak about climate-friendly solutions; (b) access to climate information services can influence the formation of positive climate perceptions, and (c) young and older farmers have different views and perceptions on climate change, food production, and climate risk management. The results from the study corroborate findings by Habtemariam et al. (2016) who established a direct correlation between access to climate information and the formation of positive perceptions for effective

Table 2. Basic resources that can be found within the sublocation/clan at Katuk Odeyo village.

Resources	Obinju	Kamango	Kamwana	Kobiero	Warieya	Nyagol
Village development office	0	0	0	0	0	0
Church	1	1	1	1	1	1
Piped drinking water	0	0	0	0	0	0
Agriculture extension office	0	0	0	0	0	0
Market	1	1	1	0	0	0
Cold storage	0	0	0	0	0	0
Agro seed sales shop	0	0	0	0	0	0
Veterinary extension office	0	0	0	0	0	0
Milk collection centre	0	0	0	0	0	0
Primary school	1	1	1	1	1	1
Secondary school	0	0	1	0	0	1
Nursery school	0	1	0	1	0	1
Primary health centre	0	0	1	0	0	0
Paved road	0	0	0	0	0	0
Cooperative saving facility	0	0	0	0	0	0
Mobile money (Mpesa) kiosk	1	1	1	1	1	1
Score	4/16	5/16	6/16	4/16	3/16	5/16

Table 3. Climate impacts that are undermining food production in Katuk Odeyo.

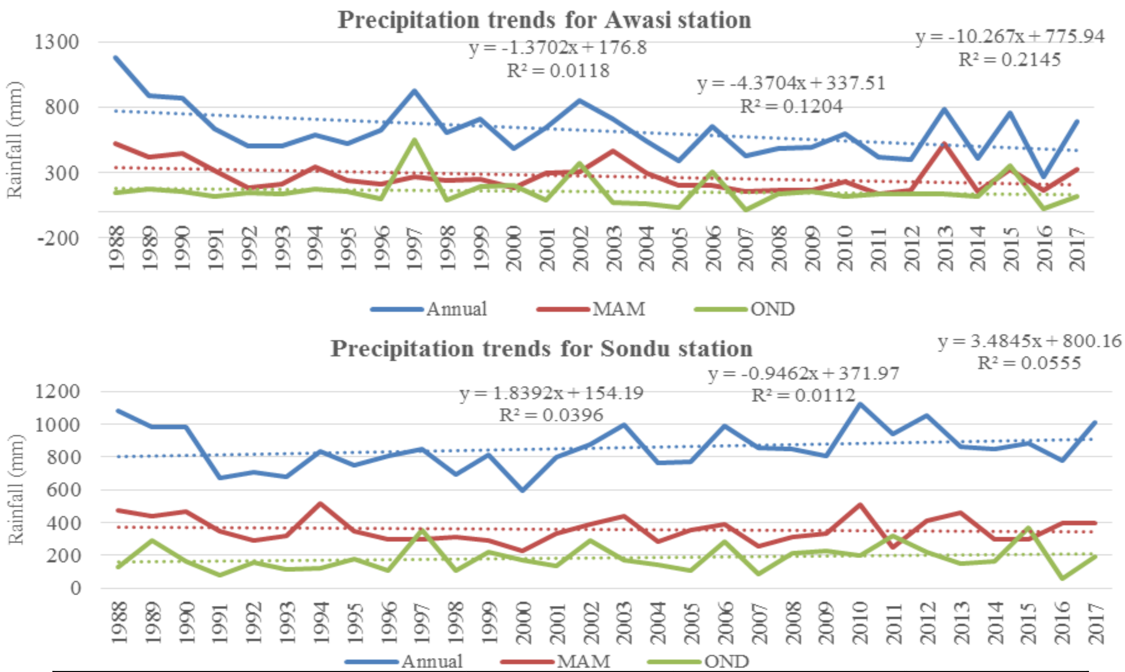
Rising temperature	Changing rainfall patterns
Drying crops and seedlings	Washing away of crops
Drought	Late and unpredictable rains
Emerging weed and pest species	Unpredictable planting patterns
High food prices	Higher food prices
Water stress	Land degradation (gulley's)
Changing ecosystem species	Soil infertility
Health problems	Increased incidences of malaria
Rural-urban labour migration	Destruction of properties and infrastructure by floods and water runoff
-	Family separated by the huge gulley

management of climate risks and food systems.

Table 3 presents the perceptions of farmers towards negative climate impacts. An analysis of findings that have been presented in the table further justifies an endless cycle of low income and food insecurity at the community level. It is important to note that perceptions in Table 3 corroborate findings from Figures 1 and 2 on climatic trends and selected adaptation drivers by Opande et al. (2019b). On the other hand, marginal farmers with small land holdings or whose farms had been washed away by floods somehow shifted their livelihoods away from on-farm work to other alternatives such as remittances from outside the community, small-scale businesses, and migrating to urban areas for off-farm paid jobs. Indeed, the findings of this study indicate that negative perceptions or lack of perception towards climate change can exacerbate climate vulnerability, and food insecurity and in the long term shift farmer focus to off-farm alternatives.

An analysis of local climate trends between 1988 and 2017

An analysis of local climate trends shows annual increasing maximum and minimum temperatures of about 0.022 and 0.034°C, respectively. The climate data further shows that the rise in minimum temperature is significant in comparison to that of maximum temperature. Similarly, an analysis of precipitation data shows variability in decreasing amounts and increasing incidences of floods. Finding from the FGDs that precipitation trends are changing, and the onset of March-May (MAM) and October-December (OND) planting seasons were delaying, somehow complements findings from the analysis of secondary climate data. A deep dive into



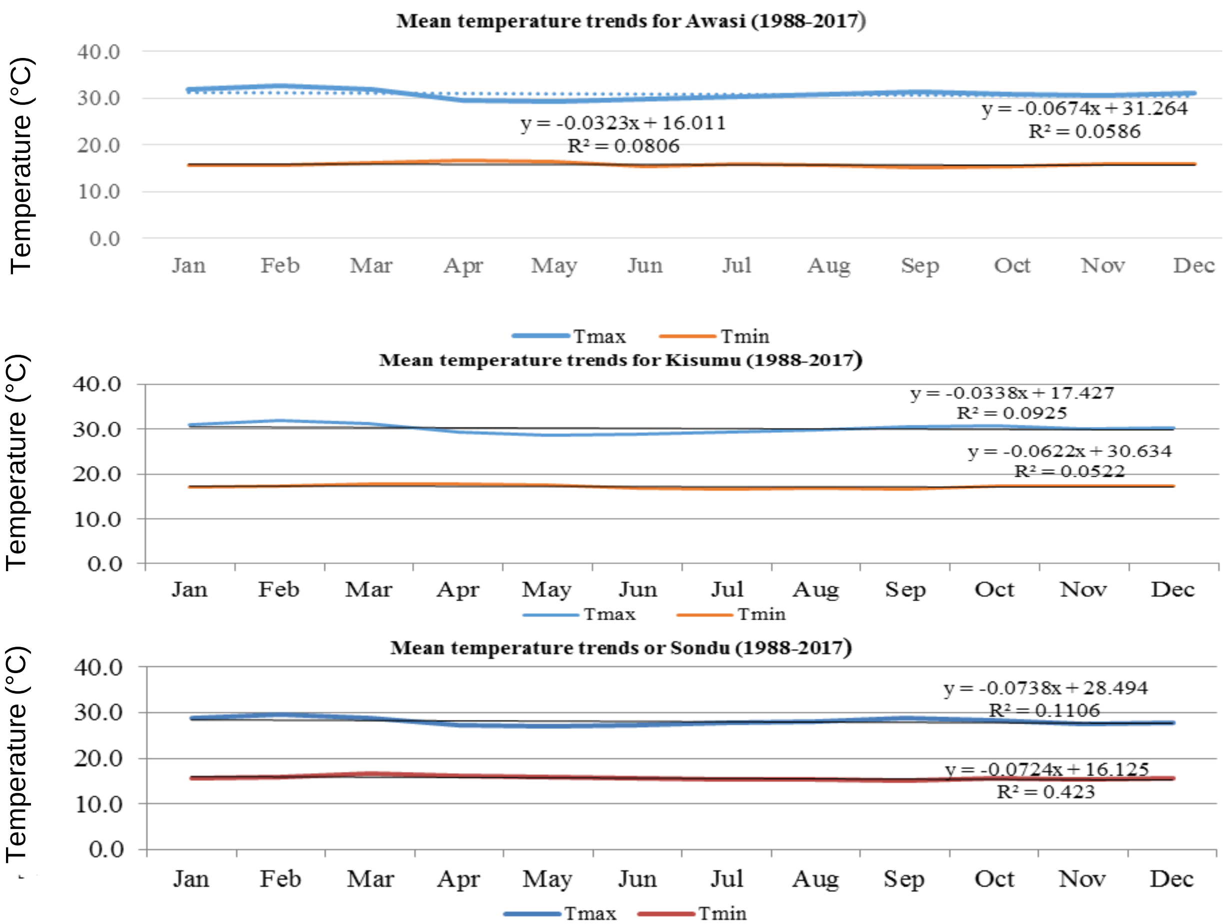
Station		Annual	MAM	OND
Awasi	Kendall's Tau	-0.2966	-0.3130	-0.1984
	P-value	**0.0216**	**0.0160**	0.1292
Kisumu	Kendall's Tau	0.0989	-0.0783	0.1172
	P-value	0.4574	0.5560	0.3760
Sondu	Kendall's Tau	0.1872	-0.0912	0.1406
	P-value	0.1613	0.4994	0.2934

Figure 1. Time series of observed precipitation trends for Awasi, Kisumu and Sondu stations between 1988 and 2017. Kendall's Tau significance tests: the –ve sign means a negative trend and the +ve sign means a positive trend. Further, a p-value less than 0.05, indicates a significant trend while a p-value greater than 0.05 means the trend is insignificant. Bold values mean significant trends for respective climate parameters.

weather patterns (Figure 1) confirms irregular annual precipitation patterns with a slight decline in the long rainy season of MAM. The analysis however revealed an increased precipitation from September to February in some years. This increase has been attributed to a tendency of the short rainfall season (OND) to extend into the normally hot and dry months of January and February (Recha et al., 2017). This variability in temperature and precipitation impacted farmers' ability to produce food given that they practiced rain-fed agriculture.

CONCLUSIONS AND POLICY IMPLICATIONS

Climate change and food security are significant concerns for most African nations. While emissions from Kenya, are not significant, the agricultural and deforestation sectors contribute the most carbon emissions. It is worth noting that food production in Kenya heavily relies on rainfall, and therefore the ongoing variations in temperature and rainfall patterns persistently affect the socioeconomic progress and food security of the community under study. Despite their limited ability to adapt, the community has responded in both beneficial and detrimental manners. Hence, it is crucial to acknowledge the necessity of endorsing cost-effective and feasible technologies to enable the farmers to enhance their food security position. Nevertheless, this necessitates a fundamental change in the way policy frameworks are formulated and food security measures are implemented. Hence, this article suggests a comprehensive reassessment of the strategies and methods now being implemented by the Kenyan government for climate adaptation. The plans should be revised to incorporate growing climatic and socio-economic concerns. This can be achieved by initially



Station		Tmax	Tmin
Awasi	Kendall's Tau	-0.0606	-0.1212
	P-value	0.8406	0.6384
Kisumu	Kendall's Tau	-0.0606	-0.1515
	P-value	0.8406	0.5452
Sondu	Kendall's Tau	-0.1212	-0.4242
	P-value	0.6384	0.0629

Figure 2. Time series of observed mean monthly temperature trends for Awasi, Kisumu and Sondu stations between 1988 and 2017. Kendall's Tau significance tests: the –ve sign means a negative trend and the +ve sign means a positive trend. Further, a p-value less than 0.05, indicates a significant trend while a p-value greater than 0.05 means the trend is insignificant. Bold values mean significant trends for respective climate parameters.

assisting communities in identifying how they might take advantage of climate-related opportunities. One way to achieve this is by facilitating their comprehension of climate dynamics within their immediate surroundings and utilizing this understanding to encourage the development of climate-friendly solutions in the areas of food production, distribution, and marketing. This will facilitate their cognitive process in perceiving climate change in a constructive rather than pessimistic approach. Furthermore, it is crucial to identify and promote suitable strategies that are tailored to the specific local context to expedite the community's response to perceived climate risks and their repercussions. This strategy should motivate individuals to take initiatives and have a future-oriented mindset, rather than relying on extension systems that are sluggish or unresponsive. This could significantly mitigate the prevalence of maladaptive responses, which are frequently executed hastily and without informed deliberation. Perceptions should be received, interpreted, and explained promptly, accurately, and with knowledge as a cognitive process.

It is important to further note that the accuracy of perception is dependent on the level of knowledge and experience of a particular individual and/or family. Based on this backdrop, this paper tried to look at two things. First, perceptions of the smallholder and marginal farmers to climate change, and climate risk management, and second, how farmer perception can influence on and off-farm adaptation responses. The findings of this paper indicate that farmers are aware of climatic trends concerning temperature and precipitation fluctuations. The paper further suggests that passive adaptation is common among farmers despite ignorance about the causes of climate change. This, therefore, makes it necessary to promote effective adaptation practices by first making the farmers knowledgeable so that they see beforehand the negative impacts of maladaptation. The findings also confirm that perception around deforestation and soil erosion is important for taming land degradation and in this context gulley formation. While perception around sustainable land management is known to be an important signal for enhancing crop yields and improving community livelihoods, this study has proved that print and digital media (newspapers, TV, radio, and smartphones) and, social networks are important catalysts for enabling positive perceptions. According to Singh et al. (2016) sharing climate information and farmer advice through mobile phones is more convenient than using traditional print media especially if farmers own smartphones. The study has further proved that farmers tend to rely on social networks when support from extension services is limited or not available. Social networks, particularly gatherings such as funerals, churches, and women and peer group meetings, are therefore important catalysts for enabling positive farmer perceptions and outreach pathways. It is therefore beneficial to set up organized social networking platforms where farmers can learn and share ideas about climate change, risk management, and food security. This study thus concludes that perceptions are somehow linked to the local knowledge and experience of the household head. This linkage should thus be taken into consideration as key in the development and implementation of policy frameworks for enhancing food security and climate risk management.

In conclusion, we recognize constraints in achieving internal validity because of inadequate controls and a limited sample size. Consequently, these discoveries may not be universally applicable to other regions. It is important to understand that focus groups are particularly suitable for conducting exploratory research and are not commonly employed for explanatory or descriptive research purposes. However, our work aimed to address these limitations by conducting a comparative analysis of our findings using secondary data obtained from earlier studies.

RECOMMENDATIONS

Based on the insights provided in the excerpt, the following four recommendations were proposed:

Promote climate literacy and knowledge sharing

Farmers' perceptions of climate change are influenced by their level of knowledge and experience. Therefore, there is a need to prioritize climate literacy programs that educate farmers about climate dynamics, its impacts on agriculture, and adaptation strategies. This could involve leveraging various communication channels such as mobile phones, social networks, and community gatherings to disseminate climate information effectively. Government agencies, NGOs, and other stakeholders should collaborate to develop and implement educational initiatives tailored to local contexts.

Facilitate community-based adaptation strategies

Community-based adaptation approaches should be encouraged to empower farmers to develop and implement context-specific adaptation strategies. By involving farmers in identifying climate-related opportunities and developing climate-friendly solutions, communities can enhance their resilience to climate risks. This could include promoting sustainable land management practices, such as afforestation and soil conservation, and supporting the adoption of climate-smart agricultural techniques.

Enhance extension services and social networking platforms

Given the limited access to formal extension services, particularly in remote areas, there is a need to strengthen extension networks and establish organized social networking platforms for farmers. These platforms can serve as valuable channels for knowledge sharing, capacity building, and peer learning. By leveraging existing social networks, such as community gatherings and peer groups, farmers can access vital information on climate change, risk management, and agricultural best practices.

Integrate local knowledge into policy frameworks

Policy frameworks for enhancing food security and climate risk management should be developed with a deep understanding of local knowledge and experiences. Policymakers should engage with local communities to incorporate their perspectives and priorities into adaptation planning and decision-making processes. This could involve establishing participatory mechanisms, such as community forums or advisory committees, to ensure that policies are contextually relevant and responsive to the needs of smallholder farmers.

By implementing these recommendations, policy-makers, stakeholders, and development practitioners can support smallholder farmers in sub-Saharan Africa, including those in Kenya, in building their resilience to climate change and improving food security outcomes.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Heavy metal resistant *Aspergillus* species from soil and water environments impacted by solid wastes dumping exhibit mycoremediative traits

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This study assessed the growth and metal tolerance of fungal species from water and soil samples impacted by solid wastes in Ibadan, Nigeria. Isolated fungi species were exposed to two metals each (pb 100 to 600 and Co 50 to 300 mgl^{-1}; Fe100 to 600 and Sn 25 to 300 mgl^{-1}; and Mn 100 to 600 and Ag 25 to 100 mgl^{-1}). These were filter-sterilized and incorporated into malt extract agar and mycelial radial growths were recorded over 13-days. Cultural, macroscopic and microscopic morphology revealed fungal identities as *Aspergillus niger*, *Aspergillus nidulans* and *Aspergillus flavus.* With *A. niger* exposed to pb and Co, *A. nidulans*, Fe and Sn and *A. flavus*, Mn and Ag, all species exhibited no statistical difference (*p*>.05) to controls. Throughout the incubation period, species revealed significant (*p*<.05) response and growth patterns comparable to controls. Furthermore, species' metal tolerance index (0.95-1.04) indicated high to very high tolerance. *A. niger* and *A. nidulans* demonstrated exceptional tolerance ≥1 to Co and Sn concentrations. Overall, *A. niger*, *A. nidulans* and *A. flavus* expressed tolerance to all test metals at elevated concentrations exceeding world permissible limits. These characteristic traits of the *Aspergillus* species indicate their valuable potential as mycoremediative candidates for the clean-up of heavy metal polluted environments.

Key words: *Aspergillus* specie, heavy metal tolerance, mycoremediation, indiscriminate solid waste disposal, tolerance index rating.

INTRODUCTION

Ineffective waste management results in indiscriminate solid waste disposal, street littering and illegal waste dumping on the soil environment. Solid waste management especially in the Third world is a huge challenge. Usually,

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in this region, wastes are disposed of carelessly on undesignated lands. This eventually leads to environmental nuisance, pose a menace and eventually pollution, impacting negatively on the air, water and soil environments. This is shown via clogging of the water ways, flooding, emission of Greenhouse gases, transmission of diseases by vectors such as mosquitoes, flies and rodents etc., posing threat to human and public health. In developing countries, illegal, open waste dumpsites are very common (Oladipo et al., 2011; Omotayo et al., 2020). This may be ascribed to negligence, low budget allocation for proper waste management and non-stringent environmental policy measures and compliance. Of more concern is the metal deposition into soils which eventually get leached and percolate into groundwater bodies and contribute to water pollution. A times, from the soils, crops can also take-up these metals and may eventually get into food chain (Manirakiza et al., 2020).

Specifically, in Nigeria, the detection of heavy metals in soils and water bodies associated with solid waste dumpsites has been well established by several authors. In the Southwestern, Nigeria, Ademola et al. (2015), confirmed the occurrence of elevated Cd, Cu and Zn concentrations from soil samples obtained around five major dumpsites in Lagos and Ogun States. Another study conducted in Ibadan, Oyo State by Saheed et al. (2020), sampled five dumpsites and detected Pb and Ni concentrations in ground water and Cd, Co, Pb, Ni and Cr in soils which exceeded the World Health Organization (WHO) permissible limits. Furthermore, Gbadamosi et al. (2021), sampled soils from three dumpsites in Ijebu-Ode, Ogun State, Nigeria and recorded elevated Pb, Cd, Cr, Ni, and Zn concentrations. Oladejo et al. (2021), in their own study found Cd, Cu and Zn in elevated concentrations in soils of a major dumpsite in Osogbo, Osun State. While, Isah et al. (2023) confirmed the presence of elevated levels of Co, Cd, Hg, and Pb in both soil and water samples associated with an open dumpsite in Ede, Osun State, which had been in operation for 50 years.

Furthermore, Onwukeme and Eze (2021), conducted a comprehensive study in Southeastern, Nigeria comprising of four (Abia, Anambra, Ebonyi and Imo) States on heavy metal presence in dumpsites. The study sampled 10 major solid waste dumpsites and confirmed elevated concentrations of Cr, Mn, Co, Fe, Ni, Cu, Zn, As, Pb and Cd in soils beyond the Food and Agriculture Organization of the United Nations (FAO) and WHO permissible limits. Lastly, in the Northern part of Nigeria, Wunzani et al. (2020) recorded high Zn, Ni and Pb concentrations in soils of three dumpsites within Kafanchan metropolis in Kaduna State. Likewise, Ibrahim et al. (2020), confirmed the detection of Cd, Cu and Pb in soils of 10 solid waste dumpsites in Potiskum, Yobe State Nigeria which were above the WHO set limits. In addition, Ojiego et al. (2022) reported the heavy metal pollution of Ni, Cr, Pb, Cd and Zn from 24 soils sampled from Kuje and Kwali solid waste dumpsites, Abuja, Nigeria.

Li et al. (2019), stated that about 5 million soil sites worldwide are heavy metal polluted exceeding regulatory levels. Hence, the restoration of such sites has become crucial. Many physical and chemical strategies have been adopted for the reclamation of such heavy metal contaminated sites though these have been adjudged ineffective, expensive and eco-friendly. Bioremediation which involves the use of biological agents such as microorganisms have been reported environmentally safe and cost effective. According to González and Ghneim-Herrera (2021), microorganisms have evolved diverse coping strategies via multiple mechanisms to detoxify heavy metal toxicity.

Mycoremediation deploys the use of fungal species to clean-up metal polluted sites. Fungi have been classified as a unique group of microbes with inherent capability to efficiently break down a wide variety of toxic xenobiotics (Muksy and Kolo, 2023). Fungal species during remediation process utilize xenobiotics as sources of energy and nutrients (Ellouze and Sayadi, 2016). Hence, they produce several intracellular and extracellular enzymes that can eliminate heavy metal contaminants through metal cation adsorption with functional fungal cell wall groups, complexation, ion exchange, etc. (Tomasini and León-Santiesteban 2019; Ayele et al., 2021; Gomaa et al., 2022; Muksy and Kolo, 2023).

The filamentous fungus group - *Aspergillus*, is known for its biomass degradation ability which it achieves through the production of a number of enzymes. According to Dusengemungu et al. (2020), *Aspergillus* species, are effective for heavy metal bioremediation as a result of their capability to create metal sinks and produce organic acids. It has been reported that heavy metal tolerant/resistant microorganisms are generally present in heavy metal contaminated/polluted environments (Oladipo et al., 2016; Palanivel et al., 2023). Studies have documented the isolation of *Aspergillus* species from various contaminated/ polluted sites and attested to their bioremediative potentials.

Rose and Devi (2018) isolated three *Aspergillus* species - *Aspergillus awamori, Aspergillus flavus and Aspergillus niger* from wastewater and sludge samples of a steel industry and confirmed their metal tolerance to Cu and Ni. Likewise, Vaˇsinkov´a et al. (2021), confirmed Zn, Cu and Cr tolerance of six *Aspergillus* species (*A. niger, A. candidus, A. iizukae, A. westerdijkiae, A. ochraceus* and *A. clavatus*) isolated from anthropogenically contaminated lagoons. Titilawo et al. (2023), recently reported the Pb tolerance of *A. flavus*, *A. niger*, *A. awamori*, *A. terreus* and *A. ochraceus* isolated from waste dumpsites.

Studies on *Aspergillus* species and their metal tolerance potential have been conducted. However, a dearth in knowledge exists with their response to specific metals such as Co, Ag, Mn and Sn at varied concentrations. Hence, this study was designed to evaluate the response, growth pattern, metal tolerance and metal tolerance rating to Fe, Pb, Co, Ag, Mn and Sn at varied concentrations by

Table 1. Sampling location and sources of fungal isolates from Galilee River and Ori-Ile waste dumpsite, Ibadan, Nigeria.

Isolate code	Site sampled/location	Sample type	GPS location
A1	Galilee River, Ibadan, Nigeria	Water	7°42′965″N, 3°99′880″W
F8	Ori-Ile waste dumpsite, Ibadan, Nigeria	Soil	6°22′186.7″S, 9°24′185.6″W
E3	Galilee River, Ibadan, Nigeria	Water	7°42′965″N, 3°99′880″W

Table 2. Heavy metals, salts and concentrations used for tolerance experiments.

Heavy metals	Metal salts[a]	Heavy metal concentrations (mgl^{-1})
Lead (Pb)	Lead sulphate ($PbSO_4$)	100, 200, 300 and 600
Cobalt (Co)	Cobalt chloride ($CoCl_2$)	50, 100, 150 and 300
Iron (Fe)	Ferric chloride ($FeCl_3$)	100, 200, 300 and 600
Tin (Sn)	Tin chloride ($SnCl_2$)	25, 75, 100 and 300
Manganese (Mn)	Manganese chloride ($MnCl_2$)	100, 200, 300 and 600
Silver (Ag)	Silver nitrate ($AgNO_3$)	25, 50, 75 and 100

[a]Salts used were of analytical grade (Sigma-Aldrich, JNB, South Africa).

A. niger, *A. nidulans* and *A. flavus* isolated from soil and water environments impacted by solid waste dumping.

MATERIALS AND METHODS

Description of the study areas

Two study areas impacted by solid waste dumping were selected. These sites (Table 1), are the Galilee River (located at Olodo garage, Egbeda Local Government Ibadan, Oyo State) and the Ori-Ile Waste Dumpsite (located at Ikumapaiyi Olodo garage, Egbeda Local Government Ibadan, Oyo State). The Galilee River, receives wastes being dumped into it on a daily basis while the Ori-Ile Waste Dumpsite is the dumpsite that receives all the wastes generated in the area.

Sample collection

Water samples were collected in triplicates at 5 different points along the Galilee River. The samples were collected into 500 ml sterilized sampling bottles and labeled. Soil samples were randomly collected from different locations from the Ori-Ile Waste Dumpsite to obtain representative samples. Firstly, the soil surface was removed of wastes and debris then the subsurface soil was dug to a depth of 0-15 cm using sterile soil auger, samples were put in triplicates into new, clean Ziplock bags and labeled appropriately. All samples were preserved in coolers containing ice chests and transported to the laboratory for microbiological analysis.

Microbial analysis

Isolation of soil fungi

The isolation of fungi from both water and soil samples was performed using serial dilution. Potato Dextrose Agar (PDA) using the spread plate method was then used and incubation was carried out at 30°C for five days as described previously (Oladipo et al., 2018). In order to prevent bacterial growth, 35 $mgmL^{-1}$ of streptomycin supplement was added into the medium. After incubation, single spores of fungal isolates were sub-cultured successively on PDA to obtain pure isolates. Fungal species were then characterized phenotypically using macroscopic observations - shape, pigmentation, colony and texture appearance and diameter (Oladipo et al., 2016). Microscopic characterization (mycelia septation, form, shape, texture and diameter of conidia/spore) was detected using lactophenol cotton blue to stain the fungal slides and observed under the phase contrast microscope - model T390 - NL040 (Amscope, Irvine, CA, USA). The fungal cultural and morphological features were then determined. For the purpose of this study, only *Aspergillus* species identified based on these characteristics were purposely selected for heavy metal tolerance assessments.

Heavy metal tolerance examination

The isolated and identified *Aspergillus* species were assessed for heavy metal tolerance by being exposed to two different heavy metals each on a random basis. In total, 6 (Pb, Co, Fe, Sn, Mn and Ag) heavy metals were used for this study and at 5 concentrations based on toxicity (Table 2). The heavy metal salts were membrane filter sterilized (0.25 µm pore size) and were incorporated into sterile Malt Extract Agar (MEA). The media were supplemented with 35 $mgmL^{-1}$ streptomycin while pH was maintained at 5.6 by adding 3 M NaOH. The experimental set-up was conducted in triplicates with the control and 4 varied test concentrations. The amended media with heavy metals were the test while the un-amended media served as the control.

Aspergillus species of 8 mm diameter disks from fully matured 7-day old pure culture each were inoculated individually into 8 mm well bored aseptically at the centre of control and test MEA plates. All experimental plates were then incubated at 29 ± 1° C over a period of 13 days. During the incubation period, mycelial radial growth was monitored and recorded every two days. Heavy metal tolerance potential of the *Aspergillus* species in the test medium was calculated In comparison with the control radial growths (Equation 1). The

Table 3. Morphological and microscopic characteristics of fungal isolates from Galilee River and Ori-Ile Waste Dumpsite.

Sample ID	Macroscopic characteristics	Microscopic characteristics	Fungal identity
A1	Growth is initially white but changes to black after few days producing conidial spore with pale yellow reverse and powdery texture	Produced finely roughened to rough-walled conidia with about 3.2-3.7 µm in diameter Spores are brown to black, very rough, and globose-shaped	*A. niger*
F8	Colonies were dark green with white mycelia, abundant conidia, and dark brown color on the reverse	Revealed very short conidiophores that were smooth-walled which turned brown with age. Conidia were green and spherical with smooth to slightly rough walls.	*A. nidulans*
E3	Colonies were powdery masses of yellowish-green spores on the upper surface and reddish-gold on the lower surface	Production of a bright yellow-green conidial color, Vesicles bear crowded phialides, or metulae and phialides, which are characteristically all borne simultaneously	*A. flavus*

Cultural and morphological characteristics were then compared with those enumerated by Samson et al. (1984).

$$\text{Tolerance Index} = \frac{Radial\ growth\ (mm)\ of\ test\ fungus\ in\ heavy\ metal\ incorporated\ medium}{Radial\ growth\ (mm)\ of\ fungus\ in\ non{-}heavy\ metal\ incorporated\ medium} \quad (1)$$

mycelial fungal heavy metal tolerance response was then interpreted according to Oladipo et al. (2018).

Statistical analysis

Statistical analysis of obtained data was carried out using one-way analysis of variance (ANOVA) at 5% level of significance using the Statistical Package for Social Sciences (SPSS) version 25 (IBM, Armonk, NY, USA). Post hoc test was then performed using the Duncan's New Multiple Range Test.

RESULTS AND DISCUSSION

This study presents findings on identified *Aspergillus* species isolated from water and soils impacted by solid waste dumping, their tolerance to different heavy metals at varied concentrations, growth patterns in the metal enriched media in comparison with the controls over a 13-day period and their metal tolerance index.

Fungal identity

Table 3 and Figure 1 present the morphological and microscopic characteristics of the *Aspergillus* isolates obtained from the Galilee River and Ori-Ile waste dumpsites impacted by solid wastes. On comparing these characteristics with those enumerated by Samson et al. (1984), the identities of the fungal species were found to be *Aspergillus niger, Aspergillus nidulans* and *Aspergillus flavus*. The occurrence of *Aspergillus* species in soils and water sources impacted by solid waste dumping has been confirmed (Ezeagu et al., 2023; Simon-Oke et al., 2023; Titilawo et al., 2023). Fungi are a dominant group of microorganisms that play significant ecological services in the environment (Frac et al., 2018). Specifically, the detection of the fungal species in polluted sites as identified in this study, is owned to their marked capability and versatility to degrade efficiently a wide range of complex and harmful xenobiotics (Muksy and Kolo, 2023).

Fungal response to varied heavy metal concentrations

The three *Aspergillus* isolates studied in this article, were assessed for tolerance to two different heavy metals each at varied concentrations based on toxicity (Table 2) over an incubation period of 13 days. While *A. niger* was exposed to Pb {100, 200, 300 and 600 mgl^{-1}} and Co {50, 100, 150 and 300 mgl^{-1}}, *Aspergillus nidulans* was incubated in Fe {100, 200, 300 and 600 mgl^{1}}and Sn {25, 75, 100 and 300 mgl^{-1}} enriched media and *A. flavus*, Mn {100, 200, 300 and 600 mgl^{-1}} and Ag {25, 50, 75 and 100 mgl^{-1}}.

On exposure to Pb concentrations, *A. niger*, exhibited mycelial growth at all test concentrations (100, 200, 300 and 600 mgl^{-1}) with no significant differences ($p > .05$) to the control (Table 4). Hence, *A. niger*, expressed tolerance to Pb at all test concentrations. Similarly, when exposed to Co enriched media at 50, 100, 150 and 300 mgl^{-1}, *A. niger*, revealed no significant differences ($p>.05$) in mycelial growth to the control during the incubation period. The finding of this study is in agreement with previous results and the remarkable tolerance of *A. niger* to Pb and Co

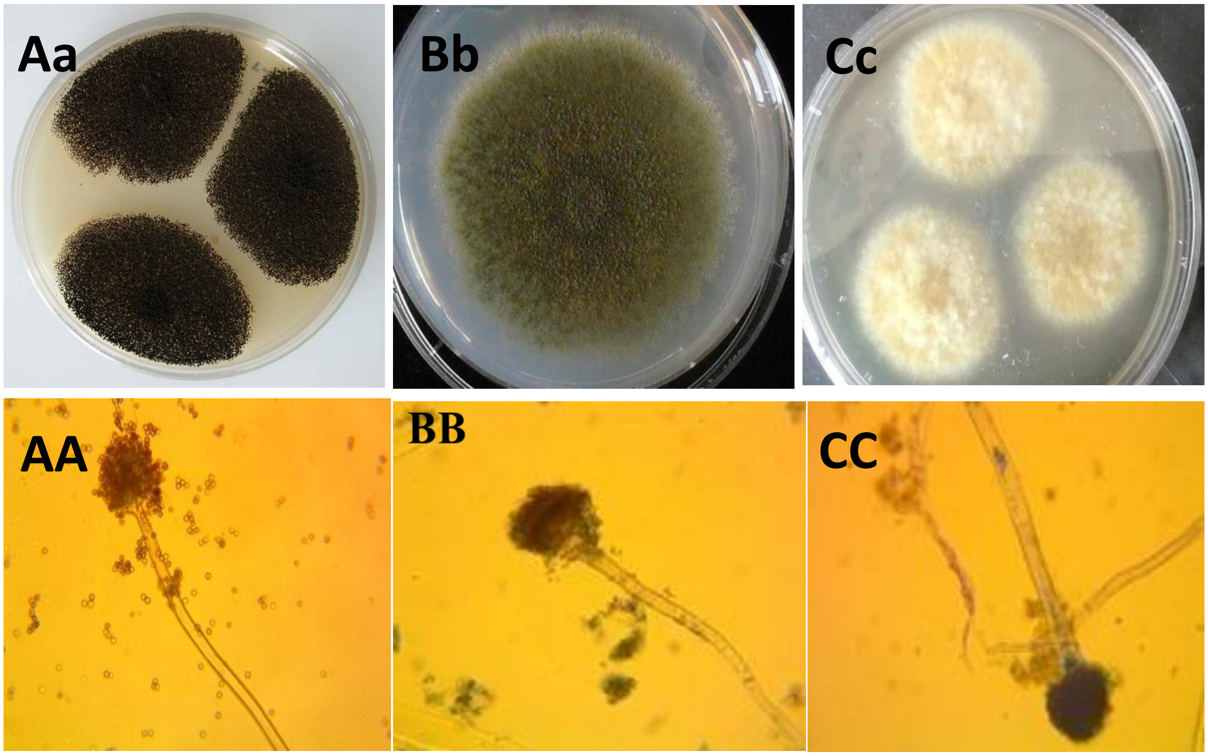

Figure 1. Identification of isolated *Aspergillus* species from soil and water sampling sites impacted by solid waste dumping. Top images display the morphology of the fungal cultures after 5 days of growth in PDA. Bottom images reveal the microscopic characterization of the fungal structures. Aa and AA {*A. niger*}, Bb and BB {*A. nidulans*} and Cc and CC {*A. flavus*}.

Table 4. Radial growth (mm) of *Aspergillus* species in varied heavy metal concentrations over 13 days' exposure.

Isolate	Heavy metal	Growth in control and test concentrations (mgl^{-1})						
A. niger	Pb	0	100	200	300	600	F	P
		58.33±7.28^a	57.55±5.75^a	59.00±5.86^a	56.54±5.71^a	56.26±5.73^a	0.038	0.997
	Co	0	50	100	150	300	F	P
		64.04±8.04^a	63.92±6.49^a	64.19±6.45^a	64.51±6.45^a	64.31±6.49^a	0.001	1.000
A. nidulans	Fe	0	100	200	300	600	F	P
		55.51±7.98^a	56.06±6.39^a	53.13±6.67^a	53.85±6.65^a	56.14±6.48^a	0.043	0.996
	Sn	0	25	75	100	300	F	P
		60.91±8.41^a	63.52±6.58^a	62.99±6.60^a	62.68±6.62^a	62.32±6.63^a	0.017	0.999
A. flavus	Mn	0	100	200	300	600	F	P
		59.00±7.82^a	57.78±6.99^a	56.84±6.88^a	57.07±6.99^a	55.97±6.82^a	0.022	0.999
	Ag	0	25	50	75	100	F	P
		59.53±7.95^a	59.87±6.60^a	57.38±6.65^a	58.10±6.63^a	57.35±6.89^a	0.030	0.998

Means of three replicates (± SE) followed by the same letters in the same row are not significantly different ($p < .05$) according to Duncan's new multiple range test.

heavy metals is affirmed. Tian et al. (2019) confirmed that *A. niger* responded well to Pb heavy metal on exposure. In addition, Shazia et al. (2013) reported that *A. niger* showed tolerance to 1000 mgl^{-1} Pb concentration while Bala et al. (2020) reported that *A. niger* isolated from refuse dumpsite revealed tolerance to 400 mgl^{-1} Pb. With

Table 5. Heavy metal tolerance capability of *Aspergillus* species in comparison to permissible limits.

Fungi	Heavy metals	Highest concentration ($mgkg^{-1}$) tolerated	World permissible limit in soils ($mgkg^{-1}$)[a]
[b]*A. niger*	Lead	200	27.0
	Cobalt	600	11.3
[b]*A. nidulans*	Iron	600	[c]
	Tin	300	2.5
[b]*A. flavus*	Manganese	[d]600	488
	Silver	25	0.13

[a]FAO (1984) and Kabata-Pendias (2011); [b]Mean concentration of triplicate samples in the study was used; [c]Not available. Dependent on different soil parental constituents; [d]Fungal growth was between 1.2 and 3.0mm < than control though statistically indifferent.

regards to Co, Yang et al. (2020) in their study confirmed that *A. niger* tolerated high cobalt concentrations on exposure.

Likewise, when *Aspergillus nidulans* was exposed to Fe and Sn concentrations, it followed the same trend as *A. niger*. *Aspergillus nidulans* exhibited tolerance to Fe at 100, 200, 300 and 600 mgl^{-1} with mycelial growth showing no significant difference ($p>.05$) compared with the control. On exposure to Sn in enriched media of 25, 75, 100 and 300 mgl^{-1}, there was no significant difference ($p>.05$) in the mycelial growth between the test and the control (Table 4). Previously, the tolerance capability of *A. nidulans* to Cd, Cu and Pb heavy metals had been reported with particular reference to its tolerance to Fe at 800 mgl^{-1}concentration (Oladipo et al., 2016). Also, Emri et al. (2021), reported that *Aspergillus nidulans* tolerated Cd concentrations. However, studies on the exposure and tolerance of *A. nidulans* to Sn were not found and generally, literature on the exposure of *A. nidulans* to heavy metals were highly limited. Hence, this study contributes some baseline information on the tolerance capability of *Aspergillus nidulans* to heavy metals especially Sn.

With regards to *A. flavus,* the mycelial growth in test media of Mn (100, 200, 300 and 600 mgl^{-1}) and Ag (25, 50, 75 and 100 mgl^{-1}) heavy metals, at all test concentrations showed no significant difference ($p>.05$) to the control. Fouda et al. (2022) reported that *A. flavus* tolerated Ag up to high concentrations and was able to form Ag nanoparticles. However, there is a dearth of information on the exposure of *A. flavus* to Mn concentrations. Although, generally, *A. flavus* has been reported to exhibit tolerance to heavy metals. Iram et al. (2013) had published that *A. flavus* showed resistance to Cr and Pb while Kurniati et al. (2014), established the resistance of *A. flavus* to 100 mgl^{-1} Hg. In addition, Abdullahi and Machido (2017) reported its tolerance to Fe, Cr and Cd while Rose and Devi (2018) notified of the tolerance of *A. flavus* to Cu and Ni. All these confirm that *A. flavus* possesses heavy metal tolerance traits.

Overall, the response of these *Aspergillus* species - *A. niger, A. nidulans* and *A. flavus* to the six tested heavy metals (Pb, Co, Fe, Sn, Mn and Ag) at varied concentrations is noteworthy. When compared with the world permissible limits (Table 5), these *Aspergillus* species, exhibited far higher tolerance to heavy metals. For instance, the limit for Co in soils is 11.3 $mgkg^{-1}$ and *A. niger* tolerated as high as 600 mgl^{-1}, with no significant difference with the control. Likewise, *A. nidulans* and *A. flavus* with tested heavy metals (Table 5).

These findings are supported by Shalaby et al. (2023), that *Aspergillus* spp. is an identified multimetal tolerant fungus group. In addition, Vaˇsinkov´a et al. (2021) had also reported on the unique ability of *Aspergillus* species to tolerate a variety of heavy metals (Cu, Zn, Ni and Cr). Oladipo et al. (2016), confirmed the high-level tolerance some *Aspergillus* species displayed to different heavy metals (100 mgl^{-1}Cd, 1000 mgl^{-1} Cu, Pb 400 mgl^{-1}, As 500 mgl^{-1} and Fe 800 mgl^{-1}) with comparable mycelial growth with the controls.

Growth pattern of *Aspergillus* species in metal enriched media over 13 days exposure

Growth pattern is a measuring index that determines and monitors the response or survival of microorganisms, especially in contaminated and polluted environments. Hence, this study, assessed the growth pattern of the isolated *Aspergillus* species in different metal exposures. With reference to the mycelial growth pattern of the isolated *Aspergillus* species in varied heavy metal enriched media over 13-days incubation period, there were no visible outstanding differences between the controls and all test exposures (Figure 2). *A. niger*, *A. nidulans* and *A. flavus* expressed steady and comparable growth with their controls even at the highest concentrations of Pb & Co, Fe & Sn and Mn & Ag exposure respectively (Figure 2A, B and C).

Specifically, in Co (300 mgl^{-1}) enriched media, *A. niger*, throughout the 13-days incubation period, revealed a matching growth pattern with the control (Figure 2A). Although, in Pb media, between day 1 and day 5, *A. niger*, exhibited sharp, steady, exponential mycelial growth increase, there was no observable growth between day 5

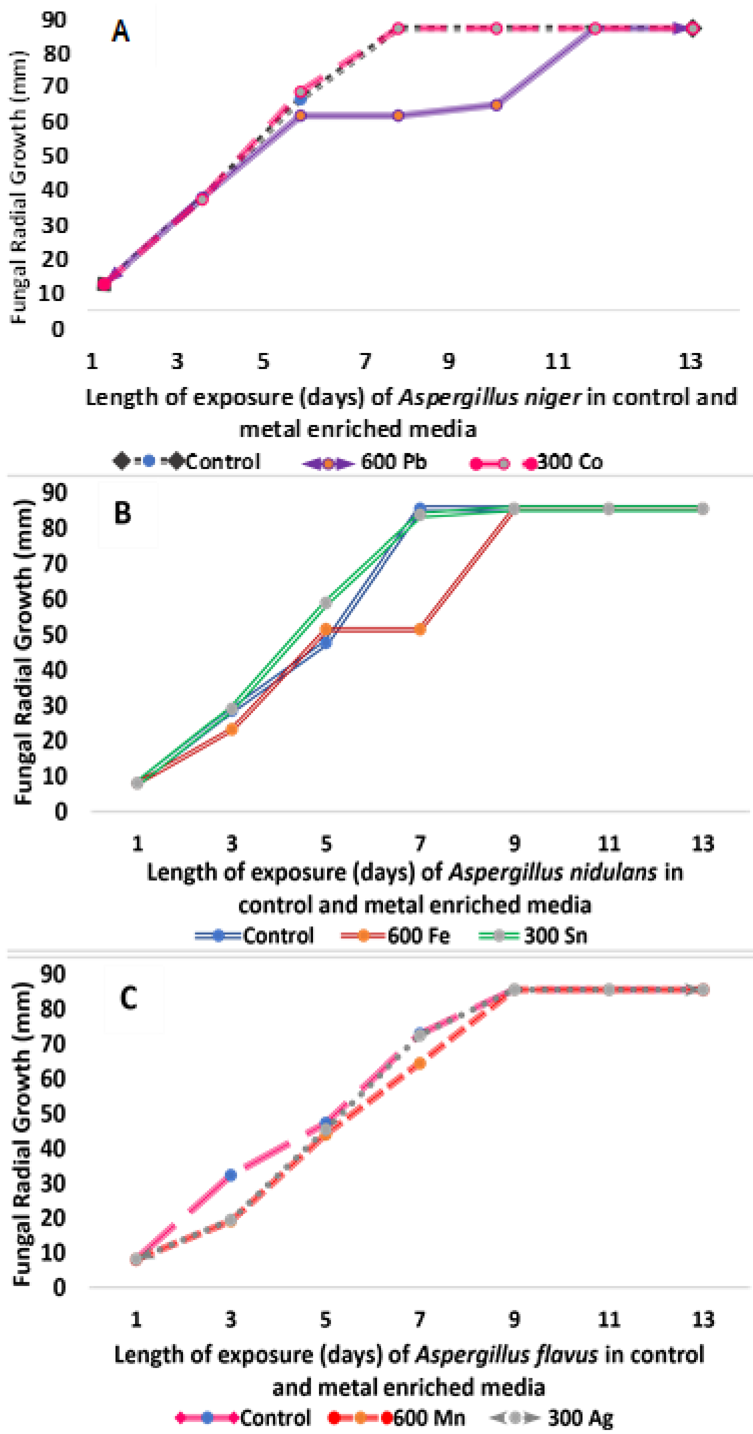

Figure 2. Effect of length of exposure on mycelial growth (mm) of (A)- *A. niger* exposed to lead and cobalt; (B) *A. nidulans*, to iron and tin and **(C)** - *A. flavus* to manganese and silver over 13-days incubation period.

and 7 compared with the control. However, by day 9 a noticeable slight growth indication was observed which sharply increased by day 11, comparable with the control and was sustained till day 13 when the exposure was terminated (Figure 2A).

These findings are consistent with previous studies. Anahid et al. (2011) reported a continuous growth pattern of *A. niger* in 500 mgl^{-1} Co enriched medium over a 10-day period. In addition, Prakash et al. (2023), also confirmed the steady growth of *A. niger* in 200 mgl^{-1} Pb over a 5-day incubation period. The potential of *A. niger* to thrive well in Pb enriched medium has been ascribed to its possession of major pathways that enhance its tolerance properties and reduce lead toxicity (Tian et al., 2019). Prakash et al. (2023) further reported that *A. niger*, secretes oxalic acid which reacts with insoluble lead minerals. This enhances the absorption of Pb by the formation of new cell wall borders which prevents Pb transportation into the fungal hypha. Filote et al. (2021), also stated that *A. niger* due to its unique traits, has been identified as an established and effective fungus for the remediation of heavy metal polluted soils.

Aspergillus nidulans expressed sharp and steady exponential growth to 600 mgl^{-1} Fe concentration from the start day of exposure (Figure 2B). However, between day 5 and day 7, no observable increase in growth was recorded. Although, this trend took a dramatic turn between days 7 and 9 with significant growth increase comparable to the control which lasted till the end of the exposure period. Interestingly, in Sn enriched media, at the highest level of exposure (300 mgl^{-1}), *Aspergillus nidulans*, exhibited vivid growth increase higher than the control between days 3 and 7 (Figure 2B). Afterwards, *A. nidulans* revealed very similar growth pattern of both control and test exposures which was maintained till the 13th day of incubation when the experiment was terminated. This steady growth progress displayed by *A. nidulans* in metal rich media throughout the 13-days exposure period indicates the metal tolerance ability of the strain. This finding displayed by *Aspergillus nidulans* has been confirmed in literature. A similar study conducted by Oladipo et al. (2016), revealed that *A. nidulans* exhibited stable growth pattern in 400, 800 and 1000 mgl^{-1} Pb, Fe and Cu media, respectively. However, information on the growth pattern of *A. nidulans* to Sn were not found in literature.

With regards to the growth patterns of *A. flavus* in 600 mgl^{-1} Mn and 100 mgl^{-1} Ag exposure during 13-days incubation period, a similar trend was observed. Initially, *A. flavus* exhibited slightly slower growth in both metal-enriched media compared with the control. This may be ascribed to the fungus getting stabilized in the metal-amended media. However afterwards, (by the 5th day for Ag and 9th day for Mn), steady and sustained growth was observed by *A. flavus* in both test media that were comparable with the control till the 13th day when the exposure period was terminated. These findings of comparable growth patterns with the control, establish the tolerance of *A. flavus* to Mn and Ag heavy metals. It was however observed that there is a dearth in literature on the growth patterns of *A. flavus* to these metals to buttress this finding. Hence, to the best of our knowledge, this information provides first hand evidence/literature on the growth pattern and response of *A. flavus* to Mn and Ag.

Tolerance index rating of *A. niger, A. nidulans* and *A. flavus* to Pb, Co, Fe, Sn, Mn and Ag concentrations

This study ascertained the tolerance potential of test *Aspergillus* species to different heavy metals at varied concentrations (Table 4). Using the data gathered, we further evaluated and ranked the metal tolerance levels of the *Aspergillus* species. This was obtained by calculating the tolerance index as stated in Equation 1. The ranking was then determined. Here, fungi heavy metal tolerance in heavy metals was rated as: 0.00-0.39 (very low tolerance), 0.40-0.59 (low tolerance), 0.60-0.79 (moderate tolerance), 0.80-0.99 (high tolerance) and 1.00->1.00 (very high tolerance), the higher the values, was the higher the fungal tolerance to the tested heavy metal.

Hence, Table 6, presents the tolerance index of the tested *Aspergillus* species in metal enriched media. To Pb concentrations (100 to 600 mgl^{-1}), *A. niger* had a high to very high tolerance rating which ranged between 0.96-1.01. In 50 - 300 mgl^{-1} Co media, an exceptionally 'very high tolerance' rating was recorded by *A. niger* with a range of 1.00 to 1.01. This further confirms that *A. niger* possesses potentials for Pb and Co metal tolerance which may indicate it's bioremediative traits. Our finding is corroborated by similar studies conducted by Shazia et al. (2013) and Prakash et al. (2023) with tolerance index of 0.71 at 1000 mgl^{-1} Pb and 1.07 at 200mgl^{1} Pb respectively.

In this study, a similar heavy metal tolerance index trend displayed by *A. niger* was observed with *Aspergillus nidulans* in 100 to 600 mgl^{-1} Fe and Sn 25 to 300 mgl^{-1} enriched media. The tolerance index of *A. nidulans* ranged between 0.96-1.01 and 1.02-1.04 in Fe and Sn respectively indicating high to very high tolerance rating. Likewise, for *A. flavus* in Mn (100 - 600 mgl^{-1}) and Ag (25 - 100 mgl^{-1}) concentrations, a tolerance index of 0.95-0.98 and 0.96-1.01 with high and very high tolerance rating was established respectively. These findings further buttress the tolerance capability of these *Aspergillus* species to the tested heavy metals.

Conclusively, with regards to the tolerance index rating of *A. niger, A. nidulans* and *A. flavus* to tested Pb, Co, Fe, Sn, Mn and Ag varied concentrations, a tolerance index of 0.95 to 1.04 which ranked between high to very high tolerance was confirmed. Specifically, the tolerance index of *A. niger* and *A. nidulans* to Co and Sn concentrations revealed very high tolerance with 1.00-1.01 and 1.02-1.04 respectively, indicating ≥ growth with their controls. These findings bring to fore the exceptional tolerance qualities inherent in these *Aspergillus* species towards heavy metals. Noteworthy, are *Aspergillus nidulans* and *A. flavus*

Table 6. Tolerance index levels of *Aspergillus* species in metal-enriched media concentrations.

Fungus		Heavy metals concentrations (mgl^{-1}) and tolerance index			
A. niger	Pb	100	200	300	600
		0.99	1.01	0.97	0.96
	Co	50	100	150	300
		1.00	1.00	1.01	1.01
A. nidulans	Fe	100	200	300	600
		1.01	0.96	0.97	1.01
	Sn	25	75	100	300
		1.04	1.03	1.03	1.02
A. flavus	Mn	100	200	300	600
		0.98	0.96	0.97	0.95
	Ag	25	50	75	100
		1.01	0.96	0.98	0.96

Tolerance index rating values indicate: 0.00-0.39, very low metal tolerance. 0.40-0.59, low metal tolerance. 0.60-0.79, moderate metal tolerance. 0.80-0.99, high metal tolerance. 1.00->1.00 - very high metal tolerance (Oladipo et al., 2018).

of which there is dearth in literature on their tolerance traits and rating to tested heavy metals but with significantly high tolerance index and rating.

Conclusion

Indigenous filamentous *Aspergillus* species isolated from water and soil environments impacted by solid waste dumping exhibited astonishing and remarkable response, growth pattern, tolerance index and tolerance rating in heavy metal enriched media. The three *Aspergillus* species - *A. niger, A. nidulans* and *A. flavus* were examined in Pb and Co, Fe and Sn and Mn & Ag respectively and at varied concentrations based on toxicity. On exposure, all three *Aspergillus* species revealed response and growth patterns which differed not with their respective controls in heavy metal amended media. Worthy of note is the extraordinary tolerance displayed by *A. niger* and *A. nidulans* to Co {50 - 300 mgl^{-1}} and Sn {25 - 300 mgl^{-1}} at all test metal concentrations with very high metal tolerance and index values ≥ 1. The exceptional traits proved by these *Aspergillus* species to elevated heavy metal concentrations indicates their characteristic bioremediative capacities as candidates for remediation of metal polluted sites.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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