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Climate Change and Type 2 Diabetes in Senegal, a Sub-Saharan Country: Interconnected Threats to Health and Development

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ABSTRACT

Type 2 Diabetes Mellitus (T2DM), a disease once thought to be rare and only affecting the wealthy, is now on the rise across Senegal, a sub-Saharan African country. Genetics play a role in insulin production, a key factor in type 2 diabetes, however, the disease is also heavily influenced by environmental factors. There is limited data available regarding diabetes in sub-Saharan countries, which highlights the importance of discussing the underlying reasons for rapid progression of the disease in the region. Here, we provide a broad view of the influence of climate change on the multifactorial drivers of type 2 diabetes across the population in Senegal, and to discuss the potential mechanisms behind the intersecting effects between them. This review highlights evidenced-based information to shed light on the potential linkage between T2DM and environmental factors like climate change, pollution, urbanization and lifestyle choices (such as the consumption of ultra-processed foods, limited physical activities). We propose that these modifiable risk factors are promoting diabetes in Senegal and other sub-Saharan countries. We discuss the impact (mechanistic) of air pollution and diet on the gut microbiome and the resulting chronic inflammation that could propel the development of T2DM. Finally, this paper recommends various public health policies, to curb the progression of diabetes, which is is still in the initial stages in Senegal. Taken together, this paper outlines opportunities to design new and effective targeted prevention strategies, which can be applied to mitigate the rapid increase of diabetes in Senegal and beyond.

Keywords: Type 2 diabetes, Senegal (sub-Saharan), Climate change, Extreme weather, Pollution, Gut microbiome, Inflammation, Insulin resistance.

INTRODUCTION

Diabetes is a global epidemic. The International Diabetes Federation reports there are 537 million adults with diabetes worldwide, a figure which is expected to rise to 643 million by 2030 [1]. Over four million people die from diabetes every year, and it is among the top 10 causes of disability worldwide [1,2]. There are an estimated 15.9 million adults living with

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T2DM in sub-saharan Africa [3], and estimates indicate that as many as 69% of these cases are undiagnosed [4]. Moreover, the prevalence of diabetes is predicted to see the largest percentage increase in sub-Saharan countries [5], including Senegal, in the coming decades. We have focused on the increase in incident and prevalence of T2DM in Senegal amongst other sub-Saharan countries because of rapid urbanization, moving of populations from the rural regions to urban areas, growing sedentary lifestyle and augmented consumption of processed foods, increased of pollution, and these are considered as risk factors for T2DM. The WHO reports a diabetes prevalence of 5.1% in Senegal as of 2016, or 771,579 people living with diabetes [6]. Like many countries, the economic burden that includes both direct cost and indirect costs such as the loss of productivity, are likely to be substantial due to the paucity of adequate healthcare services.

While genetics can propel T2DM, recent studies demonstrate a strong association between the environment and diabetes risk [7]. Importantly, environmental risk factors for diabetes are often impacted by climate change. Previous studies described the potential effects of climate change to human health in Sub-Saharan Africa [8]. Increased flooding, extreme heat, draught, and urbanization have been found to augment the risk of food insecurity and malnutrition, which are linked to diabetes [9,10]. Early-life malnutrition has also been linked to the development of hyperglycemia [11].

Our search for evidence-based information shows that there is limited data and studies on environmental conditions and their association with the prevalence of diabetes in Senegal. Lifestyle changes attributed to rapid urbanization, reduced physical activity, and the increased access to and consumption of processed foods compounded with the impact of exposure to air pollution, extreme heat and draught due to climate change are shifting the healthcare landscape in Senegal. In this paper, we describe how these external factors perturb the gut microbiome hypothesize that this stimulates low-grade chronic inflammation involved in development of Type 2 diabetes. In this review, we sought to gather evidence on environmental exposures that could have an impact on incidence and prevalence of diabetes in Senegal, which can inform the development and implementation of tailored prevention and management strategies. To the best of our knowledge, this review is the first to postulate the significant impact of climate change on the multifactorial propellers of type 2 diabetes in Senegal, and to expand on the potential mechanisms behind the intersecting effects between them.

DIABETES AND ITS MECHANISMS

The exact cause of most types of diabetes is unknown but it is thought to be a multi-factorial disease (Figure 1). T2DM is a metabolic chronic disorder where sugar builds up in the bloodstream because the pancreas does not produce enough insulin, which is the hormone that helps cells to absorb blood glucose [12]. Insulin resistance occurs when there are high blood sugar levels for extended periods; eventually, cells stop responding to insulin as effectively. Insulin resistance develops early in T2DM and is characterized by the inability of cells and tissues to properly absorb blood glucose for energy People with T2DM are unable to make enough insulin, or their cells are unable to respond to it effectively, which results in elevated blood glucose levels, also known as hyperglycemia (Figure 2) [13].

Beta cells are responsible for making insulin in the pancreas [14].In patients with T2DM, the beta cells are significantly more taxed to generate enough insulin to control blood glucose.

Impacts on beta cell function occur early in diabetes development and continue to decline as the disease progresses [15]. In addition to the negative impacts on pancreatic insulin production, high blood sugar levels can lead to disorders of the circulatory, nervous, and immune systems [16–18].

The exact cause of type 2 diabetes is unknown, however, risk factors such as a sedentary lifestyle, obesity, and consuming ultraprocessed foods are major drivers (Figure 1). Recent studies indicate that air pollution and altered gut microbiome composition are also implicated in the development of T2DM by inducing chronic inflammation [19,20]. There is growing evidence that there are moderate to strong genetic components to diabetes [21]. Since diabetes development depends on environmental factors and genetics, epigenetic mechanisms are likely to play an important regulatory role (Haque & Pant, in preparation). Several studies also suggest disparities in T2DM prevalence among ethnic minority groups [22,23].

Symptoms of T2DM can develop slowly and may go unnoticed by many patients. Common symptoms include frequent urination, increased thirst, increased hunger, fatigue, weight loss, cuts or wounds that heal slowly, impaired vision, numbness or itching in the hands or feet, and areas of darkened skin (usually in the armpits and neck) [24]. Clinical diagnosis is typically done using the glycated hemoglobin (A1C) test; a result below 5.7% is considered normal, 5.7% to 5.4% is prediabetic, and a result of 6.5% or higher on two separate tests indicates diabetes [25]. If an A1c test is not feasible, then a random blood glucose test can also be used; a value of 200 mg/dl suggests diabetes [25].

Type 2 diabetes is a complex disease, which has no known cure. Although the mechanisms of type 2 diabetes development are poorly understood, many molecular and cellular mechanisms contribute to its development (Figure 2). For example, oxidative stress acts as a mediator of insulin resistance and can damage cells to promote diabetic complications [26]. Additionally, adipose tissue inflammation has been identified as a key factor in the development of insulin resistance and type 2 diabetes [27] (Figure 2). Inflammation induced by different environmental risk factors is a major contributor to the development of type 2 diabetes. Pro-inflammatory cytokines, such as IL-6 and TNF-alpha, play an important role in the pathogenesis of type 2 diabetes [28,29] (Figure 2). These cytokines can cause insulin resistance which leads to impaired glucose homeostasis [30]. Overall, insulin resistance, inflammation in target organs (liver, adipose tissue, muscles, etc.), and pancreatic dysfunction have a fundamental role in diabetes pathogenesis (Figure 2) [29]. Losing weight, eating well, exercising and living in a pollution free environment can go a long way toward disease prevention or management. Without early identification and intervention, prediabetes often progresses to type 2 diabetes, which then may require more vigorous interventions such as diabetes medications or insulin therapy [31].

DIABETES IN SENEGAL

Located in the westernmost part of the African continent, Senegal is bordered by Mauritania, Mali, Guinea, Guinea-Bissau and Gambia (Figure 1). Its population is 16.7 million, with a quarter of the population living in the Dakar region (0.3% of the territory) [32]. Dakar is also home to about 80% of the country's economic and industrial activities [33]. The climate in Senegal is tropical and is characterized by two distinct seasons: the rainy season from June to October and

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the dry season between November and May. Peak humidity occurs during the rainy season when sea temperatures are warmer [34].

Currently, there is a lack of data regarding an accurate national diabetes burden in Senegal, however, one recent survey in the city of Saint-Louis (northern region) reported a prevalence of 10.4% with two-thirds of patients lacking awareness of this disease [35]. Moreover, marked disparities have been reported between urban and rural regions where lifestyle and food habits vary, differences in testing methods, and access to diabetes care vary [35–37]. There is an urgent need to establish efficient programs based on real-time data for the prevention and management of diabetes across all populations in Senegal. In this paper, we focus on the impact of modifiable environmental factors on type 2 diabetes, since the recent surge of diabetes in Senegal is mainly in this category.

THE POTENTIAL ROLE OF CLIMATE CHANGE AS DRIVERS OF DIABETES INCIDENCE

Africa was identified as the continent most impacted by climate change [38]. Furthermore, sea-level rise along African coastlines is higher than the mean global rate and is likely to increase in the future, thereby contributing to coastal flooding in low-lying cities and increasing the salinity of groundwater [39]. Frequent droughts and extreme heat events have increased demand for water in Africa and water scarcity is likely to trigger conflict among people, especially those facing economic challenges. Other challenges exacerbate these impacts in sub-Saharan countries are for example, urbanization, land use change, energy poverty, economic inequality, and external influences such as political conflict and unrest in Africa and other parts of the world affecting food supply.

Excessive Heat

Heat and diabetes combined pose a dangerous combination. Extreme heat triggers excessive sweating which may cause a person's blood glucose levels to rise through dehydration; decreasing the amount of water in the bloodstream increases the concentration of blood sugar. The physiological response to heat stress is the cutaneous vasodilation that allows for the necessary redirection of blood flow to the skin’s surface for heat dissipation, which may impair our body's ability to absorb insulin [40]. Thermal stress can alter insulin absorption and diffusion properties while stressful conditions, such as hypoglycemia, can prompt the release of various counter-regulatory hormones like glucagon, adrenaline, cortisol and growth hormone [41].

Hypersomatic dehydration, caused by heat, impedes the insulin-induced uptake of potassium ions and cell swelling in the liver [42]. Extreme heat waves greatly impact acute and even chronic glycemia management as more frequent blood sugar testing is needed and access to treatments may be compromised. Dehydration could increase vasopressin levels that can stimulate gluconeogenesis in the liver and promote insulin resistance by acting on the liver, adipose tissue, pancreas, and the pituitary gland. Protein kinase B (PKB/Akt) often activated by growth factors and insulin regulates processes like cell survival, growth, metabolism, and apoptosis. There is a dearth of research on the relationship between extreme temperatures and diabetes, and further studies are needed to characterize the effects of thermal stress in detail.

Of note, cold weather can be just as bad as heat for some diabetes outcomes. Prior studies demonstrate poorer glucose control in patients with type 2 diabetes in winter [40]. Other

confounding factors may be changes in physical activity, eating habits, fluid consumption, the ability to seek medical care, and other psychosocial stressors associated with colder weather.

Drought

As a part of Sub-Saharan Africa, Senegal is highly vulnerable to global climate change. Senegal is predominately an arid desert scrubland, which means that months can pass without rainfall [43]. In recent years droughts have become common, with the most severe on record occurring between June and August 2010. During this time, extremely high temperatures combined with drought caused famine and illness across the Sahel, the vast semi-arid region separating the Sahara Desert in the north from the southern tropical savannas. These devastating weather patterns have been worsened by climate change; for the inhabitants of the Sahel, their agricultural livelihoods have become increasingly precarious due to the desertification [43]. Land once thriving with life and fertile soils are turning to dust. Desertification and land degradation are the primary barriers to agricultural productivity in Senegal, which has caused poor food security due to inadequate availability of locally grown healthy food [44].

The limited agricultural opportunities have been linked with increased migration to urban areas. Rising sea levels and land degradation may prompt the population of Senegal to migrate to more temperate or urban areas [45,46]. Displacement and the burden of adaptation to a new way of life may prompt a stress response, the consequence of which includes chronic low-grade inflammation, an important factor in developing type 2 diabetes [47,48]. Individuals feeling stressed release stress hormones such as cortisol, which is released from the adrenal glands; glucagon, which is released from the pancreas; and adrenaline, which is released from the adrenal gland medulla [49,50]. These hormones all help raise blood sugar levels to provide an energy boost in support of a “fight or flight” response [51]. Cortisol raises blood sugar by releasing stored glucose, and when glucagon and adrenaline (epinephrine) levels rise, more glucose is released from the liver (Figure 2). As a result, more glucose is available in the bloodstream, which causes body tissues (muscle and fat) to be less sensitive to insulin. However, the impact of cumulative exposures to drought on diabetes risk is little known and further investigation is warranted.

Air Pollution

Fossil fuel emissions are likely the main driver of climate change in Africa [52]. Energy generated by fossil fuels (such as coal, nuclear, and gas) contributes to the effects of climate change by polluting air, water, and soil. Air pollution exposure occurs mainly through the respiratory tract and ambient or outdoor air pollutants are a complex mixture of pollutants, including particulate matter of various sizes, chemicals, and gaseous compounds. Their effects on human health depend on their dispersion, reactivity, and toxicity.

Exposure to pollutants leads to inflammation, which is closely linked to the pathogenesis of type 2 diabetes and chronic inflammation is one of the main causes of insulin resistance [30]. Several meta-analyses have found associations between chemical pollutants (such as persistent organic pollutants, pesticides, and heavy metals) and an increased risk of type 2 diabetes [53,54]. Recent studies also implicate inflammation in the hypothalmus for disrupting signals that modulate appetite and satiety [55].

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The impact of pollution on metabolic disorders specifically has garnered great interest recently as air pollution is considered an important risk factor for T2DM development [56]. Potential pathways impacted by pollution that abet T2DM development include insulin resistance, beta cell dysfunction, neurohormonal dysfunction, impaired mitochondrial function and oxidative stress [55,57,58]. Individuals exposed to pollutants can also demonstrate impacted adipogenesis, a risk factor for T2DM [59,60]. Metals can also influence glucose regulation by disrupting pancreatic β-cells, causing hyperglycemia and impaired insulin signaling. Pollutants have also been implicated in epigenetic modifications to key signatling pathways regulating coagulation, inflammation, and endothelial function [61,62]

The air quality in Dakar is considered unhealthy and the city is confronted with particulate pollution with levels far exceeding the thresholds set by WHO for much of the year [33]. Generally, the air quality at Dakar starts deteriorating in late October and continues to decline through the dry season. Every December to April, dust from the Sahara Desert moves to Dakar. As a result, citizens in Dakar are overwhelmed by severe dust storms and poor outdoor air quality [63] (Figure 1). In addition, the infamous Mbeubeuss dumpsite is located just outside of the city. Trash burning at the dumpsite is a major contributor to air pollution in Dakar. Little is known about the air quality of other places in Senegal.

There is also a dearth of information around the kinds of pollutants affecting both urban and rural areas of Senegal. There are reports by international organizations detailing that air pollutants could include ground-level ozone, particle pollution (also known as particulate matter, including PM2.5 and PM10), carbon monoxide, sulfur dioxide, and nitrogen dioxide [64]. In India, researchers found that one month of exposure to PM2.5 led to elevated levels of blood sugar; prolonged exposure of one year or more led to an increased risk of diabetes [65]. Further studies on the link between pollutants and T2DM could enable the implementation of targeted prevention strategies and discovery of novel treatments.

LINKS BETWEEN POLLUTION, GUT MICROBIOME AND DIABETES

Air pollution has been shown to impact the composition and diversity of the gut microbiota [66,67]. The gut microbiome is known to influence numerous physiological processes related to the development of disease and specific gut microbial profiles have been observed in patients with obesity and type 2 diabetes. Recent studies have shown the association between ozone exposure, lower gut microbial diversity, and higher Bacteroides caecimuris [68]. Exposure to pollutants may also modify gut microbial function, including the production of gut bacterial-derived metabolites that have been implicated in obesity and T2DM [69]. The gut microbiota also play a crucial role in the metabolism of environmental toxins.

Recent studies demonstrate the role of gut microbiota in mediating obesity and diabetes mellitus [19,70]. *Lactobacillus* is positively correlated with fasting blood glucose and glycosylated hemoglobin (HbA1c), while *Clostridium* is negatively associated with HbA1c, insulin, and plasma triglyceride [71]. Studies show that the levels of class *Clostridia* were reduced in diabetic subjects when compared to controls [72]. Conversely, increases in class *Betaproteobacteria* and genus *Lactobacillus* that correlated with increased plasma glucose levels were observed in diabetic patients [72]. Disruptions to the gut microbiota have been linked to the emergence of obesity, metabolic syndrome, and the onset of type 2 diabetes through decreased glucose tolerance and insulin resistance (Figure 2). It has been shown that

intestinal dysbiosis was consistently observed in diabetic individuals, contributing to reduced insulin sensitivity and poor glycemic control [73]. Microbial dysbiosis can also compromise the integrity of the intestinal barrier, leading to increased intestinal permeability. Leakage of intestinal microbiota or their metabolites can cause a cascade of immune responses causing low-grade chronic inflammation, as is seen in diabetes [74,75].

There are currently no longitudinal studies that have thoroughly investigated the relationship between air pollution, the gut microbiome, and the subsequent implications for type 2 diabetes risk over time. To better understand the mechanisms underlying this link, future studies should focus on whole genome sequencing of the gut microbiota and fecal metabolomics to better understand impacts to the function and composition of the gut microbiome.

ENVIRONMENTAL RISK FACTORS FOR TYPE 2 DIABETES IN SENEGAL

Rural Areas

Given the physiology of sub-Saharan Africans (low BMI) and their diets (relatively low fat-based food especially in rural areas), they should be less prone to diabetes. However, industrial farming practices and the paucity of healthy food options are shifting the paradigm.

Rural areas are facing challenges such as land grabbing for industrial farming, which often occurs under the guise of development and philanthropy by foreign interests. These farming practices destroy vast areas of pristine environment, exacerbating the effects of climate change. An estimated 25% of global greenhouse gas emissions are caused by this senseless destruction of the environment [76]. Local farmers are also convinced to adopt industrial-scale farming techniques, which deploy chemical fertilizers and pesticides on monocrops, to protect crops and increase productivity for export [77]. Unfortunately, monocrops are less resistant to severe weather events thus perpetuating the cycle of food insecurity and climate change in Africa.

Poverty is another important factor linked to diabetes and studies demonstrate the correlation between income and type 2 diabetes [78,79]. A meta-analysis reviewed five different studies to reveal that individuals with the lowest income had a 40% higher risk of developing type 2 diabetes when compared to those at the highest income level [80]. Additionally, income can impact access to healthy, whole, and locally sourced foods and lower-income individuals are more prone to chronic stress, which again can impact biomolecular processes that abet the development of type 2 diabetes. Of note, the poverty seen in Senegalese populations could also be associated with inequality of diabetes care, as observed in northeast Asian populations [79]. Further studies can help uncover the mechanisms underlying sustained low income and the risk of type 2 diabetes development.

Urban Areas

Diabetes, once limited primarily to affluent populations in Senegal, is now becoming more widespread across the general population, following trends observed globally [81]. Urbanization of cities like Dakar has resulted in lifestyle changes and the adoption of behaviors that promote diabetes. For example, owning a car and living in apartment blocks may promote a more sedentary lifestyle, since walking far distances is no longer unnecessary. Those who relocate to urban areas often leave behind an active lifestyle centered on farming and access to non-processed locally grown foods. Moreover, marked disparities have been reported between urban and rural regions where lifestyle habits and access to care are different [37,82].

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Furthermore, several international food corporations have recently opened locations in Senegal, offering access to processed foods. Local grocery chains have also started to make imported ultraprocessed foods available due to increasing demand. Studies indicate that individuals living in urban areas were over five times more likely to have diabetes than their rural counterparts [83].

Additionally, perceptions of body image also differ in urban areas, where weight gain, particularly after marriage, is viewed as a sign of prosperity, especially among women, who experience higher rates of diabetes and obesity in Senegal [84]. The disparity in type 2 diabetes between genders could be attributed in part to the tendency for women to be less physically active, especially when they take on the traditional role of homemakers.

Urbanization and adiposity are modifiable risk factors for diabetes. Studies demonstrate the independent association of higher adiposity with diabetes in sub-Saharan Africa [85–87]. Urbanization paired with climate change present the perfect storm for developing metabolic diseases such as diabetes. Education and other targeted public health interventions and campaigns can go a long way in addressing these modifiable risk factors (Figure 3). One of the authors (AH) observed younger adults (under 40) engaging in physical activities, such as exercise, at a far greater rate than older adults in Dakar. Promoting these healthy habits can go a long way in mitigating the rapid increase of type 2 diabetes in this region.

CAN ULTRA-PROCESSED FOODS CAUSE DIABETES?

Food can be categorized as processed any time after it is changed from its natural state. This can take several forms, and even simple tasks such as cutting or washing produce will result in it being categorized as processed. There are numerous benefits and reasons for food processing such as adding preservatives to extend shelf life, fortifying with nutrients to add beneficial vitamins/minerals, and pasteurizing to eliminate pathogens. Therefore, processed foods are not inherently unhealthy or bad. Issues arise when processing practices involve adding excess sugar, fat (including harmful trans fats), sodium, and artificial colors and flavors. These ultra-processed foods (UPF) also tend to be stripped of beneficial nutrients such as fiber, vitamins, and minerals present in whole foods and have ingredients such as high-fructose corn syrup that decrease manufacturing costs [88,89].

A large observational study observed the consumption of UPF with an increased risk of developing diabetes [90] (Figure 2). Another recent study found that the consumption of UPF increased the risk of type 2 diabetes in a dose-response relationship [91]. The excess sugar in UPF can directly impact insulin resistance and indirectly through weight gain to cause obesity, diabetes, and heart disease. Fructose and sucrose, the sugars most commonly used in UPFs, may also not be easily absorbed and metabolized by the liver, leading to increased lipid accumulation in the liver [92]. Fructose may also increase inflammatory responses, another risk factor for diabetes [93]. Furthermore, UPFs have been shown to elicit a higher glycemic response compared to less processed or minimally processed foods [94]. In addition to sugar directly impacting the onset of type 2 diabetes, studies show that other facets of food processing, such as artificial flavors and preservatives are linked to the onset of type 2 diabetes [89]. Finally, studies show that foods high in fat and sugar content may impact behavior through gut-brain communication and encourage increased consumption of such foods [95,96]. Overall,

there is a clear need for further longitudinal studies to confirm these findings in different populations.

Avoiding processed foods in favor of whole foods, including lots of vegetables, fruits, legumes, and whole grains can go a long way to protect against diabetes [97]. Current advice for managing type 2 diabetes mostly focuses on eating foods high in fiber, healthy fats, and low in sugar. However, a new study suggests that people with type 2 diabetes should focus on the fiber, fat, and sugar contents of their food in conjunction with reducing or eliminating UPFs from their diet altogether [98]. Dietary fiber lowers postprandial hyperglycemia and increases satiety by delaying digestion and absorption of carbohydrates and improving blood lipids, body mass, and inflammation, and is therefore recommended for diabetes management [99]. Interestingly, some UPFs with high fiber content may reduce the risk of diabetes [100]. Soluble dietary fiber may be metabolized by gut microbes, which could increase peripheral insulin sensitivity through the short-chain fatty acids generated through this process[101,102]. Short chain fatty acids may regulate glucose homeostasis by decreasing production, increasing uptake and regulating insulin secretion [103]**.** On the other hand, ultra-processed foods (UPF) also affect the composition and diversity of the gut microbiome [104,105] (Figure 2).

STRATEGIES TO TACKLE DIABETES IN SENEGAL

To mitigate the effects of climate change in Senegal and the world, it is critically important to limit global warming to 1.5°C [106]. This can be achieved by regulating the fossil fuel industry and seeking alternative energy sources needed to develop in many low-income countries. However, it is important to note that alternative fuel options could be more expensive and pose an economic burden on developing nations. Further research is needed to find alternative non-polluting energy sources that are well-adapted to each geographic region. The risks greatly outweigh the benefits as air pollutants affect the lungs, heart, brain and other organs, which ultimately manifest in disease [107]. Recently air pollution has been shown to disrupt the functioning of various immune cells [108].

While genetic susceptibility is a critical factor in type 2 diabetes development and severity, non-genetic aspects such as diet, gut microbiota, and the environment clearly also play a significant role. The field of epigenetics investigates how endogenous and exogenous factors impact the human phenotype without altering the DNA sequence but instead by modifying gene transcription. In these instances, better investigation of epigenetic mechanisms and their interplay with exogenous factors may lead to a new area of exploration in basic and clinical research for type 2 diabetes (Haque & Pant, in preparation).

In addition to targeted therapies and treatment, it is important to strengthen awareness of diabetes in Senegal; only 28% of diabetic people in Senegal are aware that they have type 2 diabetes [109] (Figure 3). It is necessary to raise awareness about the symptoms of diabetes (frequent urination, feelings of thirst, constant hunger, weight loss, impaired vision, and fatigue) to allow for early diagnosis and prevent serious complications. Knowledge about diabetes could encourage people to adopt preventive habits [110,111] (Figure 3). The aim will be to deliver essential high-impact interventions using the primary health care approach to strengthen early detection and prompt treatment. Many patients are fearful after diagnosis about the expenses of medication, the cost of recommended dietary changes, and becoming dependent on others to manage the disease. Therefore, public health campaigns should be

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tailored to address the specific concerns of population segments in urban and rural areas [112,113] (Figure 3).

Robust epidemiological surveillance of diabetes through community screening is required to truly understand the extent of diabetes in Senegal. A recent study shows diabetes is becoming a pressing public health concern, even in rural areas of Senegal. While the country faces the double burden of communicable diseases (such as malaria, HIV, and tuberculosis) and non-communicable diseases (such as diabetes) [114], the lack of data from sub-Saharan Africa on diabetes considerably limits the development of potential preventative strategies. The available data is often limited to more urban settings, demonstrating the need for accurate real-time data to tailor and deploy public health measures effectively. In Senegal, the prevalence of diabetes in the population was determined at a national level through the STEPS survey with hopes that the results could inform a national prevention strategy. In Senegal, the 2015 STEPS survey found a national prevalence rate of 2.1% [115]. In 2016, the proportional mortality rate for diabetes in the general population was 3% [116,117]. The HbA1c blood test is relatively simple to perform and it is advised to test average blood sugar levels every two to three months. Redirecting funding to support surveillance efforts can inform robust, effective, and culturally competent communications and public health campaigns (Figure 3).

Despite the country's commitment to the fight against non-communicable diseases, the management of diabetes presents many challenges. In fact, according to the WHO, the number of global diabetes cases in 2030 will reach an average of 643 million [118]. In 2021, 81% of adults with diabetes lived in low-income countries [81]. About three in four people live in low and middle-income countries, where access to healthcare services can be limited [119]. Limited healthcare infrastructure, including a shortage of healthcare professionals and diagnostic equipment, can impede the early diagnosis of diabetes (Figure 3). Again, policy interventions can allocate funding and resources to support diabetes management and develop a robust and skilled workforce.

Senegal is the first country in French-speaking Africa to implement the global BeHealthy BeMobile program to improve diabetes management [120]. The project is dubbed the mDiabetes project, and it leverages mobile phones to disseminate simple diabetes prevention messages directly to individuals. In 2014, this platform sent millions of prevention messages regarding the Ebola outbreak and during the COVID-19 pandemic. This program has been evaluated and shown to improve beneficiaries' glycemic control.

In order to combat a multi-factorial disease, a multidisciplinary approach will likely be the most effective. An integrated strategy that involves education and communication, functional medicine, and policy reform will be critical in promoting early identification and intervention to improve outcomes and manage the rise of type 2 diabetes in Senegal (Figure 3). Education paired with a strong communications campaign can influence the knowledge, attitudes, and practices of patients and providers alike. Educational campaigns should clearly communicate the benefits of screening and the adoption of healthy lifestyle choices. Functional medicine and training promote a holistic view of diabetes, where medical and family history, the environment, and other socioeconomic risk factors are taken into consideration when prescribing interventions. Lastly, policy reform can have immediate and long-term impacts on diabetes management. Policies that codify educational requirements for clinicians and bolster

public health campaigns through funding and resource allocation can be developed and implemented relatively quickly. In the long term, policies around incentives to build up a workforce of skilled personnel or the control of environmental contributors (pollution, climate change, land degradation etc.) should be considered (Figure 3). However, it is important to note that developing countries, including Senegal, face challenges in creating and maintaining clean-air policies. Again, we must be cognizant of the fact that these policies may place an undue financial burden on developing nations.

CONCLUSION

Environmental factors in conjunction with unhealthy lifestyle choices, are fueling the increase of diabetes in Senegal. Changes in lifestyle associated with urbanization, which involves increased processed food consumption and reduced exercise in addition to gut microbiota perturbation contribute more to augmentation of diabetic diseases. There are still many unknowns regarding the mechanisms underlying the development of diabetes, as multiple factors are involved in its pathogenesis. Evaluation of associated variables including exposure to pollution, lifestyle choices, demographics, genetics, socioeconomic and clinical factors, as well as differences in treatment, can accelerate the identification of effective and targeted intervention strategies. Sub-Saharan countries must balance the impacts of climate change with economic development, which requires increased adaptive capacity and resilience across all sectors. As the progression of diabetes is still in the initial stages in Senegal, this presents an opportunity to identify new and effective therapeutics and prevention strategies, which can be leveraged across sub-Saharan Africa to mitigate the rapid increase of diabetes in Senegal and beyond.

Figure Legends

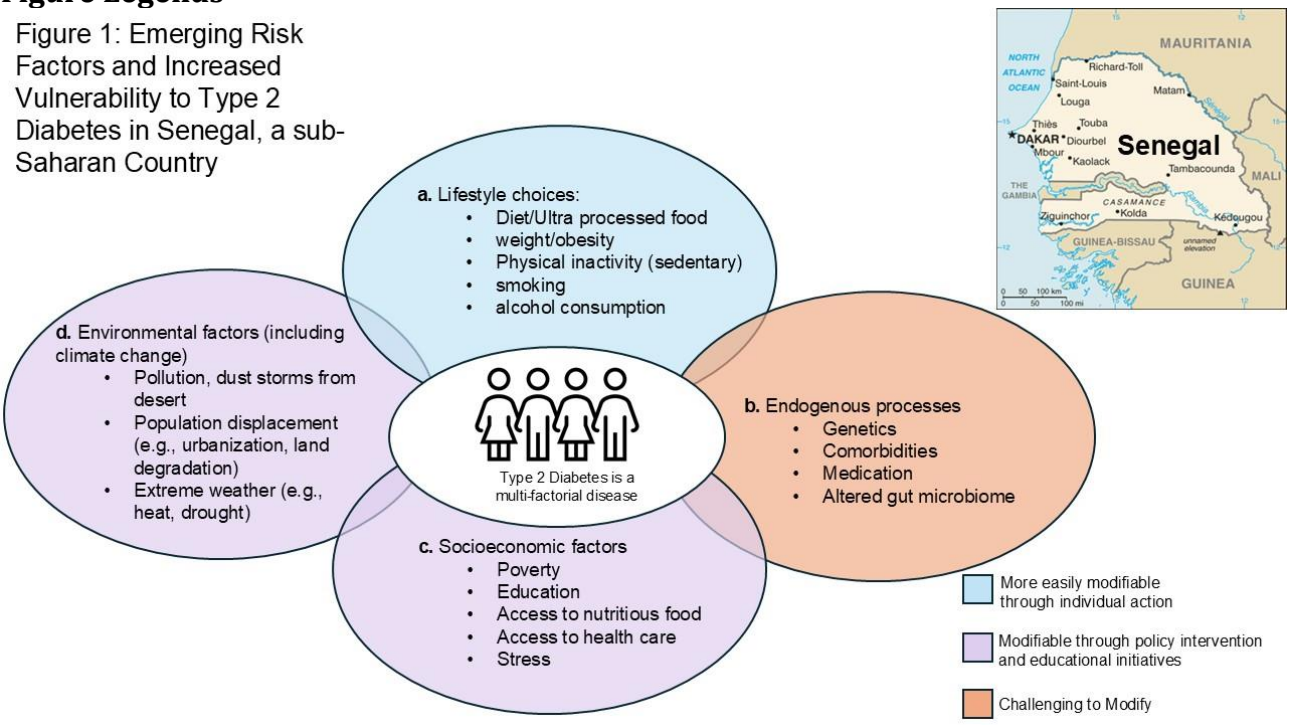

Fig 1: Emerging Risk Factors and Increased Vulnerability to Type 2 Diabetes in Senegal, a sub-Saharan Country.

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This figure highlights that diabetes is a multi-factorial disease; (a) lifestyle choices, (b) endogenous processes, (c) socioeconomic factors, and (d) environmental factors (including climate change) can all promote diabetes. Many of these risk factors are emerging in Senegal and they could be linked to the increased incidence of diabetes across the country. Lifestyle choices may be the easiest to modify through individual action; environmental and socioeconomic risk factors may be addressed through policy intervention and education campaigns; endogenous processes are likely the hardest to modify.

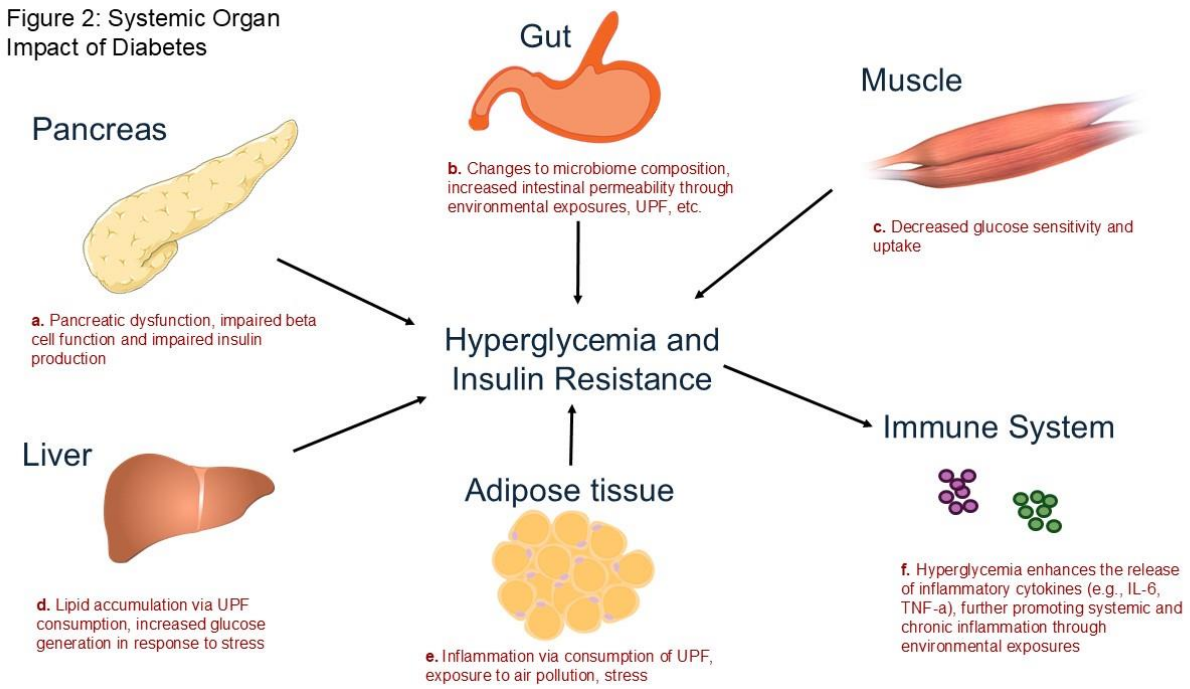

Fig 2: Systemic Organ Impact of Diabetes.

This figure illustrates the systemic organ dysfunctions that can abet hyperglycemia, insulin resistance, and eventually diabetes. This condition is a result of (a) pancreatic dysfunction associated with impaired beta cell function; (b) impacts on gut microbiome composition and permeability following environmental exposures or ultra-processed food (UPF) consumption; (c) diminished glucose sensitivity and uptake in the muscle; (d) lipid accumulation in the liver via UPF consumption and increased glucose generation in response to stress; (e) induction of inflammation through consumption of unhealthy foods (e.g. fatty or UPF), exposure to air pollution, or stress; (f) exposure to detrimental environmental factors enhances the release of inflammatory cytokines, further promoting systemic and chronic inflammation. Inflammation and organ dysfunction, as a result of exposure to endogenous and exogenous risk factors, are major contributors to the development of diabetes.

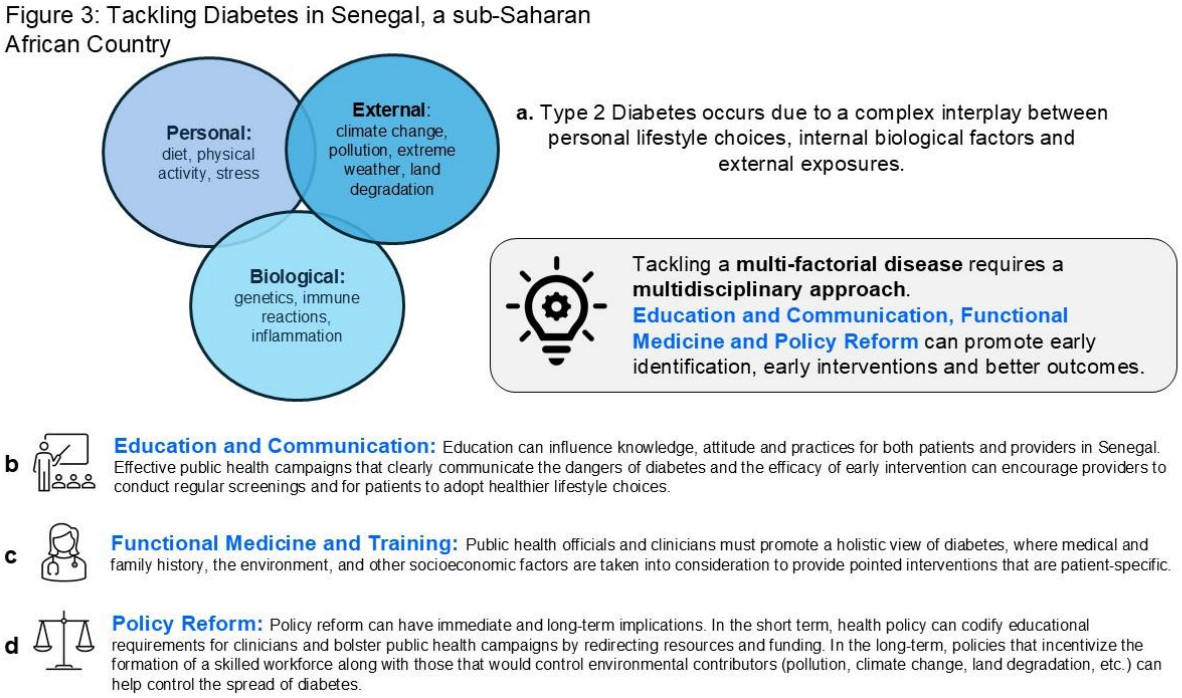

Fig 3: Tackling Diabetes in Senegal, a sub-Saharan African Country.

(a) Diabetes occurs due to a complex interplay between personal, external, and internal biological factors. Due to its complex and multi-factorial nature, diabetes may be most effectively tackled by utilizing a multidisciplinary approach; (b) effective, targeted, and culturally informed public health campaigns that clearly communicate and educate the community on diabetes; (c) functional medicine and training to provide efficacious screening, prevention and interventions which consider diabetes holistically and, (d) reforming health policies to allocate resources to support the formation of a skilled workforce along with policies that would control environmental contributors (pollution, climate change, land degradation, etc.) can help control the spread of diabetes. Developing an integrated strategy that addresses multiple risk factors of diabetes disease will go a long way toward controlling the spread of diabetes in Senegal.

Declarations

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Author Contributions

A.H. conceived the concept and design of the paper and wrote the original draft. A.B.P. participated in the revision and editing process and contributed to the preparation of the figures.

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